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NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 8-93

COMMERCIALLY AVAILABLE MARES REGULATORS

ENC(DV/SW) J. A. NOE

SEPTEMBER 1993

Navy Experimental Diving Unit

2

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

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)
Evaluations were conducted to determine which commercially available open-circuit SCUBA regulators were capable of meeting performance goal standards for Navy use. Bench testing of all candidate regulators was conducted to establish flow patterns and air delivery capacity. Unmanned testing using a breathing simulator at ventilation rates of 22.5, 40, 62.5, 75, and 90 L/min at test depths of 0 to 60 msw (0 to 198 fsw), in 10 msw (33 fsw) increments was conducted to determine work of breathing (WOB) values. Each candidate regulator model was subjected to five runs each and a mean of the WOB was established by using a one sample T-test with a significance established at $P<0.05$. This mean WOB value was then compared to the Performance Goal Standard of 1.37 Joules per Liter (J/L) at 60 msw (198 fsw). Testing was conducted in ambient temperature water, approximately 21°C (70°F), with supply pressures of 10.34 and 3.44 MPa (1500 and 500 psi). Manned testing was conducted in two phases to subjectively rate regulator performance as well as fit and function. Phase one consisted of dives in the Ocean Simulation Facility (OSF) to 58 msw (190 fsw) and phase two consisted of open sea dives not to exceed 40 msw (130 fsw). Human factors data were collected and analyzed and were used as part of the acceptance criteria. All testing conducted determined that the MR-12 VOLTREX was capable, and that the MR-12 BETA was not capable, of meeting the requirements for acceptance by the US Navy.

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GLOSSARY

ANU	Authorized for Navy Use List (NAVSEAINST 10560.2 series)
fsw	Feet of Seawater
J/L	Joules per liter, unit of measure for "Work of Breathing" normalized for tidal volume.
kPa	Kilopascals, newtons/meter^2
MPa	Megapascal
msw	Meters of Sea Water
NAVSEA	Naval Sea Systems Command
NEDU	Navy Experimental Diving Unit
OSF	Ocean Simulation Facility
psi	Pounds per Square Inch
RMV	Respiratory Minute Volume
SCFM	Standard Cubic Feet per Minute
SLM	Standard Liters per Minute
WOB	Work of Breathing, a computer derived estimate of total respiratory effort obtained when breathing a regulator with a mechanical breathing simulator.

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INTRODUCTION

The requirement for an open circuit SCUBA regulator with the ability to perform within the Performance Goal Standard[1] to a depth of 60 msw (198 fsw) has evolved from changes in diver mission profiles and concern for diver safety in the FLEET DIVER community.

To achieve this end, NEDU was tasked[2] to test and evaluate production models of commercially available open circuit SCUBA regulators to determine which ones meet the US Navy's demanding performance criteria.

MARES, HTM Sports, Rapallo, Italy, provided two models for evaluation. The MR-12 VOLTREX has a balanced diaphragm first stage with a Dynamic Flow Control system and a vortex assist second stage. The MR-12 BETA has a balanced diaphragm first stage with a Dynamic Flow Control system, fitted with an enhanced venturi action second stage.

UNMANNED EVALUATION

Unmanned evaluations of the two candidate regulator models measured Work of Breathing (WOB) levels and compared them to Performance Goal Standards[1], which represent ideal performance levels for open circuit SCUBA regulators. WOB levels are a computer derived estimate of total respiratory effort obtained when breathing a regulator with a mechanical breathing simulator, measured in joules per liter (J/L). WOB averages were derived from the mean of five runs per model (± 1 standard deviation).

For the purpose of this study, the target goal of 1.37 J/L at 40 msw (132 fsw) with a 62.5 RMV and first stage supply pressure of 10.34 MPa (1500 psi) was extended to include 50 and 60 msw (165 and 198 fsw).

Testing was also conducted at extended depths, at high ventilatory rates, and reduced first stage supply pressure to characterize the performance of the regulators beyond the current performance standards. These extended tests were not part of the acceptance criteria.

METHODS

A hierarchical series of standardized testing[3] was conducted on each candidate regulator. Dry bench testing was first conducted to determine if the candidate regulators meet the manufacturer's specifications for air delivery. Inhalation pressures were recorded at 141 SLM ± 1 SLM (5 SCFM) increments from 0 to 849 SLM (0 to 30 SCFM) of flow. A mean of the inhalation pressure (± 1 standard deviation) was derived from five test regulators per candidate model. Bench testing was terminated if cracking pressure varied from manufacturer's specifications by ± 0.13 kPa (0.50 inches of water).

A mechanical breathing simulator (Reimers Consultants, Falls Church, VA) provided sinusoidal breathing loops ranging from 40 to 90 RMV, thus emulating varied diver work rates. Supply pressure to the first stage was maintained at 10.34 MPa (1500 psi) for the downward excursion, then reduced to 3.44 MPa (500 psi) to simulate worst case, for the upward excursion. Work of Breathing loops were taken at 10 msw (33 fsw) increments in both conditions. Test depths ranged from 0 to 60 msw (0 to 198 fsw). Water temperature was maintained at ambient, approximately 21°C (70°F).

Testing at a specific RMV/depth parameter was terminated if inhalation or exhalation pressure exceeded 4 kPa, the working limits of the pressure transducers currently used in the Experimental Diving Facility. Additionally, if two regulators of one model exceeded 4 kPa within the Performance Goal Standard RMV/depth parameters, testing of that model was terminated.

Descriptive statistics were used to obtain the mean and standard deviation of the data. To determine acceptability of WOB values that were slightly higher than Performance Goal Standard, a one sample T-test with significance established at $P < 0.05$ was performed.

RESULTS

Dry bench testing of all candidate regulators revealed that the MR-12 VOLTREX delivered at least 849 SLM (30 SCFM) at an average inhalation pressure of 0.29 kPa (1.1 inches of water). The MR-12 BETA delivered a maximum of 742 SLM (26 ± 0.5 SCFM) at an extremely high inhalation pressure of 1.22 ± 0.06 kPa (4.7 ± 0.1 inches of water). Flow characteristics for the MR-12 VOLTREX are shown in Figure 1. Figure 2 shows the flow characteristics for the MR-12 BETA.

WOB values for the MR-12 VOLTREX at 10.34 MPa (1500 psi) as well as 3.44 MPa (500 psi) supply pressures are summarized in Table 1. WOB levels remained fairly constant at 40 RMV and increased slightly with each increase in test depth at 62.5 RMV, all within Performance Goal Standards. At 75 RMV, WOB levels were acceptable to 50 msw (165 fsw), and at 90 RMV, WOB values exceeded goal at 50 msw and were beyond termination criteria at 60 msw (198 fsw). At the lower supply pressure, WOB levels were well within Performance Goal Standard at 40 and 62.5 RMV. Acceptable performance was obtained to 50 msw (165 fsw) at 75 RMV and 30 msw (99 fsw) at 90 RMV.

Figure 3 shows MR-12 VOLTREX comparative WOB levels obtained with a 10.34 MPa (1500 psi) supply pressure. WOB levels were well within Performance

Goal Standard at 40 and 62.5 RMV for all test depths. At the extreme ventilatory rates of 75 and 90 RMV WOB levels exceeded goal at 60 and 50 msw (198 and 165 fsw) respectively.

Figure 4 shows comparative WOB levels of the MR-12 VOLTREX obtained with a 3.44 MPa (500 psi) supply pressure. WOB levels remained well within Performance Goal Standard throughout all test depths at 40, 62.5, and 75 RMV. Acceptable performance levels were maintained to 30 msw (99 fsw) at 90 RMV increased markedly between 30 and 40 msw (99 and 132 fsw) and were beyond termination criteria at the deeper depths.

Table 2 summarizes WOB values for the MR-12 BETA at 10.34 MPa (1500 psi) and 3.44 MPa (500 psi) supply pressures. At the higher supply pressure acceptable WOB levels were obtained at 62.5 RMV/40 msw (132 fsw). At the extended Performance Goal Standard of 62.5 RMV/50 and 60 msw (165 and 198 fsw), WOB levels increased beyond acceptable limits (1.62 and 1.78 J/L respectively). At the lower supply pressure, acceptable performance levels were maintained at 40 RMV for all test depths. At 62.5 RMV WOB levels increased markedly with each increase in test depth, beyond goal at 40 msw (132 fsw) and deeper. The higher ventilatory rates showed high WOB levels as well.

Figure 5 shows comparative WOB levels of the MR-12 BETA obtained with a 10.34 MPa (1500 psi) supply pressure. WOB levels at 40 RMV progressively increased with each increase in test depth, but remained with extended Performance Goal Standards. At 62.5 RMV the WOB levels increased markedly with each increase in test depth until levels went beyond acceptable limits at 50 and 60 msw (165 and 198 fsw). A clearly marked increase in WOB levels is evident in the extreme ventilatory rates of 75 and 90 RMV.

Figure 6 shows comparative WOB levels of the MR-12 BETA with a supply pressure of 3.44 MPa (500 psi). WOB levels at 40 RMV remained within Performance Goal Standards throughout all test depths. At 62.5 RMV, WOB levels remain within Performance Goal Standards to 30 msw (99 fsw), then went beyond acceptable limits at 40 msw (132 fsw). At the extreme ventilatory rates of 75 and 90 RMV, acceptable performance was obtained to depths of 20 and 30 msw.

MANNED EVALUATION

Manned data was collected per two NEDU Test Plans[3,4] where divers subjectively rated candidate regulator performance, as well as regulator fit and function during open sea dives to a maximum depth of 39.6 msw (130 fsw) as well as in the NEDU Ocean Simulation Facility (OSF) to a depth of 58 msw (190 fsw).

All diver subjects were military divers with between 2 to 24 years of SCUBA diving experience and are highly familiar with the operation and use of SCUBA equipment.

HUMAN FACTORS EVALUATION

Diver subjects used the Human Factors Questionnaire (Appendix A), to evaluate fit and function subjectively as well as work of breathing in candidate regulators.

All ratings are on a 1-6 scale, with 1 being "extremely poor" and 6 being "excellent."

A total of thirty-five divers completed questionnaires following each dive to evaluate the two candidate regulator models.

RESULTS

Ten diver subjects conducted open sea dives to evaluate the **VOLTREX**. All work of breathing parameters were rated as *adequate* or better by all divers. Figure 7 shows the overall inhalation and exhalation effort as uniformly *acceptable* or better. Of the fit and function parameters rated, two divers rated the mouthpiece as *not quite adequate*, and one rated it as *poor*. Range of motion was rated as *not quite adequate* by one diver, and one diver rated buoyancy of the regulator as *not quite adequate*. The overall comfort with using this regulator is shown in Figure 8, where one diver rated it as *unacceptable* while nine divers rated this parameter *acceptable* or better.

OSF dives conducted to evaluate the **VOLTREX** were completed by fourteen diver subjects. Of the work of breathing parameters rated, one diver rated head up exhalation as *poor*. One diver rated prone exhalation *poor*. One diver rated supine inhalation as *not quite adequate* while one diver rated it as *extremely poor*. Supine exhalation was rated as *extremely poor* by one diver. As shown in Figure 9, the overall inhalation and exhalation effort was rated as *acceptable* or better by all divers. Fit and function evaluations show one diver rating the mouthpiece as *extremely poor*, and one diver rated range of motion as *poor*. Figure 10 shows the overall comfort with using this regulator rated as *acceptable* or better by all fourteen divers.

BETA evaluations conducted in the OSF consisted of eleven diver subjects. 45° upright inhalation was rated as *poor* by one diver. Supine inhalation was rated as *not quite adequate* by three divers, as *poor* by two. Supine exhalation was rated as *poor* by one diver. Figure 11 shows the overall inhalation and exhalation effort rating, where all divers gave an overall rating of *acceptable* or better. Evaluations of fit and function rated the mouthpiece as *not quite adequate* by three divers. Figure 12 shows overall comfort with using this regulator rated *unacceptable* or worse by four divers, while seven divers gave an overall rating of *acceptable* or better to this regulator.

Because of the BETA's inability to meet the Performance Goal Standard, no open sea dives were conducted.

CONCLUSIONS/RECOMMENDATIONS

It is important to note that the establishment of *performance criteria* to 60 msw (198 fsw) is solely a Navy requirement and is not an endorsement by NEDU that casual/standard SCUBA dives be conducted to such depths with these regulators. Additionally, performance goals are not acceptance criteria for diving equipment approval and diving equipment that exceed these goals are not necessarily unsafe for diver use.

Work of Breathing results obtained from the VOLTREX clearly identify this as a superior performing regulator, capable of surpassing the extended Performance Goal Standard, even at reduced supply pressure. Results also clearly indicate that good performance can be expected from this regulator at the extreme ventilation rates to depths of 50 msw (165 fsw) at 75 RMV and 40 msw (132 fsw) at 90 RMV. Human Factors results provide compelling evidence of acceptability by Navy divers, with twenty-three of twenty-four diver subjects rating their overall comfort with using this regulator as *acceptable* or better.

Based on the results obtained during unmanned and manned evaluations of the MR-12 VOLTREX, recommend that this regulator be <u>approved</u> for use to a depth of 58 msw (190 fsw).

Work of Breathing results obtained from the BETA show that this regulator is not capable of meeting the demanding performance criteria of the US Navy. Human factors results also indicate a substantial number of diver subjects were not comfortable diving with this regulator.

Based on the results obtained during the unmanned and manned evaluations of the MR-12 BETA, this regulator is <u>not recommended</u> for approval or addition to the ANU List.

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1. J. R. Middleton and E. D. Thalmann, *Standardized NEDU Unmanned UBA Test Procedures and Performance Goals,* NEDU TR 3-81, Navy Experimental Diving Unit, July 1981.

2. NAVSEA Task 89-064, *Commercial Open Circuit SCUBA Regulator Test and Evaluation*, October 1989.

3. *Evaluation of Commercial Open Circuit SCUBA Regulators (Unmanned/Manned),* NEDU Test Plan 93-21 (Limited Distribution), Navy Experimental Diving Unit, May 1993.

4. *Evaluation of Commercial SCUBA Regulators OSF Bounce Dive Series to 190 FSW (Manned),* NEDU Test Plan 92-44 (Limited Distribution), Navy Experimental Diving Unit, November 1992.

TABLE 1

UNMANNED MARES MR-12 VOLTREX OPEN CIRCUIT SCUBA REGULATOR WORK OF BREATHING RESULTS EXPRESSED IN JOULES PER LITER (J/L)

10.34 MPa (1500 PSI) SUPPLY PRESSURE

DEPTH IN METERS	RESPIRATORY MINUTE VOLUME			
	40	62.5	75	90
0	0.66 ± 0.06	0.71 ± 0.08	0.74 ± 0.08	0.79 ± 0.09
10	0.74 ± 0.07	0.77 ± 0.12	0.82 ± 0.16	0.84 ± 0.16
20	0.73 ± 0.07	0.82 ± 0.14	0.88 ± 0.19	0.99 ± 0.25
30	0.79 ± 0.22	0.84 ± 0.18	0.94 ± 0.23	1.13 ± 0.29
40	0.74 ± 0.12	0.86 ± 0.16	1.01 ± 0.23	1.32 ± 0.33
50	0.76 ± 0.14	0.95 ± 0.22	1.18 ± 0.31	2.22 ± 0.59
60	0.77 ± 0.14	1.05 ± 0.25	1.52 ± 0.45	#

3.44 MPa (500 PSI) SUPPLY PRESSURE

DEPTH IN METERS	RESPIRATORY MINUTE VOLUME			
	40	62.5	75	90
0	0.81 ± 0.03	0.79 ± 0.08	0.80 ± 0.10	0.83 ± 0.11
10	0.77 ± 0.06	0.79 ± 0.09	0.82 ± 0.15	0.87 ± 0.17
20	0.72 ± 0.05	0.79 ± 0.08	0.89 ± 0.18	1.05 ± 0.26
30	0.73 ± 0.07	0.86 ± 0.17	0.97 ± 0.22	1.19 ± 0.23
40	0.76 ± 0.11	0.94 ± 0.17	1.11 ± 0.23	2.15 ± 0.39
50	0.79 ± 0.12	0.99 ± 0.25	1.38 ± 0.42	#
60	0.81 ± 0.17	1.22 ± 0.26	#	#

# Denotes WOB value beyond termination criteria

TABLE 2

UNMANNED MARES MR-12 BETA OPEN CIRCUIT SCUBA REGULATOR WORK OF BREATHING RESULTS EXPRESSED IN JOULES PER LITER (J/L)

10.34 MPa (1500 PSI) SUPPLY PRESSURE

DEPTH IN METERS	RESPIRATORY MINUTE VOLUME			
	40	62.5	75	90
0	0.61 ± 0.05	0.74 ± 0.05	0.81 ± 0.04	0.90 ± 0.04
10	0.78 ± 0.03	0.88 ± 0.05	0.98 ± 0.04	1.15 ± 0.06
20	0.89 ± 0.05	1.04 ± 0.05	1.17 ± 0.07	1.48 ± 0.14
30	0.94 ± 0.05	1.17 ± 0.12	1.49 ± 0.13	1.92 ± 0.14
40	0.99 ± 0.04	1.41 ± 0.09	1.82 ± 0.14	2.63 ± 0.30
50	1.04 ± 0.04	1.62 ± 0.13	2.22 ± 0.17	3.41 ± *
60	1.12 ± 0.06	1.78 ± 0.15	2.86 ± 0.35	#

3.44 MPa (500 PSI) SUPPLY PRESSURE

DEPTH IN METERS	RESPIRATORY MINUTE VOLUME			
	40	62.5	75	90
0	0.82 ± 0.10	0.85 ± 0.05	0.91 ± 0.07	1.00 ± 0.07
10	0.91 ± 0.04	0.96 ± 0.04	1.04 ± 0.05	1.20 ± 0.10
20	0.91 ± 0.05	1.08 ± 0.05	1.22 ± 0.10	1.55 ± 0.11
30	0.94 ± 0.05	1.25 ± 0.07	1.58 ± 0.14	2.13 ± 0.17
40	1.00 ± 0.05	1.45 ± 0.10	1.95 ± 0.14	2.80 ± 1.53
50	1.08 ± 0.07	1.75 ± 0.16	2.88 ± 0.36	2.38 ± *
60	1.17 ± 0.06	2.25 ± 0.24	#	#

* Denotes no standard deviation in the averaging

\# Denotes WOB value beyond termination criteria

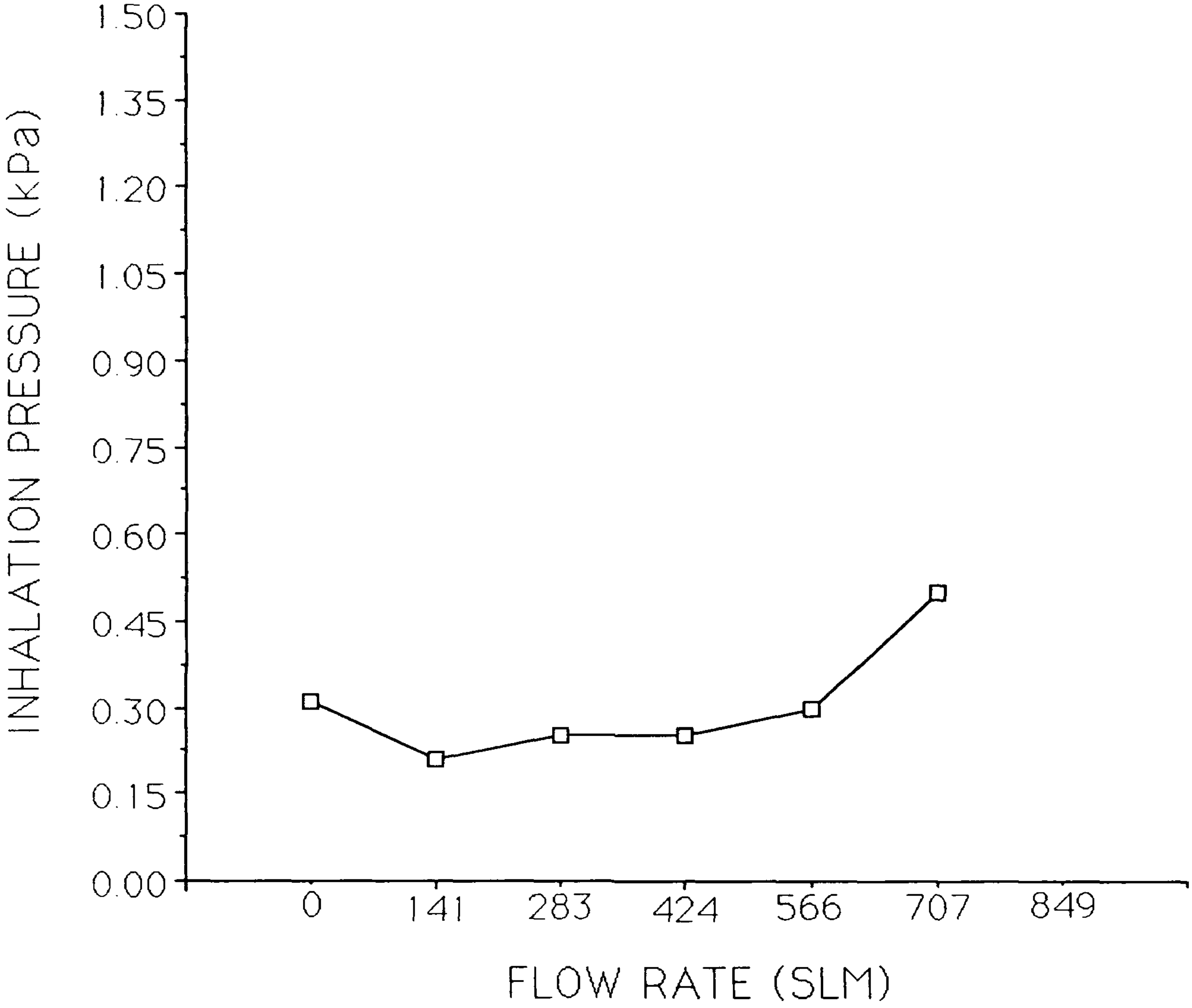

Figure 1. MR-12 VOLTREX Flow Characteristics

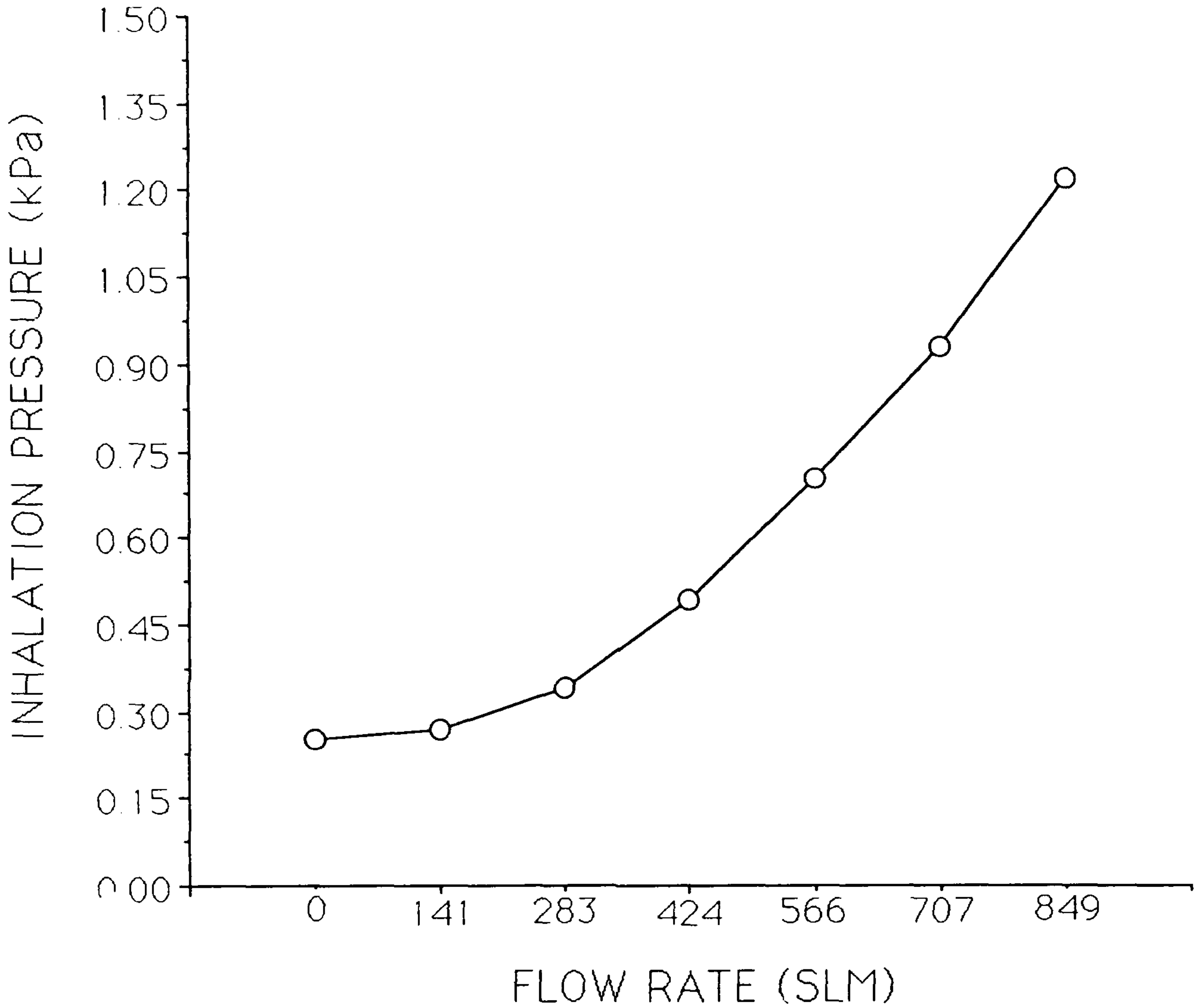

Figure 2. MR-12 BETA Flow Characteristics

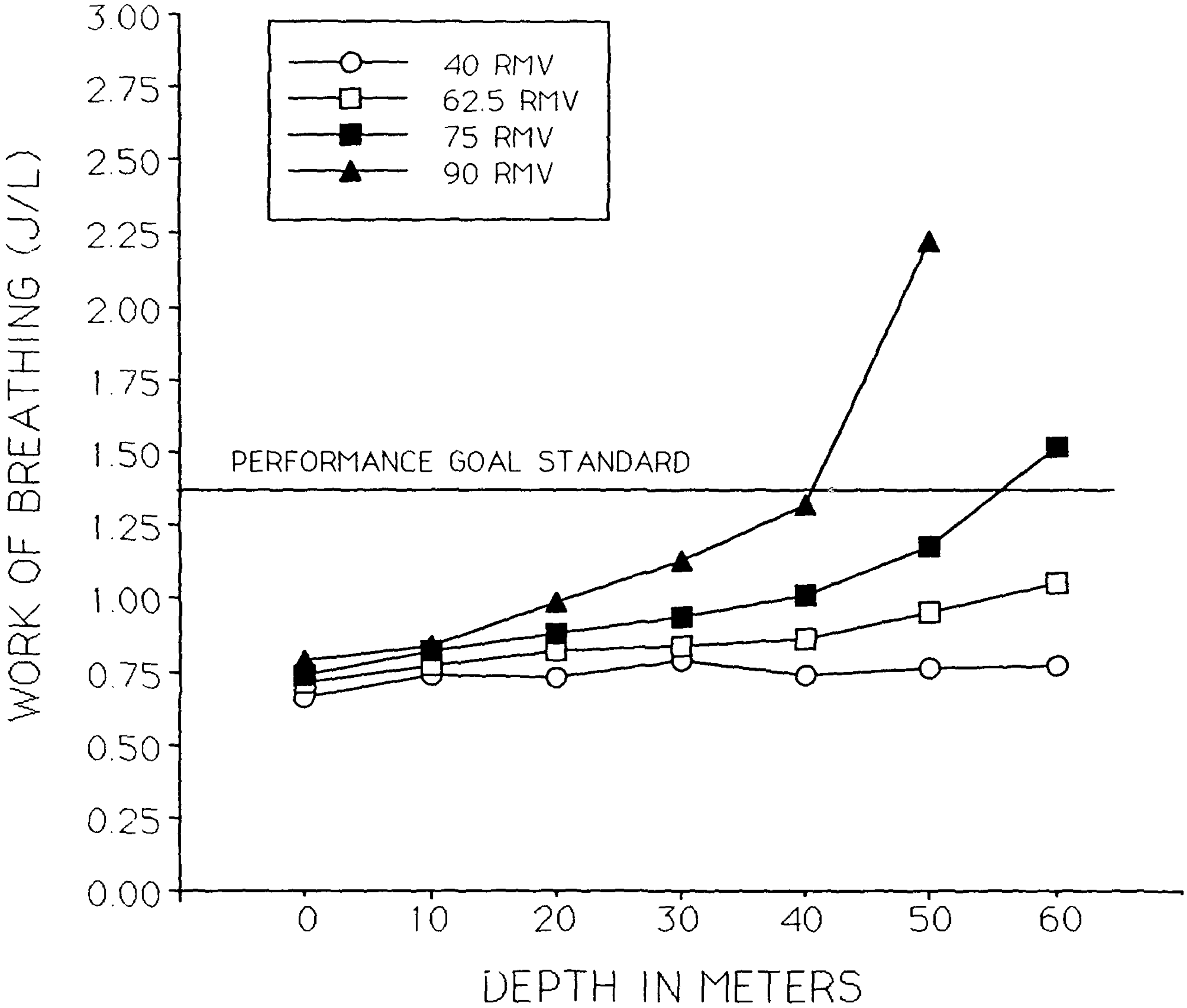

Figure 3. MR-12 VOLTREX, 10.34 MPa (1500 PSI) SUPPLY PRESSURE

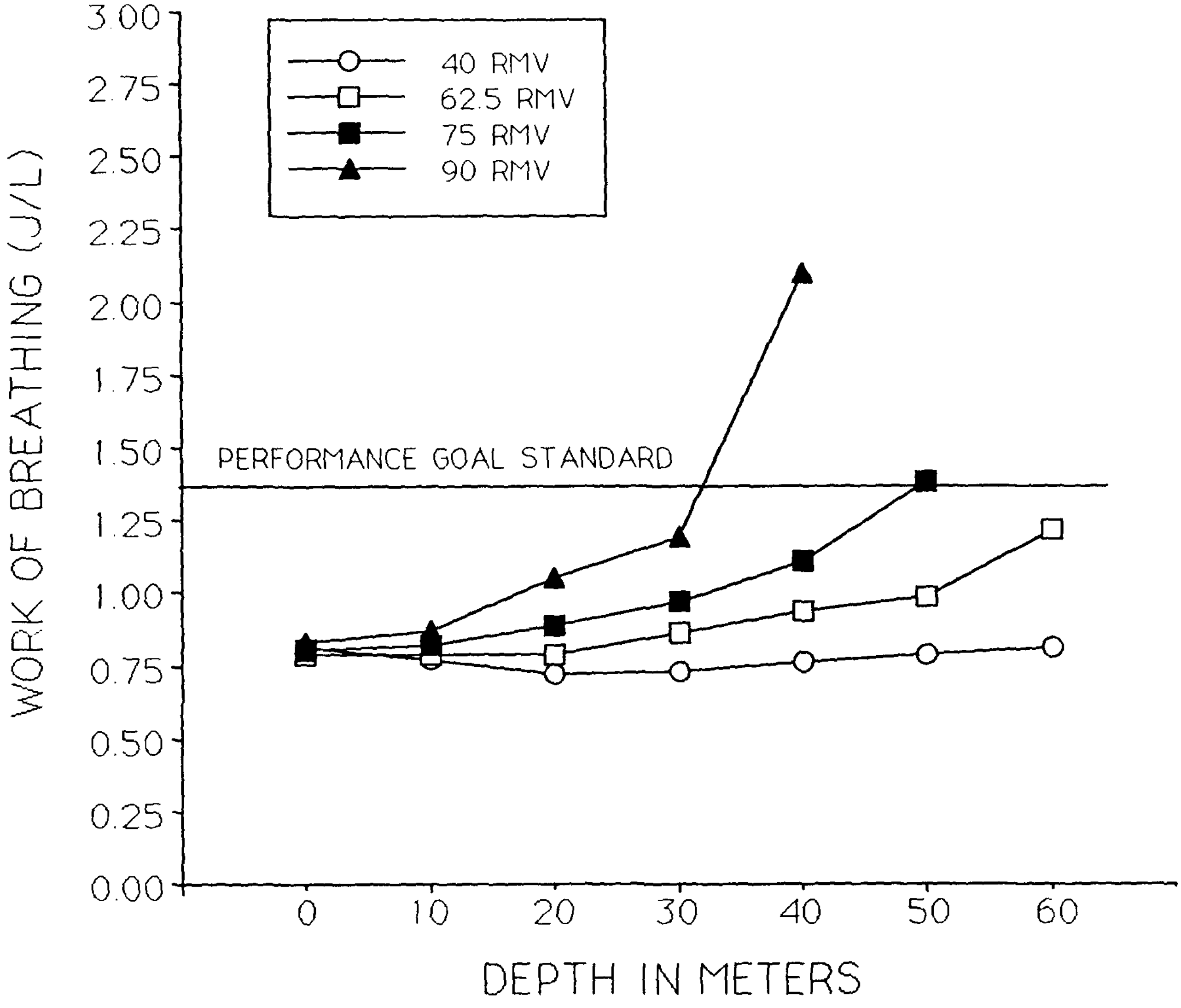

Figure 4. MR-12 VOLTREX, 3.44 MPa (500 PSI) Supply Pressure

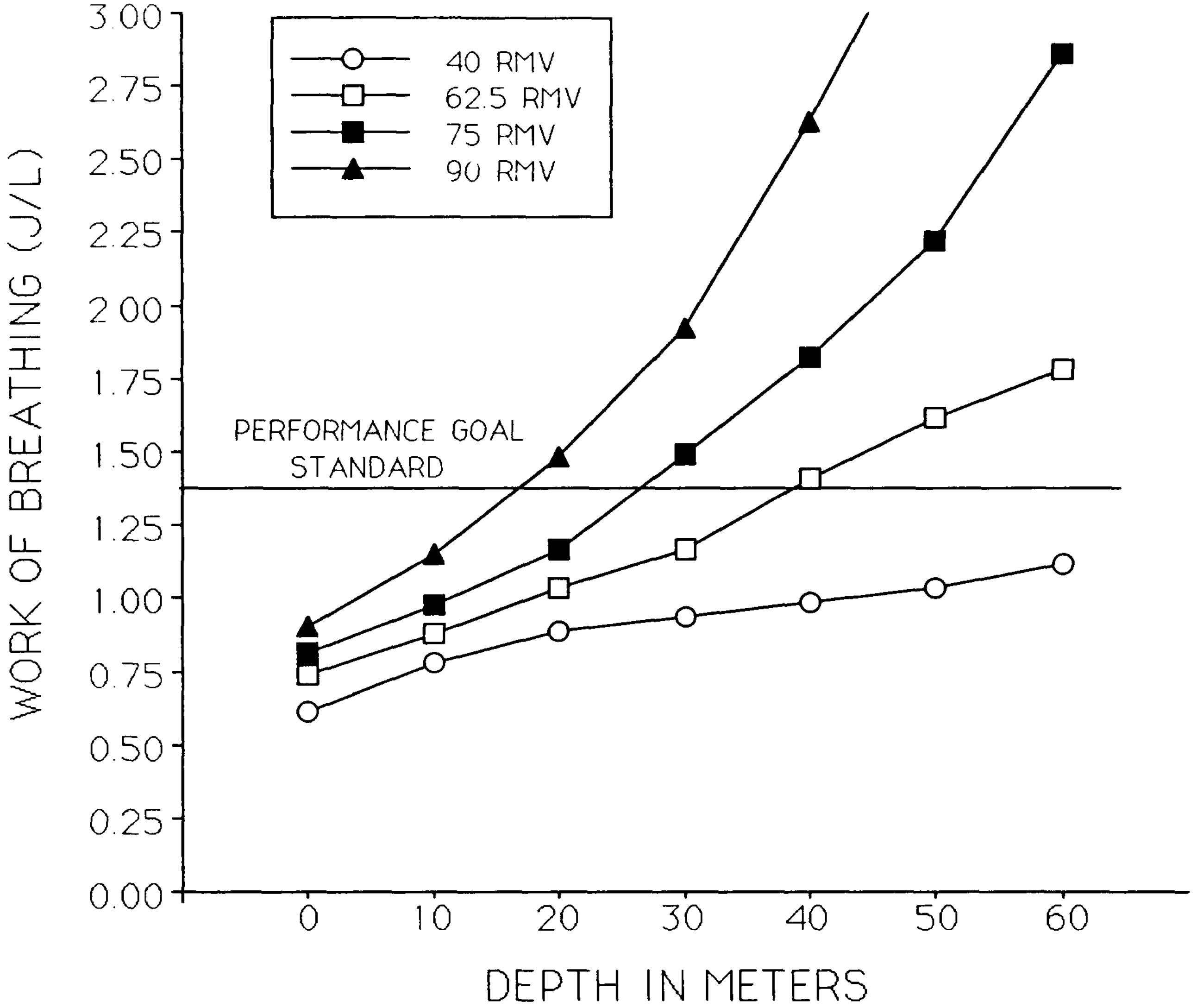

Figure 5. MR-12 BETA, 10.34 MPa (1500 PSI)
Supply Pressure

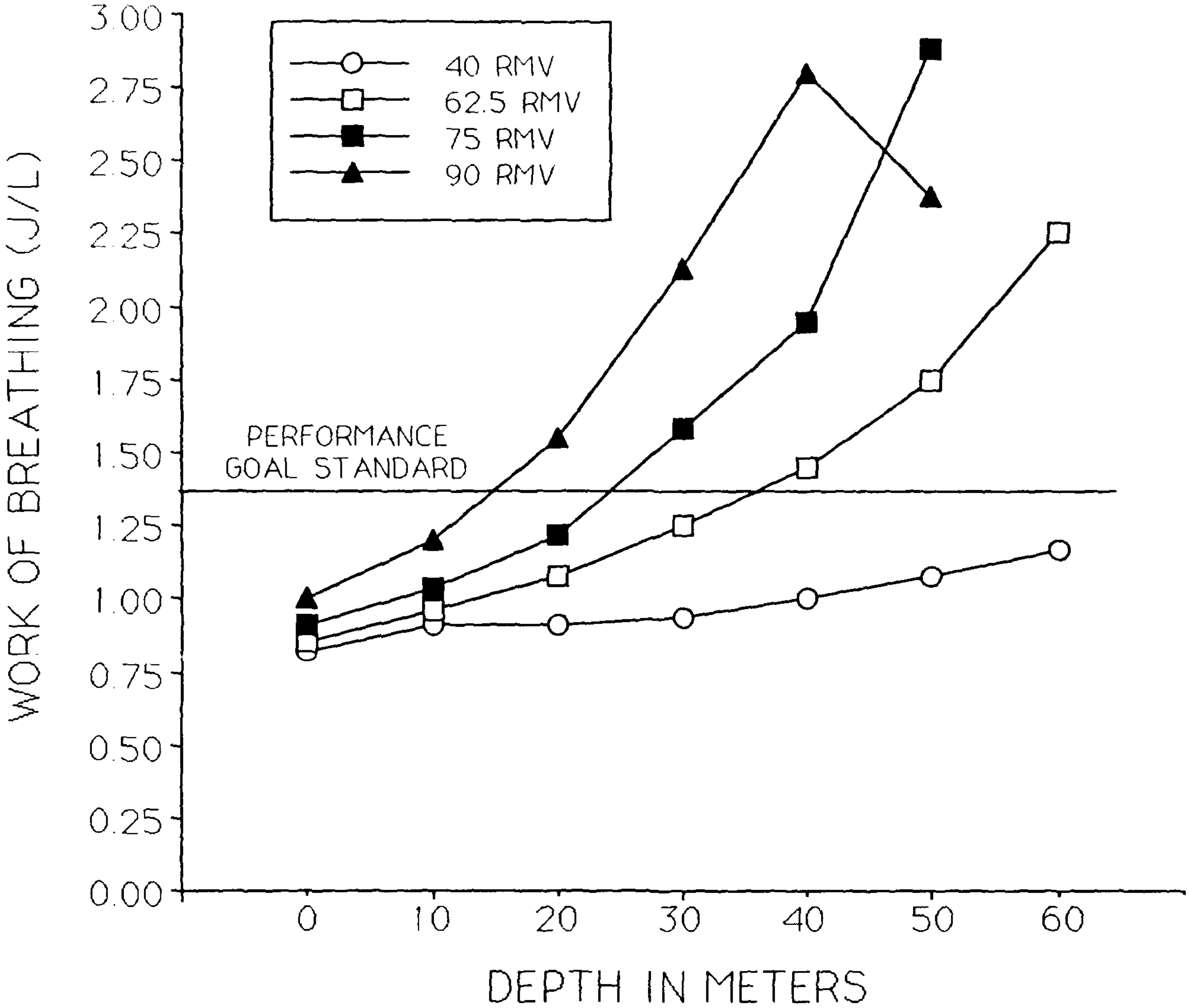

Figure 6. MR-12 BETA, 3.44 MPa (500 PSI) Supply Pressure

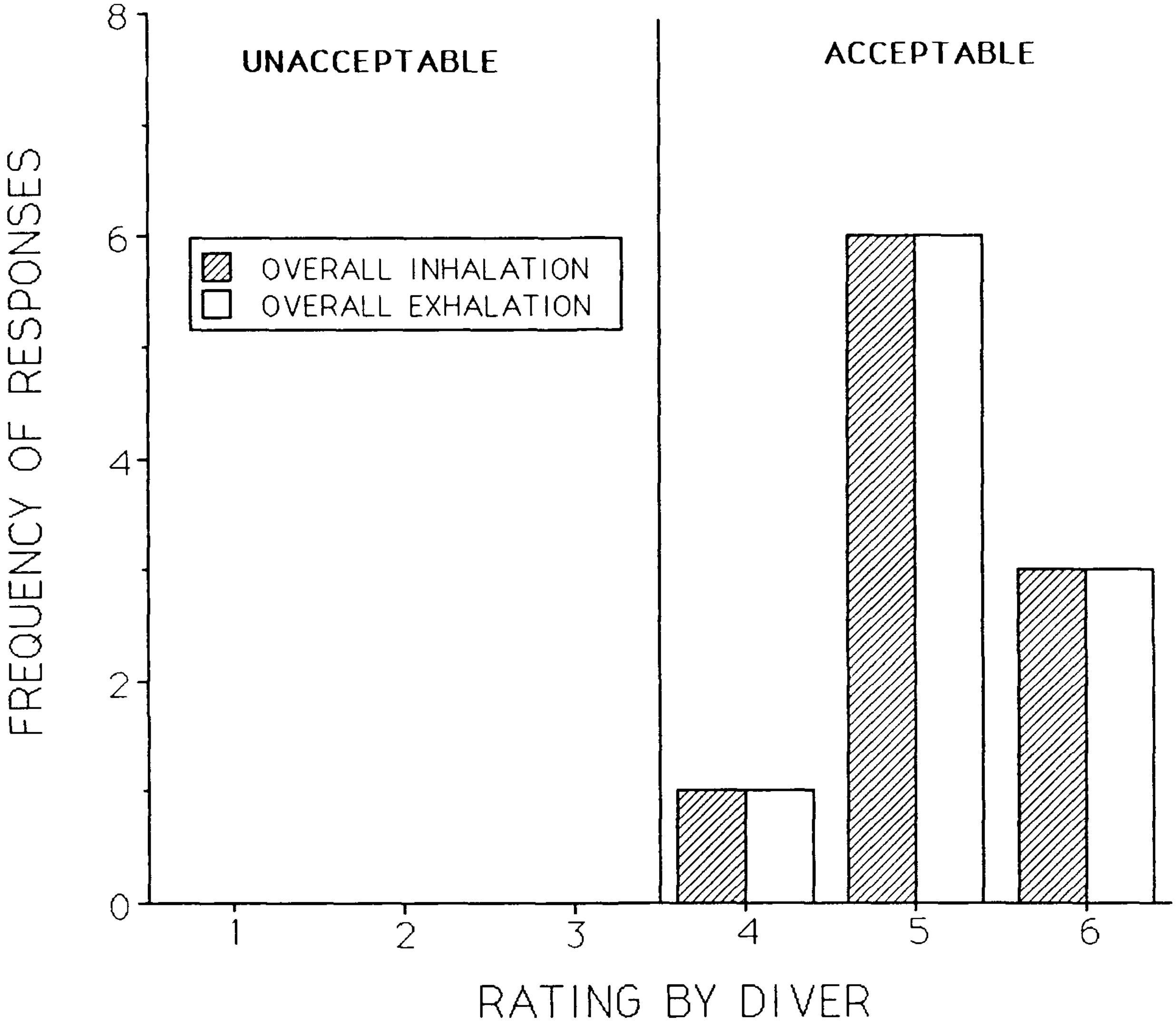

Figure 7. VOLTREX, Open Sea, Overall Inhalation/Exhalation

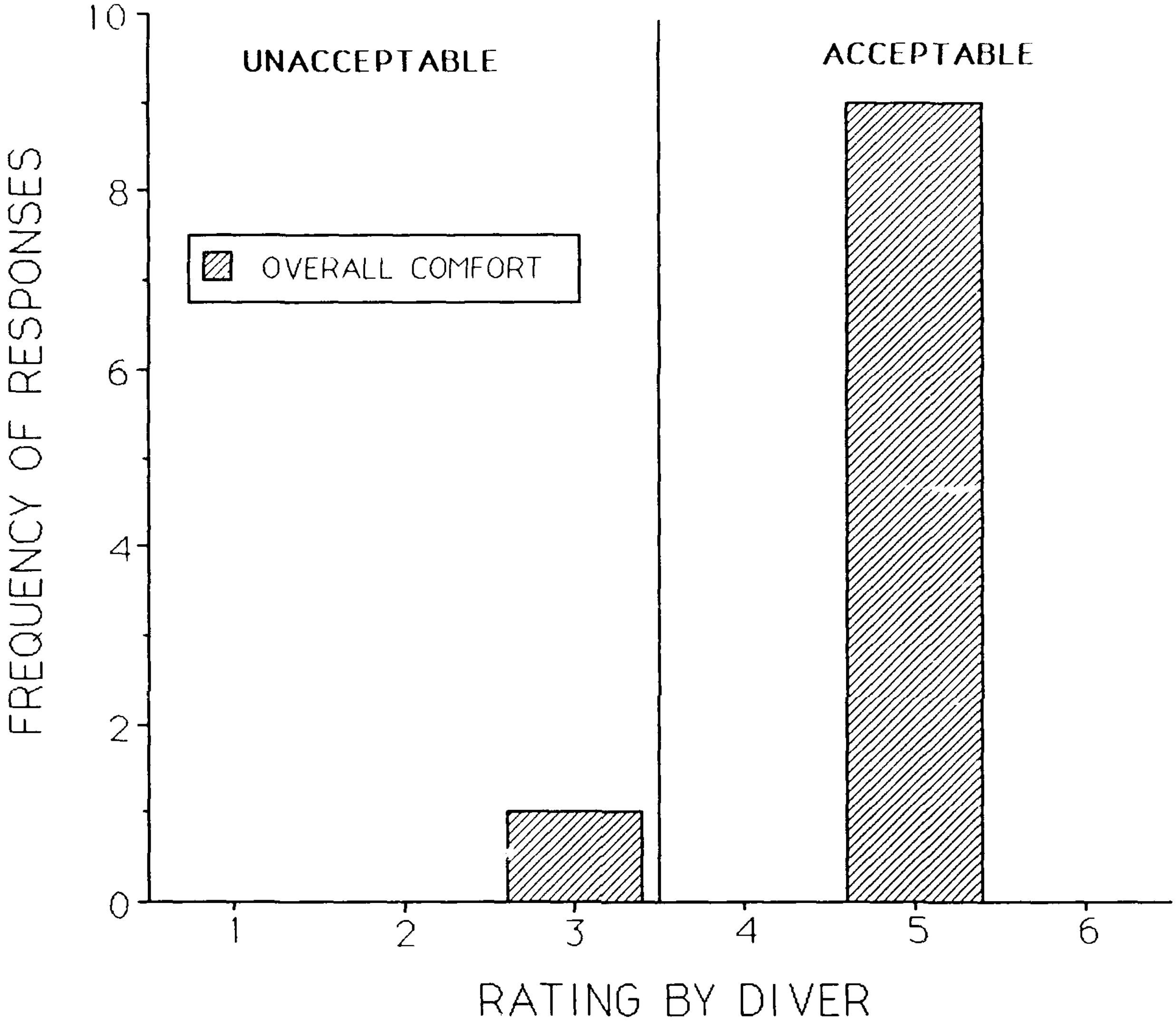

Figure 8. VOLTREX, Open Sea, Overall Comfort With Use

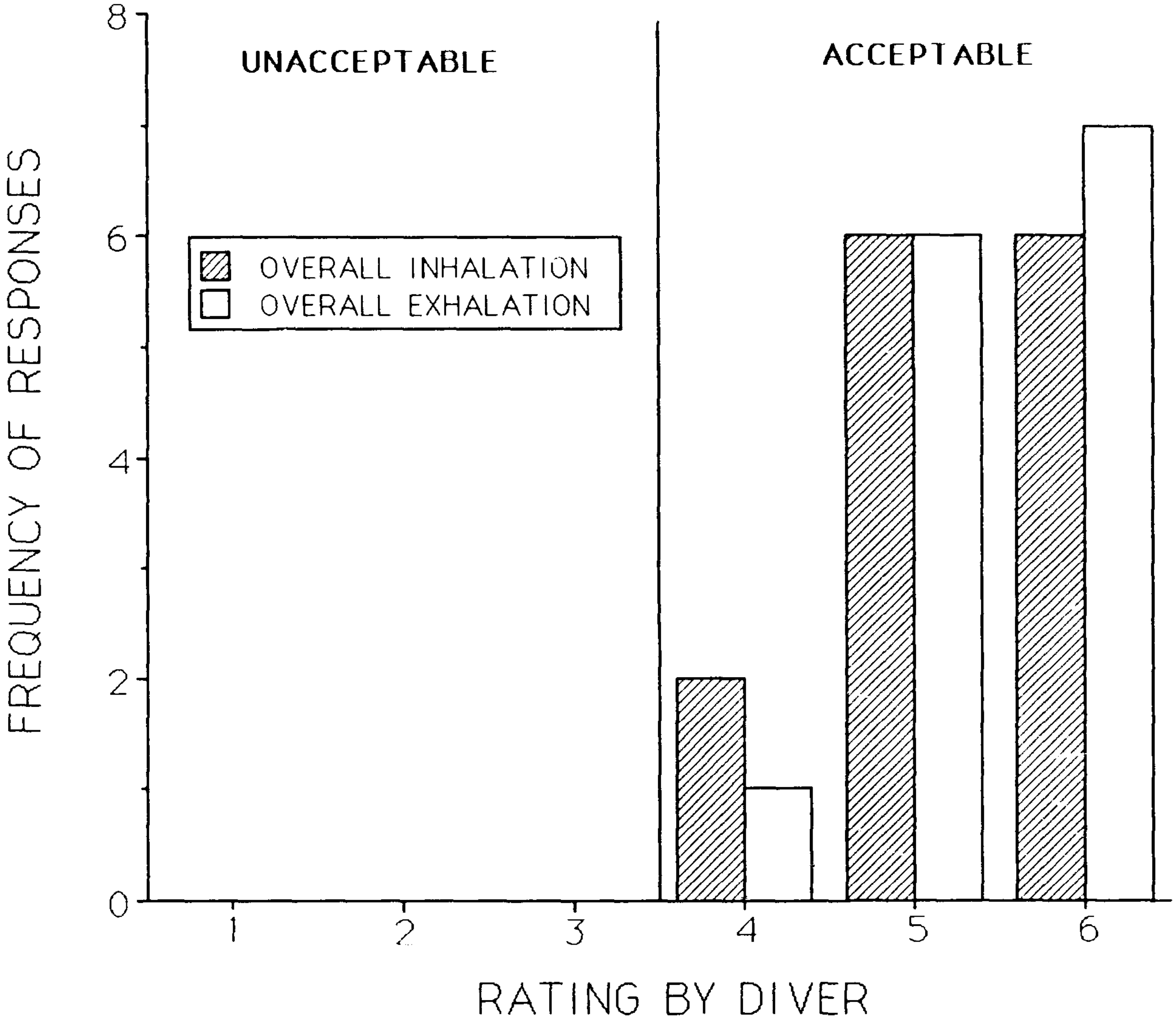

Figure 9. VOLTREX, OSF, Overall Inhalation/Exhalation

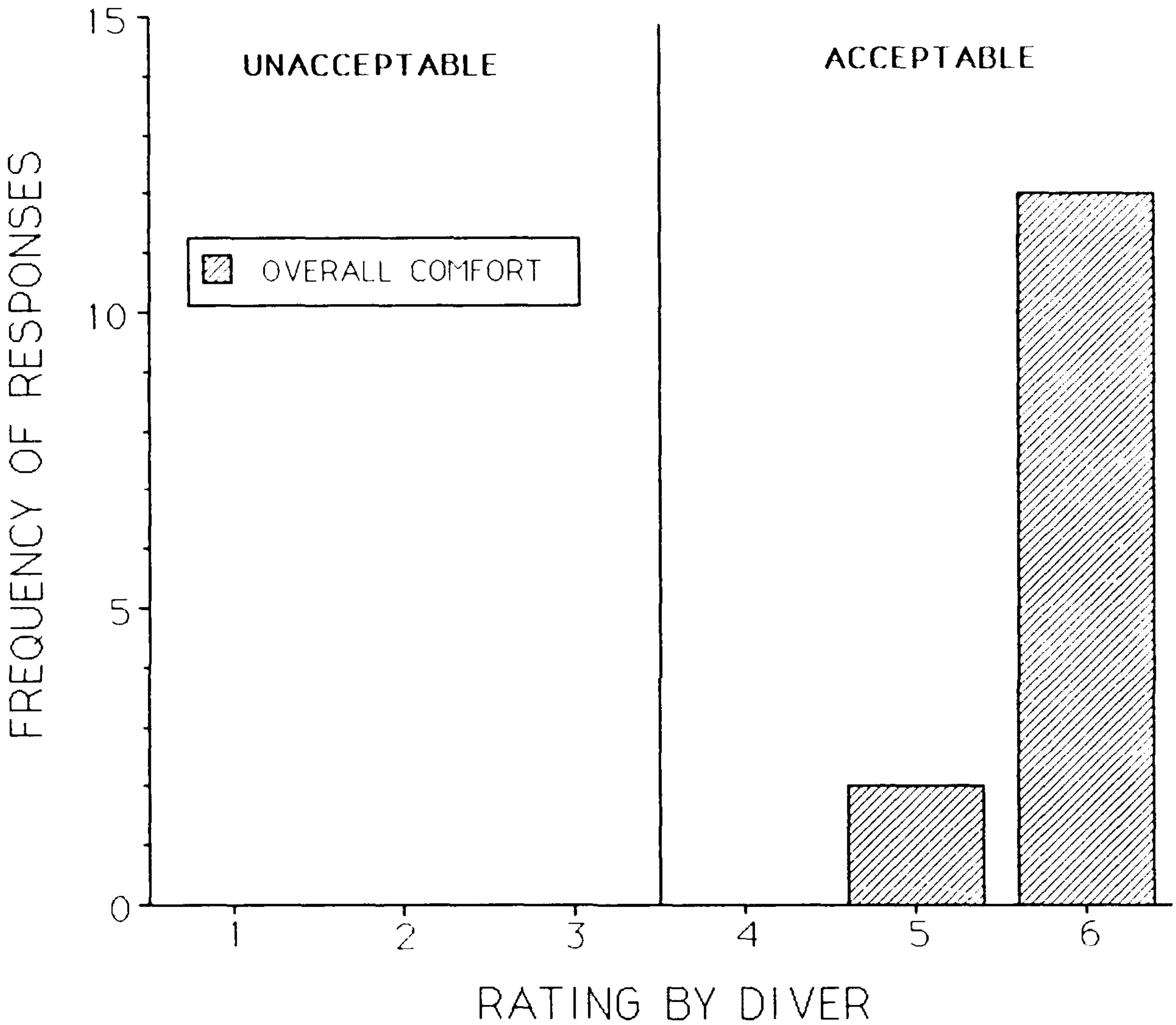

Figure 10. VOLTREX, OSF, Overall Comfort With Use

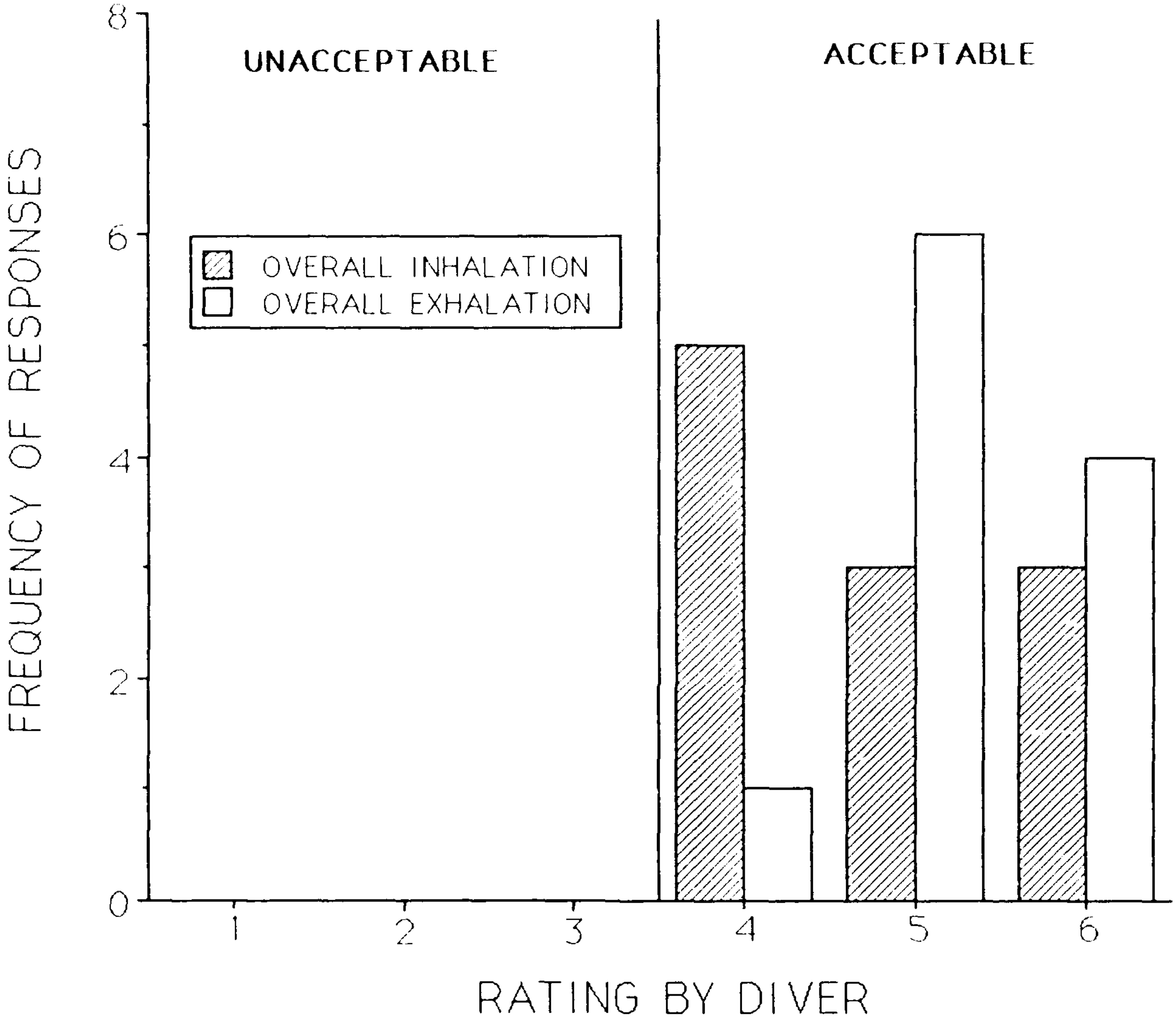

Figure 11. BETA, OSF, OVERALL INHALATION/EXHALATION

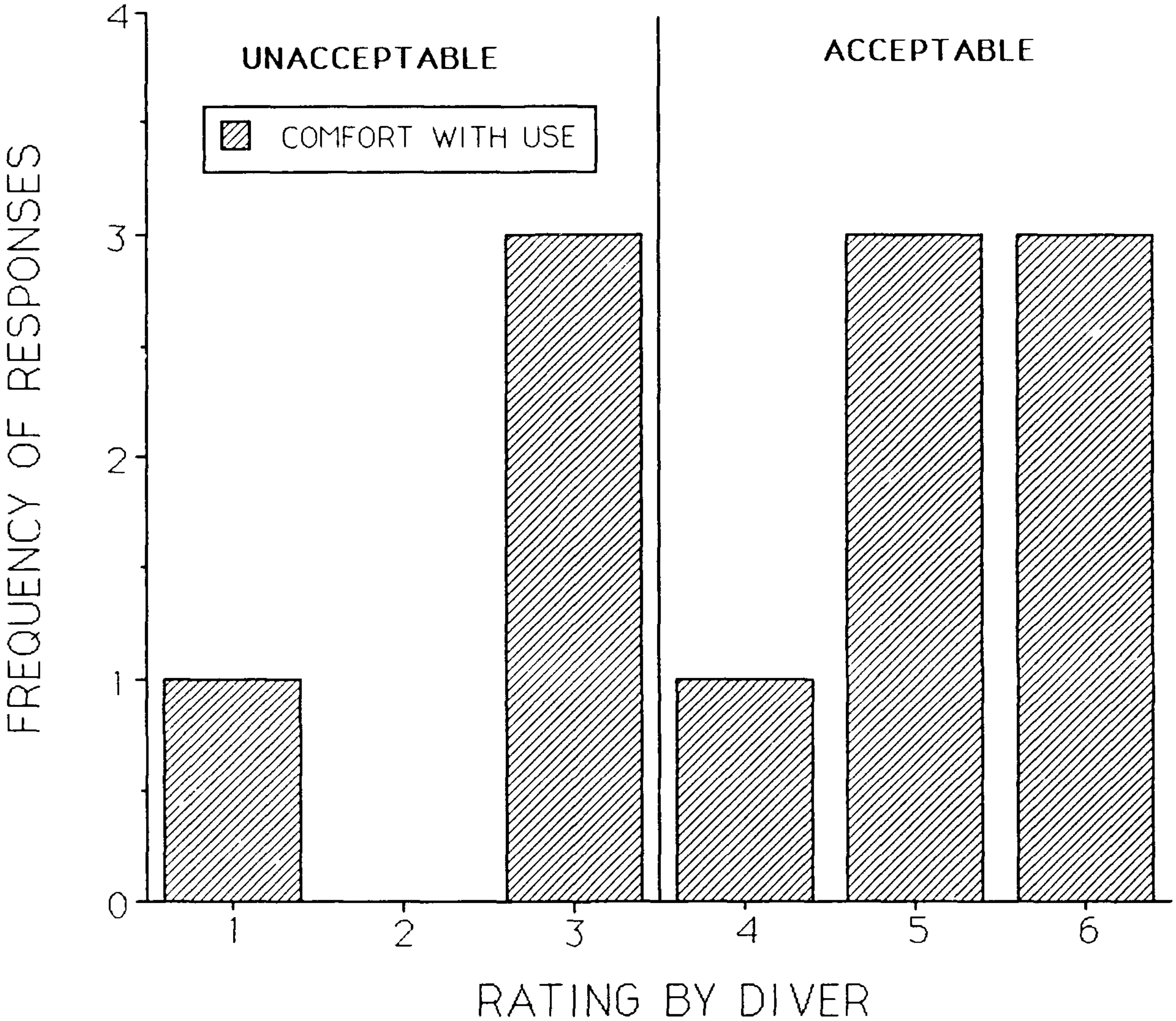

Figure 12. BETA, OSF, OVERALL
COMFORT WITH USE

APPENDIX A

HUMAN FACTORS EVALUATION QUESTIONNAIRE SCUBA REGULATOR

Name of diver ______________________________

Date: __________ Regulator tag # ____

Number of years experience diving SCUBA? ________

Dive profile: (circle one) OSF / GULF Depth (fsw) _____ Duration (min)___ Water Temp (°F) ____

Brief description of dive ______________________________

Describe dress used for dive ______________________________

Were gloves worn during dive (yes/no)? ____ Type ______________________________

<u>Testing associate</u>: **Mfg/model of regulator** ______________________________

Overbottom pressure (kPa): Pre-test _____ Post-test ____

<u>RATING SYSTEM</u>:

1=extremely poor | 3=not quite adequate | 5=good

2=poor | 4=adequate | 6=excellent

<u>RATE THE FOLLOWING WORK OF BREATHING PARAMETERS</u>:

	inhalation	exhalation
a. Standing upright		
b. At a 45° face-up position		
c. At a 45° face-down position		
d. In a head-down position		
e. Prone position		
f. Supine position		
g. Overall rating		

<u>OVERALL COMFORT OF REGULATOR</u>:

4. How would you **rate** the comfort of the regulator bit in your mouth? . . . . ___
5. How would you **rate** the comfort of the regulator in terms of its relative buoyancy? . . ___
6. How would you **rate** the comfort of the regulator in terms of its range of motion? . . . ___
7. How would you **rate** the dispersion of air bubbles by the whisker? . . . . ___

USE AND OPERATION OF MASK:

8. How would you **rate** the ease of breathing the mask while at rest? . . . . ___
9. How would you **rate** the ease of breathing the mask at moderate work levels? . . . . . . ___
10. How would you **rate** the ease of breathing the mask at heavy work levels? . . . . ___
11. How would you **rate** the size and location of the purge button? . . . . ___
12. How would you **rate** the operation of the purge button *with bare hands*? . . . . ___
13. How would you **rate** the operation of the purge button *with gloved hands*? . . . . ___
14. How would you **rate** the accessibility and operation of the dial-a-breath? . . . . ___
15. How would you **rate** the reduction in breathing resistance provided by the dial-a-breath? ___
16. How would you **rate** your comfort level diving this regulator? . . . . ___
17. Did you encounter a sustained, forceful free-flow with this regulator (yes/no)? . . . . . ___
18. If yes, describe the circumstances triggering the free-flow: ______________________________

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19. Briefly describe what you consider the *best* feature of this regulator: ____________________

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20. Briefly describe what you consider the *worst* feature of this regulator: ____________________

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Please provide any additional comments about the regulator that you think are important, including suggestions you feel would enhance its performance/safety: ______________________________

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