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NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 7-93

OMMERCIALLY AVAILABLE IDI SCUBA 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 none of the candidate test regulators were 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
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 those which meet the US Navy's demanding performance criteria.

International Diver's Inc., La Mirada, CA., provided three models for evaluation. The SR-3 STAR, the RAZOR (Adjustable), and the RAZOR. All three candidate models are balanced flow through first stage regulators with demand valve second stages. The RAZOR (Adjustable) is fitted with a diver adjustable orifice.

UNMANNED EVALUATION

Unmanned evaluations of the three candidate regulator models measured Work of Breathing (WOB) levels and compared them to Performance Goal Standards[1], which represent ideal levels of performance 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 three to 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 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 three regulators of the same 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 revealed that the SR-3 STAR was capable of delivering up to 849 SLM (30 SCFM) at relatively low inhalation pressures. Flow characteristics for the SR-3 STAR are shown in Figure 1.

Figure 2 shows the flow characteristics for the RAZOR (Adjustable). Clearly, inhalation pressures increase markedly with each increase in delivery rate, to a maximum attainable flow rate of 622 SLM (22 SCFM).

Results of bench testing the RAZOR are shown in Figure 3. Marked increases in inhalation pressures are evident with each increase in delivery rate, to a maximum attainable flow rate of 650 SLM (23 SCFM).

WOB values for the SR-3 STAR at 10.34 MPa (1500 psi) as well as 3.44 MPa (500 psi) supply pressures are summarized in Table 1. WOB levels increased noticeably at all RMVs with each increase in test depth. Performance Goal Standard was exceeded at 40 RMV/40 msw (132 fsw) and deeper. At 62.5 RMV, WOB levels far exceeded the goal, starting at 10 msw (33 fsw). At the higher ventilatory rates, WOB levels were extremely high; at 90 RMV 50 and 60 msw (165 and 198 fsw), levels were beyond termination criteria. At the reduced supply pressure, WOB levels far exceeded Performance Goal Standard at all depths and RMVs.

Figure 4 shows comparative WOB levels of the SR-3 STAR obtained with a 10.34 MPa (1500 psi) supply pressure. Clearly, WOB levels are well beyond Performance Goal Standard at all RMVs.

Figure 5 shows the comparative WOB levels of the SR-3 STAR obtained with a 3.44 MPa (500 psi) supply pressure. WOB levels exceeded Performance Goal Standard at all RMVs.

Table 2 summarizes WOB values for the RAZOR (Adjustable) obtained with a 10.34 MPa (1500 psi) supply pressure. At 40 RMV, WOB levels exceeded Performance Goal Standard at 30 msw (99 fsw) and increased progressively with each increase in test depth to 60 msw (198 fsw) where it went beyond termination criteria. At 62.5 RMV, WOB levels exceeded goal at 10 msw (33 fsw) and increased progressively with each increase in test depth to 50 and 60 msw (165 and 198 fsw) where it went beyond termination criteria. At the higher ventilatory rates WOB levels were beyond goal and exceeded termination criteria at 75 RMV/40 msw (132 fsw) and deeper and 90 RMV/ 30 msw (99 fsw) and deeper. Because of the extremely high WOB values obtained at the higher supply pressure, no testing was conducted at the lower supply pressure.

Figure 6 shows the comparative WOB levels obtained at 10.34 MPa (1500 psi) with the RAZOR (Adjustable). A steady increase in WOB is evident at 40 RMV with each increase in test depth. At the higher ventilatory rates, increase in WOB is markedly greater with each increase in test depth.

WOB values obtained from the RAZOR at 10.34 MPa (1500 psi) and 3.44 MPa (500 psi) are contained in Table 3. At 10.34 MPa (1500 psi), WOB levels exceeded termination criteria at 40 RMV/60 msw (198 fsw), 62.5 RMV/50 msw (165 fsw) and deeper, 75 RMV/40 msw (132 fsw) and deeper and at 90 RMV/30 msw (99 fsw) and deeper. Clearly, this regulator does not meet the Performance Goal Standard. At the lower supply pressure, WOB levels were extremely high and exceeded 4 kPa at 62.5 RMV/40 msw (132 fsw) and deeper, 75 RMV/40 msw (132 fsw) and deeper, and at 90 RMV/30 msw (99 fsw) and deeper.

Figure 7 shows comparative WOB levels obtained at 10.34 MPa (1500 psi) with the RAZOR, WOB levels exceeded Performance Goal Standard.

Comparative WOB levels of the RAZOR obtained at 3.44 MPa (500 psi) are shown in Figure 8. At 40 RMV there is a steady increase in WOB levels with each increase in test depth. At the higher ventilatory rates, WOB levels increase markedly with each increase in test depth, to a point of exceeding 4 kPa.

MANNED EVALUATION

Manned data was to be 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 1 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 were on a 1-6 scale, with 1 being "extremely poor" and 6 being "excellent."

A total of thirty-eight divers completed questionnaires following OSF dives to evaluate the three candidate regulators.

RESULTS

Manned dives were authorized to be conducted in the controlled environment of the OSF prior to unmanned testing of candidate regulators. Results obtained from these manned evaluations showed a majority of divers rating the three candidate regulators as *acceptable* or better in the measured parameters. However, because of the extremely high WOB levels obtained from these three candidate model regulators during unmanned testing, no open ocean manned dives were conducted.

CONCLUSIONS/RECOMMENDATIONS

WOB levels obtained for the SR-3 STAR were more than double the Performance Goal Standard.

The RAZOR (Adjustable) and RAZOR had WOB levels that were more than double the Performance Goal Standard to a depth of 40 msw (132 fsw), beyond that depth, WOB levels exceeded termination criteria.

Although Human Factors evaluations were conducted in part, due to the results from unmanned testing, these data have no bearing on the recommendation.

Clearly, none of the candidate regulator models meet the demanding performance requirements of the US Navy. Based on the results obtained during unmanned testing, recommend that the SR-3 STAR, RAZOR (Adjustable), and RAZOR be not recommended for approval or addition to the ANU List.

REFERENCES

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 IDI SR-3 STAR 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	0.73 ± 0.14	0.98 ± 0.15	1.17 ± 0.16	1.42 ± 0.18
10	1.00 ± 0.13	1.42 ± 0.18	1.73 ± 0.23	2.08 ± 0.30
20	1.15 ± 0.17	1.74 ± 0.29	2.13 ± 0.37	2.50 ± 0.67
30	1.32 ± 0.20	2.03 ± 0.34	2.50 ± 0.51	2.95 ± 0.78
40	1.43 ± 0.24	2.29 ± 0.43	2.83 ± 0.61	3.69 ± 0.81
50	1.58 ± 0.28	2.53 ± 0.57	3.26 ± 0.76	#
60	1.73 ± 0.34	2.91 ± 0.64	3.33 ± *	#

3.44 MPa (500 PSI) SUPPLY PRESSURE

DEPTH IN METERS	RESPIRATORY MINUTE VOLUME			
	40	62.5	75	90
0	0.88 ± 0.04	1.12 ± 0.10	1.30 ± 0.15	1.51 ± 0.18
10	1.03 ± 0.14	1.47 ± 0.21	1.74 ± 0.25	2.10 ± 0.31
20	1.24 ± 0.19	1.78 ± 0.29	2.14 ± 0.39	2.65 ± 0.49
30	1.35 ± 0.26	2.04 ± 0.41	2.58 ± 0.54	3.04 ± 0.70
40	1.47 ± 0.26	2.36 ± 0.48	2.98 ± 0.58	3.49 ± *
50	1.58 ± 0.28	2.62 ± 0.55	3.44 ± 0.87	#
60	1.72 ± 0.33	2.95 ± 0.62	3.83 ± *	#

* Denotes no standard deviation in the averaging
# Denotes WOB value beyond termination criteria

TABLE 2

UNMANNED IDI RAZOR (ADJ) 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	0.79 ± 0.11	1.10 ± 0.10	1.28 ±0.07	1.50 ± 0.02
10	1.04 ± 0.06	1.45 ± 0.04	1.76 ± 0.04	1.98 ± 0.08
20	1.30 ± 0.04	1.87 ± 0.10	2.19 ± 0.08	3.11 ± 0.20
30	1.45 ± 0.04	2.23 ± 0.10	3.35 ± 0.15	#
40	1.60 ± 0.05	3.30 ± 0.31	#	#
50	1.74 ± *	#	#	#
60	#	#	#	#

3.44 MPa (500 PSI) SUPPLY PRESSURE

DEPTH IN METERS	RESPIRATORY MINUTE VOLUME			
	40	62.5	75	90
0	#	#	#	#
10	#	#	#	#
20	#	#	#	#
30	#	#	#	#
40	#	#	#	#
50	#	#	#	#
60	#	#	#	#

* Denotes no standard deviation in the averaging

\# Denotes WOB value beyond termination criteria

TABLE 3

UNMANNED IDI RAZOR 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	0.97 ± 0.19	1.22 ± 0.13	1.37 ± 0.14	1.57 ± 0.11
10	1.24 ± 0.06	1.59 ± 0.15	1.88 ± 0.19	2.16 ± 0.15
20	1.45 ± 0.04	1.94 ± 0.13	2.58 ± 0.55	2.88 ± 0.33
30	1.57 ± 0.07	2.17 ± 0.10	3.20 ± 0.26	#
40	1.69 ± 0.11	2.83 ± 0.08	#	#
50	1.80 ± 0.24	#	#	#
60	#	#	#	#

3.44 MPa (500 PSI) SUPPLY PRESSURE

DEPTH IN METERS	RESPIRATORY MINUTE VOLUME			
	40	62.5	75	90
0	1.00 ± 0.14	1.27 ± 0.10	1.39 ± 0.09	1.67 ± 0.05
10	1.22 ± 0.10	1.62 ± 0.07	1.93 ± 0.08	2.20 ± 0.12
20	1.41 ± 0.03	1.97 ± 0.08	2.25 ± 0.14	3.21 ± 0.18
30	1.57 ± 0.07	2.03 ± 0.42	3.70 ± 0.16	#
40	1.70 ± 0.07	3.24 ± 0.02	#	#
50	1.77 ± 0.07	#	#	#
60	1.90 ± 0.17	#	#	#

* Denotes no standard deviation in the averaging
# Denotes WOB value beyond termination ci iteria

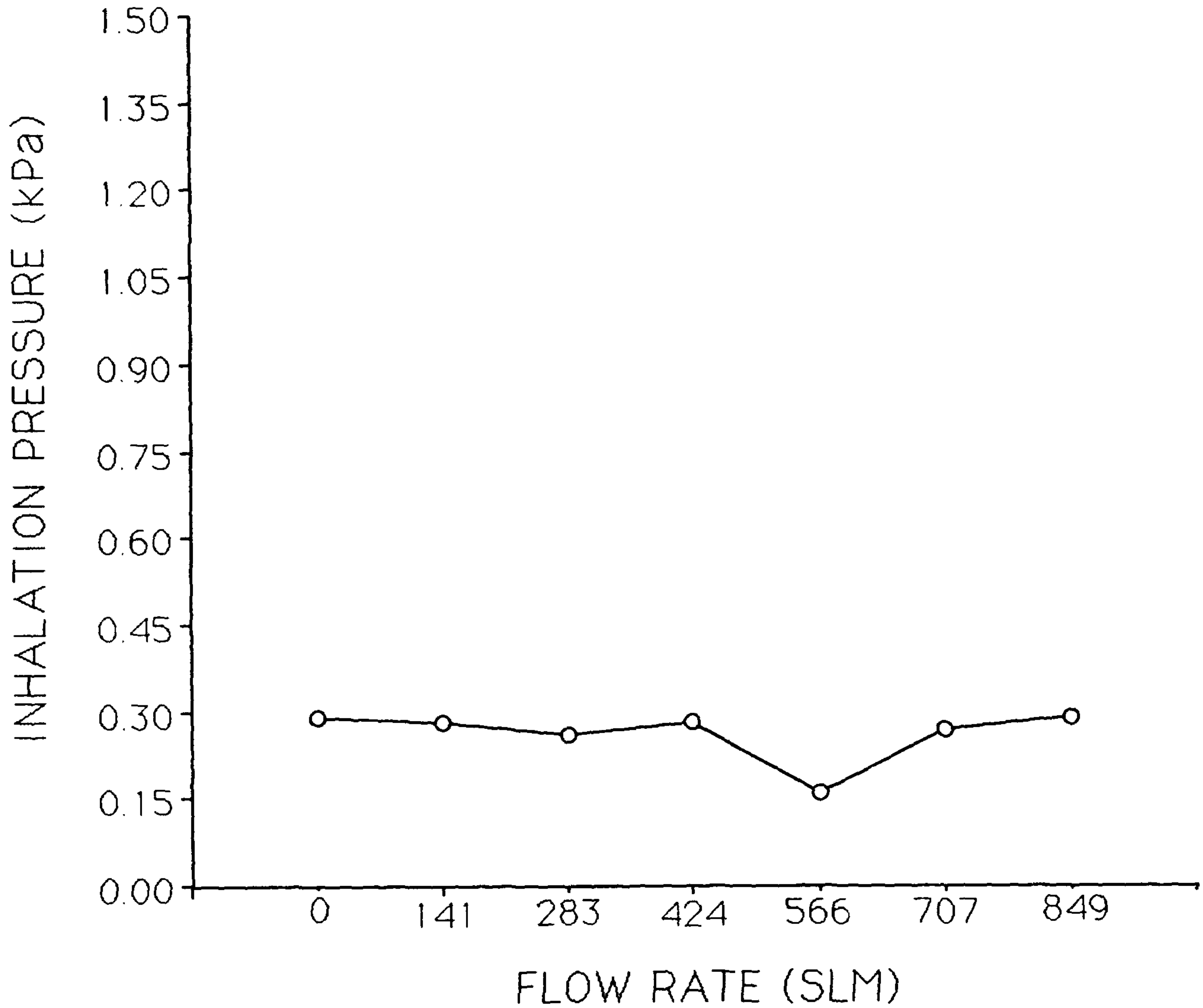

Figure 1. SR-3 STAR Flow Characteristics

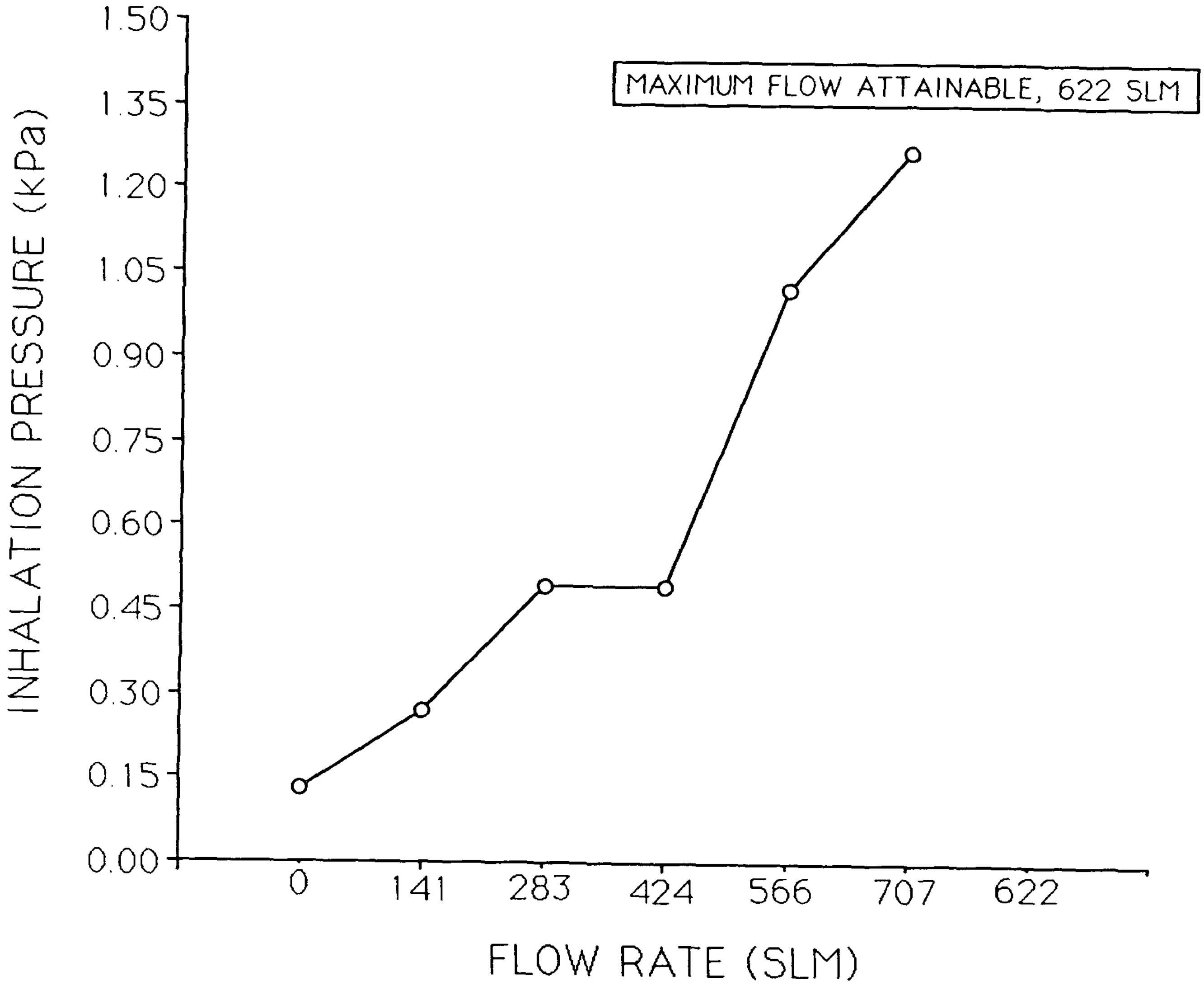

Figure 2. RAZOR (Adjustable) Flow Characteristics

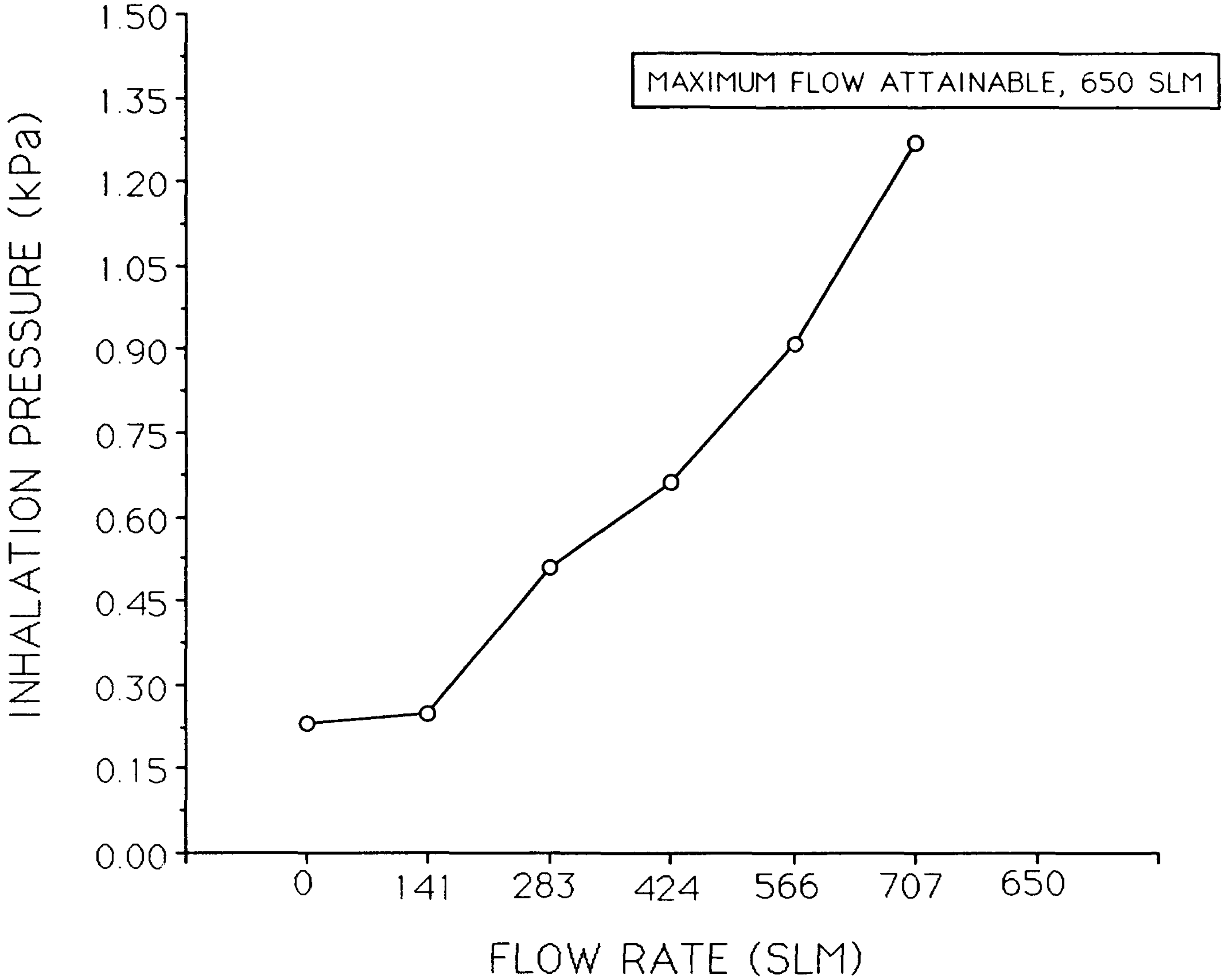

Figure 3. RAZOR Flow Characteristics

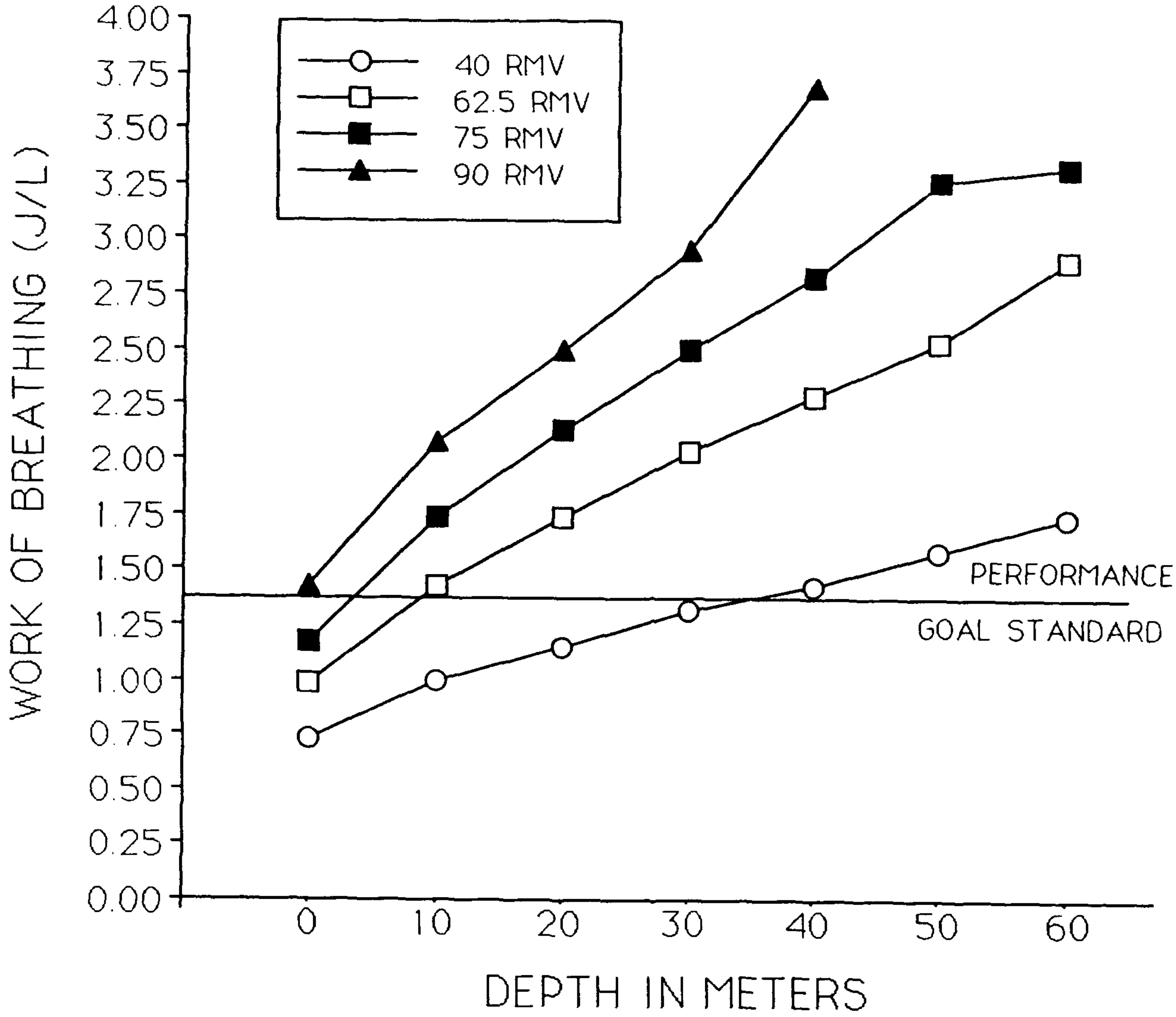

Figure 4. SR-3 STAR, 10.34 MPa (1500 PSI) Supply Pressure

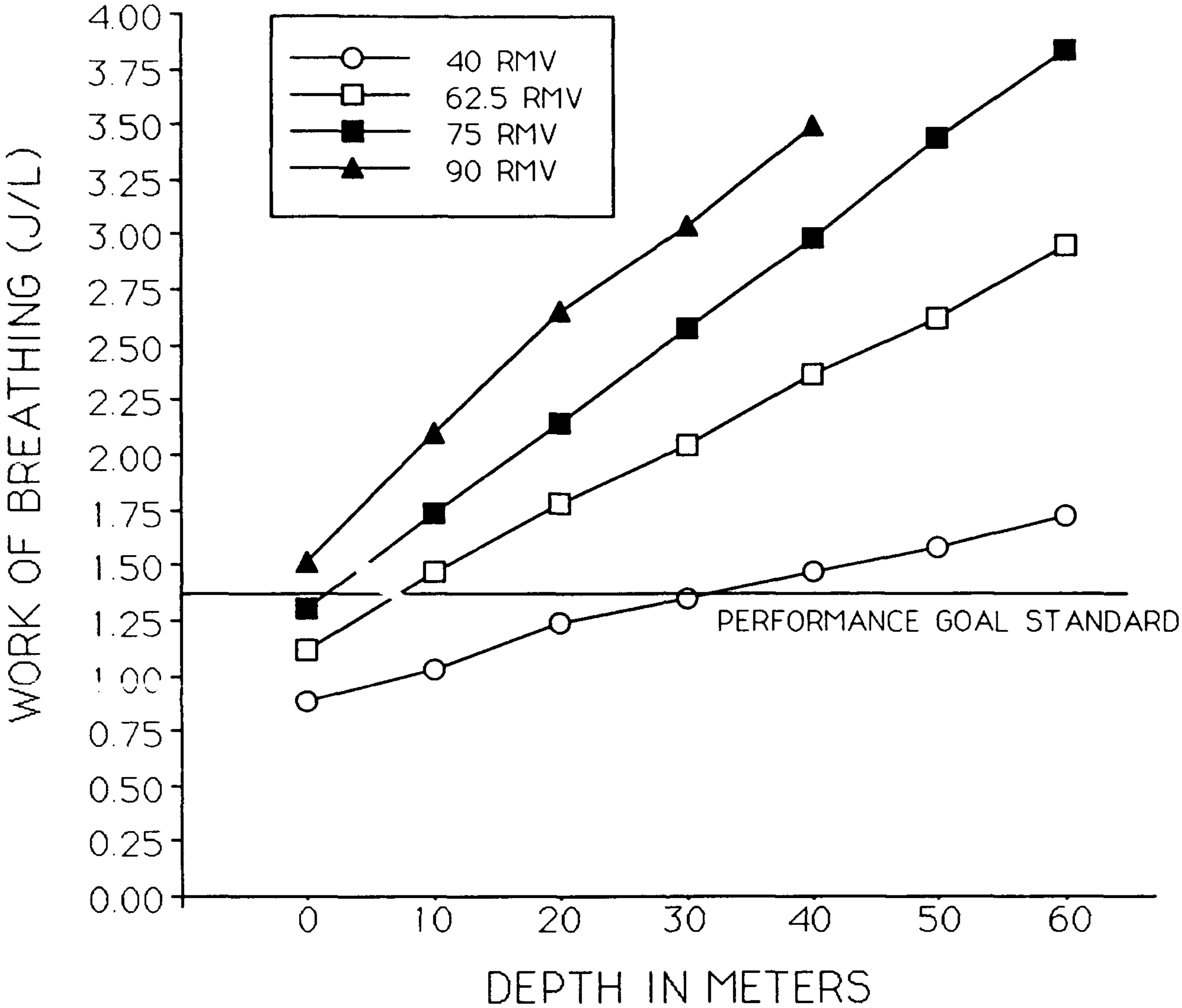

Figure 5. SR-3 STAR, 3.44 MPa (500 PSI) Supply Pressure

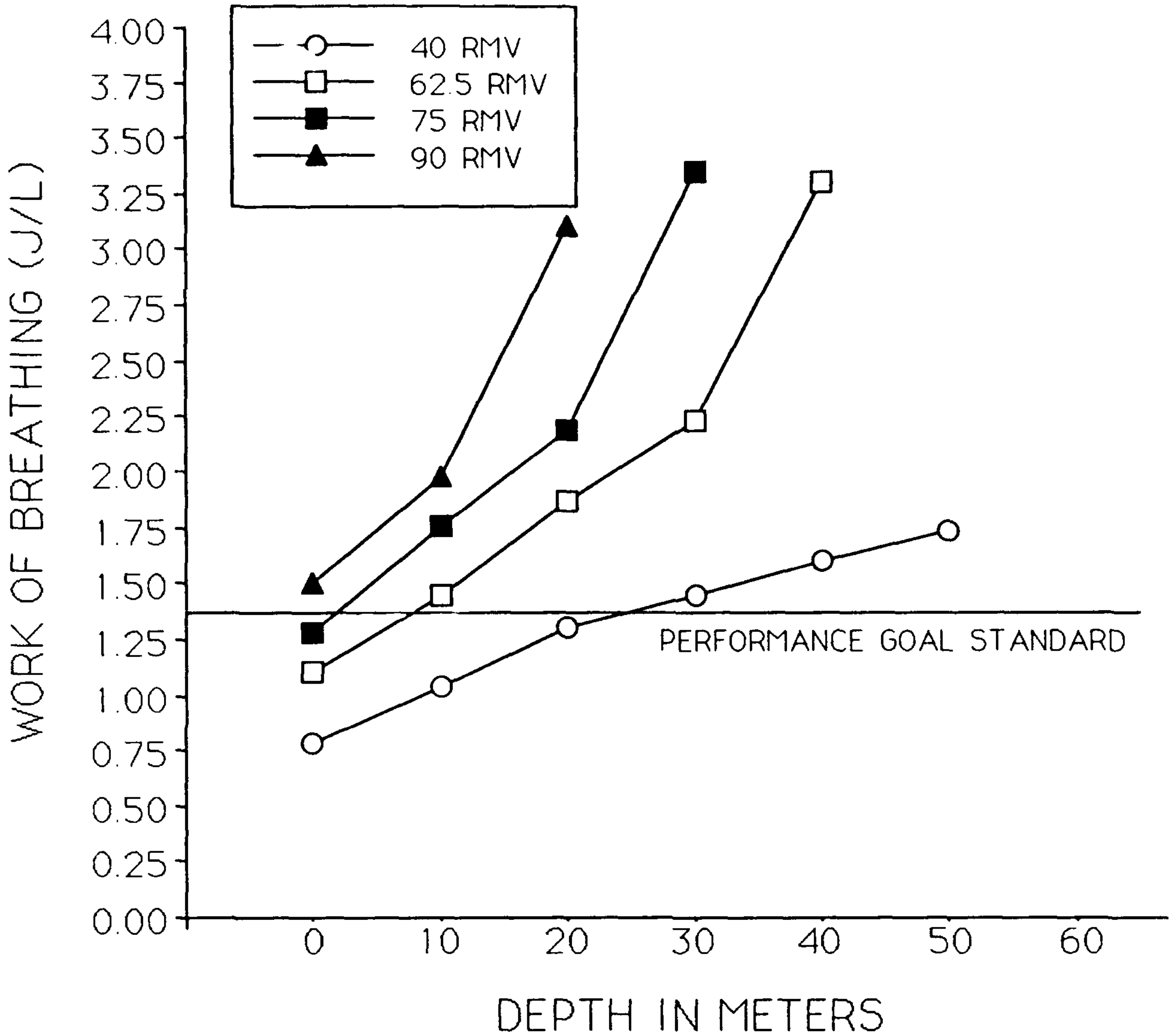

Figure 6. RAZOR (Adjustable), 10.34 MPa (1500 PSI) Supply Pressure

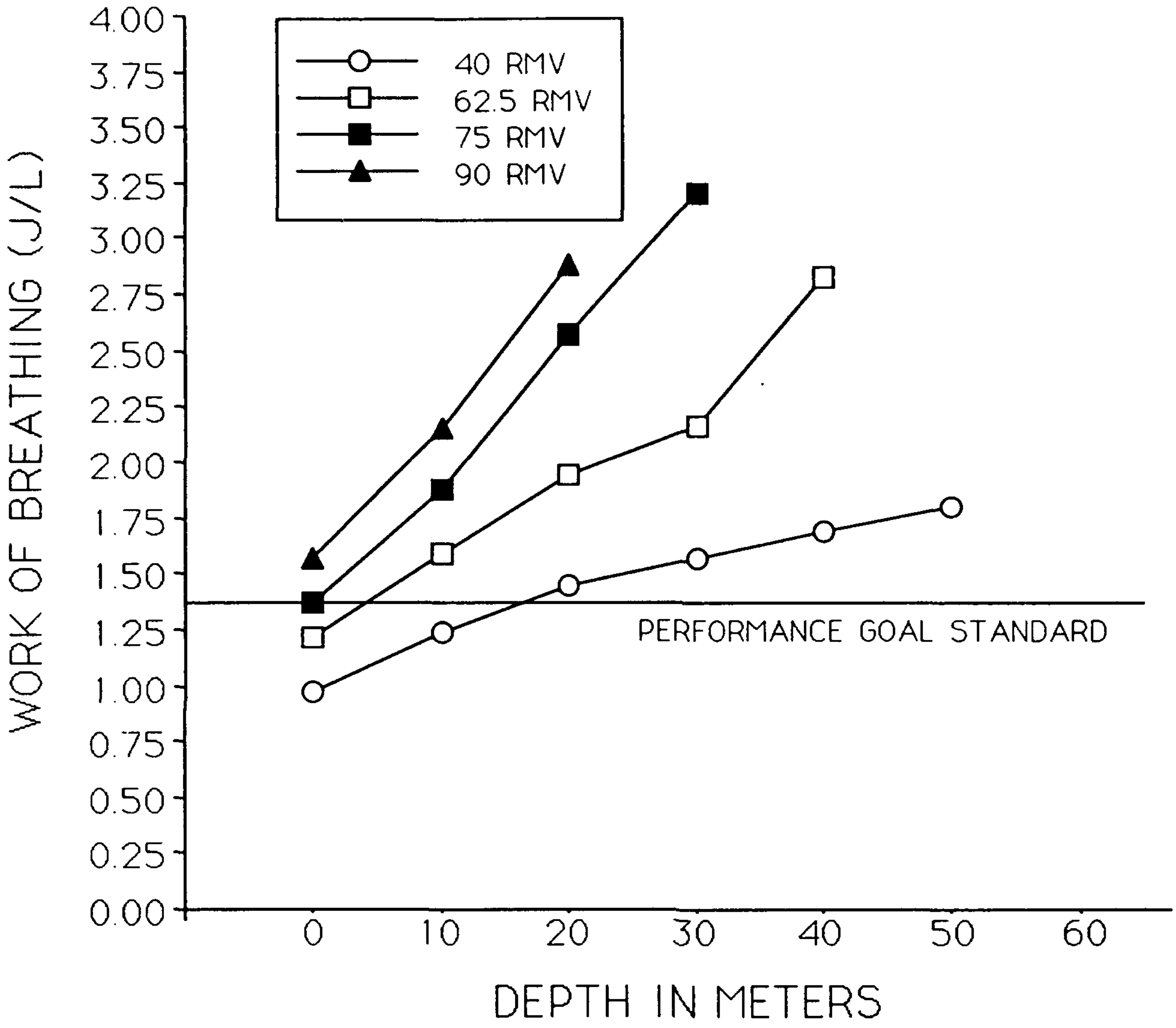

Figure 7. RAZOR, 10.34 MPa (1500 PSI) Supply Pressure

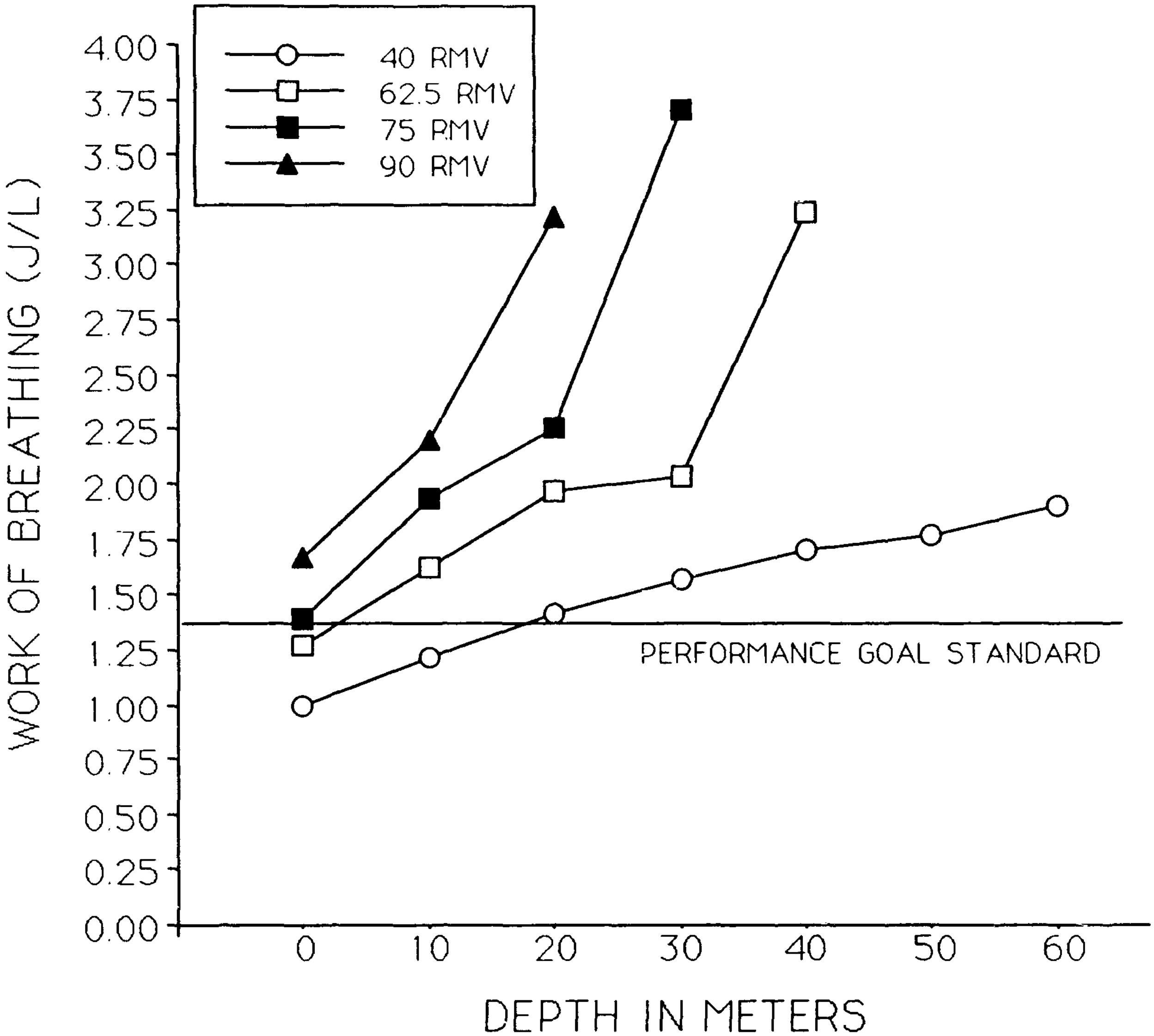

Figure 8. RAZOR, 3.44 MPa (500 PSI) Supply Pressure

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 ______________________________

Testing associate: Mfg/model of regulator ______________________________

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

RATING SYSTEM:

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

2=poor **4**=adequate **6**=excellent

RATE THE FOLLOWING WORK OF BREATHING PARAMETERS:

	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		

OVERALL COMFORT OF REGULATOR:

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: ______________________________

____

____

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

____

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

____

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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