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NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 8-77

EVALUATION OF SCUBAPRO MK V PILOT OPEN-CIRCUIT SCUBA REGULATOR

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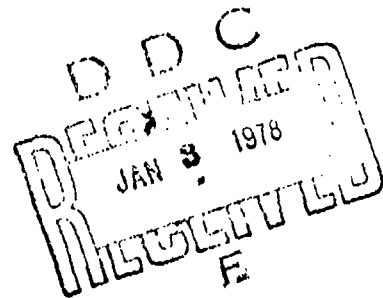
DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
Panama City, Florida 32407

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REPORT NO. 8-77

EVALUATION OF SCUBAPRO MK V
PILOT OPEN-CIRCUIT SCUBA REGULATOR

JAMES R. MIDDLETON

MAY 1977



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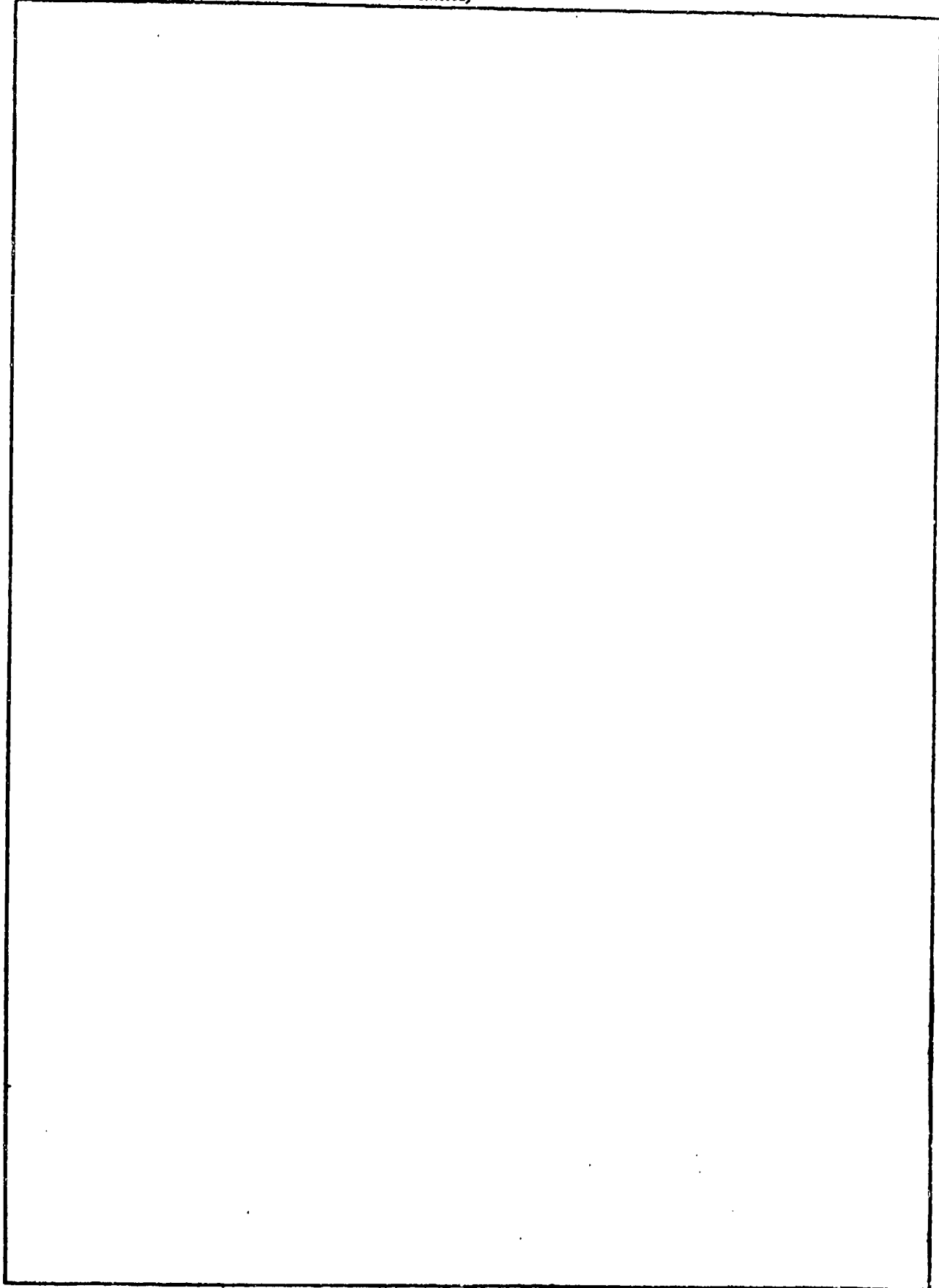
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The Scubapro MK V Pilot Open-Circuit Scuba Regulator was tested by the Navy Experimental Diving Unit in accordance with MIL-R-24169A. The tests showed that the MK V regulator meets mil spec requirements. The MK V Pilot regulator is recommended for placement on the list of equipment authorized for Navy use.		

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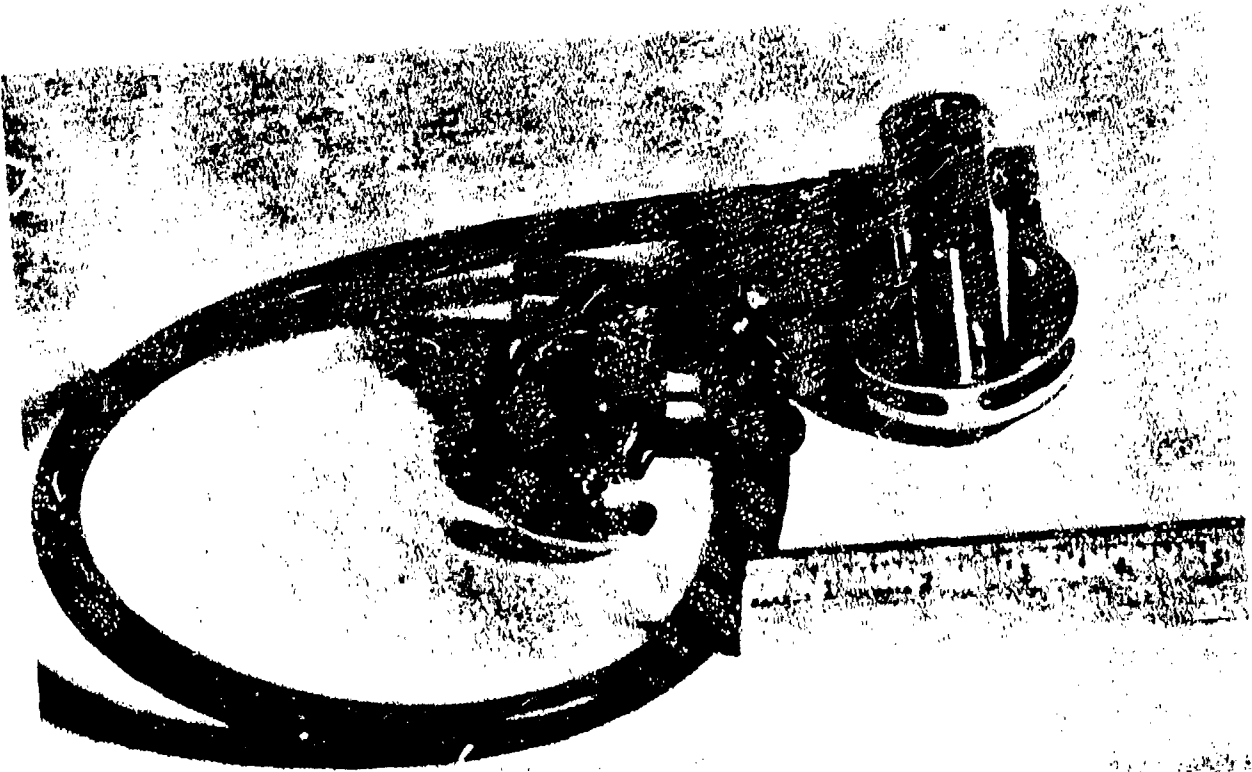
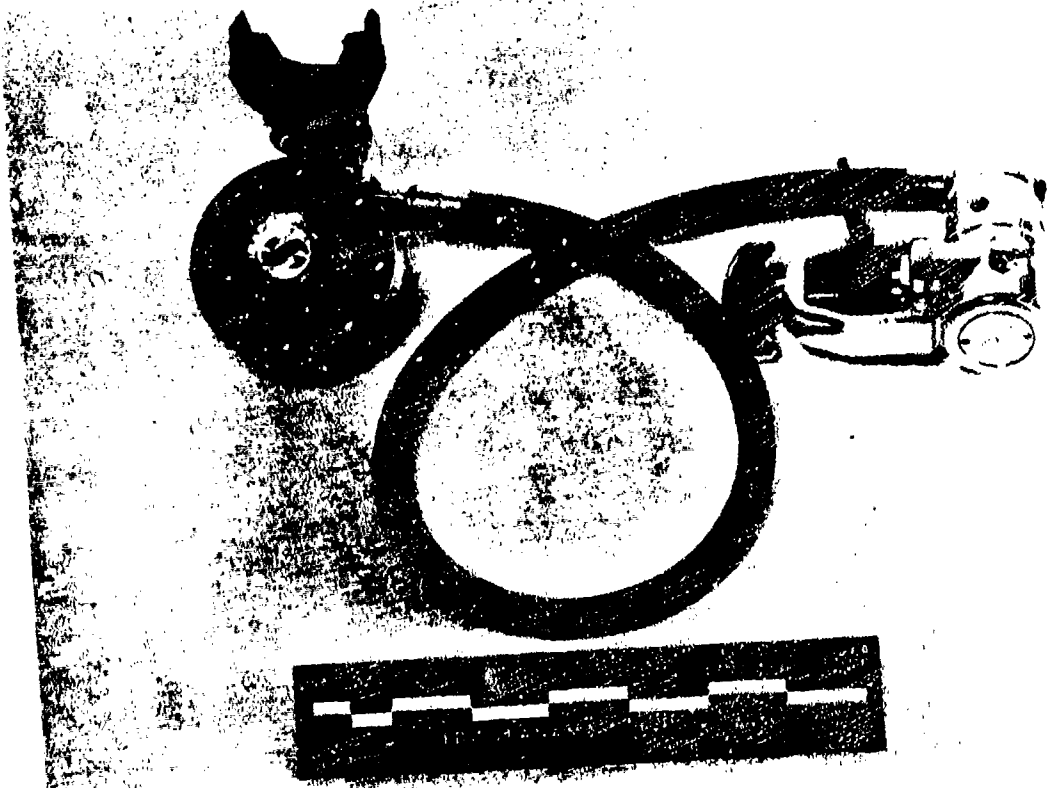
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LIST OF ABBREVIATIONS

<u>ABBREVIATION</u>	<u>DEFINITION</u>
BPM	breaths per minute
cm H ₂ O	centimeters of water pressure (differential)
fsw	feet of seawater
kg·m/l	breathing work in kilogram meters per liter ventilation
mil spec	military specification MIL-R-24169A
NEDU	Navy Experimental Diving Unit
O/B	over bottom pressure
psig	pounds per square inch gauge
ΔP	pressure differential
RMV	respiratory minute volume in liters per minute

ABSTRACT

The Scubapro MK V Pilot Regulator was tested by NEDU in accordance with MIL-R-24169A. Results of breathing resistance, first-stage regulator performance, and work of breathing tests showed that it meets mil spec requirements. The MK V Pilot regulator is recommended for placement on the list of equipment authorized for Navy use.



SCUBAPRO MK V PILOT OPEN-CIRCUIT SCUBA REGULATOR

INTRODUCTION

In October 1976, NEDU, by direction of the Supervisor of Diving (reference 1), tested the MK V Pilot Regulator, a single-hose, demand-type regulator produced by Scubapro, 3105 East Harcourt, Compton, California 90221.

The regulator was tested in accordance with MIL-R-24169A (reference 2) and other applicable mil specs. Various RMV's were also used during the test to simulate diver light and heavy work rates. Intermediate pressure between the regulator first and second stages was monitored to measure first stage performance. Breathing work required to operate the regulator was also measured. These measurements were supplementary guides to evaluation.

Test results show that the regulator meets mil spec requirements. The Scubapro MK V Pilot Regulator is recommended for placement on the list of equipment authorized for Navy use.

TEST PROCEDURE

TEST PLAN

NEDU test equipment was set up as shown in Figure 1 and all testing of the MK V Pilot Regulator was in accordance with the applicable mil spec. The actual test plan is given in Appendix A. The breathing machine simulated inhalation and exhalation at various depths and diver work rates with the following parameters controlled, measured, computed, and plotted. The test equipment shown in Figure 1 is listed in Appendix B.

CONTROLLED PARAMETERS

The following parameters were controlled during the regulator tests.

1. Breathing rate/tidal volume
 - a. 15 BPM/1.5 liters 22.5 RMV
 - b. 20 BPM/2.0 liters 40.0 RMV
 - c. 25 BPM/3.0 liters 75.0 RMV
2. Exhalation/inhalation time ratio: 1.10:1.00.
3. Breathing waveform: modified sinusoid.
4. Air supply pressure: 1000 psig at all depths except 0 fsw and 200 fsw where data were recorded at 1000 psig, 500 psig O/B (overbottom pressure), and 200 psig O/B.
5. Depth increment stops: 0 to 200 fsw in 33-fsw increments and 300 fsw.

MEASURED PARAMETERS

The following parameters were measured during the regulator tests.

1. Inhalation peak ΔP (cm H₂O).
2. Exhalation peak ΔP (cm H₂O).

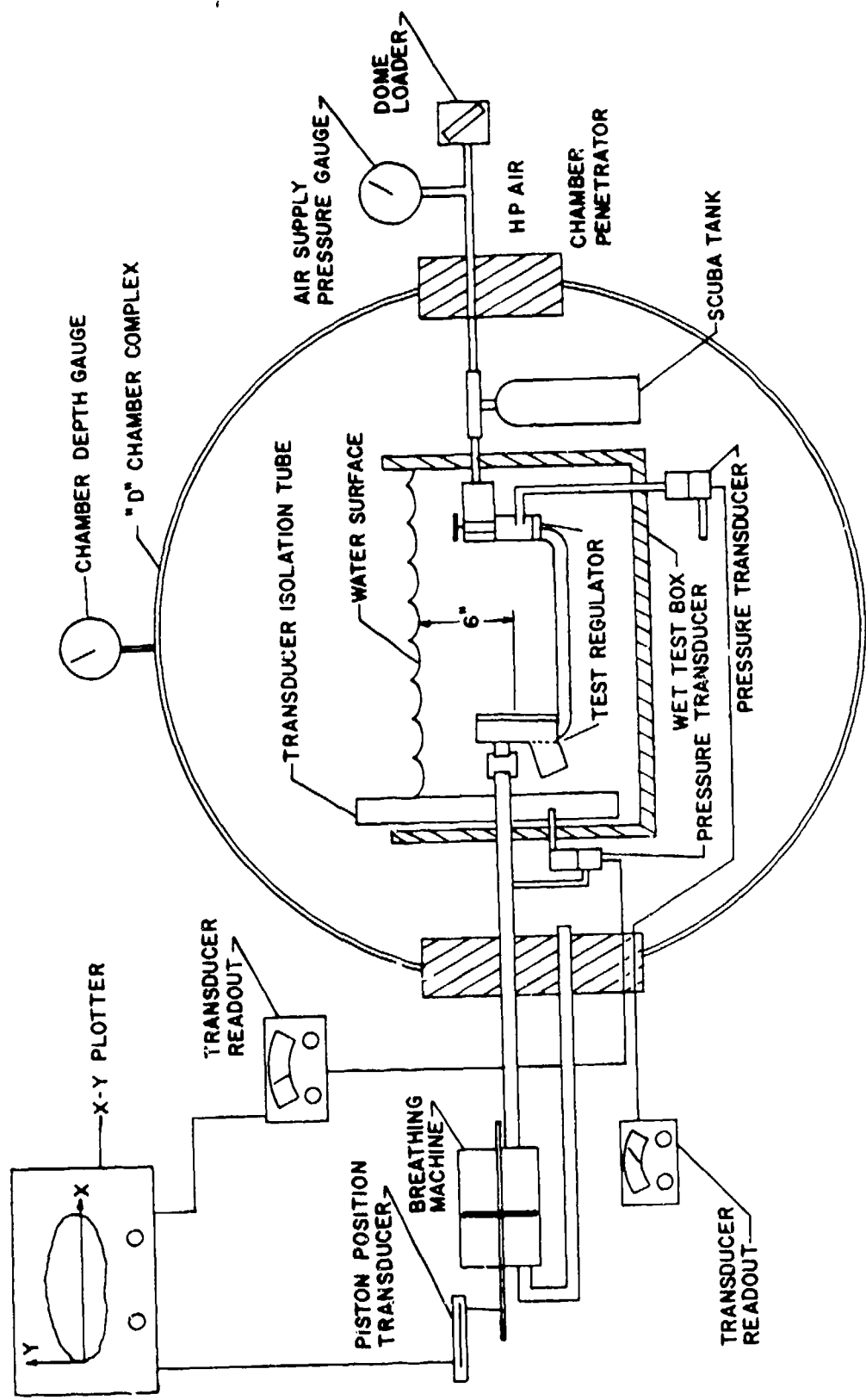


FIGURE 1. TEST SETUP

(See Appendix B for a complete description of equipment)

3. ΔP vs. tidal volume plots.
4. ΔP at zero flow condition for each depth on descent and ascent.
5. Maximum dynamic O/B at first stage outlet.
6. Minimum dynamic O/B at first stage outlet.

COMPUTED PARAMETERS

Respiratory work is the parameter computed from ΔP vs. tidal volume plots.

DATA PLOTTED

The following data are plotted in this report.

1. Inhalation maximum ΔP vs. depth.
2. Exhalation maximum ΔP vs. depth.
3. Respiratory work vs. depth at constant RMV and supply pressure.
4. Change in dynamic O/B at first stage vs. depth at constant RMV.

RESULTS AND DISCUSSION

DESCRIPTION

The MK V Pilot Regulator has a balanced, piston-type first stage with two low-pressure ports and one high-pressure port for a submersible pressure gauge. This first stage regulator is the same model that is marketed with the Navy-approved Scubapro regulator model MIL-105.

The second stage has a unique balanced pilot-assisted valve. The balanced demand valve is opened by air pressure controlled by a pilot valve. This second stage design is a basic change from a conventional second stage with a demand valve actuated by direct mechanical linkage contacting the diaphragm. The pilot valve is sensitive to the slightest pressure differential in the second stage diaphragm. Therefore, to prevent free-flow, a DIVE/PRE-DIVE switch on the front of the regulator must be set to the PRE-DIVE position whenever the mouthpiece is not in the diver's mouth. The pilot-assisted second stage is sensitive to pressure differentials of 0.50 to 1.00 cm H₂O when the regulator is out of the water. The regulator, therefore, tends to free-flow when it is bumped while the diver is out of the water. The diver can desensitize the second stage by setting the DIVE/PRE-DIVE switch to PRE-DIVE. Once in the water, the diver should set the switch to DIVE for easier breathing. However, the regulator is safe to use if the diver should forget to set the switch to DIVE. In addition, the pilot second stage has two low-pressure ports for accepting two supply hoses from either a single first stage or from two separate first stages. This feature, by keeping breathing resistance at a minimum, would be valuable in deep diving situations. Another distinguishing feature of the pilot second stage is the demand diaphragm that functions also as an exhaust valve.

BREATHING RESISTANCE TEST

Breathing resistance was measured at three RMV's to simulate light, moderate, and heavy work rates. Light work was measured at 22.5 RMV with 1.5-liter tidal volume and 15 BPM, moderate work was measured at 40 RMV with 2.0-liter tidal volume and 20 BPM, and heavy work was measured at 75 RMV with 3.0-liter tidal volume and 25 BPM. The mil spec (reference 2) calls for only 40 RMV at 1000-psig supply pressure. The other RMV's were measured, however, to indicate the full range of regulator performance.

The breathing resistances plotted in the figures are the maximum resistances measured, excluding cracking pressure, during one complete inhalation-exhalation cycle at a given depth and RMV. Air supply pressure to the first stage was 1000 psig. Resistance was measured at 500-psig O/B and 200-psig O/B supply pressures on the surface and 200 fsw at each RMV. The mil spec does not require the 300-fsw data; however, this information was obtained to simulate regulator performance at extreme depths on mixed gas (HeO₂).

The following table lists equivalent depth densities for air vs. HeO₂ down to 300 fsw on air. This table is a means of comparing regulator performance on HeO₂ mixes at depths greater than 200 fsw.

<u>Air Depth (fsw)</u>	<u>Equivalent HeO₂ Depth (fsw)</u>
50	230
100	625
150	1000
200	1350
250	1725
300	2075

a. Regulator in Dive Mode

1. Inhalation Characteristics. The inhalation resistance plotted are the maximum pressures recorded at all RMV's. In most cases, the maximum pressure occurred just after flow was initiated. As the inhalation cycle continued, resistance dropped to zero and a slight positive pressure was recorded. This characteristic indicates that the pilot-assisted second stage is an effective means of significantly reducing inhalation resistance at all RMV's.

Inhalation resistance at 22.5 RMV (figure 2) remained low to 200 fsw, reaching a maximum of only 3.5 cm H₂O. This figure is extremely low, considering that most breathing cycles showed no ΔP or a slightly positive pressure. This phenomenon occurred at all depths to 200 fsw.

The performance at 40 RMV (figure 3) was almost identical to performance at 22.5 RMV except that the regulator was slightly more stable and did not pulse between negative and positive pressures as frequently during the breathing cycle. This pressure "pulse" occurs more often in unmanned diving situations because of the large compliance volume of the test apparatus. It is not a problem under actual diving conditions.

It is significant that at 75 RMV (figure 4) inhalation resistance increased greatly but was still within mil spec limits down to 180 fsw, because most conventional regulators exceed the mil spec limits at 66 to 99 fsw at 75 RMV.

Cracking pressure at all RMV's was approximately 1.5 cm H₂O. This extremely low ΔP requires that the PRE-DIVE switch position be used when the regulator mouthpiece is not in the diver's mouth.

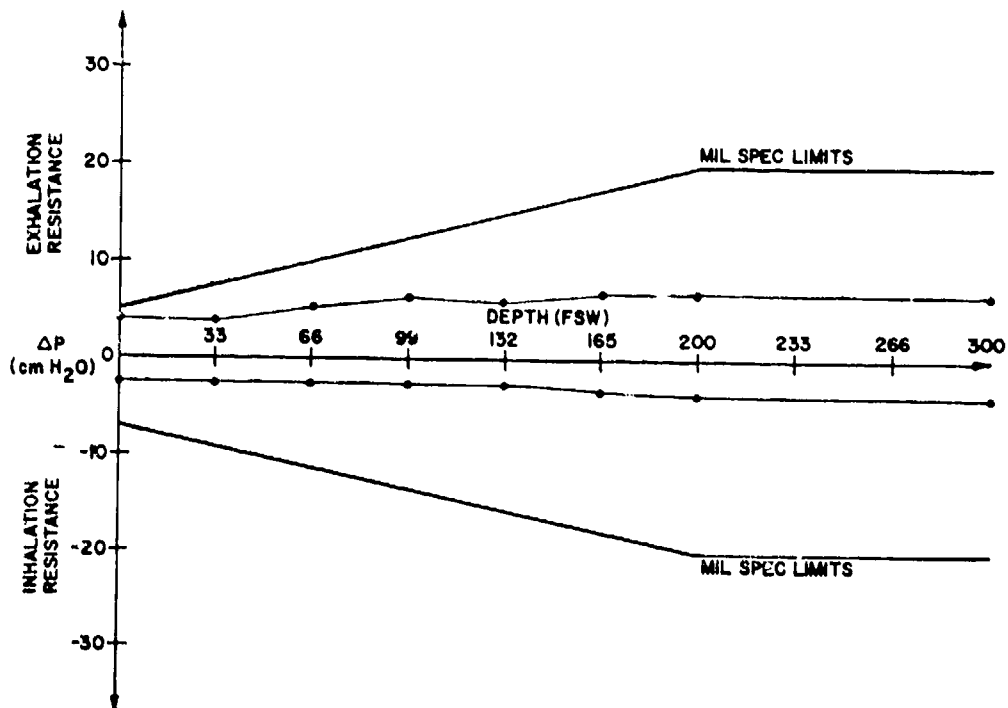


FIGURE 2. BREATHING RESISTANCE VS. DEPTH FOR MK V PILOT REGULATOR IN DIVE MODE AT 15 BPM, 1.5 TIDAL VOLUME, AND 22.5 RMV AND 1000-PSIG SUPPLY PRESSURE

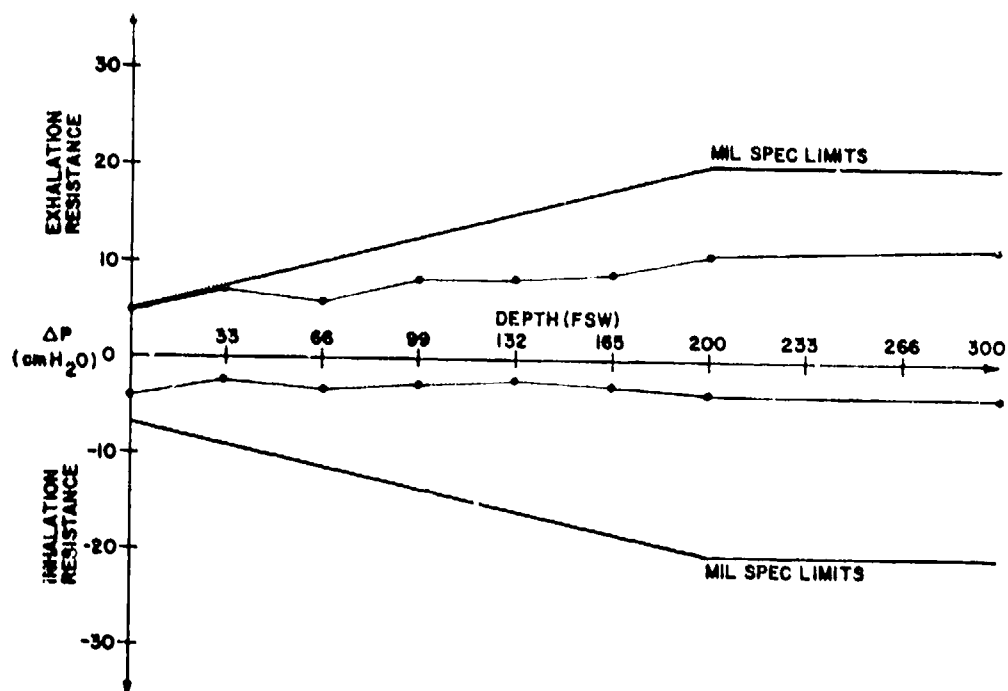


FIGURE 3. BREATHING RESISTANCE VS. DEPTH FOR MK V PILOT REGULATOR IN DIVE MODE AT 20 BPM, 2.0 TIDAL VOLUME, AND 40 RMV AND 1000-PSIG SUPPLY PRESSURE

Breathing resistance was not affected by reduction of first stage supply pressure except at 200 fsw and 75 RMV. At this point, 200-psig O/B supply pressure produced breathing pressure of 40 cm H₂O.

2. Exhalation Characteristics. Exhalation resistance at 22.5 RMV (figure 2) and 40 RMV (figure 3) was within mil spec limits and was comparable with that of most Navy-approved regulators. At 75 RMV (figure 4), exhalation pressures exceeded mil spec limits throughout the depth range, as they do with all Navy-approved regulators.

b. Regulator in Pre-Dive Mode

1. Inhalation Characteristics (figure 5). When the pilot regulator DIVE/PRE-DIVE switch is set to PRE-DIVE to prevent free-flow, a spring preloads the second stage diaphragm linkage. More pressure is required, therefore, to actuate the pilot valve, making the regulator more stable and significantly increasing inhalation resistance.

The regulator was tested only at 40 RMV and 1000-psig supply pressure in the pre-dive mode. The sole purpose of the test was to verify that the regulator meets mil spec requirements in the pre-dive mode, inasmuch as a diver could inadvertently leave the switch in PRE-DIVE while making a dive. No pressure pulses occurred and inhalation flow was smooth in the pre-dive mode. Although breathing resistance was noticeably higher than in the dive mode, it was within mil spec limits to 300 fsw.

2. Exhalation Characteristics (figure 5). Because the PRE-DIVE switch position does not affect the exhaust valve, the results of the test at 40 RMV were nearly the same as the results in the dive mode (see 40 RMV test under "Regulator in Dive Mode").

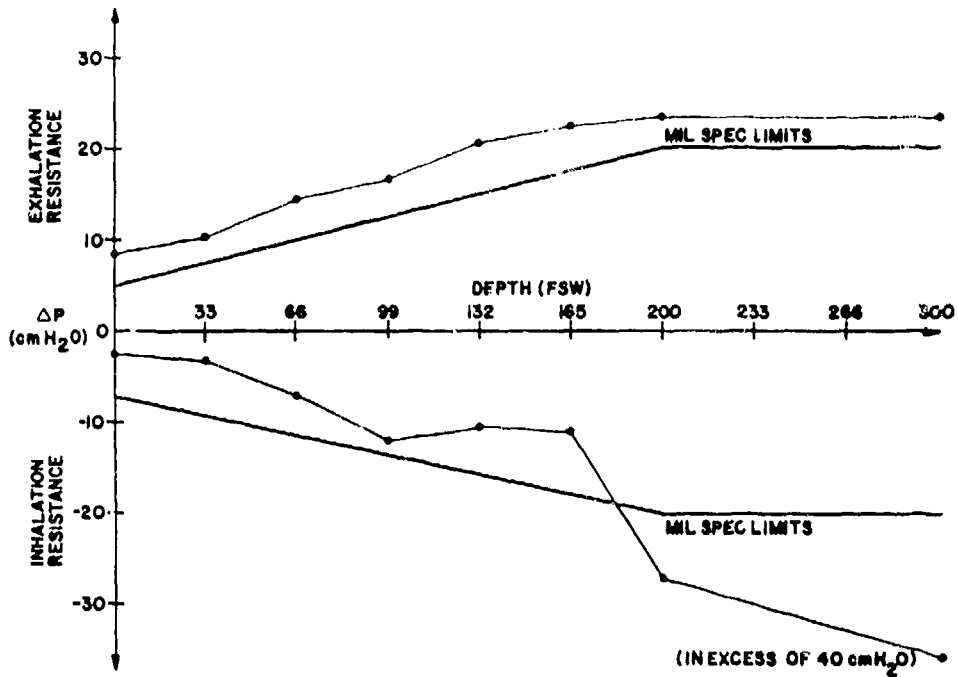


FIGURE 4. BREATHING RESISTANCE VS. DEPTH FOR MK V PILOT REGULATOR IN DIVE MODE AT 25 BPM, 3.0 TIDAL VOLUME, AND 75 RMV AND 1000-PSIG SUPPLY PRESSURE

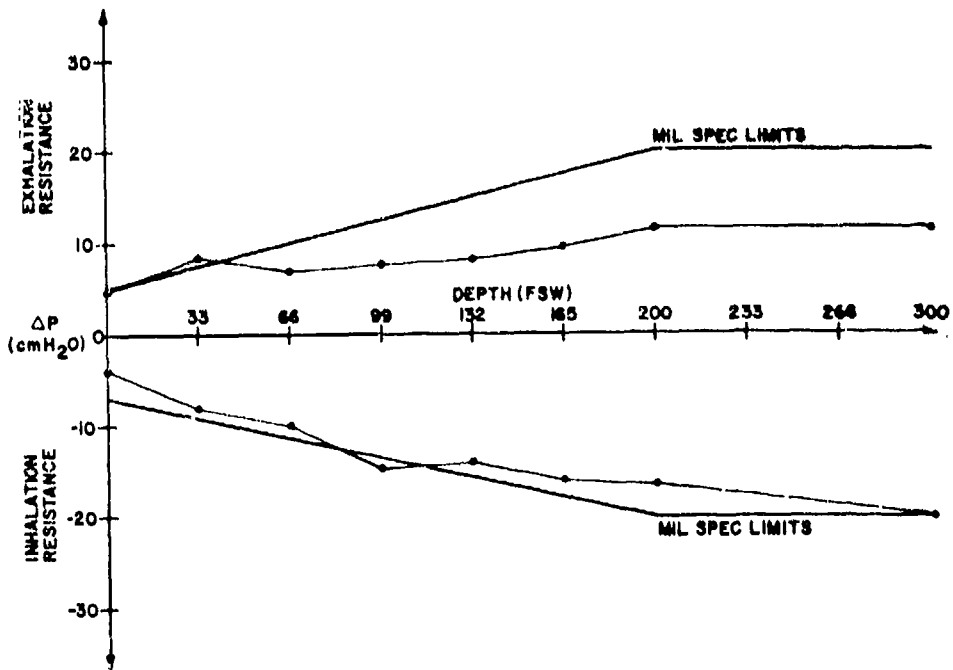


FIGURE 5. BREATHING RESISTANCE VS. DEPTH FOR MK V PILOT REGULATOR IN PRE-DIVE MODE AT 20 BPM, 2.0 TIDAL VOLUME, AND 40 RMV AND 1000-PSIG SUPPLY PRESSURE

FIRST STAGE PERFORMANCE

Intermediate pressure drop between the first and second stages under flow conditions was monitored to assess total regulator performance at specified RMV's and depths. The maximum intermediate pressure drop from the static setting was plotted. By correlating this information with breathing resistance plots, poor regulator performance can be traced to the first stage, second stage, or both.

a. Regulator in Dive Mode. The factory setting of static pressure on the Scubapro MK V Pilot Regulator is 140-psig O/B. At 22.5 RMV (figure 6), the first stage pressure drop was small, reaching a maximum of only 19 psig less than the static setting. When supply pressure dropped to 500 and 200 psig O/B, no increase in ΔP was measured. These results demonstrated why inhalation resistance at 40 RMV did not increase at low supply pressures (figure 7).

At 75 RMV (figure 8), ΔP increased rapidly beyond 132 fsw and reached a maximum of 48 psig at 200 fsw. It is unusual that, at this depth and RMV, inhalation resistance was only 27 cm H₂O. The relatively low inhalation resistance under extreme conditions is attributed to the large volume of second stage porting and to the function of the pilot valve. As supply pressure was reduced, first stage ΔP changed very little, accounting for the relatively low inhalation resistance of 40 cm H₂O at 75 RMV and 200-psig O/B supply pressure.

b. Regulator in Pre-dive Mode (figure 9). Again, the PRE-DIVE position of the regulator switch does not affect first stage operation and regulator performance was nearly identical to 40-RMV performance in the dive mode (see a above).

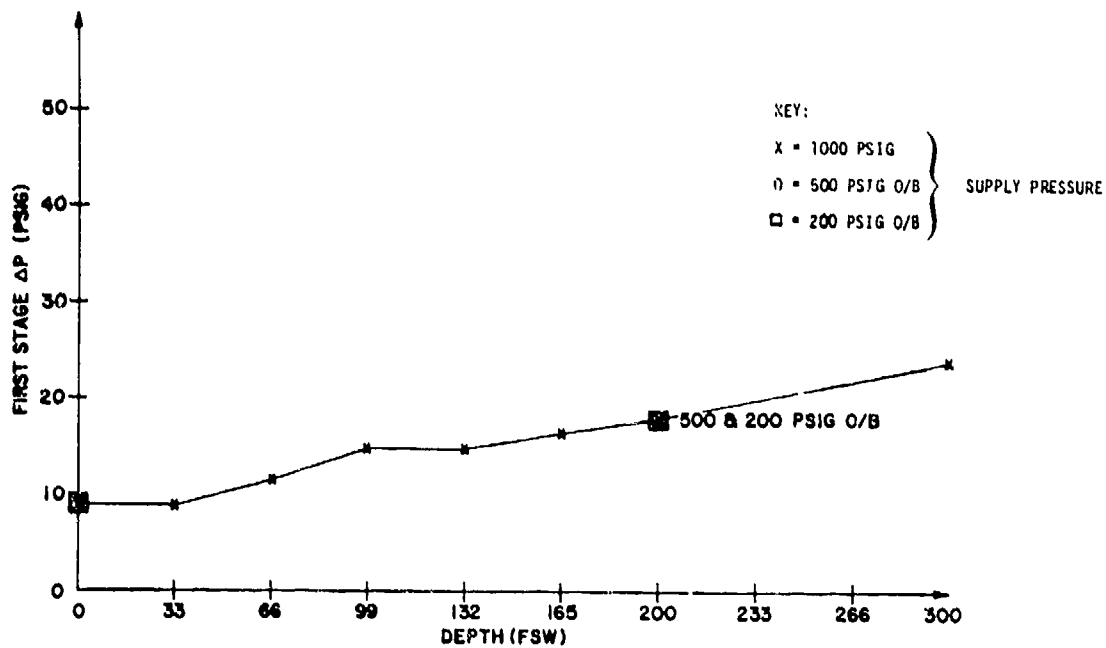


FIGURE 6. FIRST STAGE ΔP VS. DEPTH FOR MK V PILOT REGULATOR IN DIVE MODE AT 15 BPM, 1.5 TIDAL VOLUME, AND 22.5 RMV

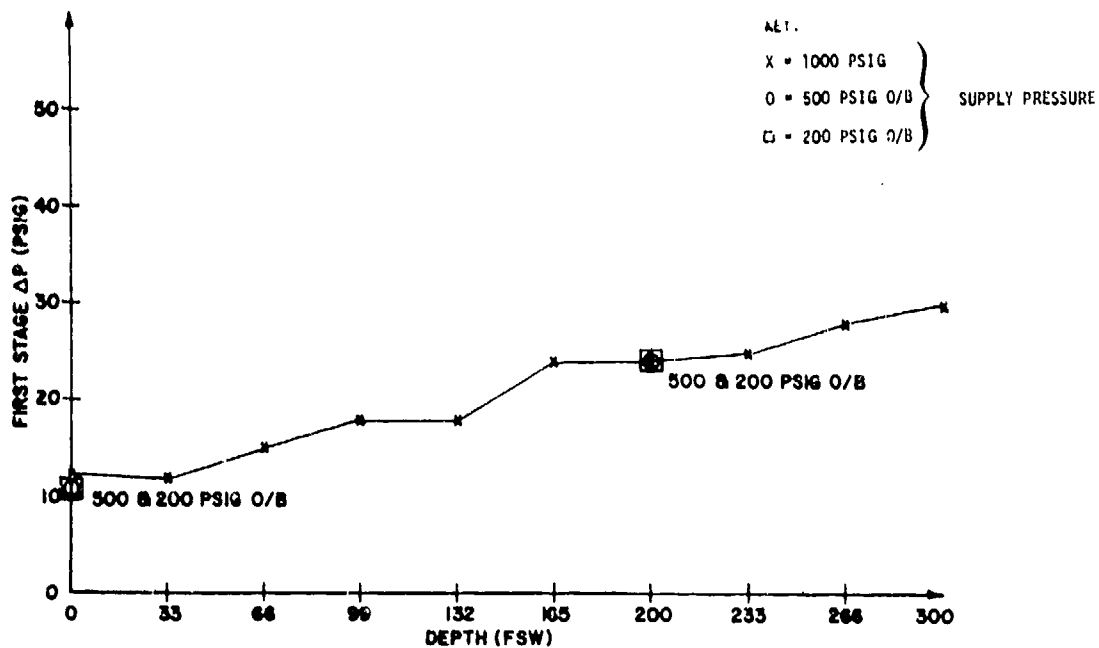


FIGURE 7. FIRST STAGE ΔP VS. DEPTH FOR MK V PILOT REGULATOR IN DIVE MODE AT 20 BPM, 2.0 TIDAL VOLUME, AND 40 RMV

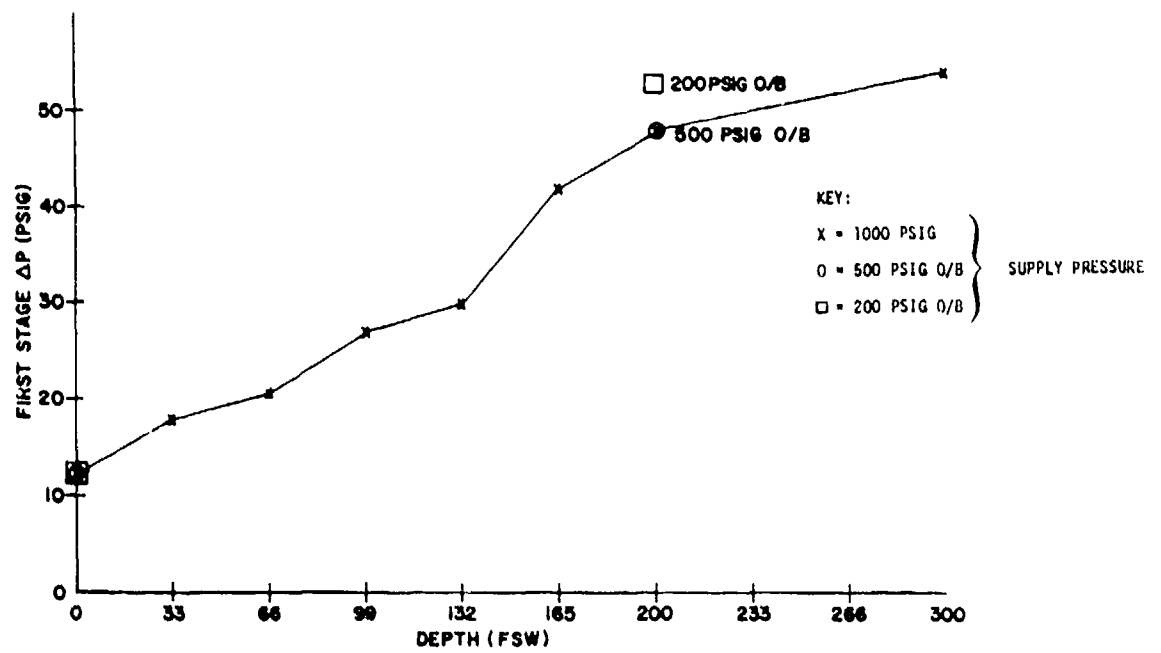


FIGURE 8. FIRST STAGE ΔP VS. DEPTH FOR MK V PILOT REGULATOR IN DIVE MODE AT 25 BPM, 3.0 TIDAL VOLUME, AND 75 RMV

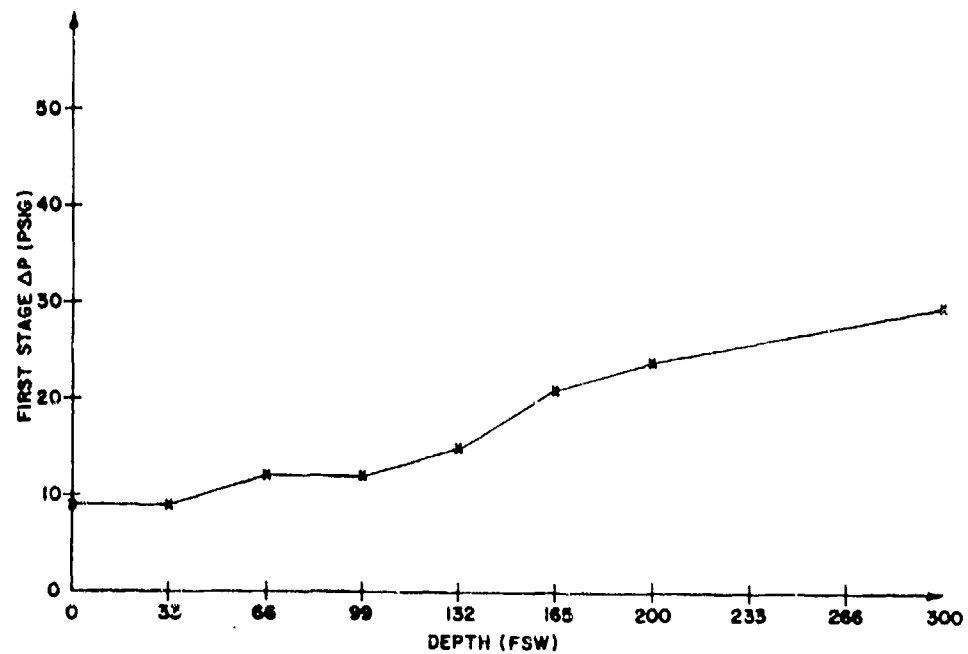


FIGURE 9. FIRST STAGE ΔP VS. DEPTH FOR MK V PILOT REGULATOR IN PRE-DIVE MODE AT 20 BPM, 2.0 TIDAL VOLUME, 40 RMV, AND 1000 PSIG SUPPLY PRESSURE

WORK OF BREATHING

The specification governing testing of all breathing apparatuses cites peak inhalation and peak exhalation pressures as the standard for evaluation (reference 3). However, recent research (reference 4) has shown that measurement of diver's external respiration work in operating his breathing apparatus yields useful data for evaluating equipment performance. In breathing apparatuses other than open-circuit demand, breathing work is probably the most valid measurement of equipment performance. With open-circuit scuba, breathing work is a supplementary indicator of regulator performance. Reference 4 proposes a standard of 0.170 kilogram-meter per liter ventilation ($\text{kg}\cdot\text{m}/\text{l}$; liter ventilation is defined as tidal volume at a given RMV) as the maximum allowable external respiratory work. This figure is used in this report for comparative purposes only. Breathing work is defined as the area enclosed by a typical pressure-volume loop generated during one complete breathing cycle.

a. Regulator in Dive Mode (figure 10). Breathing work is extremely low at 22.5 RMV, reaching only $0.075 \text{ kg}\cdot\text{m}/\text{l}$ at 200 fsw. At 40 RMV, work increases only slightly over 22.5 RMV and is well within the proposed limits. An RMV of 75 produces work rates that exceed the proposed limit at 100 fsw.

b. Regulator in Pre-dive Mode (figure 11). Breathing work is substantially greater at 40 RMV when the DIVE/PRE-DIVE switch is set to PRE-DIVE than when it is set to DIVE. Work exceeded the proposed limit at 100 fsw even though the breathing resistance was within the mil spec (see figure 5).

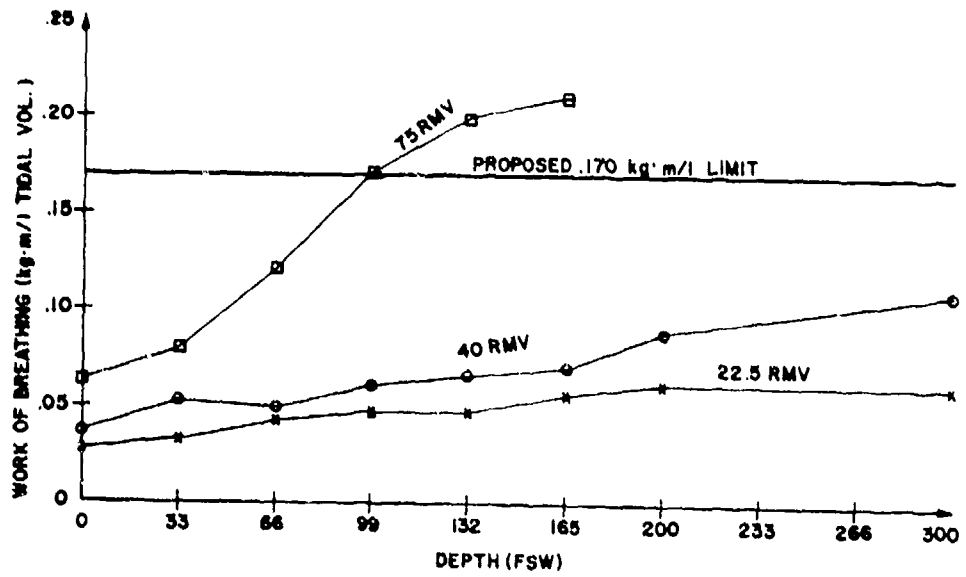


FIGURE 10. BREATHING WORK VS. DEPTH FOR MK V PILOT REGULATOR IN DIVE MODE

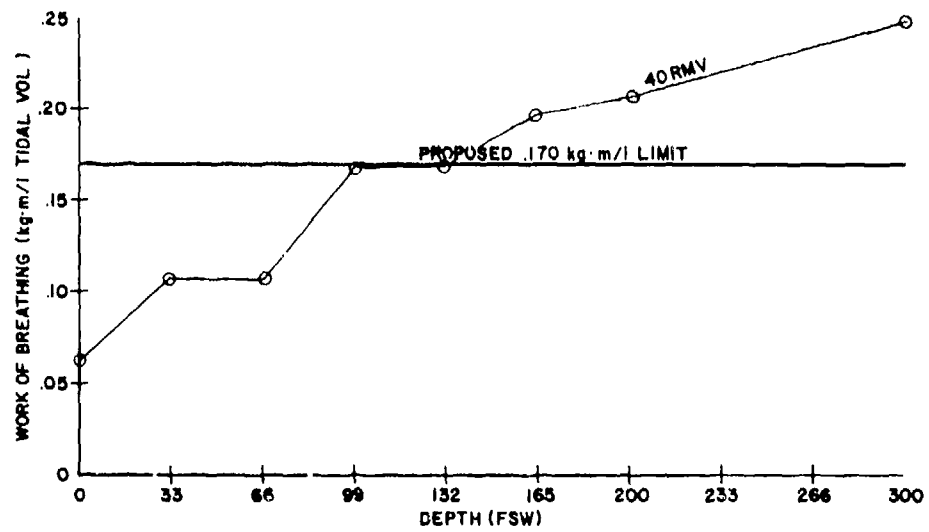


FIGURE 11. BREATHING WORK VS. DEPTH FOR MK V PILOT REGULATOR IN PRE-DIVE MODE AT 40 RMV

CONCLUSIONS AND RECOMMENDATIONS

The Scubapro MK V Pilot Regulator meets mil spec requirements and is recommended for placement on the list of equipment authorized for Navy use. The pilot-assisted second stage provides exceptionally easy breathing with low diver work rates.

First stage performance was also good. The first stage maintained intermediate pressure and flow at 200 fsw and high RMV with supply pressures of 200-psig O/B. Uniform inhalation characteristics were maintained regardless of the supply pressure.

Results of the test indicate that increased breathing resistance at high RMV was due to first stage pressure drop instead of second stage performance. Consequently, when the pilot second stage is supplied by two first stages, inhalation resistance should remain nearly constant regardless of the depth or RMV. However, the regulator has not been tested with two first stages nor will it be practical or necessary in most diving situations.

Although performance was severely affected when the regulator was used in the pre-dive mode, it was still within the mil spec requirements. Operating the regulator in the pre-dive mode does not threaten diver safety and the pre-dive mode effectively prevents free-flow on the surface.

The complexity of the pilot second stage with three times as many parts most other second stages is one area of concern. Maintenance will require considerable skill and training, and could present problems for fleet operators unless special training is made available.

REFERENCES

1. OOC Letter WRB:1F, 3960/2003, Serial 1273, 6 Aug 1976.
2. Department of the Navy Military Specification MIL-R-24169A, Regulator, Air, Demand, Single Hose, Nonmagnetic, Divers, 22 March 1967.
3. Navy Experimental Diving Unit Report 23-73, U.S.N. Procedures for Testing the Breathing Characteristics of Open-Circuit Scuba Regulators, by S. D. Reimers, p. 5, 11 December 1973.
4. Navy Experimental Diving Unit Report 19-73, Proposed Standards for the Evaluation of the Breathing Resistance of Underwater Breathing Apparatus, by S. D. Reimers, p. 36, 30 January 1974.

APPENDIX A

TEST PLAN

The plan for testing the Scubapro MK V Pilot Regulator consisted of the following steps.

1. Insure that the regulator is set to factory specifications and is working properly.
2. Insure that the chamber is on the surface.
3. Calibrate the transducers and zero the transducer by regulator position after water is added to the wet test box.
4. Open the air supply valve to test the regulator and set the supply pressure at 1000 psig.
5. Adjust the breathing machine to 1.5 liter tidal volume and 15 BPM and take readings.
6. Stop the breathing machine.
7. Establish zero flow ΔP position on the x-y plotter.
8. Adjust the air supply pressure to 500 psig O/B.
9. Repeat steps 5 through 7.
10. Adjust the air supply pressure to 200 psig O/B. (Be sure that the breathing resistance transducer stays within its range.)
11. Repeat steps 5 through 7.
12. Pressurize the chamber to 33 fsw.
13. Adjust the air supply to 1000 psig.
14. Repeat steps 5 through 7.
15. Pressurize the chamber to 55 fsw.
16. Adjust the air supply to 1000 psig.
17. Repeat steps 5 through 7.

18. Pressurize the chamber to 99 fsw.
19. Adjust the air supply to 1000 psig.
20. Repeat steps 5 through 7.
21. Pressurize the chamber to 132 fsw.
22. Adjust the air supply to 1000 psig.
23. Repeat steps 5 through 7.
24. Pressurize the chamber to 165 fsw.
25. Adjust the air supply to 1000 psig.
26. Repeat steps 5 through 7.
27. Pressurize the chamber to 200 fsw.
28. Repeat steps 4 through 11.
29. Pressurize the chamber to 300 fsw.
30. Adjust the air supply to 1000 psig.
31. Repeat steps 5 through 7.
32. Set the breathing machine to 2.0-liter tidal volume and 20 BPM.
(This replaces step 5.)
33. Repeat steps 4 through 31 in reverse order (as chamber is being brought to surface, make incremental stops in reverse order).
34. Set the breathing machine to 3.0-liter tidal volume and 25 BPM.
(This replaces step 5.)
35. Repeat steps 4 through 31.
36. Bring the chamber to the surface (no stops).
37. Check the transducer calibration.

APPENDIX B

TEST EQUIPMENT

The following equipment was used in testing the Scubapro MK V Pilot Regulator. The equipment setup is shown in figure 1.

1. NEDU breathing machine
2. Validyne model DP-15 pressure transducer with 1-psid diaphragm
3. NEDU wet test box
4. Validyne model DP-15 pressure transducer with 250-psid diaphragm
5. MFE x-y plotter, model 715M, serial number 30925002
6. Validyne model CD-12 transducer readouts (2), serial numbers 12247 and 5538
7. 71.2-cu. ft. scuba tank
8. NEDU "D" chamber complex
9. Roylyn air supply pressure gauge, model 0 to 2000 psig with accuracy to 0.25 percent; calibration date, August, 1976
10. Marotta dome loader
11. Roylyn chamber depth gauge, model 0 to 2300 fsw with accuracy to 0.25 percent; calibration date, December, 1975
12. Test regulator (first and second stage), Scubapro MK V Pilot serial number 6801298
13. Bourns piston position transducer, model 200176400B
14. Transducer isolation tube

APPENDIX C

MAN-HOURS REQUIRED

The man-hours required for the test of the Scubapro MK V Pilot Regulator are computed below.

	<u>Men</u>	<u>Hours</u>	<u>Man-Hours</u>
Test set-up	3	2	6
Test operation	3	4	12
Chamber operation	1	4	4
Post-test cleanup	2	1	2
Data reduction/report production	1	80	80
Duplicating	4	25	<u>100</u>
TOTAL			204