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(6) LIFE SUPPORT CHARACTERISTICS OF THE MARK 11 SEMI-CLOSED MIXED GAS UNDERWATER BREATHING APPARATUS AT INTERMEDIATE DEPTHS.

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A series of three saturation dives designed to evaluate the ability of the Mark 11 UBA to support a working diver in its normal semi-closed mode of operation were performed at the Navy Experimental Diving Unit. Experiments were undertaken to determine the life expectancy of Mark 11 CO_2 removal canisters in several configurations, and to investigate the ability of the system to support sustained, heavy work in cold water to depths of 450 FSW. (CONTINUED)

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Canister duration studies were performed with three types of CO_2 absorbent beds and with or without prototype baffles. Analysis of the data revealed a maximum mean Mark 11 canister life expectancy of 270 ± 50 minutes at 310 FSW and 35°F (1.7°C), which decreased substantially with depth and cold temperatures, and was highly variable from diver to diver. No changes to the basic canister configuration offered any significant increases in mean canister duration, however, canisters using Baralyme at 390 FSW had shorter durations than the other tested absorbents. Other life support characteristics such as breathing resistance, thermal protection, and P_{O_2}, were adequate to depths of 450 FSW. The large scatter in canister breakthrough data coupled with limited sample size made it difficult to establish high-confidence operational limits for the Mark 11 UBA in its present configuration.

ABSTRACT

A series of three saturation dives designed to evaluate the ability of the Mark 11 UBA to support a working diver in its normal semi-closed mode of operation were performed at the Navy Experimental Diving Unit. Experiments were undertaken to determine the life expectancy of Mark 11 CO_2 removal canisters in several configurations, and to investigate the ability of the system to support sustained, heavy work in cold water to depths of 450 FSW.

Canister duration studies were performed with three types of CO_2 absorbent beds and with or without prototype baffles. Analysis of the data revealed a maximum mean Mark 11 canister life expectancy of 270 $\pm$ 50 minutes at 310 FSW and 35°F (1.7°C), which decreased substantially with depth and cold temperature, and was highly variable from diver to diver. No changes to the basic canister configuration offered any significant increases in mean canister duration, however, canisters using Baralyme at 390 FSW had shorter durations than the other tested absorbents. Other life support characteristics such as breathing resistance, thermal protection, and P_{O_2}, were adequate to depths of 450 FSW. The large scatter in canister breakthrough data coupled with limited sample size made it difficult to establish high-confidence operational limits for the Mark 11 UBA in its present configuration.

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Introduction

The Mark 11 semi-closed mixed gas UBA and associated equipment is designed to provide the complete life support and thermal protection required for saturation divers to operate for up to four hours in 28°F (-2.2°C) water to depths of 850 FSW. The Mark 11 diver is tethered to a diver support facility by an umbilical which supplies breathing gas, hot water, and electrical connections. Hot water is routed through a breathing subsystem (Figure 1) where it warms a canister containing a carbon dioxide absorbent bed, and then to a thermal protection garment, the Mark 16 hot water suit.

During normal semi-closed circuit operation, breathing gas from the umbilical passes through an absolute pressure regulator block into an inhalation bag, and then through a hose connection to an oronasal face mask. Exhaled gas passes from the oronasal mask via a hose to an exhalation bag. From the exhalation bag, most of the exhaled gas flows through the CO_2 removal canister to the inhalation bag where it is mixed with incoming gas from the umbilical, and subsequently rebreathed. A portion of the exhaled gas does not pass through the canister but is exhausted to the water through an attitude sensitive exhaust valve (cardioid valve).

Diver safety features include two-way communication equipment, a PO_2 sensor, and switchover indication equipment. If umbilical gas supply pressure drops to a low level, the absolute pressure regulator admits breathing gas from a small emergency supply in the back-pack. If the breathing bags or canister flood, the diver can switch to open circuit on umbilical, or for a short time, emergency gas supply. Therefore, a normal operating mode and three back-up modes are available to the diver (Figure 2).

A number of parameters effect the ability of a diver to perform sustained work at depth while diving with this type of UBA. One of the most important of these parameters is the PCO_2 in the inspired gas. The PCO_2 is dependent upon gas flow rates, CO_2 absorbent efficiency, and the rate of CO_2 production by the exercising diver. A previous evaluation of the Mark 11 UBA in four feet of water demonstrated that the CO_2 absorbent canister appeared to absorb CO_2 efficiently for up to seven hours during prolonged moderate work in cold water (1). However, gas flow rates through the UBA during this study were so high (up to 16.4 actual lpm) that much of the CO_2 produced by the exercising diver bypassed the canister, and was exhausted through the cardioid valve.

In order to evaluate the ability of the Mark 11 UBA to support a working diver in its normal operating mode at intermediate depths, a series of three saturation dives were performed at the Navy Experimental Diving Unit. Experiments undertaken during these dives were designed to determine the life expectancy of Mark 11 CO_2 removal canisters and to investigate the ability of the system to support sustained heavy work in cold water at depth.

Methods

Three saturation dives with depth-time profiles of 310 FSW for twelve days, 390 FSW for fifteen days, and 350/450 FSW for thirteen days, were performed in the Ocean Simulation Facility of the Navy Experimental Diving Unit. Each dive involved six male divers in good physical condition, who were conditioned prior to the dives by running up to 7 km per day, and pedaling up to 200 watts for six minutes daily on a pedal ergometer. Two divers participated in two of the dives, and one subject participated in all three dives. Dry determinations of oxygen consumption and carbon dioxide production were obtained in six subjects immediately before and after the 350/450 FSW dive. Baseline studies were also performed at 30 FSW prior to each saturation dive to familiarize the dive subjects with the experimental protocol.

The experiments were divided into two phases; the first phase consisted of canister duration studies, and the second phase consisted of graded exercise studies. Breathing gas mixture on the 310 FSW dive was 88/12 helium-oxygen, and on the other dives it was 90/10 helium-oxygen. Rig flow rates were adjusted for an average diver oxygen consumption ($\dot{V}_{O_2}$) of 2.0 lpm with a maximum PO_2 of 1.6 ATA, and a minimum PO_2 of 0.4 ATA. A number 9 orifice was used to provide maximum mass flow through the rig.

Canister CO_2 absorbent was High Performance Sodasorb (HP-Sodasorb) or special 18% moisture HP-Sodasorb for all dives except the 390 FSW dive. Canister duration studies during the 390 FSW dive employed Baralyme as the CO_2 absorbent. The change from Baralyme to HP-Sodasorb between the first and second dives was based upon the results of unmanned Mark 11 canister tests performed at the Naval Coastal Systems Center (NCSC). These studies suggested that HP-Sodasorb increased the life expectancy of the CO_2 removal canister by a small margin (2).

All dive subjects wore the Mark 11 Mod 0 UBA with an umbilical length of 300 feet. Wet pot temperature was maintained at 35°F (1.7°C). In order to duplicate situations of cold breathing gas, a special gas chiller at the umbilical source designed to cool inspired gas to near ambient temperature was used in all studies. All divers wore a Mark 16 hot water suit with flow and temperature adjusted at 2.5 gallons per minute and not greater than 110°F (43.3°C) at the diver.

Gas samples from the canister outlet, canister inlet, and oronasal mask were monitored for PO_2 and PCO_2 with a mass spectrometer. A small diameter gas sample line, as designed by Thalmann et.al.(3), resulted in little gas sample mixing and good frequency response, thereby allowing interpretation of end tidal PCO_2 values. In addition, diver heart rate, inspired gas temperature, and rectal temperature were monitored, and oronasal differential pressure was measured with a modified Validyne pressure transducer. These parameters were recorded on a Gould eight channel strip chart recorder.

Dive subjects exercised on a special underwater pedal ergometer (4) mounted on a frame placed approximately ten feet underwater. Exercise schedules for canister duration and graded exercise studies were as outlined in Table 1. All measurements were made during the final minute of each exercise period, after steady state had been reached. It is possible that the actual work performed to overcome the combined resistance of the water, thermal garment, and ergometer was as much as twice the indicated load, as submergence alone has been estimated to increase the work of cycling by 33 to 42 percent (5). During graded exercise, the diver continued to exercise until he had completed the final work load or until he became fatigued. Incomplete work cycles were not included in the data. Canister duration studies were terminated when canister effluent CO_2 reached 7.6 mmHg or one percent surface equivalent value (SEV). Canister breakthrough was defined as that point in time when canister effluent CO_2 reached 3.8 mmHg (0.5% SEV).

Results

Figure 3 is a graphic depiction of mean canister breakthrough curves with 18% moisture HP-Sodasorb at depths of 310, 350, and 450 FSW. All curves shown are similar in configuration, and differ only at the point in time at which peak canister effluent CO_2 levels with exercise begin to rise. The 310 FSW curve represents the mean of four canisters, and the 350 and 450 FSW curves represent the means of six canisters each.

Table 2 tabulates the complete set of manned canister duration results using a variety of canister configurations at all test depths. Prototype baffles were installed in four canisters during the 310 FSW dive, but these canisters did not differ statistically in breakthrough time from unmodified canisters tested under the same conditions. All subsequent canister duration studies were performed with unmodified canisters. The canisters tested at 390 FSW used Baralyme as the CO_2 absorbent, and canister life times were uniformly brief, with a mean duration of 73 ± 15 minutes.

Unmanned testing at NCSC (2) suggested that HP-Sodasorb was a better CO_2 absorbent than Baralyme in this canister, and all subsequent canister duration studies were performed with HP-Sodasorb or special 18% moisture HP-Sodasorb. During the 310 FSW dive, special 18% moisture HP-Sodasorb appeared to have a greater life expectancy than ordinary HP-Sodasorb, but the differences in mean canister duration were not statistically significant.

Figure 4 graphs mean canister duration versus depth for canisters packed with special 18% moisture HP-Sodasorb at 35°F (1.7°C). This graph emphasizes the great variability in canister duration between individual divers at the same depths, and it shows a significant decrement in mean canister duration with increasing depth. Unmanned canister data indicates an additional 13-15 percent decrement in canister duration from 35°F to 30°F (-1.1°C) at the same test depths (6).

Table 3 is a summary of the graded exercise studies from all three dives. Peak end tidal P_{CO_2} values ($P_{ET_{CO_2}}$), oronasal differential pressures, inspired gas temperatures, and heart rates are tabulated for all test depths and work rates.

Peak $P_{ET_{CO_2}}$, as illustrated by Figure 5, increased significantly at low work rates from rest levels and then leveled off or declined at higher work rates for all depths.

High minute ventilation did not result in "CO_2 blow-by" secondary to inadequate gas residence time in the canister, as inspired P_{CO_2} did not exceed 3.1 mmHg (0.4% SEV) during graded exercise at any depth.

Figure 6 graphs oronasal differential pressure versus work rate for each test depth. Oronasal differential pressure increased with increasing work rate, and to some extent with increasing depth. Differences in oronasal pressure with increasing depth were not statistically significant. Minimum oronasal differential pressure was 13 $\pm$ 2 cm H_2O at 310 FSW during rest, while maximum oronasal differential pressure was 38 $\pm$ 2 cm H_2O at 450 FSW and 150 watts.

Mean inspired gas temperatures were six to twelve degrees Farenheit above ambient water temperature, and increased by an additional five to ten degrees Farenheit during maximum work rates. Mean inspired gas temperatures did not vary significantly with depth (Table 3). Divers occasionally complained of increased upper respiratory secretions which they attributed to cold breathing gas. Heat loss from the respiratory tract was probably substantial, but not sufficient to decrease rectal temperature during exercise.

Inspired P_{O_2} varied between 1.2 and 0.4 ATA during graded exercise. The higher P_{O_2} occured during rest and gradually decreased to the lower value as work rate was increased from 50 to 150 watts.

Table 4 summarizes oxygen consumption ($\dot{V}_{O_2}$) and carbon dioxide production ($\dot{V}_{CO_2}$) data obtained on the six 350/450 FSW dive subjects immediately preceeding and following that dive. Figure 7 graphs work rate versus mean $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$. Each diver produced CO_2 at approximately the same rate before and after the dive. Variations in $\dot{V}_{CO_2}$ between individual dive subjects did not exceed 20 percent at any work rate. Heart rate increased in a linear fashion with respect to work rate and $\dot{V}_{O_2}$. This same linear relationship can be seen with heart rate versus work rate at depth (Table 3).

Discussion

The physiology of steady state exercise in diving is complicated by the effects of increased gas density and hyperoxia (7). Both of these conditions are associated with decreased ventilatory response to exercise and CO_2 retention at depth in divers even when they are not subject to increased external breathing resistance. Increased gas density increases external breathing resistance in any UBA, which tends to further depress ventilation.

If the ability of the diver to increase ventilation with an increase in metabolic CO_2 production is impaired, arterial and tissue P_{CO_2} rise. This can invoke a number of undesirable physiological responses including increased susceptibility to decompression sickness, oxygen toxicity, inert gas narcosis, and depression of central nervous system function.

This problem of rising P_{CO_2} is demonstrable during graded exercise studies when $P_{ET_{CO_2}}$ with exertion rises to as much as 53 mmHg (Figure 5). $P_{ET_{CO_2}}$ is felt to approximate arterial P_{CO_2}, although the $P_{ET_{CO_2}}-P_{A_{CO_2}}$ gradient in divers still requires investigation. Divers are capable of working with elevated P_{CO_2} levels, but the dyspnea associated with a given work load is generally greater than at normal P_{CO_2} levels.

In view of these physiological considerations, elevated inspired P_{CO_2} is hazardous to the diver. Arterial P_{CO_2} begins to rise in subjects performing light work in air when inspired P_{CO_2} reaches 21 mmHg (8). This data and the shape of the canister breakthrough curves (Figure 3) support the 0.5 percent SEV CO_2 (3.8 mmHg) canister breakthrough criterion, as canister effluent CO_2 levels rise at a markedly increased rate once this value is reached, and inspired P_{CO_2} could reach 21 mmHg within a few minutes. The graded exercise studies did not demonstrate canister "CO_2 blow-by", provided the CO_2 absorbent bed remained active.

The Mark 11 canister life expectancy in all tested configurations is brief, decreases substantially with depth and cold, and is highly variable from individual to individual. Canisters packed with special 18% moisture HP-Sodasorb did not have a significantly longer life expectancy than canisters packed with ordinary HP-Sodasorb, although further investigation in this area is warranted.

All canister studies were also performed with the largest available gas flow orifice, which optimizes canister duration. The large orifice results in maximum ventilation through the rig, and this allows more CO_2 to bypass the canister and exhaust through the cardioid valve.

Individual diver variability in canister duration cannot be explained by differences in $\dot{V}_{CO_2}$, as all divers were within 20 percent of each other during dry exercise $\dot{V}_{CO_2}$ studies. In addition, heart rates at depth were comparable to heart rates during dry studies for given work loads, and heart rate correlates well with $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ (9). If each diver performed more work at depth than was indicated on the ergometer because of water and thermal suit resistance, then he did it at a lower heart rate than would be predicted from the dry exercise studies. Nevertheless, small individual differences in $\dot{V}_{CO_2}$ are not sufficient to explain large individual differences in canister duration.

Inspired gas temperatures met the minimum standards required by the U.S. Navy Diving Manual. Respiratory heat loss was probably substantial but not sufficient to lower rectal temperatures in exercising divers. Upper respiratory tract symptoms were noted in some cases, but could not be solely attributed to cold inspired gas, as low inspired relative humidity may have contributed to these symptoms.

In view of these findings, the Mark 11 UBA in its present configuration is operationally limited and cannot meet its original life support objectives until substantial improvements in CO_2 absorbent canister design are made. Other life support characteristics of the Mark 11, such as P_{O_2}, breathing resistance, and thermal protection appear to be adequate to depths of 450 FSW.

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APPENDIX

LIST OF FIGURES AND TABLES

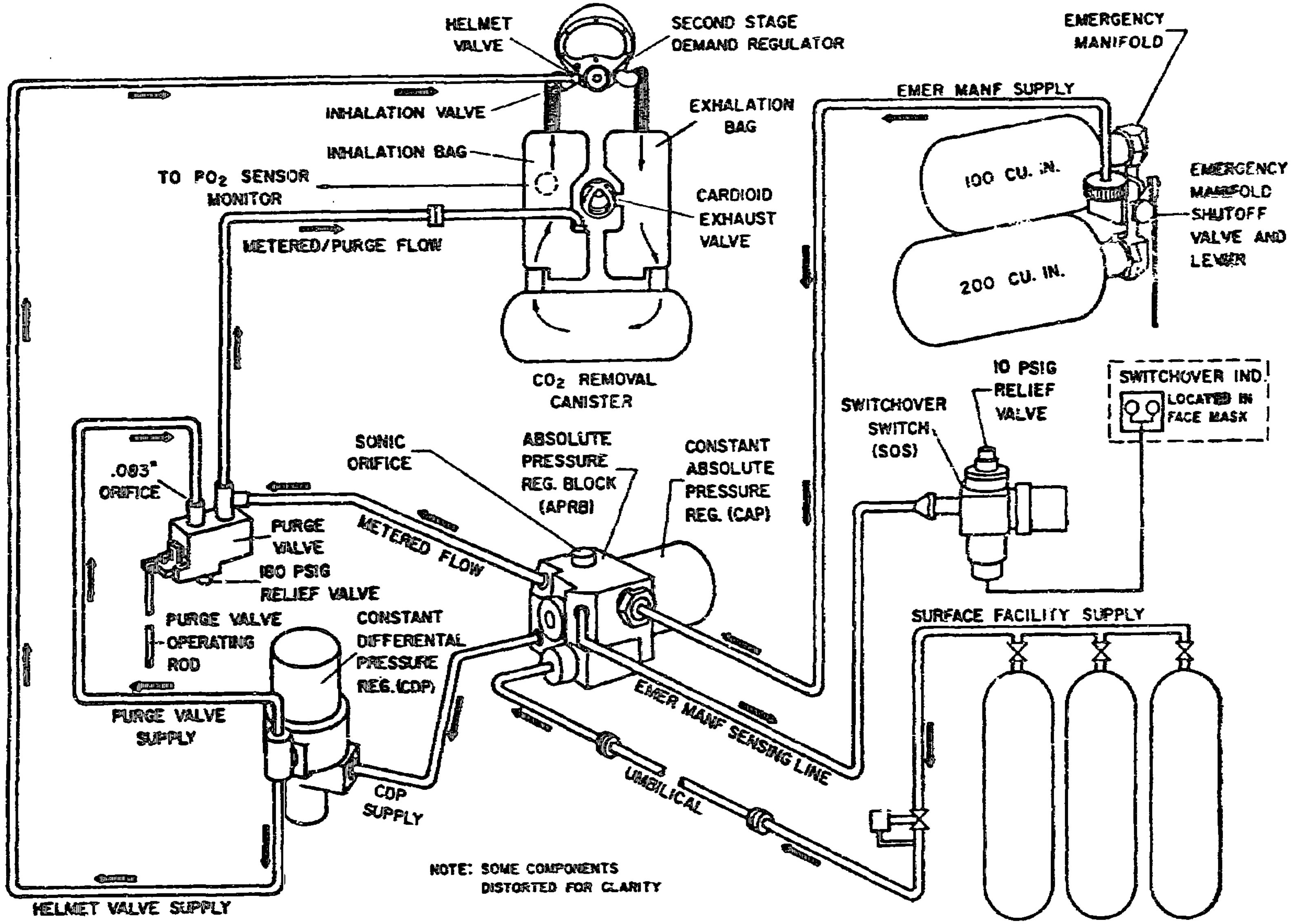
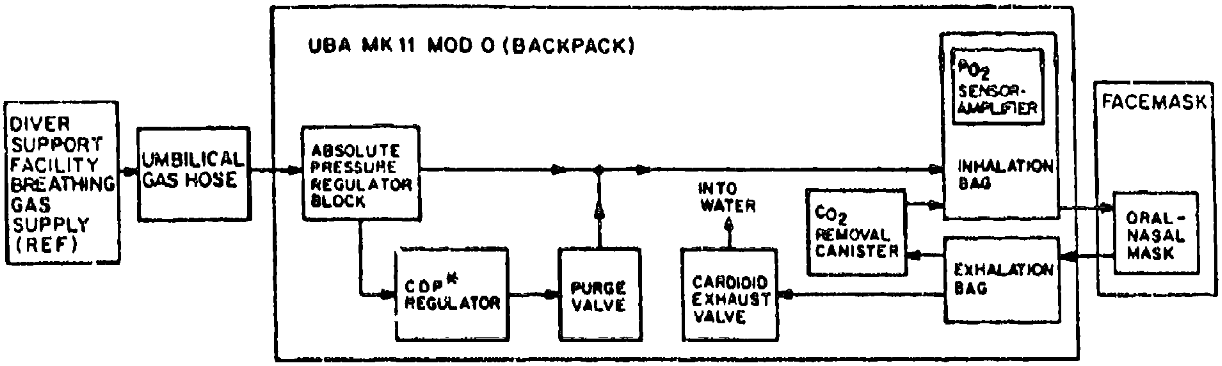
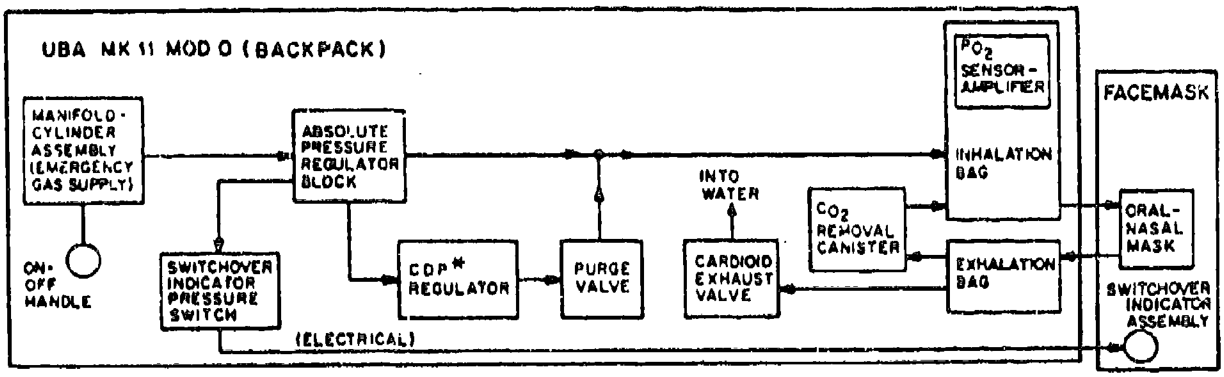


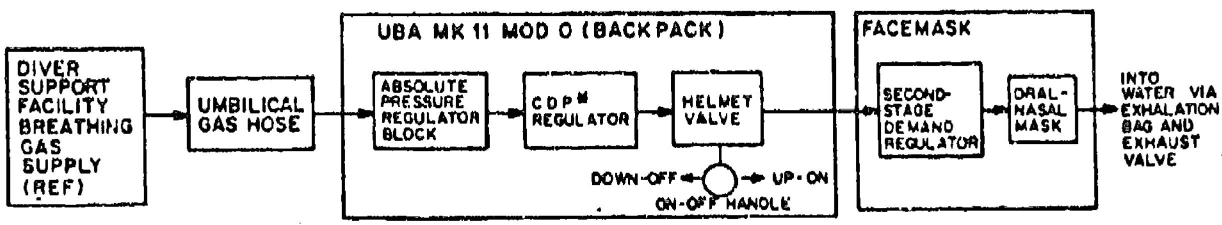
FIGURE 1. MARK 11 BREATHING SUBSYSTEM



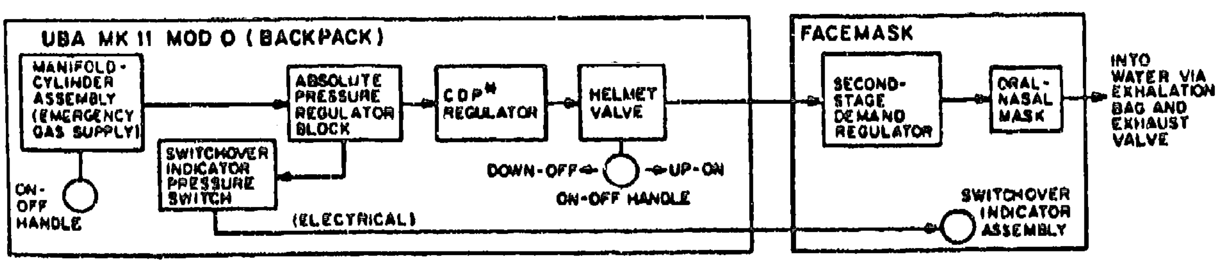
A. SEMICLOSED-CIRCUIT, UMBILICAL-SUPPLIED OPERATION



B. SEMICLOSED-CIRCUIT, EMERGENCY MANIFOLD-SUPPLIED OPERATION



C. OPEN-CIRCUIT, UMBILICAL-SUPPLIED OPERATION



D. OPEN-CIRCUIT, EMERGENCY MANIFOLD-SUPPLIED OPERATION

* CONSTANT DIFFERENTIAL PRESSURE

FIGURE 2. GAS FLOW DIAGRAM IN EACH OPERATING MODE

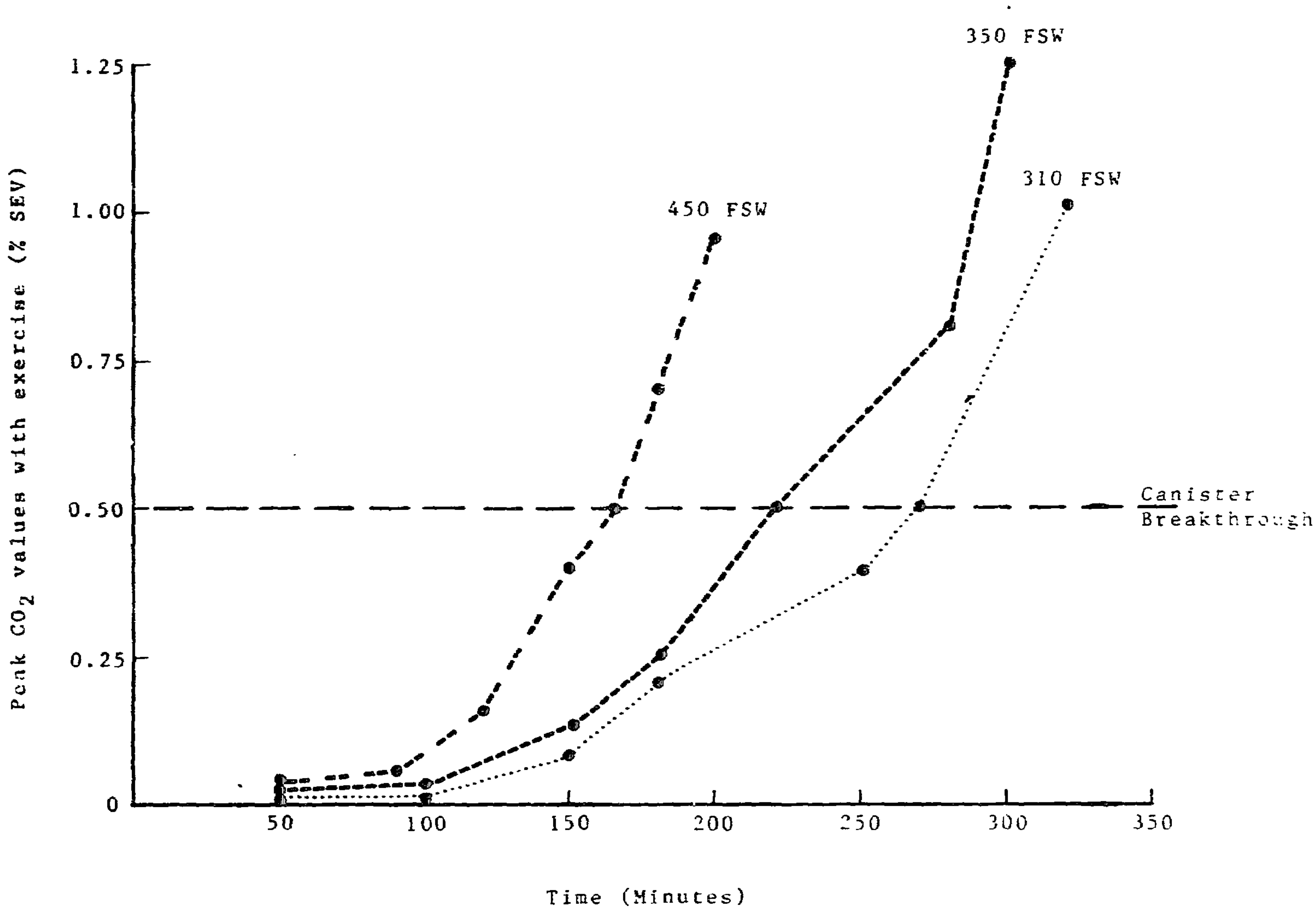


FIGURE 3 MEAN CANISTER BREAKTHROUGH CURVES AT 310, 350, 450 FSW WITH 18% HP-SODASORB AT 35° F (1.7° C)

Depth (FSW)	Mean Canister Duration
310	270 ± 50
350	221 ± 65
450	165 ± 23

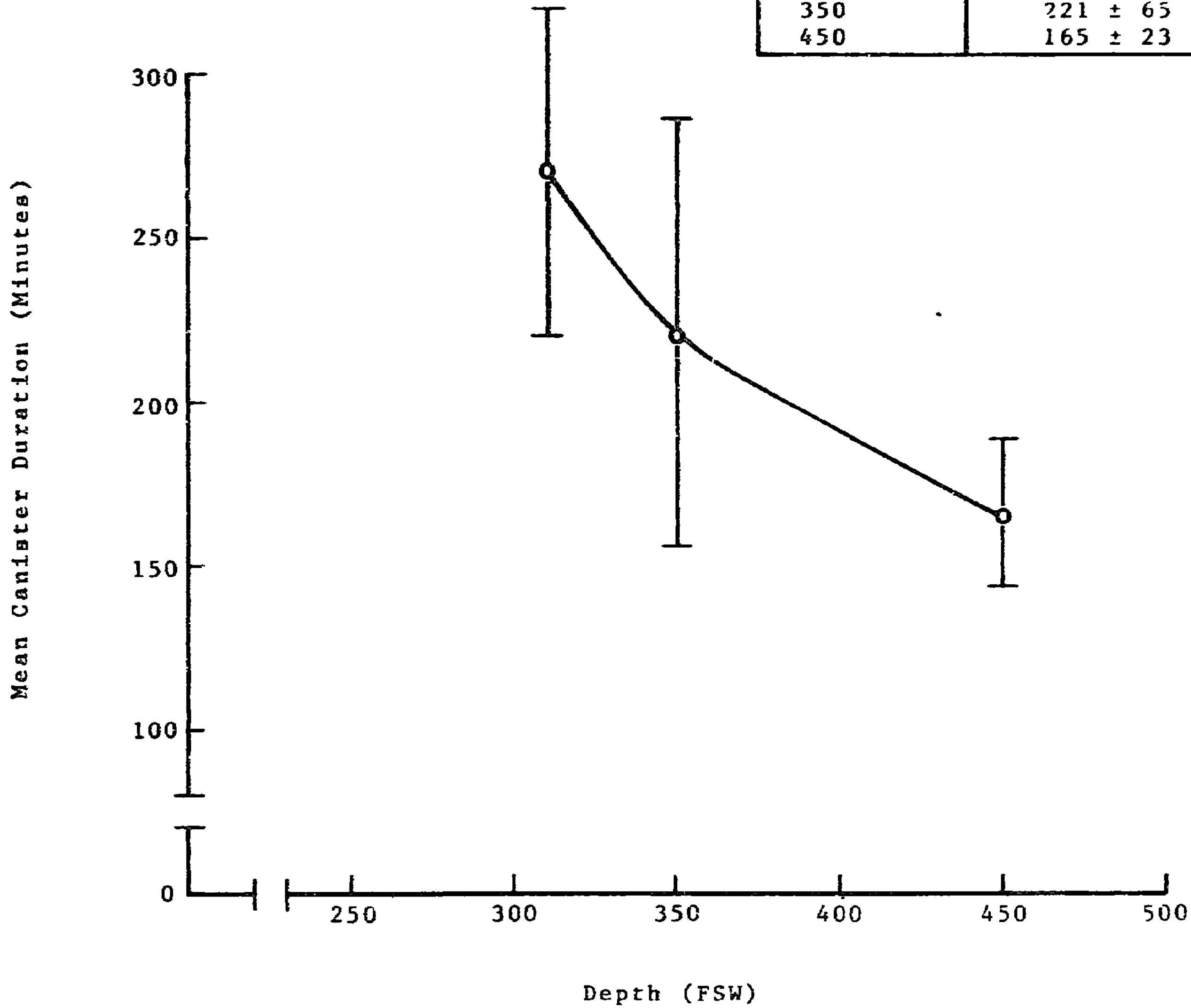


FIGURE 4 MEAN CANISTER DURATION VERSUS DEPTH - 18% MOISTURE HP SODASORB AT 35° F (1.7° C)

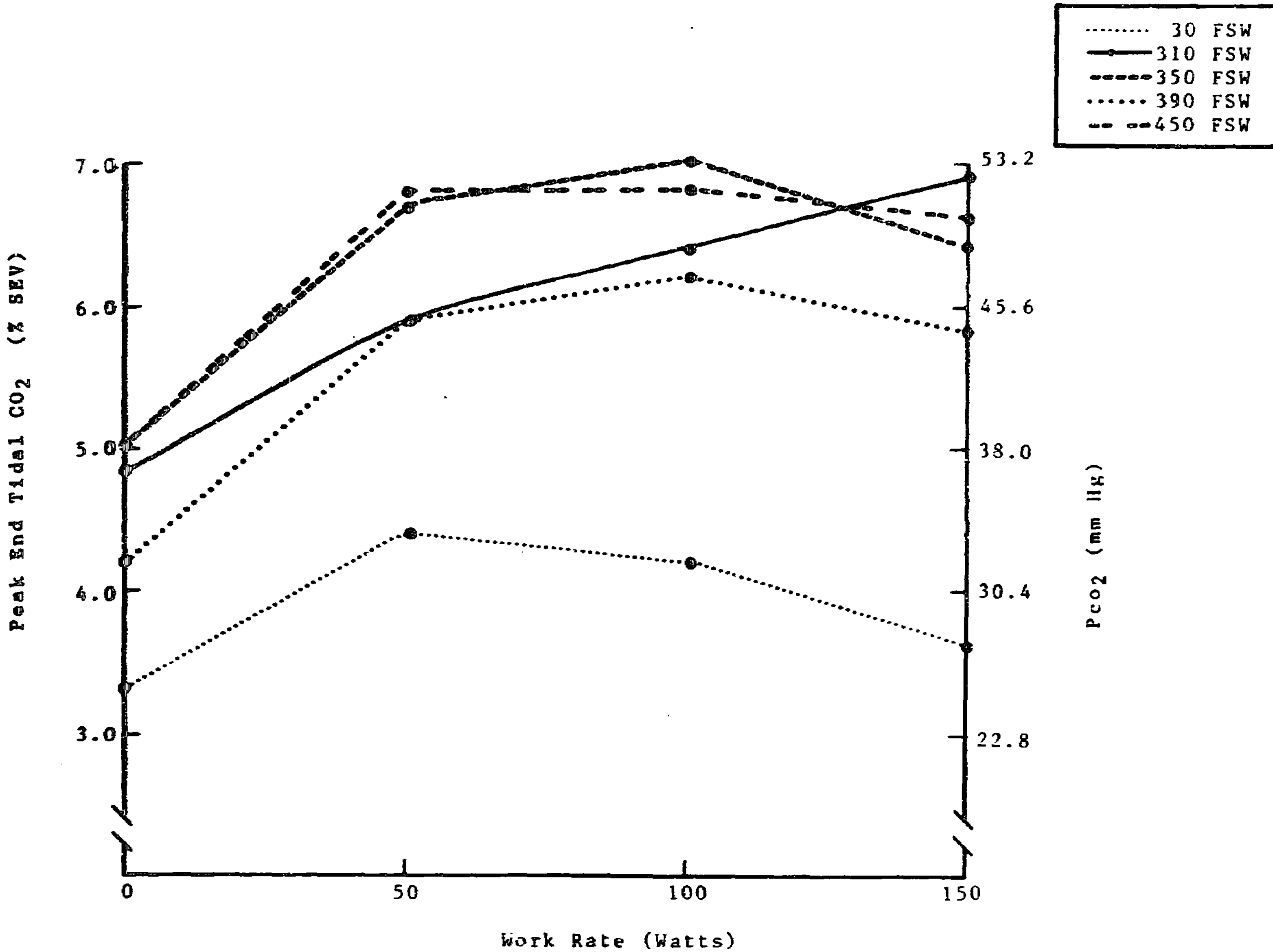


FIGURE 5 PEAK END TIDAL CO_2 VERSUS WORK RATE AT ALL TEST DEPTHS

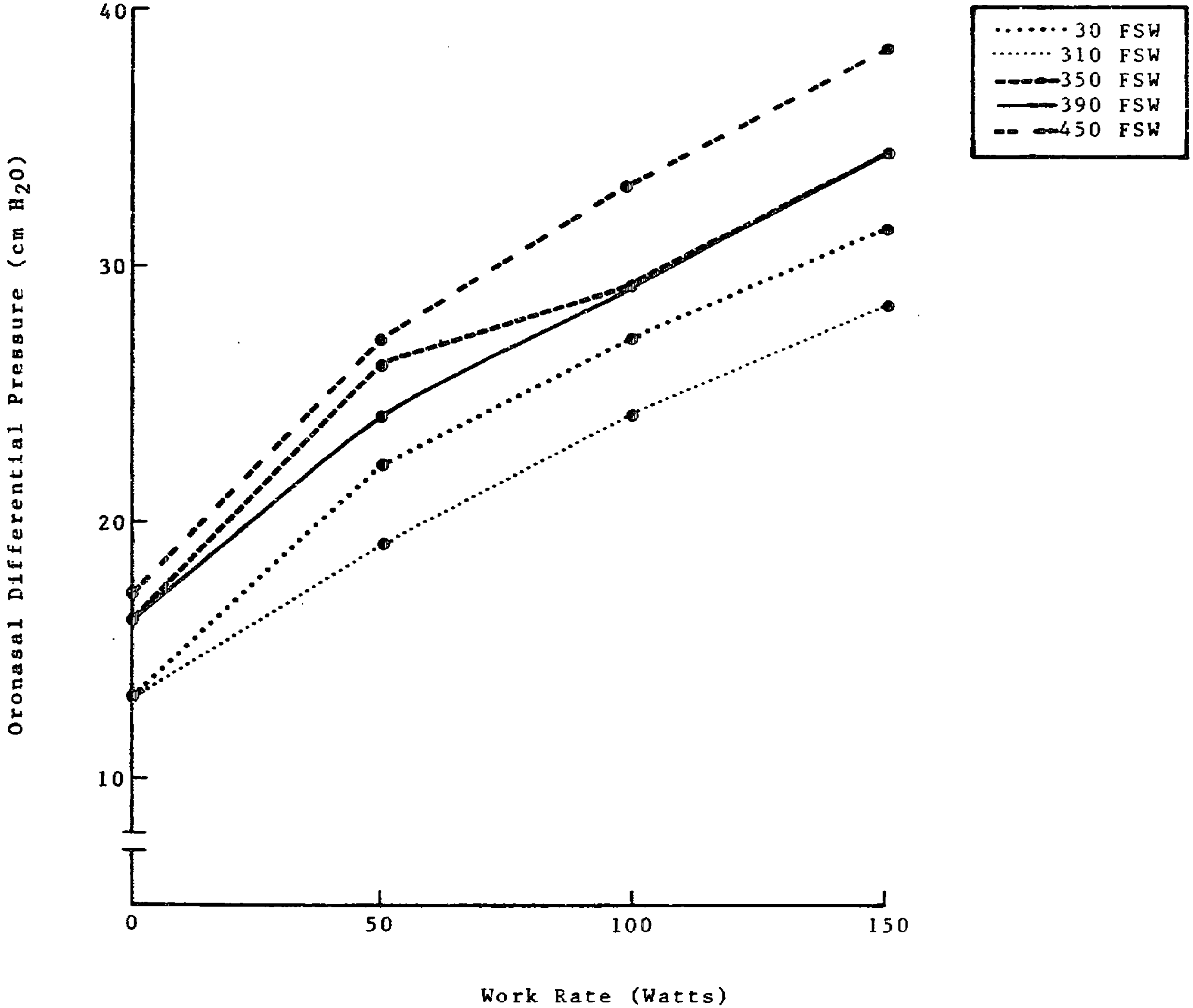


FIGURE 6 ORONASAL DIFFERENTIAL PRESSURE VERSUS WORK RATE

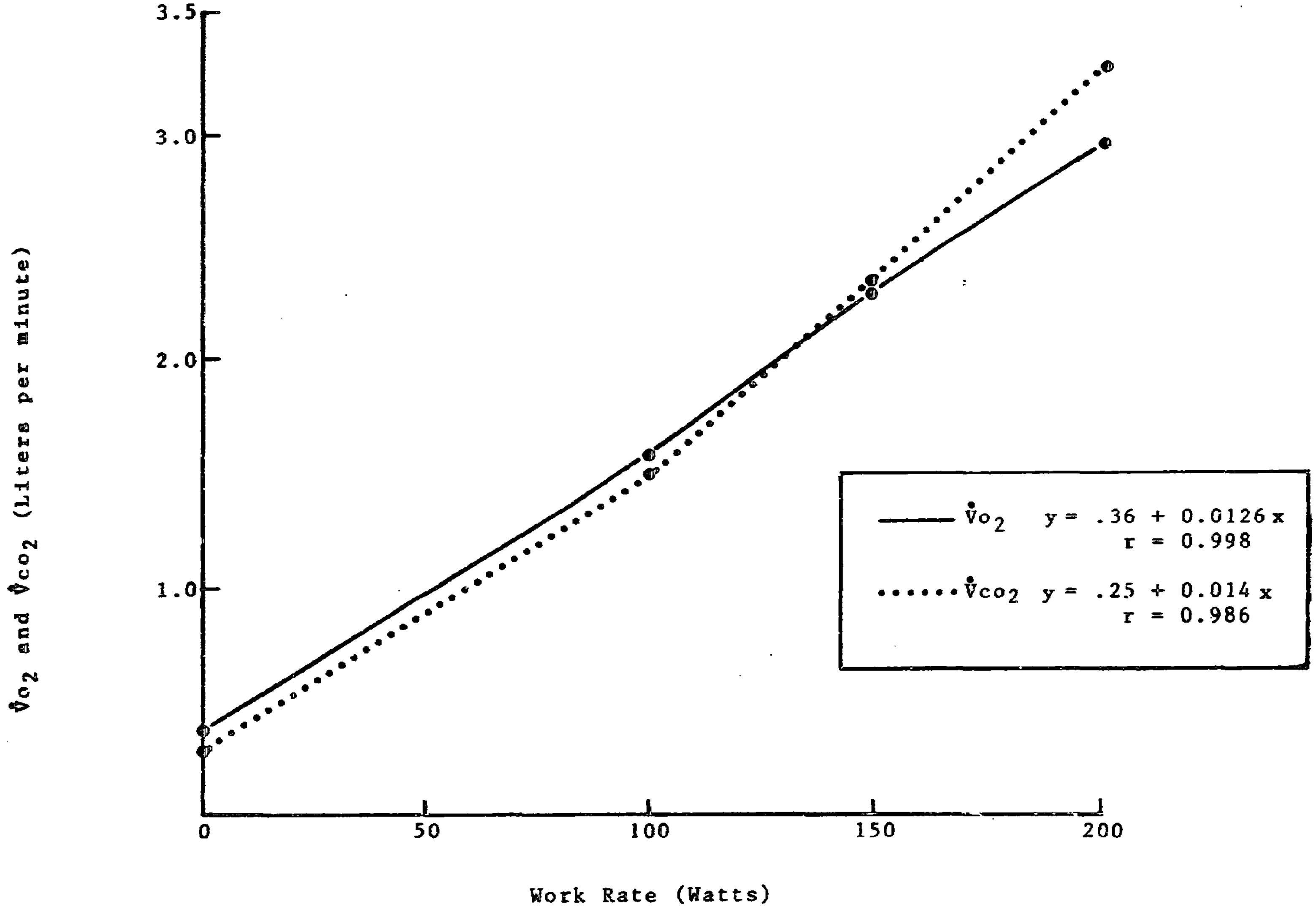


FIGURE 7 $\dot{V}o_2$ AND $\dot{V}co_2$ VERSUS WORK RATE

Type Of Study	Time	Work Rate	Duration
1. Canister duration	0-5 Min	Rest	5 Min
	5-11 Min	50 Watts	6 Min
	11-15 Min	Rest	4 Min
	15-21 Min	50 Watts	6 Min
	21-25 Min	Rest	4 Min
Work-Rest cycle continues until d ver becomes fatigued or until the canister is exhausted (7 hour limit)			
2. Graded exercise	0-6 Min	Rest	6 Min
	6-12 Min	50 Watts	6 Min
	12-15 Min	Rest	3 Min
	15-21 Min	100 Watts	6 Min
	21-24 Min	Rest	3 Min
	24-30 Min	150 Watts	6 Min

TABLE 1 EXERCISE SCHEDULES FOR CANISTER DURATION AND GRADED EXERCISE STUDIES

Depth (FSW)	Canister Configuration	Diver	Canister Duration (Min to 0.5% SEVCO$_2$)
310	HP-Sodasorb Unmodified	1	265
		2	260
		3	160
		4	185
		Mean ± SD	216 ± 54
310	HP-Sodasorb prototype baffles	1	235
		2	180
		3	192
		4	90
		Mean ± SD	174 ± 60
310	18% Moisture HP-Sodasorb Unmodified	1	250
		2	310
		3	200
		4	320
		Mean ± SD	270 ± 50
350	18% Moisture HP-Sodasorb Unmodified	1	220
		2	166
		3	340
		4	165
		5	195
		6	241
		Mean ± SD	221 ± 65
390	Baralyme Unmodified	1	67
		2	87
		3	55
		4	82
		Mean ± SD	73 ± 15
450	18% Moisture HP-Sodasorb Unmodified	1	165
		2	150
		3	165
		4	130
		5	185
		6	195
		Mean ± SD	165 ± 23

TABLE 2 TABULATION OF MANNED MARK II CANISTER DURATION STUDIES AT 35° F (1.7° C)

Parameter	Depth	Rest	Work Rate (Watts) 50	100	150
Peak	30	3.3±0.2	4.4±0.4	4.2±0.5	3.6±0.7
End	310	4.8±0.5	5.9±0.6	6.4±0.9	6.8±1.1
Tidal CO_2	350	5.0±0.8	6.7±0.5	7.0±0.4	6.4±0.5
% Sev	390	4.2±0.5	5.9±0.3	6.2±0.3	5.8±1.3
(Mean ± SD)	450	5.0±0.4	6.8±0.7	6.8±0.5	6.6±0.8
Oronasal	30	13±2	22±2	27±2	31±2
Differential	310	13±2	19±3	24±2	28±2
Pressure	350	16±2	26±5	29±4	34±4
cm H_2O	390	16±3	24±4	29±5	34±6
(Mean ± SD)	450	17±2	27±3	33±4	38±2
	30	47±2	49±3	51±3	57±4
Inspired	310	45±2	50±2	53±3	55±1
Gas Temperature	350	41±3	43±4	45±4	46±4
°F.	390	45±2	49±3	50±4	54±5
(Mean ± SD)	450	46±2	52±2	55±3	54±4
	30	82±4	120±6	145±15	174±13
Heart	310	75±5	128±6	158±8	182±6
Rate	350	76±4.	117±5	138±14	163±10
(Mean ± SD)	390	73±12	118±10	145±15	169±10
	450	79±10	121±11	141±2	168±13

TABLE 3 TABULATION OF RESULTS OF MARK II GRADED EXERCISE STUDIES

Work Rate	Heart Rate	$\dot{V}o_2$ (lpm)	$\dot{V}co_2$ (lpm)
Rest	86±6	0.39±.06	0.35±.08
100 Watts	122±13	1.56±.10	1.49±.18
150 Watts	147±14	2.28±.19	2.33±.24
200 Watts	176±19	2.90±.11	3.23±.23

TABLE 4 TABULATION OF RESULTS OF DRY EXERCISE STUDIES