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

NAVY EXPERIMENTAL DIVING UNIT
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MANNED EVALUATION OF THE SWIMMER LIFE SUPPORT SYSTEM MARK 1

LCDR J. L. ZUMRICK

February 1978

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the breathing gas was nitrogen-oxygen. Because of this and because of nitrogen narcosis considerations, the operational depth was subsequently limited to 150 FSW for nitrogen-oxygen breathing.

ABSTRACT

The Swimmer Life Support System Mark 1 (SLSS MK 1) was evaluated for its ability to support divers performing heavy work at 30, 140, and 210 FSW. Heart rate, mouth differential pressure with respiration, inspired oxygen, and inspired carbon dioxide levels were monitored. Results indicate that oxygen and carbon dioxide levels were adequately controlled at all depths and work rates, but breathing resistance was excessive at 210 FSW when the breathing gas was nitrogen-oxygen. Because of this and because of nitrogen narcosis considerations, the operational depth was subsequently limited to 150 FSW for nitrogen-oxygen breathing.

INTRODUCTION

The Swimmer Life Support System Mark 1 (SLSS MK 1), a closed circuit diving apparatus, was first evaluated in 1972 (Hawkins) as the Biomarine CCR-1000. This unit was selected due to its light weight, long duration independent of depth, and bubble-free operation. However, the CCR-1000 was found unacceptable because of deficiencies in human engineering. The manufacturer modified the apparatus and introduced it as the SLSS MK 1. This unit was found to be satisfactory during unmanned testing in 1976 (Paulsen).

The SLSS MK 1 is a closed circuit scuba apparatus. It consists of a backpack, breathing loop, pneumatics assembly, and associated electronics (Figure 1). As the diver exhales, gas passes through the exhalation check valve and hose into the carbon dioxide cannister. The cannister is filled with either Baralyme[R] (3.74 kg) or Sodasorb[R] (3.28 kg) which absorbs the carbon dioxide produced by the diver. The gas then passes over 3 oxygen sensors into a 7 liter diaphragm assembly. The oxygen sensors' signal, proportional to the partial pressure of oxygen, is compared with a calibration level. When the oxygen level falls below the calibration level (usually 0.7 ATM) an oxygen solenoid opens, admitting oxygen to the breathing loop from the oxygen supply

(21 cu. ft.). In addition to the oxygen supply, the pneumatics assembly includes a respirable diluent supply consisting of either He-O_2, or air, which is utilized to maintain breathing loop volume with changes in depth. The backpack is a base upon which to mount the various subassemblies.

Several factors determine the safety and ability of a closed circuit diving apparatus to support heavy work. Of primary importance is the maintenance of safe levels of inspired oxygen and carbon dioxide. In addition, the external breathing resistance imposed by the apparatus should not be excessive. The purpose of this study was threefold:

(1) Determine the adequacy of oxygen control.

(2) Determine the ability of the SLSS MK 1 to maintain inspired CO_2 levels within safe limits during graded exercise, and

(3) Determine the breathing resistance of the SLSS MK 1.

METHODS

An eleven day saturation dive was conducted in the Ocean Simulation Facility of the U.S. Navy Experimental Diving Unit. This mode of diving allowed time for more prolonged experiments without incurring an excessive decompression requirement. Five healthy male underwater swimmers participated in the study. For three weeks prior to the dive, all subjects performed daily calisthenics and 7 km runs. In addition, each diver performed daily underwater exercise similar to that done during the dive.

The SLSS MK 1 was calibrated to control oxygen partial pressure at 0.7 ATM (532 mmHg). Air was used as the respirable diluent gas. For all exercise sequences, the scrubber assembly was filled to capacity with Baralyme.[R]

The divers wore gas-blown neoprene full wet suits. The water temperature was 20°C.

The experimental protocol consisted of graded exercise utilizing a pedal mode ergometer (James, 1976). For half the dives, the subjects utilized a vertical ergometer simulating upright work. During the remaining dives, a horizontal ergometer was employed. Graded exercise consisted of 4 minute rest periods separating 6 minute work periods at 25, 50, 75, 100, 125, 150 and 175 watts respectively after an initial 10 minute rest period. These ergometer settings do not reflect the work imposed by the wet suit, nor the resistance of a highly viscous water medium. Costill (1971) estimated that work done in water by bathing suit clad subjects is between 32 to 40% greater than that done in air. Thus, true work levels may have been as much as 50% greater than indicated.

All experimental data was continuously collected during the final minute of the exercise period and recorded using a strip chart. Conventional ECG electrodes were applied to the divers' chests to measure heart rate. Gas samples from the inhalation hose were conducted via 1/8 inch o.d. tubing to the surface where they were analyzed for O_2 and CO_2 by a mass spectrometer. Differential pressures between the mouthpiece and surrounding water were measured utilizing a Validyne variable reluctance transducer.

Experiments were conducted in 10 feet of water in the wet chamber. Study depths listed in this report represent the dry chamber depths of 20, 130, and 200 FSW plus the immersion depth of 10 feet.

RESULTS

Throughout the study the data on heart rate, mouth differential pressure, inspired oxygen, and inspired carbon dioxide from divers utilizing the vertical ergometer did not differ significantly from those obtained from divers using the horizontal ergometer. This data has therefore been combined and plotted together. Table 1 is the number of subjects completing the full 6 minute work settings at each depth.

The mean total differential mouth pressures at the various depths and work rates are shown in Figure 2. Helium-oxygen was breathed only at 210 FSW. Nitrogen-oxygen breathing mouth differential pressures increased with increasing work rates. Greater depth increased the mouth differential pressures for each work rate. The values at 210 FSW breathing nitrogen-oxygen were generally twice the values measured at 30 FSW. Differential pressures were above 30 cm H_2O at exercise settings of 125 watts at 30 FSW, 75 watts at 140 FSW, and 50 watts at 210 FSW.

Figure 3 shows the mean inspired oxygen partial pressures and ranges for various work rates. The average inspired oxygen partial pressure for all depths and work rates was 0.72 ATM (547 mmHg) varying over a maximum range of 0.83 (630 mmHg) to 0.66 ATM (501 mmHg). There was no significant variation in oxygen control at the various depths tested. At no time during the study did the electronics assembly fail to control oxygen partial pressures within safe limits even at maximum depth and work rates.

Figure 4 depicts the maximum levels of inspired carbon dioxide at the three depths tested for various work rates, breathing nitrogen-oxygen. Mean inspired carbon dioxide increased with work rate and increased with depth at equivalent work rates. Levels ranged from 0.8 mmHg at rest to 6.4 mmHg at maximum tolerated work at 210 FSW. The maximum carbon dioxide level recorded during this study was 8.6 mmHg, obtained at a work rate of 125 watts at 210 FSW. For a given level of exercise, mean inspired CO_2 was highest at 210 FSW, and lowest at 140 FSW with intermediate values obtained at 30 FSW. The apparent effect of depth on inspired CO_2 cannot be adequately explained. It is felt, however, that differences in cannister packing between various studies may be responsible for this variation with depth.

The mean heart rates of the divers breathing nitrogen-oxygen at all three depths of the study are shown in Figure 5. Heart rate increased in a linear fashion with increasing work rates reaching a maximum of 150 BPM at maximum tolerated work. The maximum recorded heart rate was 180 BPM recorded from a diver exercising at a rate of 125 watts at 140 FSW.

DISCUSSION

If a diver is to be capable of performing heavy work underwater, he must have an adequate supply of oxygen, and be able to eliminate the carbon dioxide he produces. As work loads increase, so do oxygen consumption and carbon dioxide production. If the oxygen supply is inadequate, little warning of hypoxia and impending unconsciousness is given. Conversely, should oxygen levels rise, oxygen convulsions may develop. Oxygen partial pressure control must be maintained through all work loads. If carbon dioxide levels in the inspired gas increase, hypercarbia may be produced and result in headache, respiratory distress, somnolence, and unconsciousness. Less severe hypercarbia may result in an increased susceptability to nitrogen narcosis, oxygen toxicity and decompression sickness. In addition, the presence of carbon dioxide in inspired gas increases the diver's ventilatory requirement and thus his work of breathing. Diving apparatus therefore should not promote hypercarbia by presenting the diver with high levels of inspired carbon dioxide, nor limit the diver's ability to eliminate carbon dioxide due to high breathing resistance.

The SLSS MK 1 controlled oxygen partial pressures within 0.05 ATM of its set point for all work rates and depths (Fig. 3). Even when the extreme ranges of oxygen partial pressure measured are considered, oxygen levels remained within safe limits. During this series of tests comprising over 30 dives, there was not a single failure of the oxygen control subsystem. Thus, the control of oxygen partial pressure by the SLSS MK 1 is adequate for the anticipated depth requirement even at maximum work rates and appears to be very reliable.

The SLSS MK 1 uses a cannister filled with Baralyme[R] or Sodasorb[R] to absorb carbon dioxide produced by the diver.

Should the scrubber prove inadequate, a high inspired carbon dioxide level will increase the divers ventilatory requirement, and if this requirement is not met, carbon dioxide retention will occur. With the exception of maximum work at 210 FSW, CO_2 levels remained below 3.8 mmHg. During maximum work at 210 FSW, maximum inspired CO_2 increased transiently to 6.4 mmHg, and decreased rapidly on cessation of exercise. Thus, the SLSS MK 1 controlled inspired CO_2 to adequate levels. Increases of inspired CO_2 above 3.8 mmHg were transient occurring only at maximum work levels and were well tolerated by the divers.

Even though inspired CO_2 levels may be sufficiently low, CO_2 may be retained by the diver as the work of breathing increases. The effort a diver must exert to breathe depends upon the resistance of the gas in the diver's airways and the resistance posed by the diving apparatus gas passages. Resistance increases with increasing gas density, a function of depth. As these resistances increase, the diver usually involuntarily retains CO_2 rather than exert the effort necessary to transport all CO_2 produced. Differential pressure measured between the mouth and surrounding water increased linearly with work rate. Differential pressures at the mouth breathing nitrogen-oxygen were generally twice as great at 210 FSW as at 30 FSW. Intermediate values were recorded at 130 FSW. Breathing nitrogen-oxygen, both the maximum sustained work and heart rates were below those usually anticipated for dives to these depths, indicating that excessive breathing resistance reduced the divers' work capacity.

Excessive breathing resistance is a common problem in underwater breathing apparatus. Cetta (1973) demonstrated that in the MK 10 Mod 4, a similar underwater breathing apparatus, breathing resistance could be reduced as much as 50% by enlarging hose and other gas passages, avoiding sharp angles within the gas passages, and replacing one way valves with a larger variety. Since the SLSS MK 1 utilizes even smaller gas passages than the MK X, it is likely that a portion of the breathing resistance is due to small gas passages.

Using the SLSS MK 1 with the oxygen partial pressure set at 0.7 ATA, the percentage of nitrogen in the diver's breathing gas is proportionally greater at depth than a similar dive using air. Thus, at 200 FSW, the nitrogen partial pressure and the narcotic effects are equivalent to that experienced when diving on air to 232 FSW.

This study indicates that breathing resistance of the SLSS MK 1 is excessive and probably reduced the diver's work capacity. Subsequently, the operational depth of the nitrogen-oxygen mode SLSS MK 1 was reduced to 150 FSW. This operational limit lessens the breathing resistance problems of the gas passages.

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TABLE 1. NUMBER OF SUBJECTS COMPLETING 6 MINUTE WORK CYCLE

Depth	Gas	Work Rate (Watts)				
		75	100	125	150	175
210	$He-O_2$	5	5	4	2	1
210	N_2-O_2	5	4	2	0	0
140	N_2-O_2	5	4	1	0	0
30	N_2-O_2	5	5	4	2	1

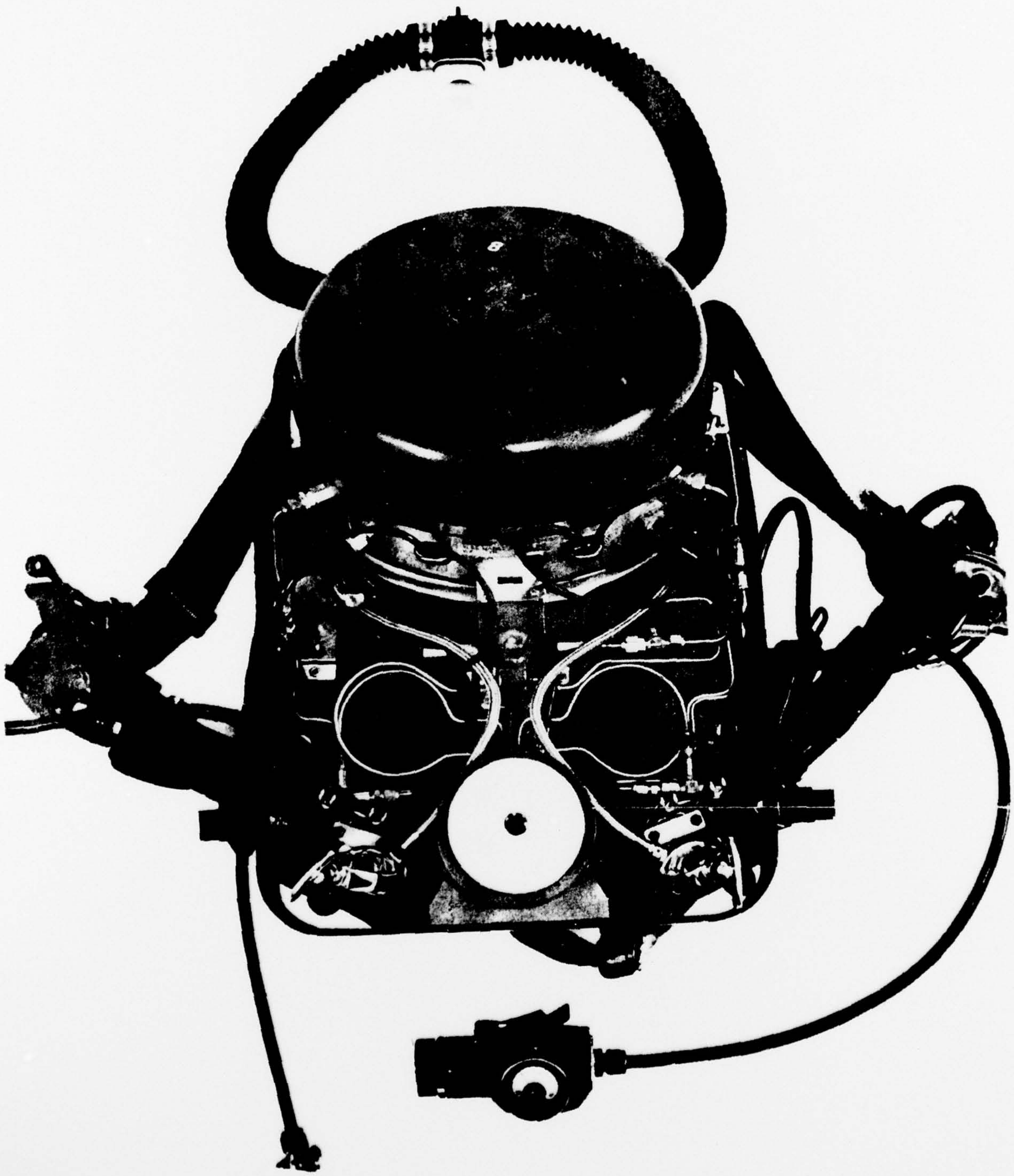

FIGURE 1. Photo of SLSS MK 1 Showing Backpack, Breathing Loop, Pneumatics Assembly, and Electronics.

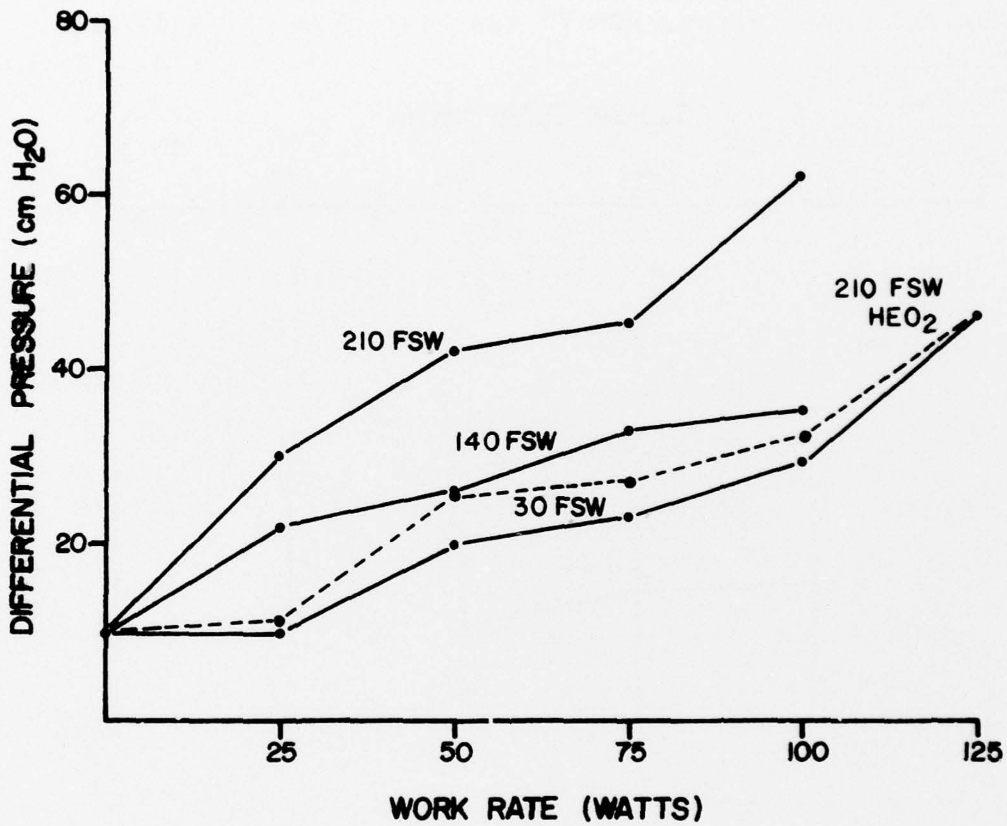

FIGURE 2. MEAN DIFFERENTIAL PRESSURES WITH GRADED EXERCISE AT 30, 140, 210 FSW ON N_2O_2, AND 210 FSW ON HEO_2

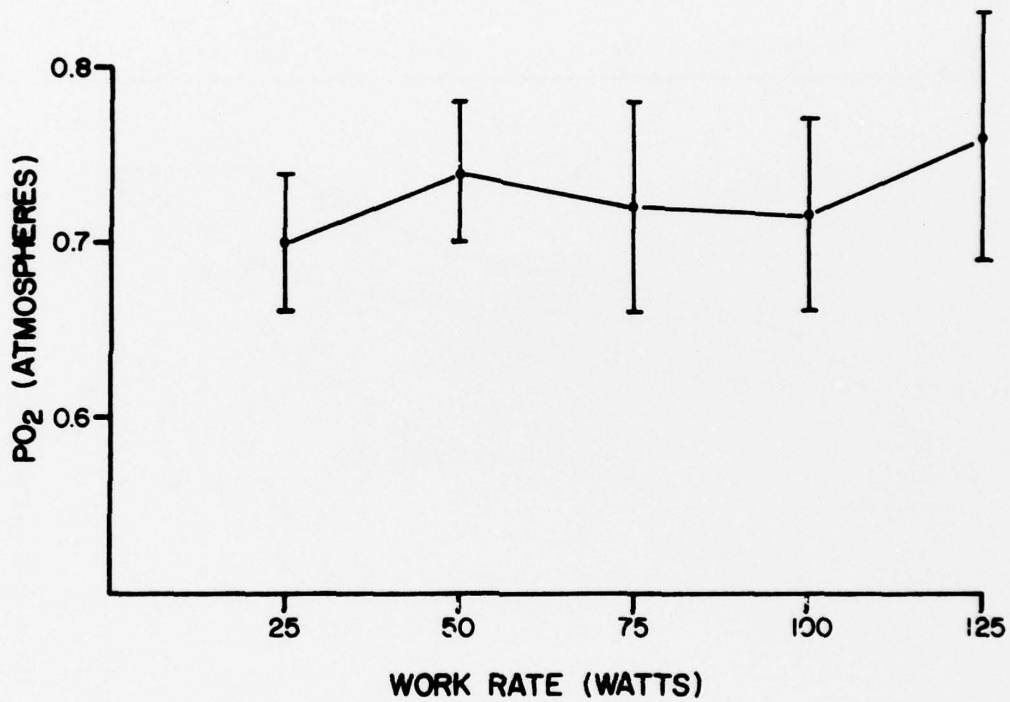

FIGURE 3. MEAN INSPIRED OXYGEN PARTIAL PRESSURE AND RANGE WITH EXERCISE FOR 30, 140, 210 FSW

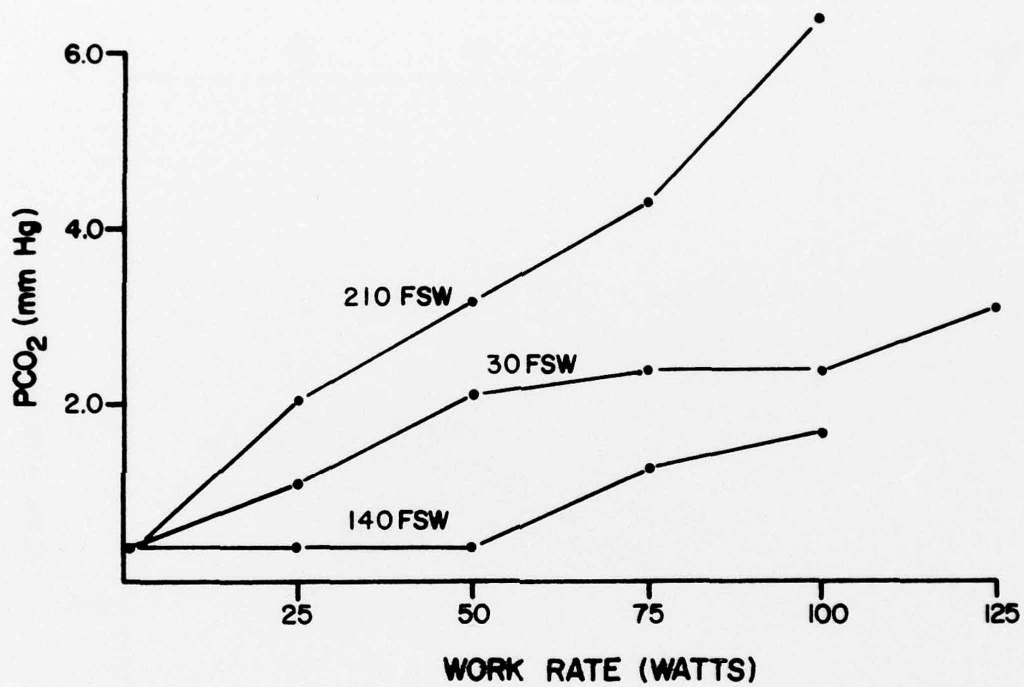

FIGURE 4. MEAN INSPIRED CARBON DIOXIDE LEVELS WITH GRADED EXERCISE AT 30, 140, 210 FSW

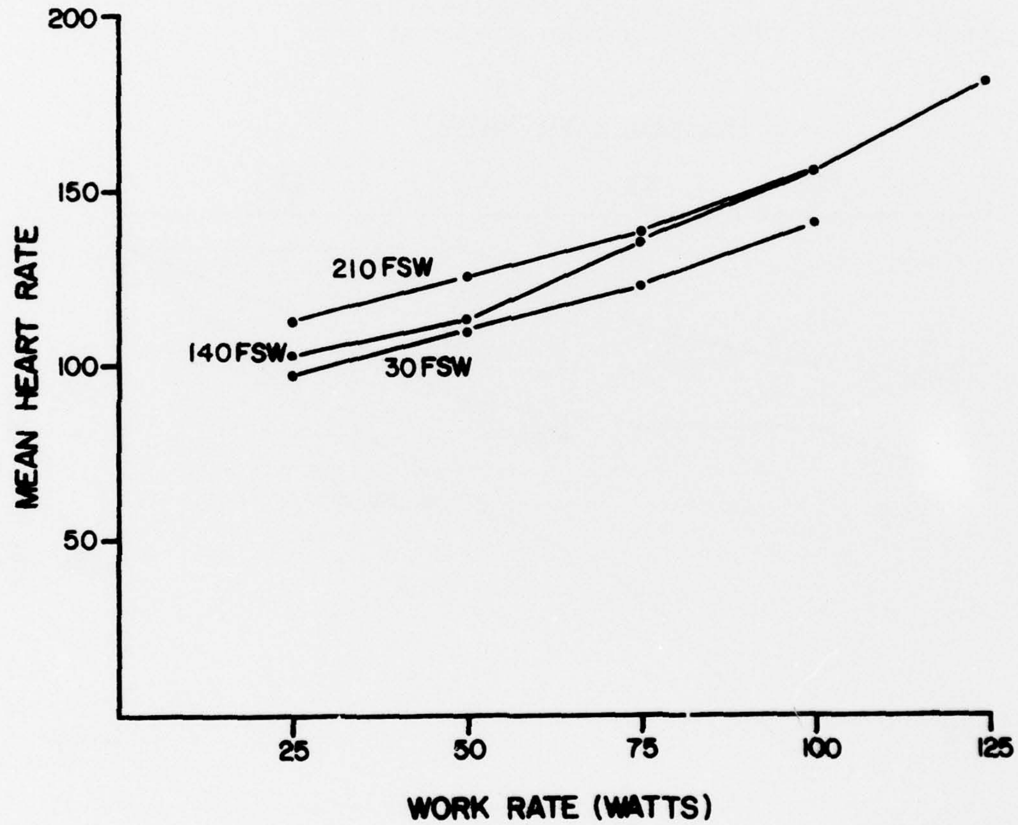

FIGURE 5. MEAN HEART RATE WITH WORK RATE AT 30, 140, 210 FSW