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MANNED EVALUATION OF THE MK 14 CLOSED CIRCUIT SATURATION DIVING SYSTEM

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ABSTRACT

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oxygen

INTRODUCTION

The MK 14 Closed Circuit Saturation Diving System (CCSDS) is a breathing apparatus designed for use in saturation diving. The design depth range of the MK 14 system is from 200 FSW to 1000 FSW. Divers may ascend 33 FSW above and 100 FSW below the Personnel Transfer Capsule (PTC), resulting in an operational depth range from 167 FSW to 1100 FSW. The diver is supplied with the atmosphere of the Personnel Transfer Capsule, and his exhaust is returned to the PTC for CO_2 removal and oxygen replenishment before recirculation to the diver. Thus, both diver gas consumption and the amount and complexity of diver carried equipment is reduced.

The MK 14 consists of four subsystems: diver worn equipment, the umbilical, pump package, and PTC equipment. These systems are illustrated in Figure 1. The pump package includes a gas delivery, or "push" pump, and a gas return or "pull" pump mounted in a pressure proof vessel exterior to the PTC. The 250 foot four-member umbilical consists of a gas supply hose, gas return hose, diver hot water hose, and a communications cable. Diver worn equipment includes the divers' hot water suit, inspired gas heater, and the MK 14 helmet with its associated valves and back pressure regulator. The PTC mounted equipment includes a gas control panel and an emergency gas supply.

In normal use, the PTC atmosphere is compressed by the gas delivery pump into a volume reservoir at a pressure sufficient to deliver gas to the diver at a minimum flow rate of 6 ACFM. When a preset positive pressure develops within the MK 14 helmet, a back pressure regulator opens to allow gas to flow back to the PTC via the umbilical. Return gas flow is assisted by the negative pressure created by the gas return pump. The existing life support system of the PTC is utilized to remove CO_2 produced by the diver and to replenish the oxygen consumed.

The ability of a diver to perform sustained heavy work depends on several factors. For the MK 14 the most important of these is the carbon dioxide level within the helmet. Factors affecting the carbon dioxide level within the helmet are helmet ventilation, carbon dioxide level of the inflowing gas, and the diver's carbon dioxide production rate. Equipment induced restrictions to ventilation is a second important factor affecting the ability of a diver to perform sustained heavy work. Physiological performance criteria for the MK 14 system are defined in NCSL Report 5216/3 (Rev. 2-72). In brief, the specification requires that for a diver working at an oxygen consumption of 3 LPM, MK 14 helmet CO_2 levels should not exceed 15.2 mmHg, and external breathing resistance should not exceed 0.17 kg-m/l. In addition, the diving suit should allow the diver to comfortably endure exposure to 1.7°C (35°F) water for 4 hours, and the gas heater should maintain breathing gas temperature within the limits specified in the U.S. Navy Diving Manual.

The purpose of this study was fourfold:

(1) To test the ability of the MK 14 to maintain acceptable levels of carbon dioxide within the helmet during graded exercise,

(2) To evaluate the amount of external breathing resistance induced by the MK 14,

(3) To evaluate the ability of the hot water suit to maintain diver comfort, and

(4) To evaluate the ability of the MK 14 gas heater to maintain an acceptable inspired gas temperature.

METHODS

Two saturation dives were conducted to evaluate the MK 14 CCSDS. The first, conducted in April of 1977, lasted 17 days. The second dive, lasting 37 days, was conducted over the period November - December 1977. For each dive, a separate group of 6 experienced, healthy male divers served as subjects. The physical characteristics of the men are shown in Table 1. All subjects performed calisthenics, swims to 2 km, and runs to 7 km five times weekly for 7 weeks prior to the dive. In addition, each diver performed ten to twelve underwater work cycles, similar to the experimental protocol, during the pre-dive period.

The MK 14 CCSDS was installed in the Ocean Simulation Facility as shown in Figure 2. The pump package and control console were mounted in two adjacent chambers. These chambers simulated the Personnel Transfer Capsule. External piping conducted the pump output to a third chamber located immediately above the wet pot, and then via a 250 foot umbilical to the MK 14 helmet. This arrangement allowed the wet pot to be located at a different depth from the pumps, thereby permitting simulated diver excursions of either 33 FSW above or 100 FSW below pump depth. Before each study, the MK 14 supply valve was regulated to provide a flow of at least 6 ACFM to the helmet. Flow was measured by a Meriam Laminar Flowmeter.

During all manned studies, the gas breathed by the divers was the helium-oxygen atmosphere in the chamber where the control panel was located. This breathing mixture had a controlled oxygen partial pressure range of 266 mmHg to 304 mmHg. Thus, the range of oxygen partial pressure available to the diver due to variations of diver depth above or below pump depth was 228 mmHg to 410 mmHg. Carbon dioxide level was maintained below 3.8 mmHg by the chamber life support system.

The experimental protocol consisted of graded exercise to evaluate the ability of the MK 14 CCSDS to support a working diver. The initial portion of each exercise sequence was a 5 minute rest period. This was followed by 6 minute work periods alternating with 4 minute rest intervals at 25, 50, 75, 100, 125, 150 and 175 watts on a specially modified underwater pedal ergometer (James, 1976). Two pedal ergometers were used. One permitted work in the upright position while the second was pedalled in a horizontal position. The subjects were equally divided between the vertical and horizontal ergometers. Studies done at the University of Buffalo have indicated that the actual work performed by a diver clad in swim trunks to overcome the resistance due to water is 25 watts. Since divers wore hot water suits in this study, their actual work rates were probably, at least 50 watts greater than the ergometer settings. Water temperature was controlled at 5.0°C throughout the studies, and hot water flow and temperature to the hot water suits were adjusted to the divers' comfort.

Table 2 shows the depths at which measurements were obtained, and the pump depths associated with these diver depths. Utilizing simulated excursions of 33 FSW above the pumps and 100 FSW below the pumps, the MK 14 CCSDS was evaluated from 167 FSW to 1100 FSW.

All data obtained was recorded on an 8 channel strip chart recorder during the final minute of each exercise sequence. Differential pressures were used only to provide an estimate of external breathing resistance, since no manned means of measuring work of breathing exists. Differential pressures generated by the divers were measured with a Validyne variable reluctance transducer fitted with a 350 cm H_2O (5 psig) diaphragm. Prior to each exercise sequence, the transducer was calibrated with a water manometer standard. Helmet CO_2 levels were measured by venting a gas sample from the exhaust umbilical through a hull penetrator to a mass spectrometer located outside the chamber. Helmet supply gas temperature was monitored by a thermistor located in the helmet immediately above the helmet gas diffuser. Heart rates were measured by placing conventional ECG electrodes to the divers' chests.

RESULTS

Table 3 shows the number of subjects on the 1500 FSW dive who completed each work setting at the depths tested. Mean values are included in this report only if 50 percent of the subjects completed the associated work level.

In this study, heart rate did not vary significantly either with depth, or the ergometer used. Figure 3 is a linear regression plot of the mean heart rates of the divers versus work rate at the depths tested. As can be seen, heart rate increased in a linear fashion with work load from a mean resting rate of 91 BPM to 164 BPM at the maximum tolerated exercise setting of 150 watts. The correlation coefficient for the linear regression line shown in the figure is 0.98.

Mean mixed helmet carbon dioxide did not vary significantly with depth for either ergometer. Figure 4 is a plot of the mean mixed helmet carbon dioxide level versus work rate for each ergometer used. In all cases, except for rest, helmet CO_2 was higher for the divers using the horizontal ergometer than those using the vertical ergometer at the same work setting. This difference in carbon dioxide level, while small, was statistically significant ($p = .05$). The mean mixed helmet carbon dioxide for those divers who used the vertical ergometer never exceeded 15.2 mmHg even at the maximum tolerated work load. For the subjects who exercised horizontally, mixed helmet carbon dioxide averaged 16.5 mmHg at 150 watts. The linear regression line for each ergometer is shown in the figure. Since both helmet flow rate and carbon dioxide level were known, the carbon dioxide production rate could be calculated. Table 4 shows the method used to calculate CO_2 production and the results. If the ergometer setting was 150 watts or greater, CO_2 production exceeded 3 LPM for either ergometer.

The mean differential pressure versus work setting is shown in Figures 5 and 6. For both ergometers, mean differential pressure increased gradually from less than 10 cm of water at rest to 20 cm of water at a work rate of 125 watts. Thereafter, differential pressure increased more rapidly with an increase in work rate to 35 cm of water during downward excursions. As depth increased, the mean differential pressure generated at a given work rate changed very little with the exception of the upward excursion at 967 FSW where the maximum differential pressure recorded was 60 cm of H_2O at a work setting of 150 watts.

Figure 7 represents the mean inspired and expired pressures generated by the subjects versus depth at a work setting of 150 watts. Inspired pressures during downward excursions varied over a range of 3.5 cm H_2O with depth, whereas expired pressures varied 4.5 cm H_2O with the maximum value reached at 1100 FSW. For upward excursions, inspired pressure decreased with depth by 9 cm of H_2O, reaching 15 cm of H_2O at 967 FSW. Expired pressure, however, increased from 5.5 cm at 167 FSW to 23.2 cm at 967 FSW, an increase of 17.7 cm of H_2O. Inspired and expired pressures recorded were consistently less during downward excursions compared to those recorded during upward excursions.

Figure 8 shows the mean inspired gas temperatures within the MK 14 helmet. The mean inspired gas temperature was 31°C (88°F) down to 567 FSW. For the depth range 700 FSW to 1100 FSW, inspired gas temperatures averaged 25.5°C (78°F). In all instances, inspired gas temperatures exceeded the minimum U. S. Navy requirements for saturation diving.

DISCUSSION

Maximum work output under surface conditions is usually limited by the cardiovascular system. At depth, however, increased gas density results in a reduction of maximum ventilation which then may become the primary limitation to work performance. If the diver's ventilatory capability is insufficient to meet his metabolic requirements, blood carbon dioxide level will increase. An increased blood level of carbon dioxide may result in a number of physiological alterations, some of which could prove hazardous or even fatal. These alterations include dyspnea, somnolence progressing to coma, convulsions, and an increased susceptability to nitrogen narcosis, oxygen toxicity, and decompression sickness. It is essential that breathing apparatus not restrict diver ventilation beyond that due to increased gas density alone.

Underwater breathing apparatus may limit ventilation in two ways. First, increased gas density will increase resistance to gas flow in the apparatus. When combined with elevated resistance to gas flow in the diver's lungs, the resulting increased work of breathing may result in decreased work capability and potential carbon dioxide retention. Second, the presence within the helmet of an elevated level of carbon dioxide results in a reduction of effective ventilation since in the presence of increased inspired CO_2 ventilation must increase to maintain blood levels of CO_2 within normal limits.

Based on previous experience at the U.S. Navy Experimental Diving Unit, a sustained helmet CO_2 level of 15.2 mmHg seems to be the maximum carbon dioxide level for helmet diving systems tolerated by divers without subjective feeling of discomfort. Costell (1971) has reported that, at the surface, subjects inspiring a gas containing a partial pressure of carbon dioxide of 21 mmHg can maintain arterial CO_2 levels near normal during severe exercise. In 1974, Thalmann showed that helmet ventilation of at least 6 ACFM was required to maintain helmet CO_2 levels below 15.2 mmHg for a diver producing CO_2 at a rate of 3 LPM. In the present study, though flow was maintained at 6 ACFM, helmet CO_2 rose to 15.8 mmHg for subjects using the horizontal ergometer at 150 watts and to 17.6 mmHg for those subjects completing work at 175 watts. In this study, however, for ergometer settings greater than 125 watts, CO_2 production exceeded 3 LPM. For CO_2 production rates exceeding 3 LPM, helmet CO_2 levels will exceed 15.2 mmHg. However, since a carbon dioxide production rate greater than 3 LPM cannot be maintained for more than 5 to 10 minutes, the MK 14 can control helmet CO_2 to safe levels at maximum sustainable work.

The breathing resistance of the MK 14, as indicated by the differential pressure generated by the divers during exercise, was generally very low. It increased slowly with work rate up to 125 watts, but increased sharply thereafter. At 150 watts, all subjects reported dyspnea. The dyspnea was associated on inspiration with the movement of the neck dam upward to maximum limits within the helmet. Dwyer and Saltzman (1977) have shown that maximum ventilation at shallow depths may reach 150 LPM and 87 LPM at 43.4 ATM (1400 FSW). Maximum instantaneous flow may be up to three times greater than minute ventilation. Thus, a diver may inhale gas at a flow of 270 LPM at maximum MK 14 operating depth. Since gas entered the hat at a flow rate of 174 LPM (6 ACFM), the additional flow required by the diver must come from within the MK 14 helmet. If the compliant volume within the MK 14 helmet is inadequate to compensate for this flow difference, differential pressure will increase sharply as it did in this study. Thus, by increasing the compliant volume of the MK 14 neck dam, breathing resistance at maximum work rates could be reduced.

Differential pressures generated by the divers were greatest during upward excursions. During upward excursions, mean expiratory pressure increased more rapidly with depth than inspiratory pressure. This effect was the result of inadequate return flow from the helmet to the PTC due to increased gas density, and the limited return pressure that could be developed by the return pumps. However, Table 1 shows that the same number of divers were able to complete the 150 watt work setting at 967 FSW as completed 150 watts at 1100 FSW where the resulting differential pressures were significantly less. Thus, this increased breathing resistance did not limit maximum work.

The differential pressures produced by six of the subjects used in this study on the MK 1 Mod S Bandmask at 1100 FSW were collected by Middleton (1978). This data compared with that from the MK 14 at similar depths is shown in Figure 8. During upward excursions, MK 14 breathing resistance was comparable to that of the MK 1 Mod S Diver's Mask, but during downward excursions resistance was substantially less. Thus, in its present state of development, the MK 14 offers less respiratory restriction than one UBA currently used in saturation diving. Thus, the MK 14 can be expected to support as much work as the MK 1 Mod S Diver's Mask with considerably improved gas economy.

The minimum limit for inspired gas temperature during deep helium-oxygen diving has not been well established. Hoke (1975) noted a profound rectal temperature drop in divers at 820 FSW in a 30°C (86°F) environment breathing 5°C (41°F) gas. In addition, the same divers developed acute respiratory distress while breathing this cold gas. Braithwaite (1972) calculated the minimum safe inspired gas temperature limits currently used by the U. S. Navy. However, due to the lack of actual data, Webb recommends that inspired gas temperature should be maintained above these levels, preferably in the 30 - 35°C range, whenever possible. The MK 14 gas heater maintained inspired gas temperatures at 31°C (88°F) to a depth of 567 FSW and at 25°C to 1100 FSW. These levels are above the current U.S. Navy minimums by at least 10°C (18°F). Using the best estimates of minimum safe inspired gas temperature, the MK 14 was capable of controlling inspired gas temperatures within satisfactory limits.

The hot water suit used by the MK 14 is a modified version of a hot water suit used successfully by the U. S. Navy and commercial divers for exposures up to 4 hours in 0°C (32°F) water. During this study, the subjects spent up to 2 hours in 5°C (40°F) water without thermal discomfort. Thus, the MK 14 hot water garment can be expected to maintain diver thermal comfort for 4 hours in 1.7°C (35°F) water provided a sufficient temperature and flow of hot water is available to the suit.

SUMMARY

The MK 14 CCSDS was evaluated during two saturation dives over its maximum operating range of 167 to 1100 FSW. During these tests, helmet breathing resistance, CO_2 levels, gas flow, and inspired gas temperature were monitored as well as the subjects' heart rate during graded exercise on a pedal ergometer. The MK 14 successfully met design parameters for breathing resistance, helmet gas flow, CO_2 levels, inspired gas temperature, and diver thermal comfort. At its present state of development, the MK 14 can be expected to out perform the MK 1 Mod S saturation diving UBA.

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TABLE 1. PHYSICAL CHARACTERISTICS OF THE TEST SUBJECTS

Diver	Age	Height (cm)	Weight (kg)
D. B.	36	173	87.4
W. C.	31	180	89.1
G. C.	31	170	75.0
F. D.	26	170	73.6
D. D.	27	182	76.4
M. H.	32	180	91.8
T. K.	27	175	83.6
D. M.	35	183	90.0
J. N.	28	185	84.6
N. P.	34	178	84.6
D. W.	25	178	83.6
J. Z.	31	175	87.3

TABLE 2. DIVER DEPTHS AND PUMP DEPTHS USED DURING THE STUDY.

Diver Depth (FSW)	Pump Depth (FSW)
167	200
200	200
283	200
567	600
700	600
967	1000
1100	1000

TABLE 3. NUMBER OF DIVERS FROM A TOTAL OF SIX WHO COMPLETED THE INDICATED WORK SETTINGS AT THE DEPTHS INDICATED DURING THE 1500 FSW DIVE.

Diver Depth (FSW)	Work Rate (Watts)				
	75	100	125	150	175
167	6	6	6	5	1
283	6	6	6	5	1
567	6	6	6	4	1
700	6	6	6	5	1
967	6	6	6	3	0
1100	6	6	6	3	0

TABLE 4. CARBON DIOXIDE PRODUCTION RATE AT VARIOUS WORK SETTINGS.

Work Setting (Watts)	Carbon Dioxide Production (LPM) Vertical Ergometer	Horizontal Ergometer
Rest	.82	.84
25	1.39	1.48
50	1.57	1.70
75	1.89	2.09
100	2.28	2.50
125	2.67	3.02
150	3.40	3.69
175	3.93	

$$\dot{V}_{CO_2} = \frac{\dot{V} pCO_2}{760} \times \frac{28.3 \text{ LPM}}{1 \text{ ACFM}}$$

Where

$\dot{V}$ = Helmet flow in actual cubic feet per minute

pCO_2 = Mixed helmet CO_2 in mmHg

760 = 1 standard atmosphere in mm

28.3 = Conversion factor for ACFM to LPM

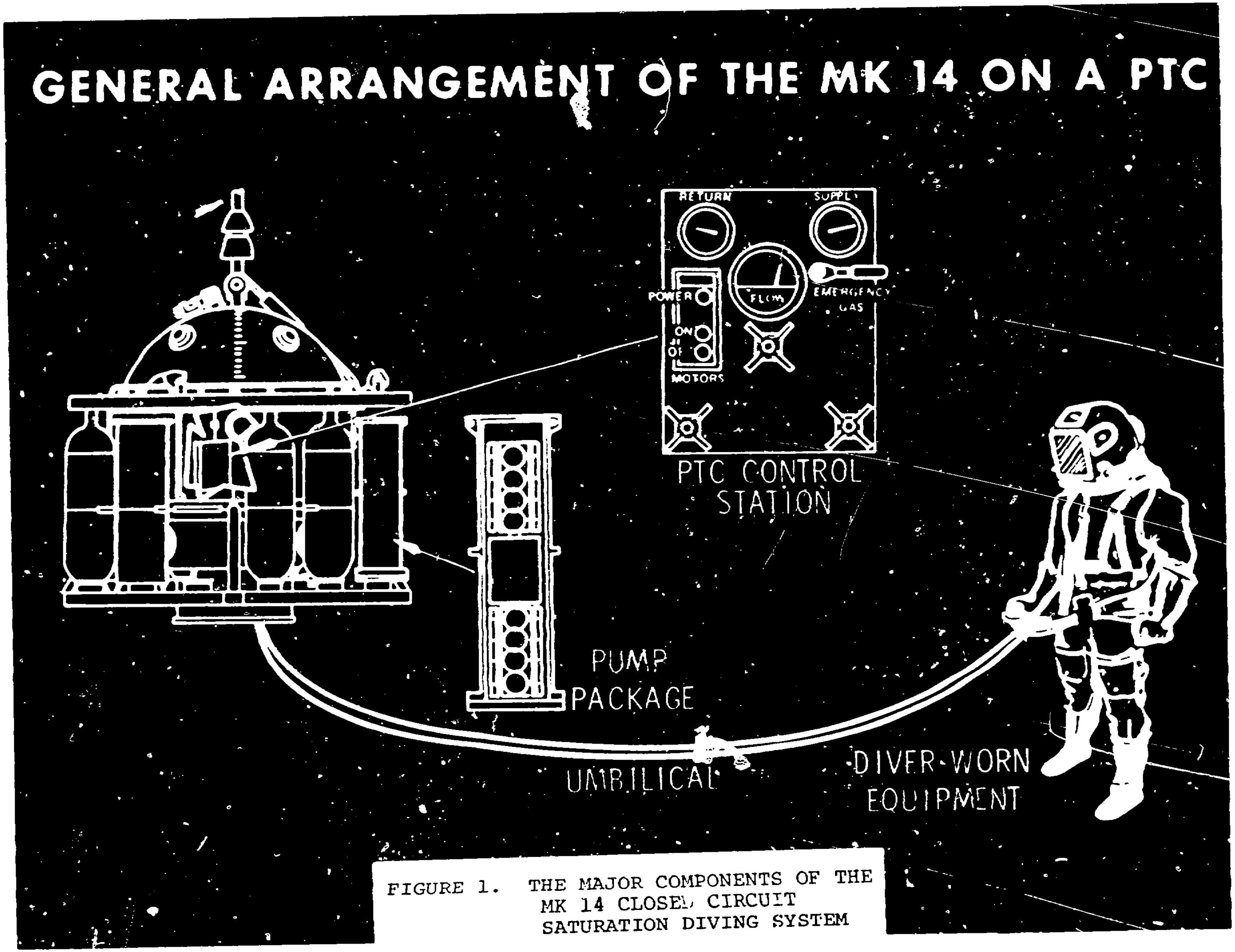

FIGURE 1. THE MAJOR COMPONENTS OF THE MK 14 CLOSED CIRCUIT SATURATION DIVING SYSTEM

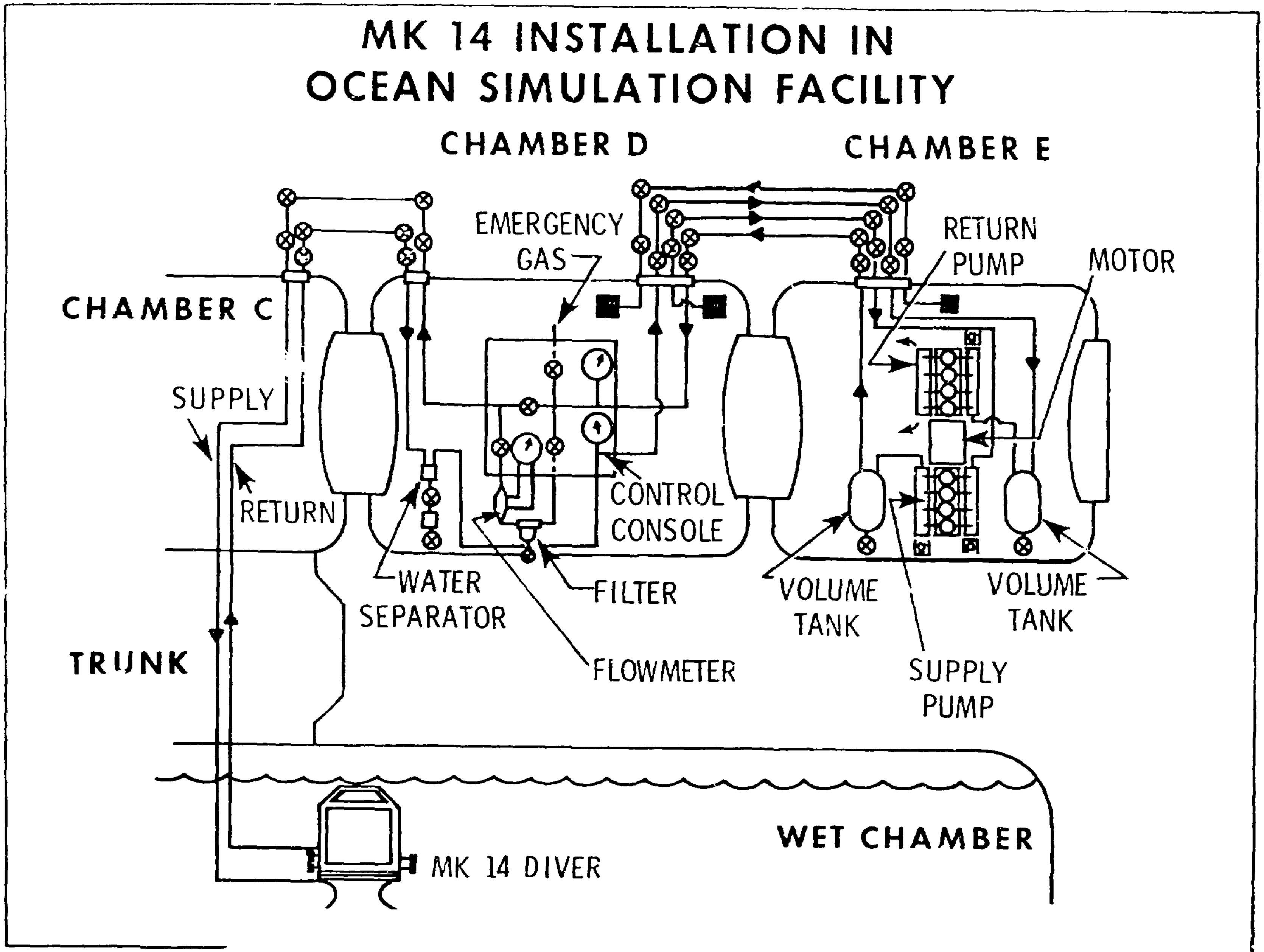

FIGURE 2. THE MK 14 CCSDS AS INCORPORATED INTO THE OCEAN SIMULATION FACILITY

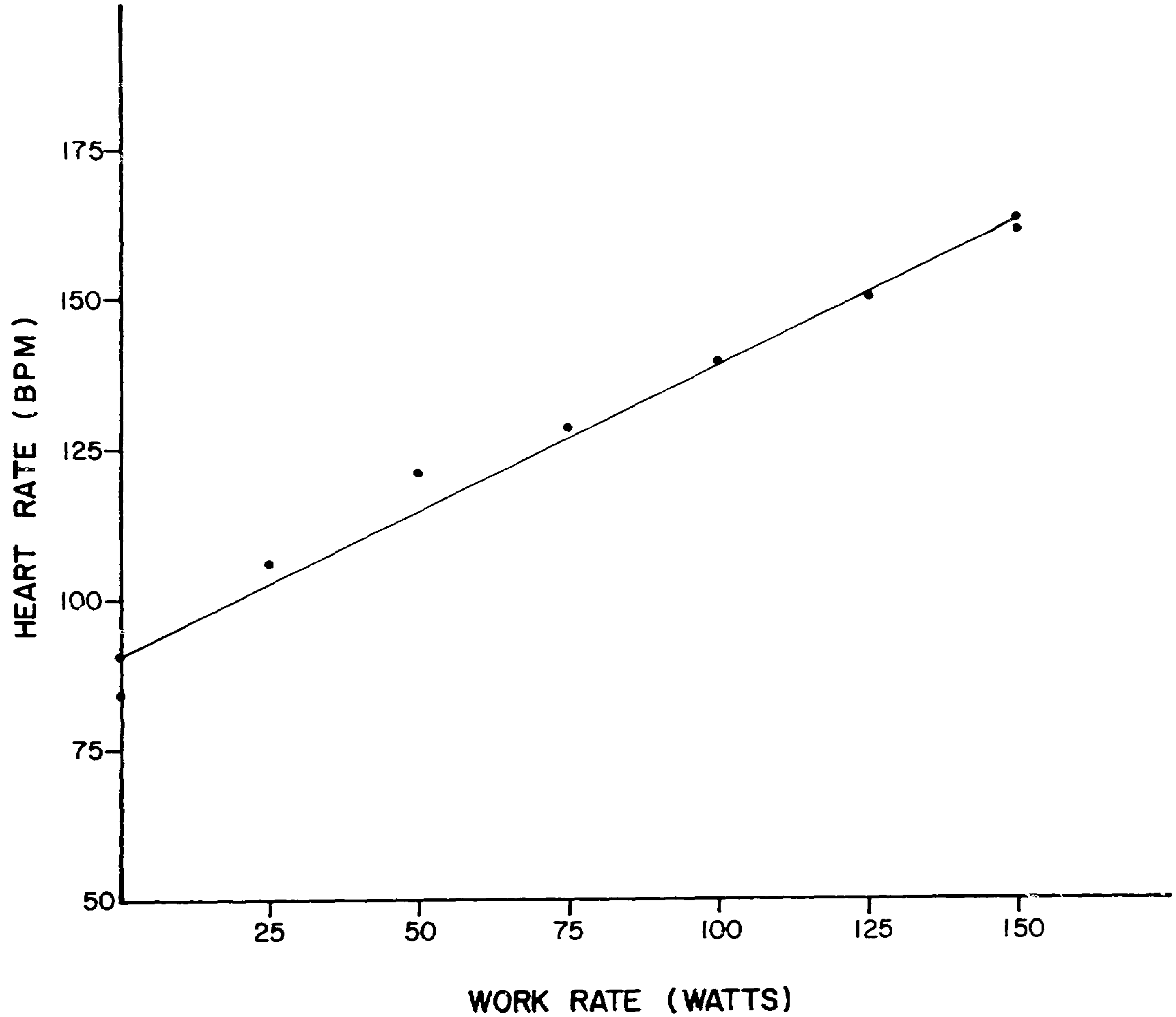

FIGURE 3. LINEAR REGRESSION OF MEAN HEART RATES FOR ALL DIVERS AT ALL DEPTHS VERSUS WORK RATE

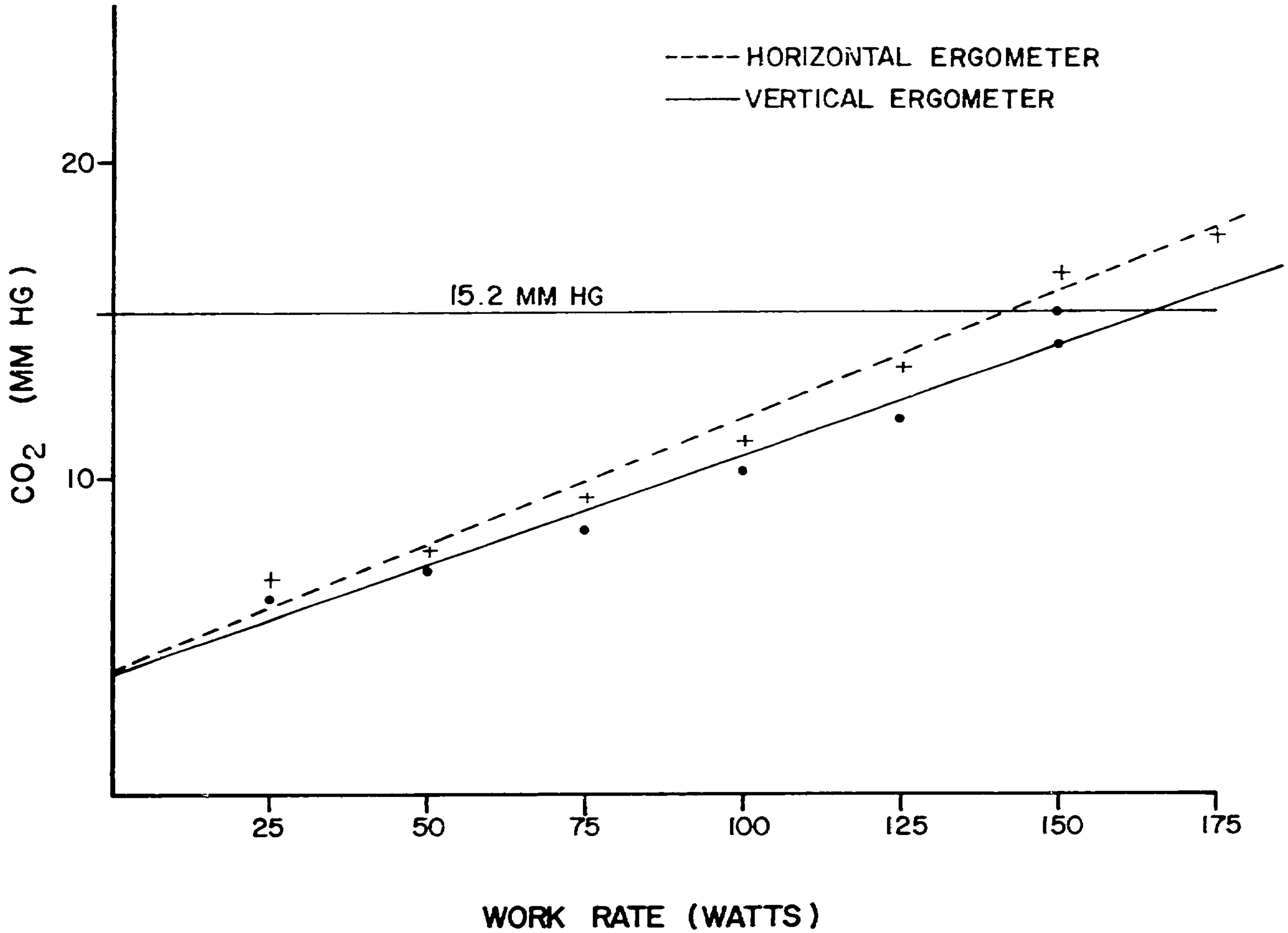

FIGURE 4. LINEAR REGRESSION OF MEAN MK 14 MIXED HELMET CO_2 FOR ALL DEPTHS TESTED VERSUS WORK RATE

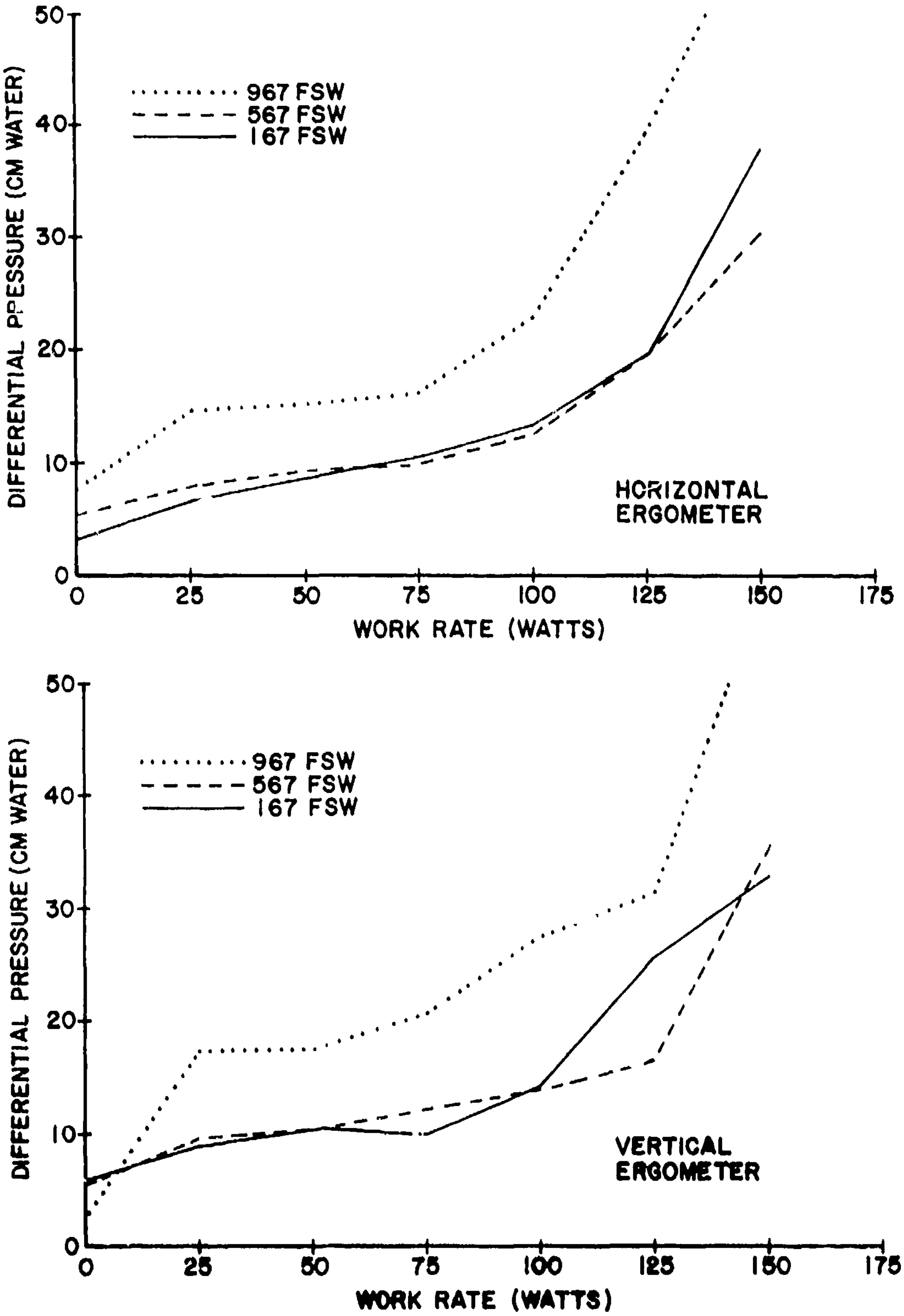

FIGURE 5. MK 14 HELMET DIFFERENTIAL PRESSURES DURING UPWARD EXCURSIONS WITH GRADED EXERCISE. VALUES ARE MEANS FOR ALL DIVERS COMPLETING ENTIRE WORK CYCLE

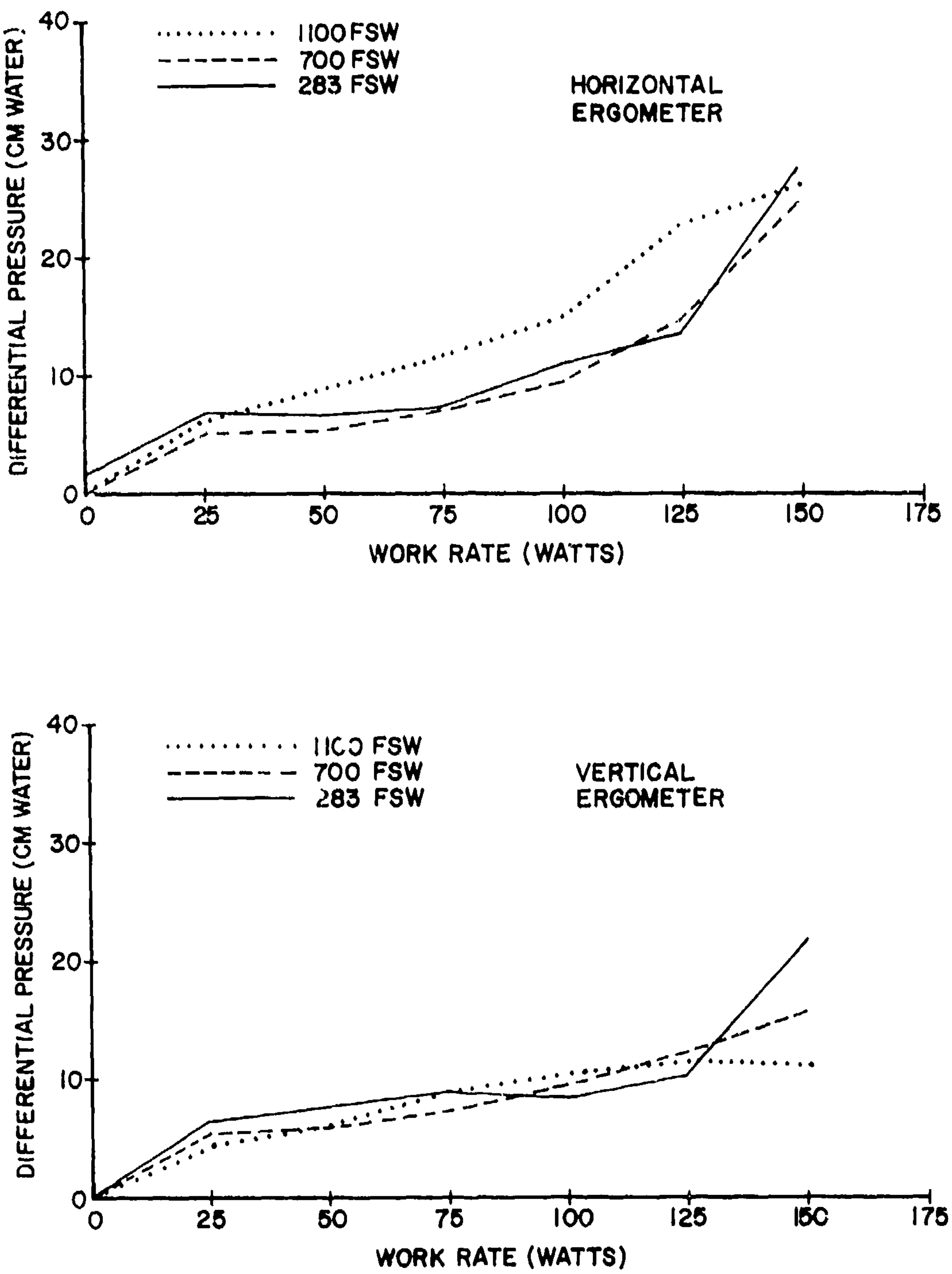

FIGURE 6. MK 14 HELMET DIFFERENTIAL PRESSURES DURING DOWNWARD EXCURSIONS WITH GRADED EXERCISE. VALUES ARE MEANS FOR ALL DIVERS COMPLETING ENTIRE WORK CYCLE

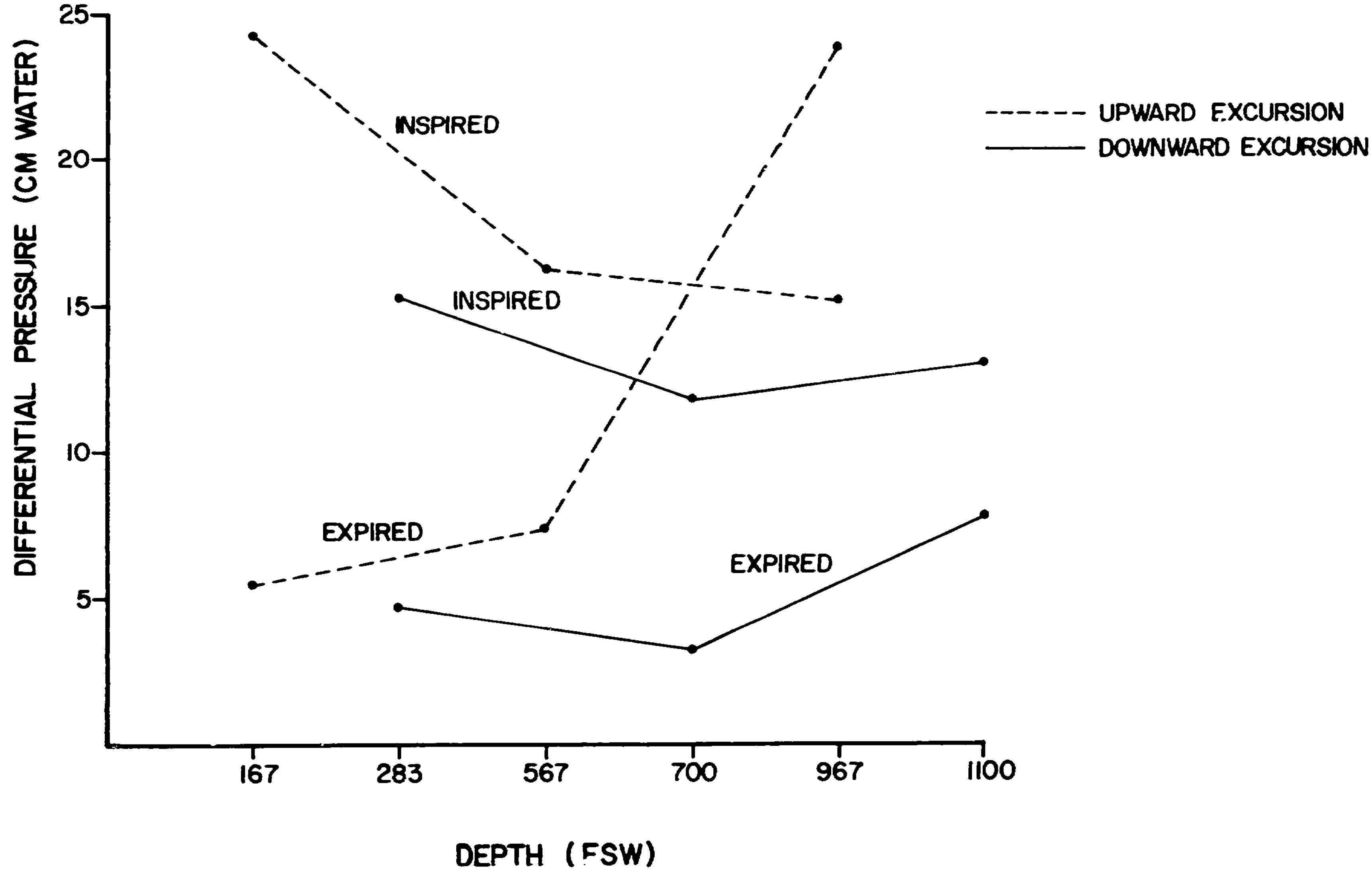

FIGURE 7. MEAN MAXIMUM INSPIRATORY AND EXPIRATORY PRESSURES FOR ALL SUBJECTS VERSUS DEPTH

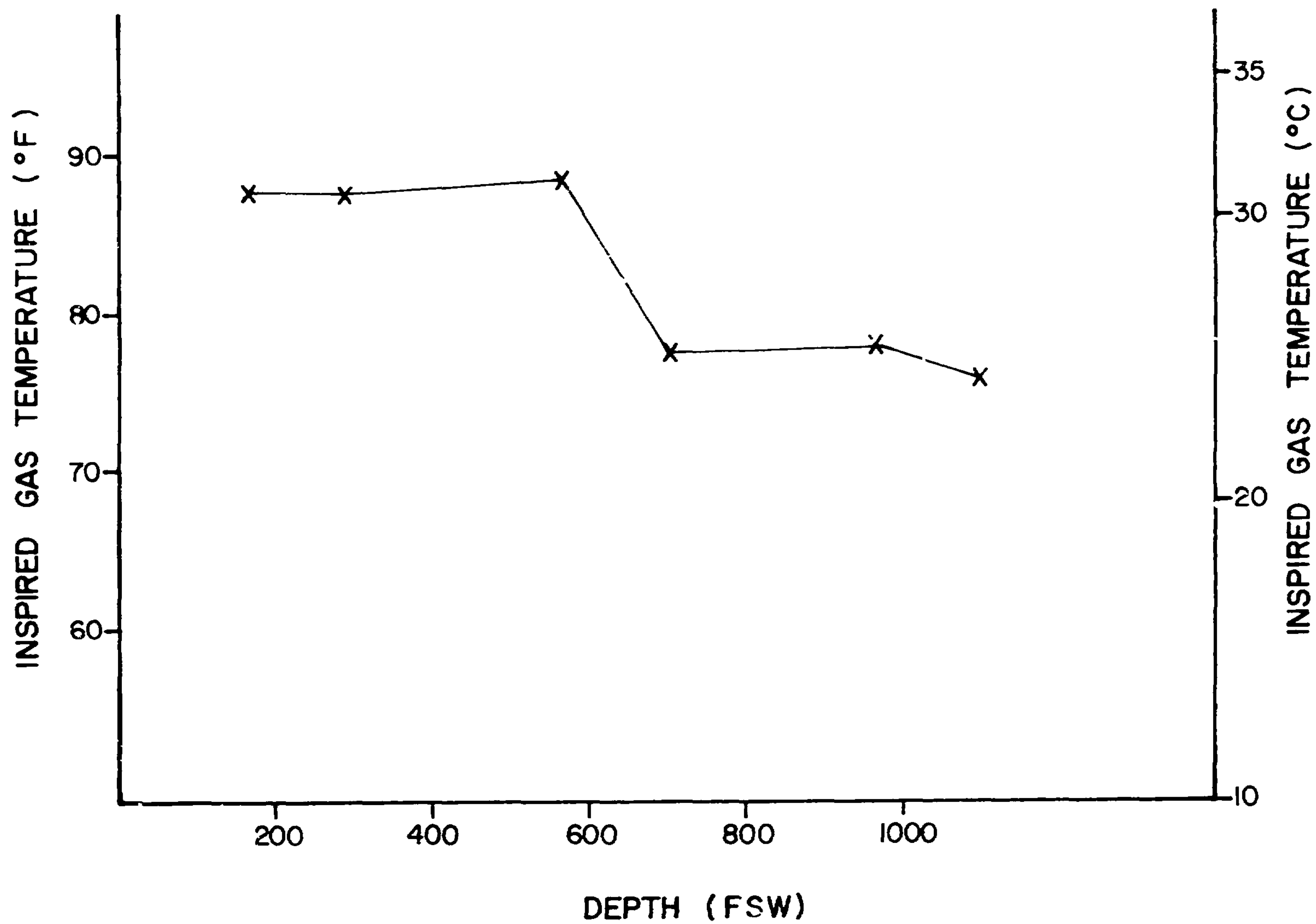

FIGURE 8. MK 14 MEAN INSPIRED GAS TEMPERATURE VERSUS DEPTH

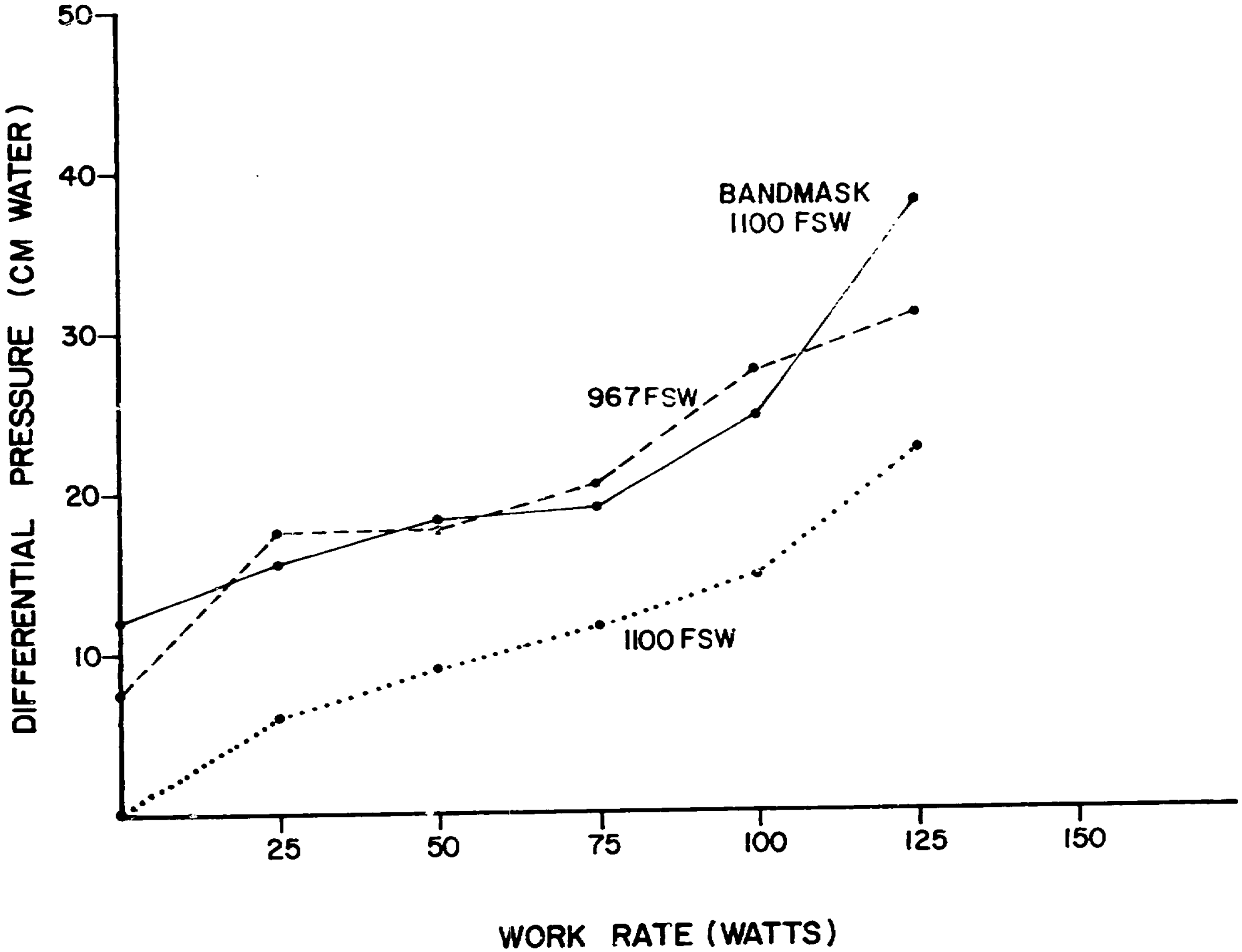

FIGURE 9. MEAN MK 14 HELMET DIFFERENTIAL PRESSURES AND MEAN MK 1 MODS BANDMASK DIFFERENTIAL PRESSURES VERSUS WORK RATE AT 1100 FSW