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PRELIMINARY STUDY ON CARBON DIOXIDE, TEMPERATURE AND HUMIDITY PROFILES IN A MANNED SUBMERSIBLE

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ABSTRACT

The purpose of this study was to investigate carbon dioxide concentration, temperature and humidity profiles in a manned submersible, to measure carbon dioxide production rates of divers at different activities, and to evaluate the carbon dioxide scrubber performance efficiency at different environmental conditions.

Carbon dioxide is continuously produced from divers and instantaneously removed by a scrubber in a manned submersible. The amount of CO_2 generated and the instaneous CO_2 scrubbing efficiency determine CO_2 concentration in the submersible atmosphere. Temperature and humidity also vary with submersible operating conditions such as compression, decompression and temperature of surrounding sea water, etc. Both temperature and humidity normally increase during the compression stage and decrease during the decompression period.

Carbon dioxide, temperature and humidity inside the submersible atmosphere are varied instantaneously at different operating stages. The study was designed to monitor the submersible atmosphere in the JOHNSON-SEA-LINK II sumbersible at Harbor Branch Foundation. The atmosphere of the acrylic pilot sphere and aluminum lockout chamber were monitored in the study. Two Beckman CO_2 and O_2 sensors, four Omega thermistors and a six channel recorder were placed in the submersible. Wet bulb and dry bulb temperatures were used to measure the temperature and humidity of the atmosphere. The temperature and humidity in the pilot sphere normally ranged between 24-27°C and 80-85%, respectively. For a non-lockout dive in the diving compartment, the temperature and humidity were around 24°C and 100%, respectively. However, for a lockout dive, temperature was generally increased from 24°C to 31°C at a depth of 80.7 meters. The CO_2 production rate for the pilots and divers in the pilot sphere and diving compartment averaged 0.49 g/man-min and 0.61 g/man-min, respectively. CO_2 removed from each air stream through the CO_2 scrubber ranged between 22% to 34% and 29% to 44% in both the pilot sphere and diving compartment, respectively.

INTRODUCTION

Carbon dioxide (CO_2) is produced from divers and instantaneously removed by a scrubber in a manned submersible. The amount of CO_2 generated and the CO_2 removal determine the CO_2 concentration in the submersible. Temperature and humidity in the atmosphere are also varied with submersible operation stages such as compression, decompression and temperature of surrounding sea water. Both temperature and humidity profiles are normally increased during compression and decreased during the decompression period. The purpose of this study was to investigate carbon dioxide concentration, temperature and humidity profiles in a manned submersible and to measure carbon dioxide production of divers and carbon dioxide scrubbing efficiency in the submersible.

The study was carried out to monitor the atmosphere in the JOHNSON-SEA-LINK II submersible (Figure 1). The JOHNSON-SEA-LINK II has a transparent, four-inch thick acrylic plastic sphere. This chamber provides panoramic underwater visibility to the pilot and a scientist or observer. The vehicle has a separate welded aluminum pressure compartment which allows scientists, engineers and divers to lock out and work directly in the sea. An atmosphere monitoring system to observe the CO_2 , temperature and humidity profiles was installed in both chambers of the submersible. Two Beckman Minos atmospheric carbon dioxide monitors were used to measure the partial pressure of carbon dioxide in the submersible. The sensors were calibrated prior to each dive and the sensor performance accuracy was ± 20%. Four Omega thermistors were used to monitor dry bulb and wet bulb temperatures of both chambers. Psychrometric charts are used to calculate the humidity content in the atmosphere (1). CO_2 sensors and thermistors were connected to a six channel chart recorder in the pilot sphere. CO_2 concentration, dry bulb and wet bulb temperatures were continuously monitored for each dive during the study period. The atmospheric monitoring system is shown in Figure 2.

RESULTS

The carbon, dioxide, temperature and humidity profiles are shown in Figures 3-7 for each dive. The profiles obtained in the study are varied with the submersible activities. The description of each activity is shown in the figures. Tables 1 and 2 indicate the CO_2 concentration, temperature and relative humidity profiles obtained from the study. For a typical lockout dive such as Dive No. 578, (Figure 6), as divers and pilots/observers entered into the chamber, the CO_2 concentration in both chambers started to build up as shown in Figure 6. When the CO_2 concentration was up to 5.0 mm Hg and 7.2 mm Hg in the pilot sphere and diver compartment, respectively, the CO_2 scrubber was turned on to scrub the CO_2 inside the submersible. CO_2 concentration was gradually scrubbed down to 1.2 mm Hg and 3.5 mm Hg, respectively, in both chambers. When the submersible reached the lockout site, the scrubber was secured and divers were ready for compression. CO_2 concentration increased up to 4.0 mm Hg during the compression period as shown in Figure 6. After inside pressure reached the bottom depth pressure, the hatch door was opened and one diver went out in the sea for the mission. While the other diver attendant remained in the chamber, CO_2 concentration was continuously building up to 7.5 mm Hg. As the mission diver completed the dive and returned to the chamber, the hatch door was closed. CO_2 was increased from 7.5 mm Hg to 9.0 mm Hg during this short period. The CO_2 concentration was then rapidly decreased as the decompression started in the chamber. The CO_2 concentration decreased during the decompression travel intervals and slightly increased at each decompression stop. During each decompression interval, diving gas was released from the chamber and CO_2 concentration in the chamber atmosphere decreased, correspondingly. At each decompression stop the CO_2 concentration tended to equilibrate inside the chamber and the divers continued to produce CO_2. CO_2 concentration was gradually increased as shown in the CO_2 profiles. For a non-lockout dive, such as Dive No. 541, (Figure 4), the CO_2 concentration in the chambers was mainly dependent upon the operation of the CO_2 scrubber. CO_2 concentration was gradually built up to about 8.0 mm Hg when the CO_2 scrubber was off and gradually scrubbed down to 1.75 mm Hg during CO_2 scrubber operation period. The CO_2 profile patterns were somewhat different for each dive as shown in Figures 3-7. CO_2 concentrations in the diving compartment were normally higher than in the pilot sphere. The variation could be due to different activities and comforts in both chambers.

An air conditioning unit was installed in the pilot sphere. The temperature and humidity in the sphere were mostly regulated by the air conditioning system. For most of the dive, the temperature normally ranged between 24-27°C and the humidity was about 80-85% in the pilot sphere. In the diving compartment, humidity and temperature were mostly around 100% and 24°C for the non-lockout dive. However, for a lockout dive, temperature was normally increased rapidly from 24°C at surface level to 31°C at 82.7 meters and then gradually decreased to 27°C in 10 minutes inside the chamber. When decompression started in the chamber, temperature was decreased to 16°C and then changed along with decompression travels and stops. During each decompression interval, temperature was decreased as diving gas was released to the ambient sea water. While at each decompression stop, atmosphere temperature tended to equiliberate inside the chamber. Temperature slightly increased as observed in the profiles. Dry bulb temperature was generally slightly higher than wet bulb temperature in the diving compartment. However, during the decompression period, the wet bulb temperature could be higher than the dry bulb temperature as shown in most of the lockout dives.

Once the CO_2 profiles is obtained from the submersible, the CO_2 production rate and CO_2 scrubber efficiency can be calculated using a material balance scheme (2,3). CO_2 is continuously carried away by the flow Q. The final equilibrium CO_2 concentration in the chambers, C_f, becomes:

$$C_f = C - (Co - C_f)\, e^{-kt}, \text{ when the scrubber is on} \quad (1)$$

or

$$C = kt + Co, \text{ when scrubber is off} \quad (2)$$

CO_2 production rate and CO_2 scrubbing efficiency can be calculated as follows:

$$E = k\, V/Q \quad (3)$$

$$G = EQC_f, \text{ when scrubber is on} \quad (4)$$

or

$$G = kV, \text{ when scrubber is off} \quad (5)$$

Where:

C = CO_2 concentration at any instantaneous time in the chamber in g/ℓ

C_f = final equilibrium concentration in g/ℓ, C_f is defined as the concentration in the chamber when the amount of CO_2 produced is equal to the amount of CO_2 removed by the scrubber

Co = initial CO_2 concentration in g/ℓ

t = elapsed time in minutes

Q = air stream scrubbing rate in ℓ/min.

V = chamber volume in liters

R = CO_2 removal rate in g/min.

E = instantaneous scrubber performance efficiency
G = CO_2 production rate
k = constant in $(min.)^{-1}$
k value could be obtained by plotting ln (concentration) or concentration vs. elapsed times in equation (1) and (2), respectively. The slope of the straight line is the k value. C_f could be obtained by knowing the k value and any instantaneous concentration at each specific elapsed time.

Tables 1 and 2 show the CO_2 production for each diver in the pilot sphere and diver compartment, respectively. The CO_2 production rate in the pilot sphere averaged around 0.42 g/man-min during the period the submersible travelled to the lockout site. As the mission was completed and the submersible was on its way back to the surface, the CO_2 production was about 0.56 g/man-min.

Divers produced CO_2 in the diving compartment averaging around 0.63 g/man-min as the submersible was travelling to the lockout site. The diver attendant during the compression period waiting for the mission diver to return to the chamber had a 0.59 g/man-min CO_2 production rate. Workload, pilot, diver's activities and environmental comforts in both chambers could contribute to the different amount of CO_2 production. Table 3 shows the CO_2 production at various workloads and activities. The workload of piloting the JOHNSON-SEA-LINK II could be said to range between driving a car in light traffic and piloting a DC-3 in a level flight (4,5,6).

The CO_2 scrubbers used in the submersible consist of two semicircular halves which clamp together around the power unit forming a doughnut-shaped ring with an inner and outer wall of perforated stainless steel lined with filter material. The dimensions of the canisters are 33 cm O.D. x 20.3 cm I.D. x 14.6 cm thickness. 5.89 kg of Sodasorb H.P. is packed in the canister. Two boxer fans in series powered with 28-31 Volts DC at 2 amps draws the air stream through the canister bed and exits through the fans in the pilot sphere. The air stream scurbbing rate at atmospheric pressure is 2.52 m^3/min. In the diver compartment, a Lindberg-Hammer motor and blower adapted to fit the canister scrubber is powered with 24-60 V AC or DC at 3-4 amps. Air streams are pulled by the motor and pushed through the canister bed. The air scrubbing rate for this scrubber configuration is 1.33 m^3/min. at atmospheric pressure and progressively decreasing to 0.849 m^3/min. in air at 8.57 atm (76.2 m of seawater).

CO_2 removal from each air stream through the scrubber at one atmosphere ranged between 22% to 34% and 29% to 44% in both the pilot sphere and diver compartment, respectively. The scrubber configuration and scrubbing rate could cause different scrubbing efficiencies in the submersible. Since the CO_2 scrubber was not operated during the compression period, CO_2 scrubber performance efficiency was not evaluated in the submersible at greater depths.

CONCLUSIONS

This is a preliminary study to investigate the profiles of CO_2, temperature and humidity in a manned submersible. Due to CO_2 sensor's performance, the results shown in this report had a range of ± 20%. This study reveals that the temperature and humidity in the pilot sphere ranged between 24-27°C and 80-85%, respectively. For a non-lockout dive in the diving compartment, the temperature and humidity were around 24°C and 100%, respectively. However, for a lockout dive, temperature was generally increased from 24°C to 31°C at a depth of 80.7 meters. The CO_2 production rate for the pilots and divers in the pilot sphere and diving compartment averaged 0.49 g/mm-min. and

0.61 g/mm-min., repsectively. CO_2 removed from each air stream through the CO_2 scrubber ranged between 22% to 34% and 29% to 44% inside both the pilot sphere and diving compartment, respectively.

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Table 1. Temperature, Humidity and Carbon Dioxide Profiles in the Pilot Sphere

Dive No.	Temperature (C°)	Relative Humidity (%)	CO_2 Concentration (mmHg)	CO_2 Production (g/man-min)		Instantaneous Scrubbing Efficiency (%)
				Travel to Working Site	Submersible Working Site	
538	17-27	75-85	0.4-	0.47±0.20	0.59±0.30	25±4
541	21-27	80-85	0.4-6.5	0.44±0.10	0.73±0.32	22±9
543	24-30	77-93	0.32-7.0	0.46±0.06	0.44±0.08	24±4
544	22-27	79-90	0.32-7.4	0.32±0.05	0.48±0.07	26±5
578	21-30	75-85	0.7-7.0	-	-	-
579	21-31	79-90	0.67-5.5	0.44±0.09	0.44±0.08	34±2
581	17-30	75-90	0.85-5.0	0.44±0.11	-	33±2
594	23-30	85-90	0.65-6.5	0.38±0.04	0.66±0.03	32±6

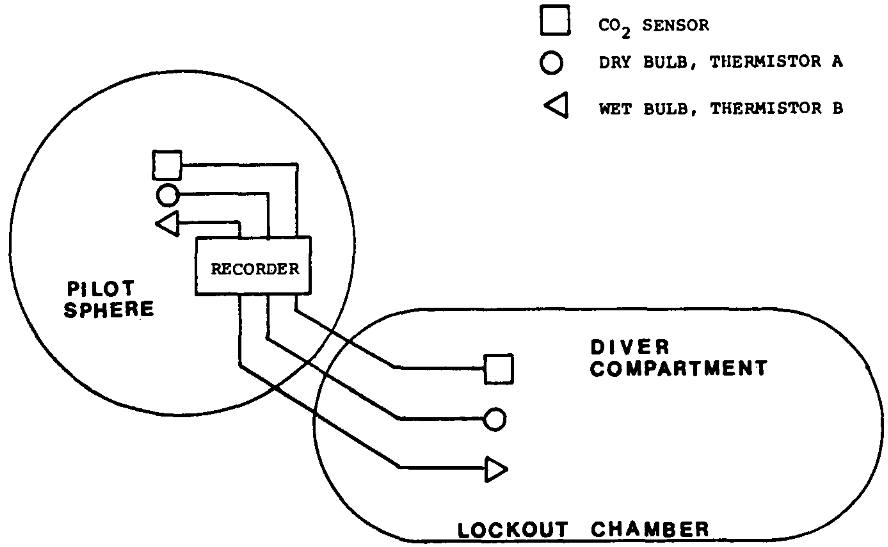
Table 2. Temperature, Humidity and Carbon Dioxide Profiles in the Diving Compartment

Dive No.	Temperature (°C)	Relative Humidity (%)	CO_2 Concentration (mmHg)	CO_2 Production (g/man-min)		Instantaneous Scrubbing Efficiency (%)
				Travel to Working Site	Compression Period (Depth in meter)	
538	17-31	96-106	0.8-7.0	0.76±0.25	0.69±0.32 (79.24)	35±19
540	19-32	97-100	1.8-10.0	0.63±4.0	0.45±0.18 (79.24)	37±15
541	24-27	97-99	1.2-7.2	0.51±0.21	-	29±15
543	19-32	97-100	0.6-5.0	0.44±0.12	0.63±0.09	32±10
544	19-31	99-100	0.6-5.2	0.85±0.27	0.48±0.10 (79.24)	44±2
579	19-31	97-100	1.2-7.4	0.64±0.11	0.70±0.03 (260)	38±6
581	17-31	75-90	0.85-9.0	0.48±0.04	-	44±4
594	23-29	97-100	1.2-5.0	0.69±.15	-	39±9

Table 3. Carbon Dioxide Production Rate at Various Workloads

	Production Rate (g/min - person)	Reference
Driving a car in light traffic	0.43	Fletcher (3)
Piloting DC-3 in level flight	0.60	Fletcher (3)
Calculating	0.59	Passmore (4)
Writing	0.62	Passmore (4)
Resting at Sea Level	0.48	Bradley et al.(5)
45.7 m (150 ft)	0.48	Bradley et al.(5)
91.4 m (300 ft)	0.56	Bradley et al.(5)
137.2 m (450 ft)	0.49	Bradley et al.(5)
182.9 m (600 ft)	0.56	Bradley et al.(5)

Figure 1. Johnson-Sea-Link Submersible



DIMENSIONS

	Pilot Sphere	Diver Compartment
LENGTH	----	8'
OUTSIDE DIAMETER	66"	59½"
INSIDE DIAMETER	58"	53"
HATCH CLEAR OPENING (DIAMETER)	18"	20"
MATERIAL	Acrylic plexiglas "G" Annealed	Aluminum Alloy 5456

Figure 2 Atmosphere Monitoring System in the Johnson-Sea-Link Submersible

Figure 3. Temperature and CO_2 Profiles (Dive No. 540)

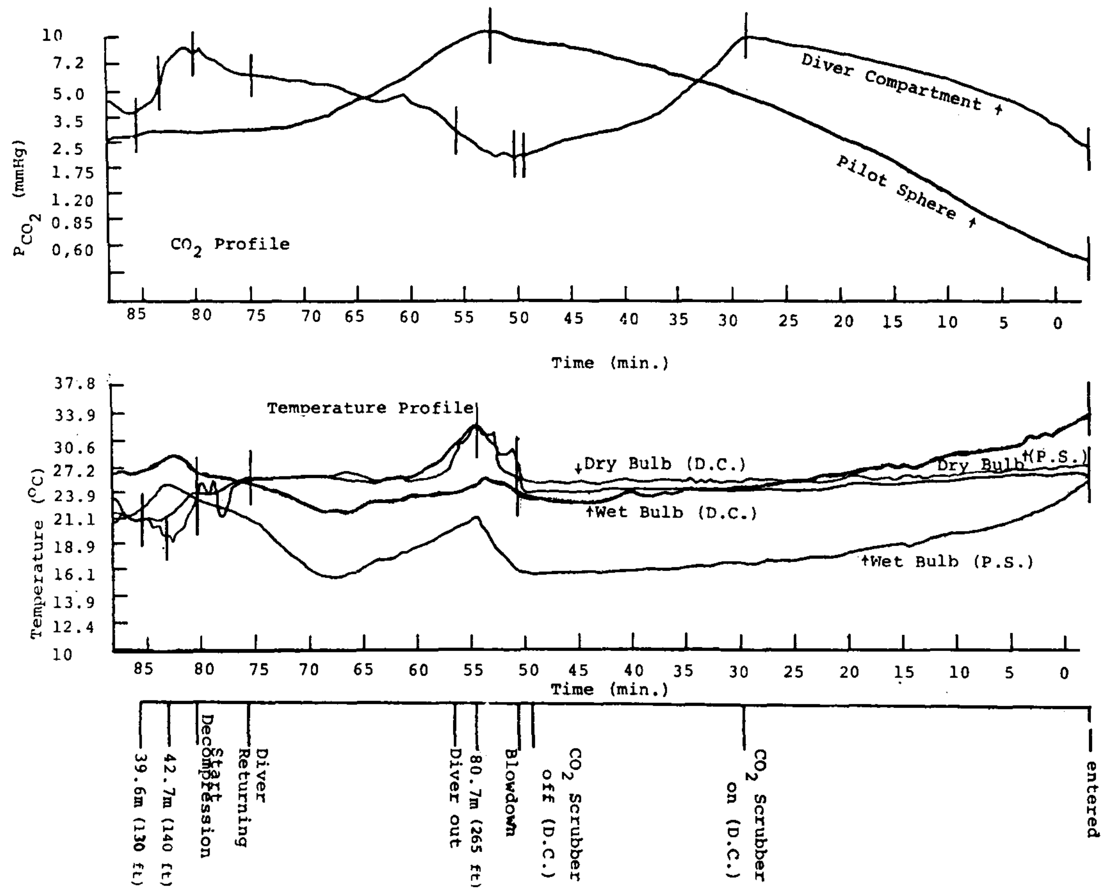


Figure 4 Temperature and CO_2 Profile (Dive No. 541)

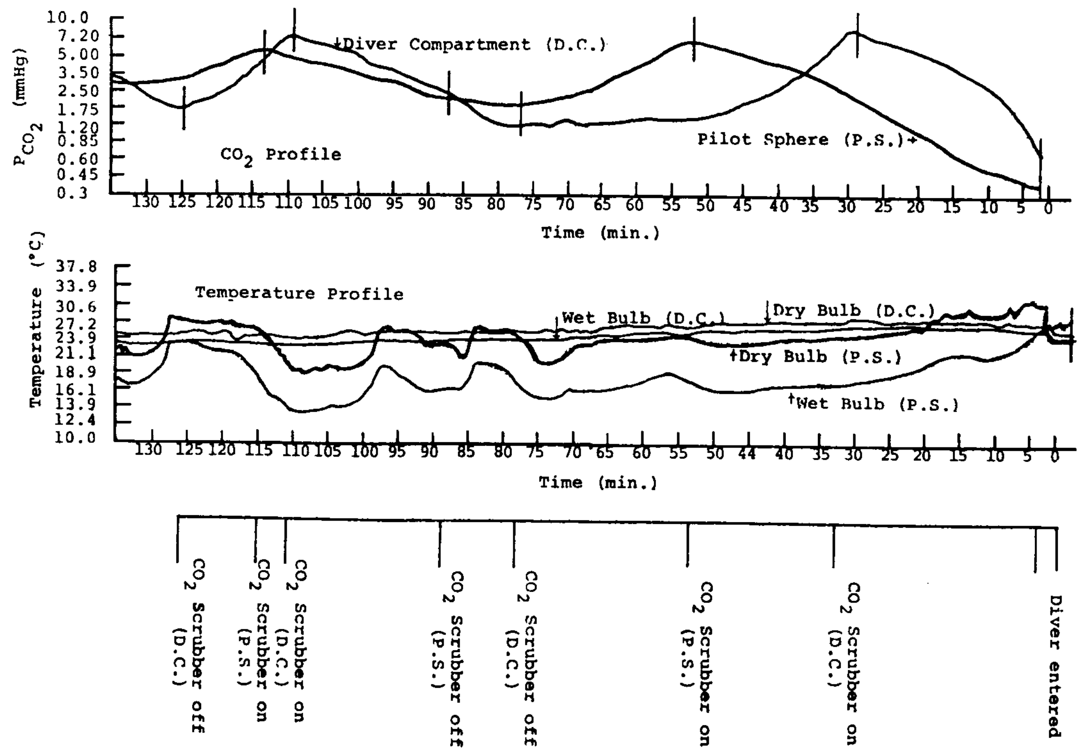


Figure 5 Temperature and CO_2 Profiles (Dive No. 544)

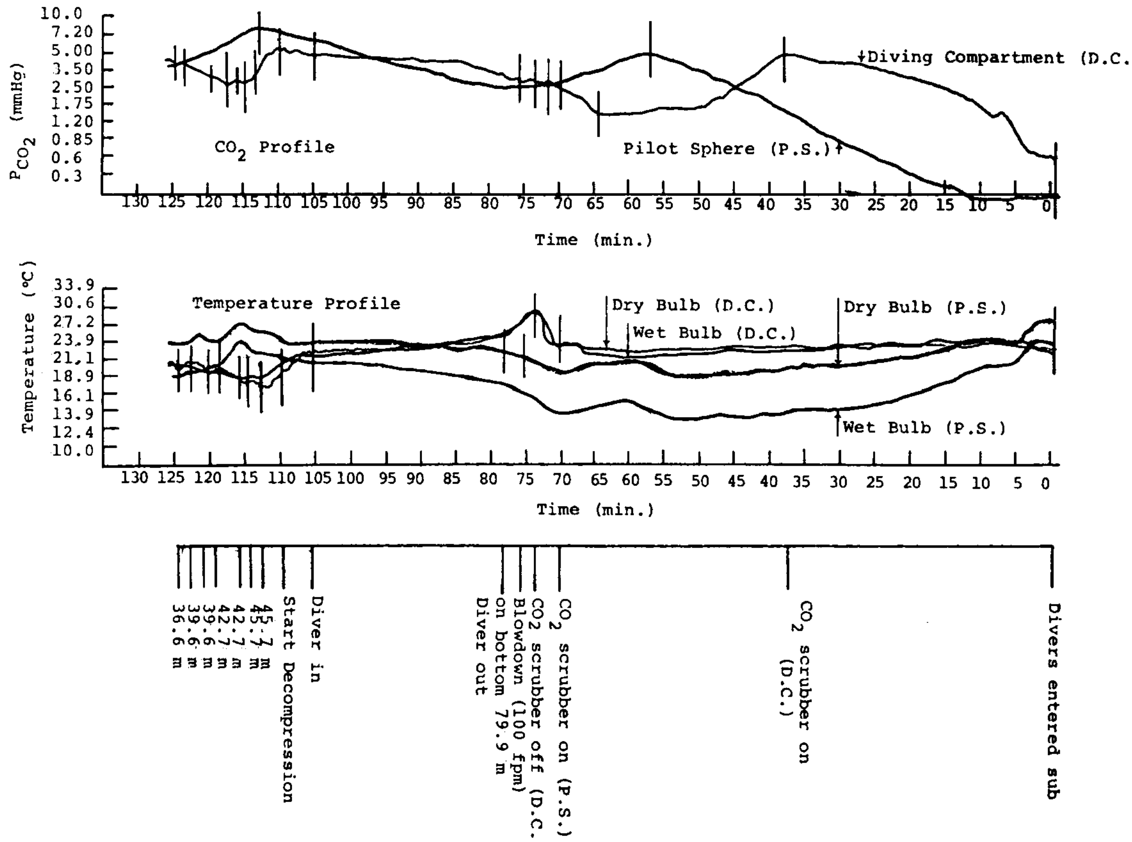


Figure 6

Temperature and CO_2 Profiles (Dive No. 578)

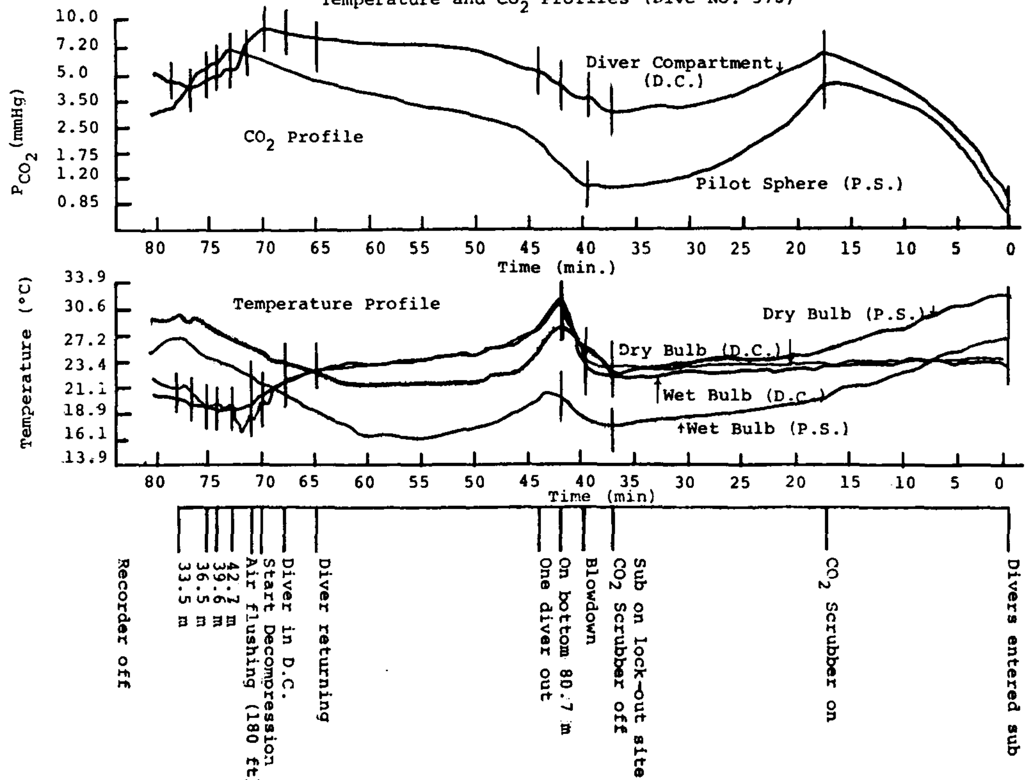


Figure 7 Temperature and CO_2 Profiles (Dive No. 581)