BuMines OFR 29(2)-85

PB85-186849

A mining research contract report
OCTOBER 1984

PHYSIOLOGICAL RESPONSES OF MINERS TO EMERGENCY

VOLUME II
Appendices

Contract J0 100092
The Pennsylvania State University

Bureau of Mines Open File Report 29(2)-85

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

PB85 186849/AS

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. BuMines OFR 29(2)-85	2.	3. Recipient's Accession No.

4. Title and Subtitle

Physiological Responses of Miners to Emergency. Volume II. Appendices

5. Report Date Oct. 2, 1984

6.

7. Author(s) Eliezer Kamon, N. Scott Deno, Max Vercruyssen, James B. Sheehy, David Kiser, and Merrill E. Noble

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Laboratory for Human Performance Research
119 Noll Laboratory
The Pennsylvania State University
University, PA 16802

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.

(C) J0100092

(G)

12. Sponsoring Organization Name and Address

Office of Assistant Director--Mining Research
Bureau of Mines
U.S. Department of the Interior
Washington, DC 20241

13. Type of Report & Period Covered

Contract research, 7/1/81--12/31/83

14.

15. Supplementary Notes

Approved for release February 28, 1985.

16. Abstract (Limit: 200 words)

This report summarizes completed research pertaining to the reaction of human subjects exposed to self-contained breathing apparatus stressors during escape conditions (resistance breathing, CO_2 breathing, hot air breathing, and static positive facepiece positive pressure breathing) and the development of an automated breathing and metabolic simulator. Volume II, the appendix, contains detailed descriptions of the studies performed.

17. Document Analysis a. Descriptors

Mining research
Self-contained breathing apparatus stressors
Resistance breathing
Hot air breathing
Automated breathing and metabolic breathing

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group 08I

18. Availability Statement

Release unlimited by NTIS.

19. Security Class (This Report) Unclassified

20. Security Class (This Page) Unclassified

21. No. of Pages 181

22. Price

DISCLAIMER NOTICE

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the Interior Department's Bureau of Mines or of the United States Government.

*************** EXECUTIVE SUMMARY ***************

Understanding the responses of miners to emergencies is essential in order to maximize the probability of survival following mine disasters. Based on the Federal Coal Mine Health and Safety Act of 1969, a section of the Code of Federal Regulations (30CFR, part 11) was established in 1972 to insure adequate protection of miners and rescue teams in emergency situations. These regulations are currently the standards by which the National Institute for Occupational Health and Safety (MSHA/NIOSH) certifies all self-contained breathing apparatus (SCBA). The 30CFR11 was written with the intent to be revised at approximately ten-year intervals in order to accommodate changes in technology and the expanding types of applications for SCBAs. Long overdue, the purpose of U.S. Bureau of Mines contract No. JO 100092 was to establish a more quantitative basis for recommending revisions to the current 30CFR11 regulations. This report summarizes completed research pertaining to the reaction of human subjects exposed to SCBA stressors during escape conditions (viz., resistance breathing, CO2 breathing, hot air breathing, and static facepiece positive pressure breathing) and the development of an automated breathing & metabolic simulator (ABMS). To facilitate the implementation of the ABMS, a breathing waveform study was undertaken to characterize flow rate waveforms of human subjects under multiple exercise and resistance breathing conditions. A mathematical model of human and oxygen bottle type SCBA performance was also developed in this contract. This model enables predictions of SCBA performance under specific conditions without actually expending an SCBA. Moreover, this model, which will operate on most scientific computers, is useful in investigating effects of SCBA design changes and can be used as an instructional tool for industrial hygienists and individuals requiring in-depth knowledge of SCBA functions.

This report is divided into two volumes. Volume I contains summaries of the studies performed under this contract. These studies are presented in seven sections: (1) resistance breathing, (2) carbon dioxide breathing, (3) positive pressure breathing, (4) hot air breathing, (5) automated breathing & metabolic simulator, (6) mathematical model of SCBA and human subjects, and (7) breathing waveforms. Volume II is an appendix which contains more detailed descriptions of these studies. Information is also available in theses, manuscripts, and publications written under this contract (see report references).

This is VOLUME II

****

FOREWORD

This report was prepared by the Laboratory for Human Performance Research at The Pennsylvania State University under U.S. Bureau of Mines contract No. JO 100092. The technical project officer was John Kovac from the Pittsburgh Research Center and the contract administrator was Janice Johnson. Research was conducted 1 July 1981 to 31 December 1983. This report was submitted 15 June 1984.

Research reported herein was under the direction of Eliezer Kamon and Scott Deno, co-principal investigators, and Max Vercruyssen, co-investigator. Other staff and students assisted in collecting data, analyzing results, and writing portions of this report. Charles Ryan's constant management of our laboratory and assistance in data collection and data analysis was invaluable. Students who had a major role in the research presented in this report include Jon Benson, Colette Bizal, Tom Brennan, Philip Crosby, Sean Gallagher, David Kiser, Peter LaChance, Donna Mah, James Pawelczyk, James Sheehy, Dean Sittig, and Claudia Turner. Students which assisted in the writing of portions of this report were Colette Bizal, Philip Crosby, Sean Gallagher, and Dean Sittig. We also must thank Tina Mihaly for her excellent editorial assistance in refining and assembling portions of this report. We thank these supporting people for their dedication.

TABLE OF CONTENTS VOLUME II

TABLE OF CONTENTS VOLUME II (continued)

LIST OF TABLES VOLUME II

LIST OF TABLES VOLUME II (continued)

LIST OF TABLES VOLUME II (continued)

LIST OF FIGURES VOLUME II (continued)

LIST OF FIGURES VOLUME II (continued)

LIST OF FIGURES VOLUME II (continued)

LIST OF FIGURES VOLUME II (continued)

APPENDIX A1:

EFFECTS OF BREATHING RESISTANCE

Introduction

Respirators and self-contained breathing apparatus (SCBA) offer resistance to breathing. If the resistance is large enough, the user's work performance capability can be reduced. Other investigators have studied the responses to resistance with regard to "comfort" and not actual physiological limits (Silverman, 1961; Gamberale, 1978; Dressendorfer, 1976; Johnson, 1976; Craig, 1970; Hermansen, 1972). Fewer investigators have systematically studied the effects of resistance on work performance, and these studies are for short duration exposure (Cerretelli,1969; Demedts, 1973).

In the described study, the reduction in work rate capability of healthy young men was studied. Exposures to resistance were of long duration (one hour). Also, associated respiratory measurements were made to evaluate the user's changes in physiological state due to the resistance imposed. A wide range of balanced resistances and imbalanced resistances were investigated where balanced resistance is defined as equal resistance on the expired and inspired breathing pathways.

The inspiratory and expiratory phases of the breathing cycle were known to have different tolerances to resistance, therefore the results from the imbalanced exposures are important in establishing an optimum ratio of expired and inspired resistance when designing an SCBA. All the combinations of resistance exposure conditions are significant in establishing resistance levels, both inspired and expired and the interelationship between the two.

Methods

Breathing resistance

Inhalation and exhalation were restricted using small diameter, 5-cm-long tubing segments. These segments were located 130cm from the subject breathing valve. The no-resistance control condition used only the breathing valve and a #3 Fleisch pneumotachograph. The breathing resistance segments were defined by the pressure developed across the segment at a flow of 60 liters per minute (L/min). The resistances tested on both expired and inspired ranged from 0 (control) to 65 cm H2O. For simplicity these resistances were placed in ranges; control (<2 cm H2O), low resistance (2<=R<10cm H2O), medium (10<=R<25), high (25<=R<40cm H2O), and very high (>40cm H2O).

Exercise

For all tests the subjects were told to perform their maximum effort. If tests were completed without requiring a maximum effort the data from that test were discarded and the test repeated at a higher work rate. Tests where the subject could not complete the test were also repeated at a lower work rate until the true maximum effort was found. Only data from maximum effort tests are included in the described study. The subjects were highly motivated and were considered to be comparable to an SCBA user would be in a life threatening situation.

Measurements

Heart rate (HR), minute ventilation (VE), oxygen consumption (VO2), respiratory frequency (fB), respiratory exchange ratio (RQ), end tidal CO2 partial pressure (PCO2), tidal volume (VT), time of expiration (TE), time of inspiration (TI), peak pressure expired (PE), peak inspired pressure (PI).

The inspired and expired flow rates, pressure at the mouth, and mouth concentrations are measured instantaneously, digitized, and analyzed using a PDP 11 mini-computer. All the above variables are calculated from these instantaneous signals by the computer.

All the reported variables are averages between the 30-to-45 minute times during each 1-hour test. This time interval is the best representation of the steady-state of the subject.

Subjects

Two subject populations were tested. The first group was composed of healthy, young college students of average or above average fitness. The second group was composed of miners from Associated Drilling Co. of Philipsburg, Pa. Each condition tested involved at least five subjects and no subject data are included for repeated trials at the same condition. Subject data are in Table A1-1.

Table A1-1: Subject Characteristics

Condition group	Age (yrs)	Height (cm)	Weight (kg)	VO2max (L/min-STPD)
YOUNG MALES				
balanced resistance	26 4 SD	178 7 SD	75 10 SD	3.77 0.56 SD
umbalanced resistance	25 6 SD	173 2 SD	74 4 SD	4.01 0.20 SD
MINERS				
balanced resistance	34 1 SD	173 3 SD	94 33 SD	3.05 0.22 SD

Procedures

The subject's VO2max was determined using a graded treadmill exercise test to exhaustion, as part of his initial medical examination. The maximum work rate which each subject could achieve at a given resistance condition was measured on the treadmill where the target duration to exhaustion was one hour. Subjects were highly motivated and instructed to perform a maximum effort. Tests where the subject could not last the hour were repeated at a lower speed or grade. Tests which were performed for the hour without a maximum effort were repeated at a higher work rate on another day. Resistance conditions were exposed to subjects in a random order. Only maximal effort results are reported.

The miner population was tested only with the balanced resistance conditions.

Results

The resistance conditions were grouped into 5 ranges of intensity. These were categorized from "NONE" to "VERY HIGH" where "NONE" is no resistance to breathing or the control condition. The "LOW" condition is all resistance conditions tested between 2 and 9.9 cmH2O @60L/min flow, the "MODERATE" conditions were resistance conditions between 10 and 24.9 cmH2O @ 60L/min flow, "HIGH" conditions were between 25 and 39.9 cmH2O @60L/min flow, and the "VERY HIGH" conditions were between 40 and

65 cmH2O @60L/min flow. All the results are presented in this grouping.

Work Rate (Young Male Group)

The decrement in work rate capability, which is of primary importance, is shown in Table A1-2. The work rate effect from the duration (one hour) alone is consistant with results from other investigators (Bonjer, 1962). Bonjer predicts 64% of maximum for one hour of work and our study measured 57% for no resistance and slightly higher value of 64% for the low resistance condition. This slight increase in work tolerance with increasing resistance should not be considered significant and is not maintained as resistance is increased.

Clearly, the decrement in performance is significant with increasing resistance imposed, however the decrement is not as great as one might expect considering the intensity of the resistances imposed. The expired effects are very similar to the inspired effects when the resistance is imbalanced. The largest drop in work rate, with the very high resistance only on one side, limits work rate to 48% and 47% VO2max for the inspired and expired sides, respectively. Balanced resistance effects are larger, as expected, than the imbalanced resistance conditions because the overall respiratory stress is increased. The largest effect of the very high balanced resistance condition is a limit of the work rate capability to 35% VO2max.

The absolute work rate results are shown in Table A1-3.

Table A1-2: Resistance Effects on %VO2MAX
Young Male Group

Expired		Inspired NONE	LOW	MODERATE	HIGH	VERY HIGH
	NONE	57.4	65.0	64.0	58.8	48.0
	LOW	64.0	54.9	53.0	--	--
	MODERATE	64.0	42.7	46.0	--	--
	HIGH	55.8	--	--	--	--
	VERY HIGH	47.0	--	--	--	35.0

Table A1-3: Resistance Effects on VO2 (L/min)
Young Male Group

Expired		Inspired NONE	LOW	MODERATE	HIGH	VERY HIGH
	NONE	2.23	2.04	2.02	1.95	1.85
	LOW	2.06	2.16	2.12	--	--
	MODERATE	2.01	1.71	1.73	--	--
	HIGH	2.06	--	--	--	--
	VERY HIGH	1.87	--	--	--	1.30

Heart Rate (Young Male Group)

Heart rate follows the work rate capability with changes in resistance conditions. Even though this study was not designed to separate resistance effects and exercise effects on heart rate, there is no indication that heart rate is elevated by the stress of the imposed resistance to breathing. The heart rate is elevated due to exercise only. The results are shown in Table A1-4.

Table A1-4: Resistance Effects on Heart Rate (bpm)
Young Male Group

		Inspired				
		NONE	LOW	MODERATE	HIGH	VERY HIGH
Expired	NONE	144	155	149	145	131
	LOW	151	151	146	--	--
	MODERATE	150	136	131	--	--
	HIGH	147	--	--	--	--
	VERY HIGH	133	--	--	--	119

Ventilation (Young Male Group)

The ventilation is the variable most directly affected by the breathing resistance . The ventilation is decreased by resistance to a much larger degree than any other variable. The ventilation is reduced to 38% at the most severe condition, as compared to the VO2max which is reduced to only 61% from the control condition. Generally both inspiratory and expiratory stress reduce overall ventilation with a slightly larger effect on the expiratory side. The ventilation results are shown in table A1-5. The ventilatory equivalent (VE/VO2) indicates dramatically the effects on the ventilation in relation to the VO2 as shown in Table A1-6. This means that gas exchange is occurring with increasing resistance in spite of reductions in ventilation.

Table A1-5: Resistance Effects on Ventilation (L/min)
Young Male Group

		Inspired				
		NONE	LOW	MODERATE	HIGH	VERY HIGH
Expired	NONE	46.5	40.4	35.5	30.9	27.1
	LOW	37.6	37.2	34.0	--	--
	MODERATE	34.5	28.1	25.4	--	--
	HIGH	33.6	--	--	--	--
	VERY HIGH	29.0	--	--	--	17.6

Table A1-6: Resistance Effects on Ventilatory Equivalent (VE/VO2)
Young Male Group

		Inspired				
		NONE	LOW	MODERATE	HIGH	VERY HIGH
Expired	NONE	20.8	19.7	17.6	15.9	14.6
	LOW	18.3	17.2	16.0	--	--
	MODERATE	17.2	16.4	14.7	--	--
	HIGH	16.3	--	--	--	--
	VERY HIGH	15.5	--	--	--	13.5

Respiratory Frequency (Young Male Group)

Reductions in respiratory frequency (fB) are similar to reductions in ventilation. The fB is consistantly reduced by resistance breathing in any combination of exposure. The detailed results for fB are shown in Table A1-7.

Table A1-7: Resistance Effects on Breathing Frequency (Breath/min)
Young Male Group

Inspired

Expired	NONE	LOW	MODERATE	HIGH	VERY HIGH
NONE	36.3	26.5	24.0	23.8	20.0
LOW	27.5	26.3	24.0	--	--
MODERATE	26.0	24.0	18.0	--	--
HIGH	25.2	--	--	--	--
VERY HIGH	23.0	--	--	--	13.0

Respiratory Exchange Ratio (Young Male Group)

The respiratory exchange ratio (RQ) has no clear trend with increasing resistance on either the expired or inspired cycles. This is expected since the RQ is an indicator of the fuel for metabolism. The fuel or energy source for metabolism is not expected to change due to resistance breathing. Results are shown in Table A1-8.

Table A1-8: Resistance Effects on Respiratory Exchange Ratio (CO2/O2)
Young Male Group

Inspired

Expired	NONE	LOW	MODERATE	HIGH	VERY HIGH
NONE	0.93	0.76	0.78	0.83	0.91
LOW	0.83	0.98	0.92	--	--
MODERATE	0.85	0.90	--	--	--
HIGH	0.85	--	--	--	--
VERY HIGH	0.95	--	--	--	--

End Tidal CO2 Partial Pressure (Young Male Group)

End tidal CO2 partial pressure (PETCO2) was consistantly increased with increased resistance to breathing. Again, the expired and inspired effects are similar. The PETCO2 plays a significant role as the indicator of blood CO2 levels, which are the limiting factor when ventilation is restricted. The PETCO2 rises quickly with increasing resistance and levels off at a PETCO2 of 53.9 mmHg. Results are shown in Table A1-9.

Table A1-9: Resistance Effects on PCO2 (mmHg)
Young Male Group

		Inspired				
		NONE	LOW	MODERATE	HIGH	VERY HIGH
Expired	NONE	42.1	45.5	46.7	47.2	--
	LOW	42.7	49.3	--	--	--
	MODERATE	45.1	--	52.2	--	--
	HIGH	47.2	--	--	--	--
	VERY HIGH	--	--	--	--	53.9

Tidal Volume (Young Male Group)

Tidal volume does not change significantly with resistance. This is in contrast to the large changes in VE and fB. The respiratory control center is reacting to the resistance stress by maintaining VT. Results are shown in Table A1-10.

Table A1-10: Resistance Effects on Tidal Volume (L/breath)
Young Male Group

Expired \ Inspired	NONE	LOW	MODERATE	HIGH	VERY HIGH
NONE	1.37	1.20	1.35	1.60	1.49
LOW	1.10	1.82	1.35	--	--
MODERATE	1.15	1.30	--	--	--
HIGH	1.39	--	--	--	--
VERY HIGH	1.41	--	--	--	--

Mouth Pressures

Both the peak expiratory mouth pressure (PE) and peak inspiratory mouth pressure (PI) are shown in Table A1-11 and A1-12. Of course, dramatic increases in pressure are observed on any portion of the breathing cycle which has the resistance imposed. Somewhat surprisingly, the peak pressure for the expiratory side for the totally imbalanced resistance case is higher (49.0 cmH2O) than the inspiratory side for the totally imbalanced resistance case (34.0 cmH2O). This is in contrast to the balanced resistance conditions where the expiratory side consistently produced lower peak pressures. The expiratory respiratory muscles are generally considered weaker than the inspiratory muscles by traditional respiratory mechanics studies. Clearly, the respiratory muscles involved in expiration have nearly equal strength to the inspiratory muscles when the stress is applied.

Table A1-11: Resistance Effects on Peak Expired Pressure (cm H2O)
Young Male Group

Expired \ Inspired	NONE	LOW	MODERATE	HIGH	VERY HIGH
NONE	4.13	17.8	23.0	33.7	34.0
LOW	4.26	19.1	17.3	--	--
MODERATE	3.70	30.0	25.4	--	--
HIGH	5.00	--	--	--	--
VERY HIGH	7.50	--	--	--	30.2

Table A1-12: Resistance Effects on Peak Inspired Pressure (cm H2O)
Young Male Group

Expired \ Inspired	NONE	LOW	MODERATE	HIGH	VERY HIGH
NONE	3.7	5.6	3.3	3.2	4.0
LOW	16.5	26.2	41.8	--	--
MODERATE	31.3	17.8	31.8	--	--
HIGH	44.0	--	--	--	--
VERY HIGH	49.0	--	--	--	44.2

Expired-Inspired Duration Ratio

The expired-inspired duration ratio (TE/TI) is an indication of which portion of the total breathing cycle is using the largest portion of the available time to transfer gas through the mouth. The balanced resistance conditions all produced ratios slightly greater than one, indicating that the expiratory portion is using slightly more of the available time. This ratio did not change significantly as the resistances increased for the balance resistance conditions (Table A1-13 diagonal values). The ratio is altered dramatically for imbalanced resistance conditions, where as expected the portion of the breathing cycle with resistance takes more of the available time to move the gases through the mouth.

Table A1-13: Resistance Effects on Expired/Inspired Time Ratio (cm H2O/cm H2O) Young Male Group

		Inspired				
		NONE	LOW	MODERATE	HIGH	VERY HIGH
Expired	NONE	1.18	1.72	2.25	2.36	2.21
	LOW	0.73	1.07	0.88	--	--
	MODERATE	0.61	1.51	--	--	--
	HIGH	0.43	--	--	--	--
	VERY HIGH	0.44	--	--	--	--

Prediction Equations for the Young Male Group

Regression prediction equations were developed for the measured variables for the young male group. Independent variables are the expired resistance (RE) and inspired resistances (RI) and the interaction term (RE*RI), which is the product of RE and RI. All independent variable resistance terms are in units of cmH2O pressure at a flow rate of 60 L/min. The predictions equations are as follows:

$$\%VO2max = 59.7 - 0.203RE - 0.139RI - 0.002RE*RI$$

$$VE = 40.3 - 0.239RE - 0.272RI + 0.001RE*RI$$

$$fB = 29.1 - 0.138RE - 0.187RI$$

$$VT = 1.05 + 0.01RI$$

$$PE = 12.8 - 0.114RE + 0.528RI$$

$$PI = 15.8 + 0.738RE - 0.204RI$$

$$TE/TI = 1.21 - 0.01RE + 0.02RI$$

Results of Miner Population

Results for the miner population tested are shown in Table A1-14 to Table A1-25. They show interesting differences from the young male group. The absolute VO2 for the miners is significantly less than the young male population (28% less on the average). However, based on VO2max, the miners VO2max were not significantly less than the young male group. The peak pressures developed by the miners were only slightly less than the young male group for the same conditions, as was the effect on ventilation.

The PETCO2 values for the miners were all lower than the young male group. This indicates that the miners, in general, were not at their respiratory limit during these tests. This also may indicate a slightly reduced motivation by the miners to their "true" work rate limit. The fact that the PETCO2 were lower for miners even at the control condition ("NONE") indicates that the miners were hyperventilating due to anxiety about the laboratory environment.

The miners responses to other variables of HR, RQ, VT, and TE/TI were similar to the young male population.

Table A1-14: Resistance Effects on %VO2max
Miner Group

		Inspired		
		NONE	LOW	MODERATE
Expired	NONE	53.8	--	--
	LOW	--	39.4	--
	MODERATE	--	--	47.8

Table A1-15: Resistance Effects on VO2 (L/min)
Miner Group

Expired \ Inspired	NONE	LOW	MODERATE
NONE	1.65	--	--
LOW	--	1.20	--
MODERATE	--	--	1.46

Table A1-16: Resistance Effect on Heart Rate (bpm)
Miner Group

Expired \ Inspired	NONE	LOW	MODERATE
NONE	172	--	--
LOW	--	114	--
MODERATE	--	--	117

Table A1-17: Resistance Effect on Ventilation Response (L/min)
Miner Group

Expired \ Inspired	NONE	LOW	MODERATE
NONE	37.7	--	--
LOW	--	21.4	--
MODERATE	--	--	30.1

Table A1-18: Resistance Effect on Ventilatory Equivalent (L/min)
Miner Group

Expired \ Inspired	NONE	LOW	MODERATE
NONE	23.4	--	--
LOW	--	17.8	--
MODERATE	--	--	20.5

Table A1-19: Resistance Effect on Breathing Frequency (Breath/min)
Miner Group

Expired \ Inspired	NONE	LOW	MODERATE
NONE	30.5	--	--
LOW	--	17.2	--
MODERATE	--	--	23.7

Table A1-20: Resistance Effect on Exchange Ratio (R)
Miner Group

Expired \ Inspired	NONE	LOW	MODERATE
NONE	0.83	--	--
LOW	--	0.81	--
MODERATE	--	--	0.80

Table A1-21: Resistance Effect on End Tidal PCO2 (mmHg)
Miner Group

Expired \ Inspired	NONE	LOW	MODERATE
NONE	29.9	--	--
LOW	--	29.7	--
MODERATE	--	--	31.6

Table A1-22: Resistance Effect on Tidal Volume (L/min)
Miner Group

Expired \ Inspired	NONE	LOW	MODERATE
NONE	0.73	--	--
LOW	--	0.89	--
MODERATE	--	--	0.84

Table A1-23: Resistance Effect on Peak Expired Pressure (mmHg)
Miner Group

Expired \ Inspired	NONE	LOW	MODERATE
NONE	2.9	--	--
LOW	--	23.1	--
MODERATE	--	--	15.0

Table A1-24: Resistance Effect on Inspired Pressure (cmH2O)
Miner Group

Expired \ Inspired	NONE	LOW	MODERATE
NONE	3.1	--	--
LOW	--	25.5	--
MODERATE	--	--	13.9

Table A1-25: Resistance Effect on Expired-Inspired Time Ratio (sec/sec
Miner Group

Expired \ Inspired	NONE	LOW	MODERATE
NONE	1.26	--	--
LOW	--	1.19	--
MODERATE	--	--	1.26

Discussion

The results set a clear profile of the responses of two populations to the stressor of breathing resistance. The most significant variable is the percentage of maximum aerobic capacity (% VO2max). The % VO2max is the most predictable variable and is a direct predictor of the subject's work performance in the respiratory use situation. In a particular situation, to estimate a user's actual escape time in a mine accident, the user's maximum aerobic capacity (VO2max) and body weight are necessary. The VO2max can be predicted from age and body weight, if not directly measurable. The actual speed of exit can be predicted, if given the grade of exit path. This means that the percentage reduction in % VO2max is proportional to the percentage reduction in escape time from the site of an accident. As shown in Table A1-2, no clearly significant reduction in % VO2max occurs until the expired resistance reaches the moderate resistance level.

The miner population tested had a lower absolute VO2 (see Table A1-15) as compared to the young male population (see Table A1-3). This difference should not be overlooked when estimating escape times in an accident situation. The miners also had a lower VO2max as measured on the exercise tolerance stress test. This difference is partially due to the age differences in the two groups (see Table A1-1), even though our miner population had no miners over age 40. Older miners should be evaluated in the future; however, one would expect a high correlation between % VO2max and resistance stress condition to be maintained for an older miner population. One would also expect the older miner population to have lower VO2max values.

The respiratory status of the subjects is well profiled by the VT, fB, PCO2, PE, PI, and TE/TI results. The expired and inspired portions of the breathing cycle responded only slightly differently to the stress of resistance. Traditional physiological studies would have predicted that the expired portion of the breathing cycle would have more difficulty than the inspiratory portion. This is based on the idea that expiration is "mostly passive." Indeed, this is not the case. The expiratory muscles are very capable of maintaining necessary flows with resistance to breathing imposed.

References

Astrand, P. O., and P. Rodahl. Textbook of Work Physiology: Physiological Basis fo Exercise, New York: McGraw-Hill,Inc., 1977.

Bentley, R. A. and O. G. Griffin, R. G. Love, D. C. F. Muir and K. F. Sweetland. Acceptable levels of breathing resistance of respiratory apparatus. Arch. Environ. Health, 27, 273-280.

Bernard,T.E., R.L. Stein, E. Kamon. Evaluation of federal amn test for self-contained breathing apparatus. Am. Ind. Hyg.,1977,38, 689-695.

Bonjer, F. H. Actual energy expenditure in relation to the physical working capacity. Ergonomics, 1962, 5, 29.

Cerretelli, P., R. S. Sikand and L. E. Farhi. Effect of increased airway resistance on ventilation and gas exchange during exercise. J. Appl. Physiol., 1969, 27, 597-600.

Comroe, J. H. Physiology of Respiration: An Introduction Text, Chicago: Year Book Medical Publishers Inc., 1974.

Consolazio,C.F., R.E. Johnson and L.J. Pecora. Physiological measurements of metabolic function in man. New York,Mc-Graw Hill,1963

Craig, F. N., W. V. Blevins and E. G. Cummings. Exhausting work limited by external resistance and inhalation of carbon dioxide. J. Appl. Physiol. 1970, 29, 847.

Demedts, M. and N. R. Anthonisen. Effects of increased external airway resistance during steady-state exercise. J. Appl. Physiol, 1973, 35, 361.

Dressendorfer, R. H., C. E. Wade and E. M. Bernauer. Combined effects of breathing resistance and hyperoxia on aerobic work tolerance., J. Appl. Physiol., 1977, 42, 444-448.

Dubois, A. B. Resistance to breathing. In :Handbook of Physiology: Respiration, Vol. 2 (Eds.) W. O. Fenn and H. Rahn. Baltimore: Waverly Press, Inc., 1964.

Flook, V. and G. R Kelman. Submaximal exercise with increased inspiratory resistance to breathing., J. Appl. Physiol., 1973, 35, 379-384.

Gamberale, F., I. Holmer, A. S. Kindblom, and A. Nordstrom. Magnitude perception of added inspiratory resistance during steady-state exercise. Ergonomics, 1978, 21, 531.

Grimby, G. Pulmonary mechanics: The load in muscular exercise and the lung. (Eds.) J. A. Dempsey and C. E. Reed, Univ. of Wisconsin Press. 1977.

Hermansen, L., Z. Vokac and P. Lereim. Respiratory and circulatory response to added air flow resistance during exercise., Ergonomics, 1972, 15, 15-24.

Johnson, A. T. The energetics of mask wear. American Industrial Hygiene Association Journal, 1976, 37, 479.

Mead, J., and E. Asostona. Dynamics of breathing. In: Handbook of Physiology: REspiration, Vol. 2 (Eds.) W. O. Fenn and H. Rahn., Baltimore: Waverly Press Inc., 1964, 411-427.

Otis, A. B., The work of breathing.In: Handbook of Physiology: REspiration, Vol. 2 (Eds.) W. O. Fenn and H. Rahn., Baltimore: Waverly Press Inc., 1964, 463-476.

Protor, D. F. and J. B. Hardy. Studies of respiratory airflow., Bulletin of the John Hopkins Hospital, Vol. 85 (Ed.) E. C. Andrus., Baltimore: John Hopkins Press, 1949, 253-280.

Rahn, H., A. B. Otis, L. E. Chadwick and W. O. Fenn. The pressure- volume diagram of the thorax and lung. Am. J. Physiol, 1946, 146, 161.

Seales, D.M., Kennedy, R.S., & Bittner, A.C., Jr. Development of performance evaluation tests for environmental research (PETER): Arithmetic computation. Perceptual and Motor Skills, 1980, 51, 1023-1031. Silverman, L., C. E. Billings. Pattern of airflow in the respiratory tract in inhaled particles and vapours, (Ed.) C. N. David., New York: Pergamon Press, 1961.

Silverman, L., R. C. Lee, G. Lee, K. R. Drinker and T. M. Carpenter. Fundamental factors in the design of protective respiratory equipment: Inspiratory airflow measurements on human subjects with and without resistance. OSRD Report number 1222,1943.

Silverman, L., G. Lee, A. R. Yancey, L. Armoy, L. J. Barney, and R. C. Lee. Fundamental factors in the design of protective respiratory equipment: A study and an evaluation of inspiratory and expiratory resistances for protective respiratory equipment. OSRD Report number 5339, 1945.

Silverman, L., G. Lee, T. Plotkin, L. Armoy, and A. R. Yancey. Fundamental factors in the design of protective respiratory equipment: Inspiratory and expiratory air flow measurements on human subjects with and without resistance at several work rates. OSRD Report number 5732, 1945.

Silverman, L., and C. E. Billings. Pattern of airflow in the repiratory tract. In: Inhaled Particles and Vapors (Ed.) C. N. Davies. New York: Pergamon Press, 1961, 9-45.

Vorosmarti, J. Influence of increased gas density and external resistance on maximum expiratory flow. Undersea Biomed. Res., 1979, 6, 339.

Whipp,B.J., K. Wasserman. Oxygen uptake kinetics for various intensities of constant-load work. J. Appl. Physiol.,1972, 33(3), 351-356.

Yamashiro, S. M. and F. S.Grodins. Optimal regulation of respiratory airflow. J. Appl. Physiol., 1971, 30, 597-602.

Zechman, F., F. G. Hallan and W. E. Hull. Effects of graded resistance to tracheal air flow in man. J. Appl. Physiol., 1957, 365-362.

HUMAN FACTORS, 1982, 24(5), 581–588

Effects of Carbon Dioxide Inhalation on Psychomotor and Mental Performance during Exercise and Recovery

JAMES B. SHEEHY, ELIEZER KAMON,[1] *and* DAVID KISER, *Pennsylvania State University, University Park, Pennsylvania*

Psychomotor and mental tests involving reaction time, rotor pursuit, short-term memory for digits and letters, and reasoning ability were administered to subjects inhaling up to 5% CO_2 *in air and in gas mixtures containing 50%* O_2*. The psychomotor and mental tests were given during the 6 min of recovery following 10 min of treadmill running at 80% of aerobic capacity. Although the subjects inhaled the* CO_2 *during the entire exercise and recovery period there was no difference in performance between the* CO_2 *inhalation condition and the control condition for any of the performance measures.*

INTRODUCTION

Exposure to carbon dioxide is not uncommon in a wide range of occupations. Observations on carbon dioxide (CO_2) exposure range from 1 to 2% in submarines and space vehicles for mostly sedentary activities, to between 3 and 10% in grain silos, oil tanks, and chemical treatment plants where physical activities are performed (NIOSH, 1976). The determination of an acceptable level of CO_2 inhalation that will not adversely affect performance depends on such factors as the level of physical work and the psychological, physiological, or clinical effects involved.

The literature is devoid of attempts to assess the effects of CO_2 as measured by psychological tests. Carbon monoxide (CO), not carbon dioxide (CO_2), adversely affected dual-task performance (Putz, 1979), whereas vigilance was shown not to decrease after exposure to concentrations of CO normally found in urban environments (Roche, Horvath, Gliner, Wagner, and Borgia, 1981). Inhalation of CO_2 during physical exertion could involve hidden psychological effects, such as deterioration of motor control, loss of orientation, and impaired mental performance or reasoning ability, although no physiological effects or clinical symptoms are reported.

Noticeable physiological responses to CO_2 inhalation were an increase in pulmonary ventilation (Dripps and Comroe, 1947), constriction or dilation of blood vessels (Lambertsen, 1971), increases of up to 75% in cerebral blood flow (Kety and Schmidt, 1948), decreases in specific airway resistance (Taskin and Simmons, 1972), changes in the electrocardiogram (McDonald and Simonson, 1953), and apparent premature cardiac contractions (McDonald and Simonson, 1953). Clinical symptoms observed were headaches,

[1] Request for reprints should be sent to E. Kamon, 104 Noll Laboratory, The Pennsylvania State University, University Park, PA 16802.

dizziness, restlessness, and dyspnea (Schaefer, 1963). After 12 to 15 h of exposure to CO_2 concentrations of 2 to 3% during sedentary activities, subjects exhibited lassitude, irritability, and unconsciousness. Within 3 min of exposure to CO_2 levels of 20 to 30%, subjects exhibited increased perspiration, flushing, restlessness, dilation of the pupils, leg flexions, and torsion spasms (Lambertsen, 1971).

Exercise compounds the problems created by CO_2 inhalation. The body's retention of CO_2 normally increases with exposure time; however, exercise increases metabolic CO_2 production, and this results in an even higher CO_2 retention. This excess CO_2 could in turn reduce the worker's endurance for strenuous physical work (Craig, Blevins, and Cummings, 1970). Inhalation of CO_2 during physical work can occur during fire fighting or following an underground mining disaster, when a self-contained respirator (SCR) is used to prevent the inhalation of ambient toxic gases. The SCR is designed to provide oxygen while absorbing the CO_2 produced by the body. Most SCRs, however, are limited in their capacity to absorb CO_2; therefore, during prolonged usage the level of unabsorbed CO_2 will increase with time.

Although physiological responses to inhalation of up to 10% CO_2 during rest and exercise did not indicate deterioration of essential body functions (Craig, 1955; Asmussen and Nielsen, 1957), unknown psychological effects, such as loss of orientation, could be crucial to the user of an SCR during an emergency situation. The duration of SCR use during emergencies is expected to be relatively short, ranging from 30 to 60 min. If there are no hidden effects, however, allowing a higher CO_2 level would permit use of the SCR for a longer period. In some circumstances, this would represent the difference between saving and losing a life.

This study is concerned with psychomotor and mental performance during the inhalation of up to 5% CO_2. Subjects inhaled CO_2 during 10 min of strenuous exercise and the following few minutes of psychomotor or mental testing.

METHOD

Subjects

Three groups of paid volunteers participated in the study. Their age and physical characteristics are summarized in Table 1.

Apparatus

A treadmill was used for the 10-min exercise period. The speed and grade of the treadmill were adjusted to yield O_2 uptake at 80% of the maximal aerobic capacity (80% $\dot{V}_{O_{2}max}$) for each subject.

The gas mixture for inhalation was stored in a 150-L Douglass bag. Mixing was controlled by using an oxygen analyzer and a medical gas CO_2 analyzer. To add humidity to the gas mixture before inhalation, it was passed from the bag through warm water.

Chest electrodes connected to a digital beat readout were used to monitor heart rate (HR). Auditory reaction time was measured with an automatic performance analyzer and remote response button. The probe stimulus was a 70-dBA tone. The choice reaction time unit consisted of eight telegraph keys mounted equidistantly from a starting button. The stimulus was a number (1-8), which appeared in an illuminated display 30 cm above the board, centered behind the keys. The rotary pursuit apparatus consisted of a light-emitting target, which moved in a circular path, and a tracking stylus that had a photosensitive tip interfaced with a timer. The short-term memory (STM) and reasoning tests were displayed on a graphics terminal. A minicomputer system with a disk drive and CRT executed the STM and reasoning-test programs, and recorded and scored the subjects' responses.

TABLE 1

Means and Standard Deviations for Age, Physical Characteristics, Maximal Heart Rate (HR_{max}), and Maximal Aerobic Capacity ($\dot{V}_{O_2max}$ in $ml \cdot kg^{-1} \cdot min$) of the Subjects

Experiment	*N*	*Height (cm)*	*Weight (kg)*	*Age (yrs)*	HR_{max}	$\dot{V}_{O_2max}$
Psychomotor	6	182.9 ± 5.8	78.98 ± 9.1	22.4 ± 7.6	186.0 ± 11.0	47.44 ± 4.3
Short-Term Memory	5	179.5 ± 7.2	78.86 ± 8.9	23.8 ± 3.5	185.6 ± 11.2	48.36 ± 4.7
Reasoning	4	182.0 ± 8.7	76.98 ± 13.8	27.5 ± 3.9	184.2 ± 13.3	46.96 ± 4.3

Tests

The experimental testing included psychomotor, short-term memory, and reasoning tests. Figure 1 gives a schematic description of the time sequence for each of the administered tests.

The psychomotor tests consisted of an auditory and choice reaction-time test, and a rotary pursuit task. The auditory reaction-time (ART) test consisted of four blocks of nine trials each. Reaction time was the interval between initiation of the tone and the subject's pressing of the hand-held response button.

The choice response time (CRT) test involved pressing the telegraph key that corresponded to the illuminated number in the display. The measured response time was the interval between the presentation of the stimulus and the depression of the key. Catch trials (i.e., the subject is given the ready signal, but the response number is not presented) and variable foreperiods (0.5, 1.5, and

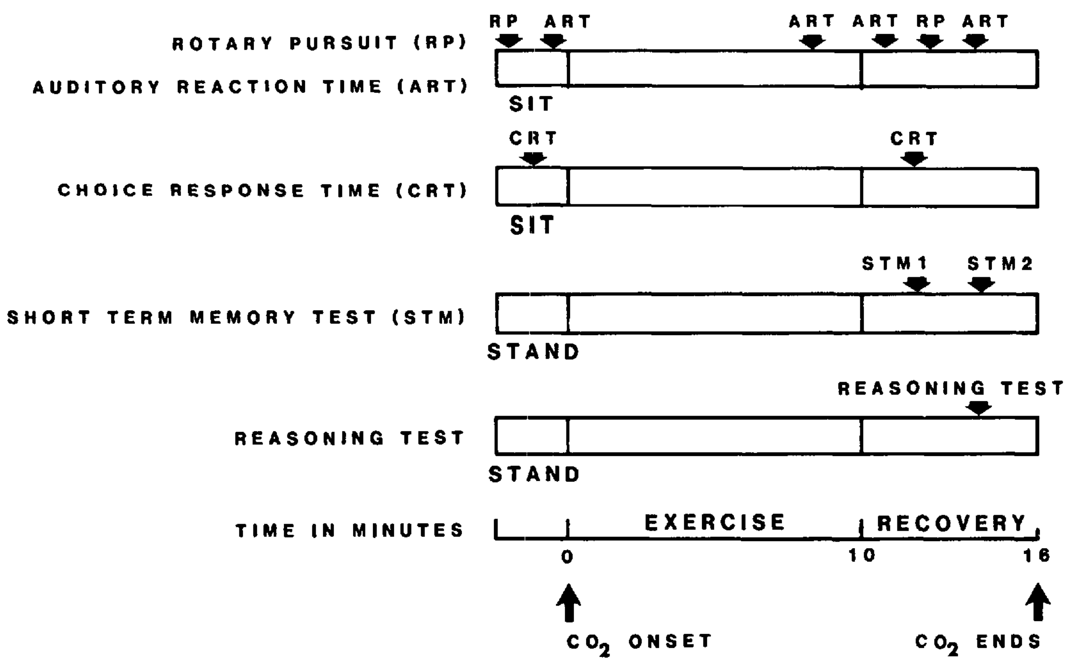

Figure 1. *Graphical description of the time sequence for each of the administered tests.*

2.5 s) were employed to eliminate anticipatory responses. Each subject received two blocks of 24 trials.

The rotary pursuit (RP) task assessed the subject's ability to track a moving object. Each subject received six 20-s trials. To eliminate practice effects, subjects were allowed to reach optimum performance levels prior to testing. All testing consisted of the target moving in a clockwise direction at 30 revolutions/min.

The short-term memory (STM) test for digit recall was based on the digit span test used in the Wechsler Adult Intelligence Scale (WAIS) (Wechsler, 1958). The digits were presented singularly for 1 s, followed by a 250-ms pause. The digits were 1.5 cm in height and appeared in the center of the graphics terminal's screen. The main test program consisted of two subroutines, forward digit and backward digit recall.

In the forward recall condition, the test started with a presentation of three digits and proceeded to a maximum difficulty of nine digits. The subroutine for backward serial recall started by presenting two digits and progressed to a maximum difficulty of eight digits. Each test trial consisted of a random grouping selected from the digits 2 through 9. The test trials did not contain repetitions or sequential progressions. The test continued until either two trials at the same difficulty level were answered incorrectly, or the subject had reached the maximum difficulty level.

The short-term memory test for serial letter recall was also based on the WAIS. The testing and sequence were the same as for the digit recall test. Both letter subprograms (forward serial recall, backward serial recall) started, however, by presenting 4 letters, and could progress to a maximum of 12 letters.

All letters were uppercase and 1.5 cm in height. Each trial consisted of a random grouping of letters, consonants only. The trials did not contain repetitions or sequential progressions. The test followed the same format as digit recall, with the criteria for ending the test being either two incorrect answers at the same difficulty level or the attainment of the maximum difficulty level.

The reasoning test was a 4-min test based on grammatical transformations (Baddeley, 1968; Carter, Kennedy, and Bittner, 1981). The subject read a statement followed by a letter pair, and then decided if the statement matched the letter pair. The following are examples of the statements presented:

True or false: D follows C. *CD*
True or false: C is followed by D. *DC*
True or false: D precedes C. *CD*
True or false: C does not precede D. *DC*

The statements comprised all possible combinations of the following six binary conditions: true or false, active or passive, precedes or follows, C or D mentioned first in the statement, letter pair CD or DC, and positive or negative. The computer randomly selected statements, waited for a response (T for true, F for false), and then continued to present statements until 4 min had elapsed.

Procedure

Upon arrival, the subject sat while being fitted with chest electrodes. The test involved 10 min of treadmill running at 80% $\dot{V}_{O_2max}$ (calculated for each subject), followed by the psychomotor or mental tests administered while the subject rested. The gas mixtures were one of the following: control; 4% CO_2, 21% O_2; 5% CO_2, 21% O_2; 4% CO_2, 50% O_2; 5% CO_2, 50% O_2. Gas mixtures were inhaled from the onset of running to the end of the post-exercise tests, which could last up to 6 min.

Subjective reports of feelings and/or discomfort were recorded after each session. All questions regarding the tests were answered at this time.

The procedures specific to the three separate substudies are described as follows.

TABLE 2

Mean Values of Psychomotor Responses during Exercise at 80% $\dot{V}_{o_2max}$ while Inhaling 5% CO_2 in 50% O_2 (CO_2)

	Auditory Reaction (ms)							
	During Running		During Sixth Minute of Recovery		Choice Response (ms) During Recovery		Rotary Pursuit(s) During Recovery	
Subject	Control	CO_2	Control	CO_2	Control	CO_2	Control	CO_2
1	180	190	169	190	593	629	10.12	8.88
2	195	224	200	170	472	522	9.88	9.47
3	179	185	171	171	531	595	11.04	11.54
4	177	187	171	181	483	559	9.22	9.50
5	171	192	151	165	686	685	9.66	7.38
6	205	225	163	179	719	754	11.01	11.27

A block of auditory reaction time (ART) and rotary pursuit (RP) tests served as controls. These were administered prior to exercise. A second block of ART trials began at the eighth minute of exercise. A second block of RP trials, and a third and fourth block of ART trials were administered during the recovery period. The rotary pursuit tests were administered with the subjects seated.

During a separate test session, the choice response time (CRT) tests were administered with the subjects seated. The CRT test was given only during the 4% CO_2 and 5% CO_2 in 50% O_2 conditions. The sequence is shown in Figure 1. Subjects received one block of 24 trials prior to exercise, and the second block in the postexercise period.

For the short-term memory tests the subjects were divided into two groups differentiated by order of recall (e.g., forward-backward, or backward-forward serial recall). The sequence of testing is depicted in Figure 1. Upon reporting for the first session, the subject took a shortened practice test. The STM test program was initiated by the experimenter after 10 min of exercise. All trials, feedback (e.g., correct, incorrect answer), and prompts (e.g., "please enter your response, then press return") were programmed and delivered via the graphics terminal. The av-

TABLE 3

Means and Standard Deviations for the Number of Digits Recalled (S) and the Number of Errors (E) per Test for CO_2-O_2 Inhalation

		Control		4% CO_2 21% O_2		5% CO_2 21% O_2		4% CO_2 50% O_2		5% CO_2 50% O_2	
		S	E	S	E	S	E	S	E	S	E
Test 1	$\bar{X}$	7.6	1.0	7.7	1.2	7.6	1.8	7.0	1.4	7.4	1.6
	SD	0.89	1.00	0.84	1.10	1.14	0.45	0.71	0.55	1.14	0.89
Test 2	$\bar{X}$	7.2	0.6	7.4	1.0	7.8	0.8	7.6	0.8	7.2	1.4
	SD	1.30	0.56	1.14	1.00	0.84	0.84	1.14	0.84	1.30	1.14
Combined 1 and 2	$\bar{X}$	7.4	0.8	7.6	1.1	7.7	1.3	7.3	1.1	7.3	1.5
	SD	1.07	0.79	0.97	0.99	0.95	0.82	0.95	0.74	1.16	0.97

erage test time per subject was 6 min. The number of errors and maximum difficulty level obtained (number of digits or letters correctly recalled) were recorded for each subject.

The STM test for serial letter recall was administered to the same subjects during different sessions. The subjects reported for 10 sessions.

Upon reporting for the first session of the reasoning substudy, the subjects received a 2-min practice test. The reasoning test was administered after exercise, and lasted 4 min (see Figure 1). The subjects were tested at the same time of day for all five sessions.

RESULTS

A representative sample of the CO_2 inhalation test data for the psychomotor tests is shown in Table 2. There were no significant differences between controls and CO_2 conditions for the auditory reaction time and rotary pursuit tests. A significant difference was observed for the choice response time test, ($F = 4.21$, $p < 0.05$), but only during inhalation of 5% CO_2 in 50% O_2. Aside from this difference, no trends or consistencies were observed. The difference indicated a somewhat slower response during CO_2 inhalation, but only for the 5% CO_2 condition.

The data for the STM tests are shown in Tables 3 and 4. The first and second STM test, for digit or letter recall, did not differ significantly in terms of the number of items recalled per condition. A significant difference was found between the number of errors ($F = 3.35$, $p < 0.10$) for the first and second STM tests for digit recall (Table 3), with higher error rates associated with the first test. However, no differences were observed in the number of errors between CO_2-O_2 experimental conditions. The other difference ($F = 4.35$, $p < 0.05$) was between subjects for average response time (in STM letter recall tests).

The data for the reasoning tests are shown in Table 5. No significant differences were

TABLE 4

Means and Standard Deviations for the Number of Letters (S) Recalled, the Number of Errors (E) per Test, and the Elapsed Test Time (ELT)

		Control			*4% CO_2 21% O_2*			*5% CO_2 21% O_2*			*4% CO_2 50% O_2*			*5% CO_2 50% O_2*		
		S	E	ELT	S	E	ELT	S	E	ELT	S	E	ELT	S	E	ELT
Test 1	$\bar{X}$	7.4	1.4	86	5.8	1.4	55	6.2	1.2	58.8	5.2	1.4	79.6	5.8	1.2	49.6
	SD	2.79	0.55	43.29	2.05	0.55	27.49	1.3	0.45	31.66	1.92	0.89	31.96	0.84	0.45	10.41
Test 2	$\bar{X}$	6.4	1.6	78.6	6.2	1.4	60.6	3.6	1.2	39	5	1.8	77.4	4.6	1.4	44.8
	SD	2.07	0.89	56.9	1.1	0.55	11.9	2.07	0.45	14.37	3.6	0.84	63.72	2.88	0.55	23.03
Combined 1 & 2	$\bar{X}$	6.9	1.7	82.3	6.0	1.4	57.8	4.5	1.2	36.9	5.1	1.6	78.5	5.2	1.3	47.2
	SD	2.38	0.82	47.83	1.56	0.52	20.16	2.27	0.42	21.13	2.72	0.84	47.54	2.88	0.48	17.03

TABLE 5

Means and Standard Deviations for the Number of Statements Completed, Errors per Session, and the Average Response Time per Question (in Seconds)

	Control	*4% CO_2 21% O_2*	*5% CO_2 21% O_2*	*4% CO_2 50% O_2*	*5% CO_2 50% O_2*
Statements Completed	51.50 ± 9.50	42.00 ± 14.7	41.00 ± 11.60	51.50 ± 14.0	43.75 ± 13.30
Number of Errors per Session	1.25 ± 0.96	1.50 ± 0.58	2.00 ± 1.40	2.00 ± 0.82	2.75 ± 2.20
Average Response Time per Question	4.78 ± 0.90	6.36 ± 2.60	6.29 ± 2.10	4.94 ± 1.40	5.80 ± 1.50

found for the number of errors or statements completed in the five conditions. However, the control and 4% CO_2−50% O_2 conditions had the same average number of statements completed, whereas in the other three conditions (4% and 5% CO_2, 21% O_2; 5% CO_2, 50% O_2), fewer statements were completed but the difference failed to reach statistical significance ($p > 0.10$).

DISCUSSION

The finding that there was no deterioration in psychomotor and mental performance as a result of inhalation of up to 5% CO_2 has important positive implications.

Unlike CO, which is an external toxic gas, CO_2 is produced internally, yet it could affect performance if it were to be retained in the body. However, although some physiological responses such as increase in pulmonary ventilation and changes in blood flow to the brain were observed, it was interesting to find that subclinical concentration of CO_2 did not affect such complicated tasks as short-term memory, reasoning ability, and psychomotor reactions. It should be noticed that the subjects of this study were young, healthy, physically fit adult males. Age and gender might constitute important factors in the deterioration of performance during CO_2 inhalation.

The observed significant difference in errors between the first and second short-term memory tests for digit recall cannot be attributed to CO_2 inhalation. If CO_2 had caused the difference then the effect would appear in error rates between the conditions of gas mixtures. The other observed significant difference in response time for short-term memory letter recall can be explained by the large individual variability in the responses.

The use of 4-5% CO_2 levels in this study was based on some pilot observations in our laboratory, in which higher CO_2 concentrations resulted in persistent headaches after the test session. This has also been observed by others (Dripps and Comroe, 1947; Schaefer, 1963; Sechzer, Egbert, Linde, Cooper, Dripps, and Price, 1960). Therefore, we set the upper limit of this study at 5% CO_2. Even under these conditions, some subjects complained of headaches and lightheadedness. In most cases, 2 or 3 min of walking in room air would alleviate these symptoms. However, for most subjects, these symptoms gradually subsided from one session to the next, until, in later sessions, the symptoms were no longer reported. This implies that "habituation" to CO_2 is possible. The lack of deterioration in psychomotor and short-term memory performance for inhalation of up to 5% CO_2 could mean an improvement in the life-support capacity of the self-contained respirator, if higher inhaled CO_2 concentrations are allowed. Increasing the permissible CO_2 levels would enable longer usage of the CO_2 scrubbing system, and, since oxygen supply is not restricted for many respirators, the usefulness of the SCR would be prolonged.

In summary, our results are encouraging with respect to acceptance of CO_2 in inhaled air. Inhalation of subclinical concentrations of CO_2 did not affect mental and psychomotor performance. It should also be noted that the short-term memory test was sensitive enough to show the effects of strenuous exercise, whereas CO_2 did not cause a decrement in performance.

ACKNOWLEDGMENTS

This study was supported by the U.S. Department of the Interior, the Bureau of Mines Contract No. J0-100092. Appreciation is extended to Dr. Robert Christina for his help and encouragement throughout this study.

REFERENCES

Asmussen, E., and Nielsen, M. Ventilatory responses to CO_2 during work at normal and at low O_2 tensions. *Acta Physiologica Scandinavia*, 1957, 27-35.

Baddeley, A. D. A. A three-minute reasoning test based on grammatical transformation. *Psychonomic Science*, 1968, *10*, 341-342.

Carter, R. C., Kennedy, R. S., and Bittner, A. C., Jr. Grammatical reasoning: A stable performance yardstick. *Human Factors*, 1981, *23*, 587-591.

Craig, F. N. Pulmonary ventilation during exercise and inhalation of CO_2. *Journal of Applied Physiology*, 1955, 7, 467-471.

Craig, F. N., Blevins, W. V., and Cummings, E. G. Exhausting work limited by external resistance and inhalation of carbon dioxide. *Journal of Applied Physiology*, 1970, *29*, 847-851.

Dripps, R. D., and Comroe, J. H. The respiratory and circulatory response of normal man to inhalation of 7.6 and 10.4 percent CO_2 with a comparison of the maximal ventilation produced by severe muscular exercise, inhalation of CO_2, and maximum voluntary hyperventilation. *American Journal of Physiology*, 1947, *149*, 43-51.

Kety, S. S., and Schmidt, C. F. The effects of altered arterial tension of carbon dioxide and oxygen on cerebral blood flow and cerebral oxygen consumption of normal young men. *Journal of Clinical Investigations*, 1948, *27*, 484-492.

Lambertsen, C. J. Therapeutic gases—Oxygen, carbon dioxide, and helium. In J. R. Di Palma, Jr. (Ed.) *Drill's pharmacology in medicine* (4th ed.). New York: McGraw-Hill, 1971.

McDonald, F. M., and Simonson, E. Human electrocardiogram after inhalation of 30% carbon dioxide. *Journal of Applied Physiology*, 1953, *6*, 304-310.

NIOSH, Criteria for a recommended standard . . . occupational exposure to carbon dioxide. U.S. Department of Health, Education and Welfare, No. (NIOSH) 76-194. Cincinnati, OH: National Institute for Occupational Safety and Health, 1976.

Putz, V. R. The effects of carbon monoxide on dual-task performance. *Human Factors*, 1979, *21*, 13-24.

Roche, S., Horvath, S., Gliner, J., Wagner, J., and Borgia, J. Sustained visual attention and carbon monoxide: Elimination of adaptation effects. *Human Factors*, 1981, *23*, 175-184.

Schaefer, K. E. The effects of CO_2 and electrolyte shifts on the central nervous system. In J. P. Schade and W. M. McMehemy (Eds.) *Selective vulnerability of the brain in hypoxemia*. Oxford: Blackwell Scientific Publications, 1963.

Sechzer, P. H., Egbert, L. D., Linde, H. W., Cooper, D. V., Dripps, R. D., and Price, H. L. Effects of CO_2 inhalation on arterial pressures, ECG and plasma catecholamines and 17-OH corticosteroids in normal man. *Journal of Applied Physiology*, 1960, *15*, 454-458.

Taskin, D. P., and Simmons, D. H. Effect of carbon dioxide breathing on specific airway conductance in normal and asthmatic subjects. *American Review of Respiratory Disorders*, 1972, *106*, 729-739.

Wechsler, D. *The measurement and appraisal of adult intelligence*. Baltimore: Williams and Wilkins, 1958.

Journal for the International Society for Respiratory Protection, 1984, 2(1).

BEHAVIORAL EFFECTS OF ONE-HOUR BREATHING OF HIGH CONCENTRATIONS OF CO_2 AND O_2 WHILE DOING PHYSICAL WORK

Max Vercruyssen and Eliezer Kamon
Ergonomics Unit
Laboratory for Human Performance Research
119 Noll Laboratory
University Park, PA 16802 USA

ABSTRACT

Attention is drawn to the lack of scientific information pertaining to the effects of breathing elevated (but subclinical) levels of carbon dioxide (CO_2) on cognitive and psychomotor performance. Furthermore, an appeal is made to reevaluate existing standards for the maximum allowable concentration of CO_2 for self-contained breathing apparatuses (SCBAs), particularly those used for escape during emergencies. An experiment is presented in which psychomotor and mental performance tests were administered to subjects inhaling room air, 50% oxygen (O_2), and 2% CO_2 (with 50% O_2) prior to, between, and following two 20-min exercise bouts at 75% of aerobic capacity. Conditions were designed to simulate a one-hour exposure to 2% CO_2 (in a high O_2 concentration similar to that of SCBAs) while running (as in a mine escape). The results showed no effects of these gases on short-term memory, reasoning, choice response time, pursuit tracking, and balance on a stabilometer. Combined with previous studies (Sheehy, Kamon, and Kiser, 1982), the authors have not yet found evidence of impaired performance due to acute (16 min) exposures of up to 5% CO_2 or chronic (60 min) exposures to 2% CO_2, when inhalation is accompanied by moderate to strenuous exercise.

This article is divided into two sections: (1) carbon dioxide: an environmental stressor, and (2) CO_2 experiment. The first section consists of discussions pertaining to the need for a reevaluation of current carbon dioxide standards and the physiological and psychomotor effects of breathing elevated levels of carbon dioxide. The second section is an experiment to ascertain the effects of breathing a high concentration of carbon dioxide and oxygen.

I. CARBON DIOXIDE: AN ENVIRONMENTAL STRESSOR

Carbon dioxide (CO_2) exposure is a very common environmental stressor. An estimated two million industrial workers are potentially exposed to high levels of carbon dioxide in their work environments (NIOSH, 1976). For example, chronic exposures to CO_2 are everyday occurrences for people who work in submarines and space vehicles (where the CO_2 concentration is 1-2%) or in oil tanks, grain silos, and breweries (where CO_2 concentrations range from 1 to 10%). Even wearing a self-contained breathing apparatus (SCBA), for protection against ambient toxic gases, does not always help. Carbon dioxide, being a normal metabolic by-product, accumulates any time one rebreathes his/her own expired air (e.g., the closed system in SCBAs). To prevent this build-up and the concomitant decrease in oxygen, SCBAs are designed to scrub CO_2 and supplement O_2. The longevity and utility of each system is sometimes determined by its ability to remove CO_2. And, since most SCBAs are limited in their CO_2 scrubbing capacity, prolonged usage results in an increase of the unabsorbed CO_2 over time. This means that as the CO_2 scrubber fails, the inspired concentration of CO_2 rises (usually in an exponential fashion). Aside from such concerns as size, weight, resistance, hot air, and seal (e.g., leakage associated with negative pressure or fitting), one of the major limiting factors in the design of these respirators is the ability of the scrubber to prevent CO_2 from exceeding the maximum allowable concentration (MAC).

A more definitive basis for establishing the MAC of CO_2 is needed. A very low limit for the inspired air would at first glance seem desirable since it would prevent possible psychological and physiological reactions. However, meeting such high standards would greatly increase the size and weight of SCBAs, making it more difficult for the wearer to use them. The MACs must, therefore, be established with attention given to minimizing the overall difficulties encountered in using the SCBAs.

Physiological Effects

Carbon dioxide serves a major role in respiration and cerebral circulation. At high concentrations, it acts as a respiratory and central nervous system (CNS) stimulant, producing increases of up to 75% in cerebral blood flow (Kety and Schmidt, 1984), an increase in pulmonary ventilation (Dripps and Comroe, 1947), decreases in specific airway resistance (Taskin and Simmons, 1972), and local vasodilation. At excessive concentrations, it is a CNS depressant, capable of producing unconsciousness, narcosis, respiratory arrest, and death (Dripps and Comroe, 1947; Friedlander and Hill, 1954). Moreover, because the solubility of CO_2 is approximately 20 times greater than that for O_2, diffusion is rapid and the respiratory and CNS effects are experienced almost instantaneously.

Exercise (physical work) may compound the effects of CO_2 inhalation due to the increased metabolic CO_2 production which results in an even higher CO_2 retention. This increased retention might then reduce the worker's endurance capacities (Craig, Blevins, and Cummings, 1970). Generally speaking, however, at rest or combined with exercise, physiological reactions to breathing up to 10% CO_2 do not seem to cause a deterioration of essential body functions (Asmussen and Nielsen, 1957; Craig, 1955).

The relative severity of clinical symptoms associated with acute exposures (less than 15 min) of varying concentrations of CO_2 are summarized in Table 1.

Table 1

Summary of the Severity of Clinical Symptoms From Acute CO_2 Exposure (< 15 min)

% CO_2	DEGREE OF SYMPTOMS
0-7	Mild, if present
7-10.5	Pronounced
> 10.5	Unconsciousness
> 30	Death

Usually, the duration of exposure determines the extent of the clinical symptoms observed. For instance, three combinations of concentration and time are summarized in Table 2 along with the clinical symptoms they produced.

Table 2

Clinical Effects of CO_2 Inhalation

% CO_2	TIME	SYMPTOMS	SOURCE
30.0	24-28 sec	Unconsciousness (n=37) (regained after 110 sec)	1
10.4 7.6	3.8 min 7.4 min	Dyspnea, headache, restlessness, dizziness, sweating, visual distortions, irritability (n=42)	2,3
3.0	5 days	Mild frontal headaches in 4 of 7 subjects during first 2 days	4

Note: 1 = Friedlander & Hill, 1954; 2 = Schaefer, 1963; 3 = Dripps & Comroe, 1947; 4 = Glatte, Motsay, & Welch, 1967.

Headache is one of the most recurrent symptoms of CO_2 inhalation and may be partially attributed to the increase in cerebral blood flow and in cerebrospinal fluid pressure (Small, Weitzner, and Nahas, 1960).

MACs for CO_2

In summarizing the standards for CO_2 exposure, Table 3 shows the maximum allowable concentrations (MACs) for different agencies.

At present the MAC for CO_2 is well below the levels known to impair physical or mental performance. Since it requires reasonably large concentrations of CO_2 (5-10%) to substantially impair physical performance or produce clinical symptoms, the question reduces to "what is the highest concentration of CO_2 that can be breathed for a given period of time without mental dysfunction?" The literature is devoid of work in this area and it appears that somewhat arbitrary standards have been implemented. If, for instance, it can be established that breathing up to 3% CO_2 for an hour

Table 3

Maximum Allowable Concentrations of CO_2

YEAR	AGENCY	% CO_2	CONDITIONS	SOURCE
1943	USPHS	0.5		1
1947	US Navy	3.0	Submarines with 17-21% O_2	2
1968	ACGIH	0.5	Up to 8 hours	3
1972	NASA	4.0 3.0 1.0	Up to 10 minutes Up to 1 hour Up to 6 months	4
1973	NASA	1.9 1.0	Up to 3 hours Mission	5
1974	ACGIH	1.5	Healthy subjects	6
1975	US Navy	2.5 1.0 0.5	Up to 1 hour Up to 24 hours Up to 90 days	7
Current	NIOSH	0.5	In 50% O_2, after scrubber, during a Man Test	

Note: 1. Gafafer, 1943; 2. Consolazio, Fisher, Pace, Pecora, Pitts, & Bennke, 1947; 3. NIOSH, 1976; 4. Calvin & Gazenko, 1975; 5. NASA, 1973; 6. ACGIH, 1974; 7. Calvin & Gazenko, 1975.

does not impair performance, then raising the MAC to as high as 2% could dramatically affect the design of respirators (e.g., decreasing the size, weight, and cost while increasing longevity) without compromising the safety of the worker. On the other hand, even if high levels of CO_2 do not impair physiological functions, great care must be taken to ensure that essential cognitive and motor skills are not affected.

Psychomotor Effects

Even though there are no disabling physiological effects or clinical symptoms associated with breathing up to 5% CO_2, there still may be psychological reactions, such as impaired motor control, slowed reactions, disorientation, or diminished mental capacities, which may jeopardize a worker's health and safety. Regardless of the CO_2 source, impaired cognitive and/or motor performance may make the worker susceptible to accidents and may decrease the probability of survival in emergency situations.

Very little attention has been given to the behavioral effects of CO_2. In the NIOSH publication, Occupational Exposure to Carbon Dioxide (1976), only seven studies were mentioned. Two of these studies reported detrimental effects on performance and three showed null results. Using a sample size of 42, Schaefer (1963) found that in 15-min exposures of 1.5, 3.3, 5.4, and 7.5% CO_2, there was a significant decrease in critical flicker fusion for CO_2 concentrations in excess of 3.3%. In the other study showing detrimental effects, Weitzman, Kinner, and Luria (1969) exposed one subject to progressively increasing concentrations of CO_2, from 0.03% to 3.00%, for 15 hours on each of six days. Visual acuity and accommodation were not affected, but color threshold sensitivity diminished (without mention of significance). Also included in their conclusions was a report on a similar experiment which resulted in no decrements in "sensory function" except for diminished color sensitivity from exposures up to 3% CO_2. As for the null results, Weybrew (1970) found that over a six-day period, 15-hour exposures to CO_2 at concentrations between 0 and 3% resulted in no impairment of one-digit addition and letter cancellation. However, Weybrew's study, like that of Weitzman et al., used only one subject and was not validated for confinement effects. Storm and Giannetta (1974) exposed six subjects to 4% (30 torr) CO_2 for 14 days and found no effects on complex tracking, eye-hand coordination, and problem solving. Glatte, Motsay, and Welch (1967) found no effects of breathing 3% CO_2 for 5 days on arithmetic, vigilance, hand steadiness, memory, problem solving, and auditory monitoring.

Not only is there a shortage of research on the behavioral effects of CO_2, but, as can be seen in this brief review, many of the previous studies have had methodological shortcomings (e.g., small sample size, inadequate controls) which severely limit their interpretation. Therefore, further behavioral research is required to make prudent decisions relative to CO_2 standards.

In recent years, two studies have used improved methodologies to investigate the behavioral effects of CO_2, but each has failed to find performance impairment. Sheehy et al. (1982) exposed their subjects to 4 and 5% CO_2 (with 21 and 50% O_2) for 16 min and found no deterioration in the performance of psychomotor (simple reaction time, pursuit tracking, and choice response time) or mental (short-term memory and reasoning) tasks. Concerned with the risks due to CO_2 retention in diving, Henning, Sauter, Reddan, and Lanphier (1983) found no effects of breathing 6% CO_2 for 10-14 min on simple and choice reaction time, hand steadiness, and postural sway.

II. CO_2 EXPERIMENT

Previous CO_2 research at The Pennsylvania State University (Sheehy et al., 1982) examined the effects of an acute exposure (16 min) of up to 5% CO_2 (with 21 and 50% O_2) on reaction time, rotary pursuit tracking, short-term memory (digit and letter recall forward and backward), and grammatical reasoning. While some of these tests were sensitive to the effects of exercise, acute exposure of CO_2 of up to 5% did not impair performance. The next step in the systematic search for the effects of CO_2 might be to increase exposure duration. Furthermore, since the SCBA user typically breathes in excess of 50% O_2 and hyperoxia has been shown to produce deterioration in short-term memory (Poulton, 1974), ascertaining the effects of hyperoxia is also important. Thus, the purpose of the present experiment was to explore the effects of prolonged breathing (60 min) of elevated but subclinical levels of CO_2 and O_2, during and following exercise, on cognitive and motor performance.

Method

Subjects

Five right-handed, beardless, male university graduate students volunteered to serve as paid subjects in this study. Prior to participating in the experiment, all subjects received a medical examination, including exercise tolerance and pulmonary function tests. All were non-smokers and in good general health. Their demographic characteristics are shown in Table 4.

PAGE 45

Table 4

Demographic Characteristics of Participants in CO_2 Inhalation Study

SUBJECT	AGE (YRS)	HT (cm)	WT (cm)	% FAT	HRmax* ($b \cdot min^{-1}$)	VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)
1	27	176.0	65.8	13.85	186	47.14
2	26	182.6	80.0	9.01	178	55.33
3	26	180.7	77.0	16.34	193	49.51
4	24	187.5	78.7	10.37	188	49.39
5	29	170.2	76.0	15.00	191	50.00
MEAN	26.4	179.5	75.5	12.91	187.2	50.27
SD*	1.8	6.6	5.64	3.11	5.8	3.03

*) Maximal heart rate (HRmax); Maximal O_2 uptake ($\dot{V}_{O_2}max$); standard deviation (SD).

Design

A two-factor, repeated measures 3 x 3 (Gas and Tests) design was employed to analyze data from each of six performance measures. Performance tests were administered prior to, between, and following two exercise bouts. For each session, each subject breathed one of three different gas mixtures during a one-hour inhalation period from the onset of the first exercise bout to the end of the post-test following the second bout. The three gas concentration conditions can be thought of as: (a) control (room air), (b) high O_2 (50% O_2 with 0.03% CO_2), and (c) high CO_2 (2% CO_2 with 50% O_2). As illustrated in Figure 1, the three test conditions were described as pre-, mid-, and post-tests referring to their relative position to the exercise bouts.

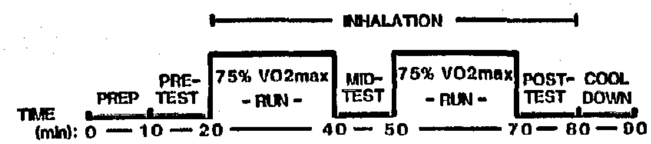

Figure 1. Testing protocol for each testing session. During the 60-min inhalation period subjects breathed either room air (control), high oxygen (50% O2), or high carbon dioxide (2% CO2, 50% O2).

The pre-test was always a fully rested, room air control condition, while the mid- and post-tests followed exercise and occurred during the gas inhalation period. Subjects were randomly assigned to gas conditions which were counterbalanced random combinations. The order of tests within each performance battery was also counterbalanced.

Exercise

Each subject underwent a treadmill progressive exercise tolerance test as part of a health assessment procedure to determine his maximal aerobic capacity ($\dot{V}_{O_2}max$). During the exercise periods, each subject ran for 20 minutes on a treadmill with the speed and grade adjusted to yield an O_2 uptake of 75% of his $\dot{V}_{O_2}max$. Each experimental session consisted of two such work bouts spaced with pre-, mid-, and post-tests, each lasting approximately 10 minutes, during which the dependent measures were collected. Oxygen uptake samples were taken during steady-state running while breathing room air in order to record actual exercise intensity. The average intensity for the group was 75 ± 3% (SD) of $\dot{V}_{O_2}$ max. While on the treadmill, the subjects were cooled with an elastic fan placed directly in front of them. Chest electrodes were connected to a Respironics Digital Exersentry (SN) for monitoring average heart rate.

CO_2 Inhalation

A 150-liter Douglas bag served as a mixing reservoir into which room air, CO_2, and O_2 were mixed before humidification by passage through warm water enroute to the subject in an open-circuit system. The inspired gas mixture was controlled by continuous monitoring of an Applied Electrochemistry S-3A Oxygen Analyzer and an LB-2 Beckman Medical Gas CO_2 Analyzer. Expired air was released into a well ventilated testing room. Three gas mixtures were used in this study: (a) room air (0.03% CO_2 and 21% O_2) as a control; (b) high oxygen (0.03% CO_2 and 50% O_2), to test for hyperoxia effects; and (c) high carbon dioxide, (2.00% CO_2 with 50% O_2), to test for hypercapnia effects (the elevated O_2 was to ensure that there was no hypoxia and to more closely approximate SCBA conditions). The prescribed gas mixture (± 0.1% SD) was inhaled for a period of 60 minutes (± 2 min SD) during each of the experimental sessions.

Performance Measures

Two types (batteries) of performance measures, each containing three individual tests, were used in this experiment: (a) Cognitive Performance Tests, and (b) Psychomotor Performance Tests. Thus, six performance tasks were administered, each in a pre-, mid-, and post-test format. Five counterbalanced orders of tests within each battery were developed with each subject being randomly assigned to one of the orders.

Cognitive Performance Tests

Three different cognitive tests were used: a grammatical reasoning test and two short-term memory (STM) tests (forward and backward serial letter recall).

Grammatical Reasoning. Reasoning, based on grammatical transformations (Baddeley, 1968), has been shown to be a stable (Carter, Kennedy, and Bittner, 1981) metric of "higher mental processes" that is sensitive to nitrogen narcosis (Baddeley, de Figuerido, Hawkswell Curtis, and Williams, 1968) and hypocapnia (Gibson, 1978). This test consisted of a four-minute task adapted from Baddeley's (1968) grammatical transformation task. Seated in front of a cathode ray terminal (Digital VT52-AE), the subjects read a statement followed by a pair of letters, decided whether or not the statement matched the letter pair, and then entered the appropriate "True" or "False" response on a standard alpha-numeric keyboard. The statements were randomly drawn from 64 possible combinations of six binary conditions (see Baddeley, 1968; Baddeley et al., 1968) and were presented one-at-a-time until the four-minute time interval elapsed. The following are examples of the statements presented:

True or False. A follows B--AB
True or False. B precedes A--BA
True or False. B does not follow A--AB
True or False. A is not preceded by B--BA

The stimulus presentation and data collection were completely on-line using a Digital Equipment Corporation (DEC) PDP-11 computer. The criterion measures were the response rate (i.e., the total number performed in each four-minute interval), accuracy (i.e., number of correct responses/total number of responses), and response times for each statement.

Short-Term Memory (Letter Recall). Based on the Wechsler (1958) Adult Intelligence Scale (WAIS), letter recall was used to assess functional memory span, a fundamental component of all human performance. A DEC PDP-11 system consisting of a disk drive and monitor was used to present the letters in a forward or backward serial fashion, as well as record and evaluate each response. The order of directional recall was counterbalanced between subjects (i.e., forward-backward, backward-forward). The letters were presented singularly for one second followed by a 250-msec pause. All letters were consonants in upper case, 1.5 cm in height, and presented in the center of a Tektronics 4006-1 graphics terminal screen. Each trial consisted of a random grouping of letters such that there occurred no repetitions of the same letter (e.g., B, F, D, D, K) or sequential progressions (e.g., P, Q, R, S, T). Beginning with a sequence of four letters, each correct recall of a series of letters would increment the number of letters presented on subsequent trials, until either two incorrect responses were recorded at the same difficulty level, or a maximum of 12 letters were reached. If the subject failed to correctly recall the sequence of letters on a particular trial, he was given a second trial at the same difficulty level (with different letters). If the subject answered the second trial correctly, he progressed to the next higher difficulty level (i.e., the number of letters presented was incremented by one); if the subject failed to answer the second trial correctly, the test was terminated.

Psychomotor Performance Tests

Three different psychomotor tasks were used: (a) Choice Response Time (CRT), (b) Rotary Pursuit (RP), and (c) Stabilometer.

Choice Response Time. A Marietta Choice Response Time (Model 14-210-M) apparatus, with eight telegraph keys mounted on a baseboard equidistance from a starting button, was used to measure choice response time (i.e., the time interval from the presentation of a visual stimulus to the completion of a correct key depression response). The stimulus appeared in a lighted display mounted approximately 30.5 cm above the baseboard and centered behind the keys (60 cm from the subject's eyes). The keys were not numbered, but were arranged in sequential order (1-8) from left to right. Each trial began with a "ready" command by the investigator after which the subject assumed the ready position by depressing the start button. At the end of a fixed 0.5 sec foreperiod (during which a red warning light positioned atop the stimulus box was illuminated), the stimulus number appeared and the response time clock began. A correct response (pressing the appropriate key) resulting in the disappearance of the stimulus display and stopping of the clock. Twenty-four trials comprised a data block, of which the first eight trials (random presentation of each key once) were used as practice and the next sixteen (random presentation of each key twice) were used for data analysis.

Rotary Pursuit Tracking. Considered a valid test of psychomotor performance (Fleishman, 1960), this measure was selected because of its use in previous stressor studies; particularly, those involving hypocapnia (Gibson, 1978), hypercapnia (Storm and Giannetta, 1974), and hyperventilation

(Labuc and Withey, 1978; Withey, Spreight, Labuc, and Legg, 1979). A Lafayette Photoelectric Rotary Pursuit apparatus was used to assess the subject's ability to track a moving object with a hand-held stylus. The apparatus consisted of a light emitting target moving clockwise in a circular manner at 30 RPM. The tracking stylus contained a photosensitive tip which was connected to a Hunter Decade Interval Timer, to limit the recording period to a 20-sec interval, and a Hunter Model 220 Klockounter to record the time on target (in msec). The subject was permitted to track for approximately 30 seconds prior to each test to reduce warm-up, practice, equipment start-up, and limb inertia effects. Three 20-sec trials, with approximately 30-sec inter-trial rest intervals, were given to each subject during each test. Ambient light was controlled and the sensitivity of the apparatus was calibrated for each experimental session to a vertical tolerance of 2.6 cm (i.e., if the stylus was raised more than this distance above the target, the clock counter would stop recording on-target performance).

Stabilometer. Since dizziness and loss of balance are characteristic clinical symptoms associated with CO_2 inhalation, the ability of the subject to maintain his balance, as measured by a horizontal pivoting platform stabilometer, was included as a psychomotor test. This measure was also selected because of the information available on its susceptibility to practice (Ryan, 1965) and fatigue (Nunney, 1963) effects as well as its retention (Ryan, 1962b) and stress reaction (Ryan, 1962a) characteristics. The apparatus consisted of a 37.5 cm x 95 cm x 2.1 cm wooden platform with an axle and bearings positioned directly beneath such that the subject could stand on it, straddling the axle, and attempt to balance (i.e., keep the platform horizontal). Microswitches were positioned on the stabilometer frame to record the amount of time the platform was tilted (off-balance). A Hunter Decade Interval Timer was used to limit the recording period to 20-seconds. A Hunter Model 220C Klockounter was used to record the total time the subject was off balance per 20-sec trial. Three trials, with approximately 30-sec inter-trial rest intervals, were given to each subject during each test.

Procedure

Each subject participated in eight sessions as presented in Figure 2.

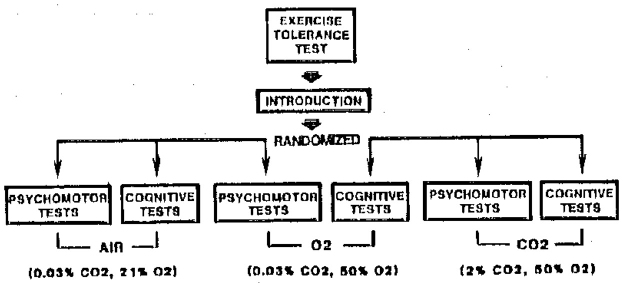

Figure 2. Schematic for the Experimental Sessions (1 box - 1 day). Subjects began with the graded exercise tolerance test from which their aerobic capacity (VO_2max) was determined. Next the subjects were familiarized with the exercise and the wearing of the breathing apparatus, and practiced all of the performance tests during the introduciton session. The the psychomotor tests (choice response time, stabilometer, and rotary pursuit) and the cognitive tests (STM forward letter recall, STM backward letter recall, and grammatical reasoning tests) were given randomly, one set per session.

Following an exercise tolerance test, the subjects participated in seven 90-minute sessions, one per day with at least 48 hours rest between the sessions involving exercise. The introductory session was used to explain the experiment, complete the informed consent documents, introduce the dependent measures and experimental protocol, and provide considerable practice on each of the performance measures. Following this introductory session, the same protocol was used each day (see Figure 1).

Upon arrival to the laboratory, the subject was fitted with chest electrodes, given a brief warm-up on each task, and then given the pre-test performance measures which were completed in approximately 10 minutes. The gas inhalation period began with the subject running on a treadmill for two 20-min work bouts at an intensity equivalent to 75% of his aerobic capacity. Between and following these work bouts were the mid- and post-tests, respectively (each also lasting approximately 10 minutes). The face mask was removed after the post-test (making the total inhalation period approximately one hour) and the subject was required to walk on the treadmill at 3 mph for at least 6 min as a "cool-down" before departing the lab. During and following the cool-down, the subject was asked to provide subjective

information on his perceived exertion, clinical symptoms (discomforts), performance quality, etc. All eight testing sessions per subject were completed within three weeks.

Laboratory Environment

The experiment was conducted in an air-conditioned laboratory where the room temperature ranged from 23 to 25° C. Also, measures were taken to control ambient light and sound.

Treatment of the Data

The dependent measures were analyzed using a multivariate analysis of variance on repeated measures. All post-hoc follow-up analyses were done using the Tukey Wholly Significant Difference (WSD) technique. In all cases, the level of significance was $p = 0.05$. An additional univariate analysis of the repeated measures was performed on each subject to test for learning (sequence) effects. (See Jackson and Raven, 1983, for a discussion of statistical and research designs for industrial respiratory research.)

Equipment failure caused seven out of 450 data values (1.6%) to be grossly inappropriate. Omitting all of the results for those subjects involved would remove 20% of the data on each measure. Therefore, five values (one for the stabilometer, two for reasoning, and two for rotary pursuit) were estimated according to Winer (1962) in a technique designed to have no effect on the individual cell means (interaction) in the data matrix. The two pre-test values for reasoning were estimated by using the average of the remaining pre-test values per subject.

Results and Discussion

Cognitive Performance Measures

The group mean and standard deviations for each of the cognitive tests for each experimental condition are shown in Table 5. None of the cognitive performance tests revealed a significant effect of hyperoxia or hypercapnia, but one non-gas test contrast was significant. As seen in Figure 3, the rate at which subjects performed the post-exercise test portion of the grammatical reasoning task ($M = 14.33$ lines/minute) was significantly [$F(2,8) = 5.72$, $p = .029$] faster than that for the pre-exercise test ($M = 13.23$ lines/minute) or mid-exercise test ($M = 13.31$ lines/minute).

Table 5

Means and Standard Deviations for the Cognitive Tests

	TEST	AIR PRE[1]	AIR MID[1]	AIR POST[1]	50% O_2 PRE	50% O_2 MID	50% O_2 POST	2% CO_2 & 50% O_2 PRE	2% CO_2 & 50% O_2 MID	2% CO_2 & 50% O_2 POST
Short Term Memory	Forward[2]: Mean (SD)[3]	6.6 (0.6)	6.2 (1.3)	7.2 (2.3)	6.8 (1.9)	7.2 (0.8)	6.8 (1.3)	6.4 (2.2)	6.4 (0.6)	5.6 (0.9)
	Backward[2]: Mean (SD)	6.8 (1.5)	6.8 (1.3)	6.4 (0.9)	7.4 (1.1)	6.8 (1.3)	6.2 (1.9)	7.0 (2.2)	5.6 (1.3)	6.2 (0.8)
Reasoning	Accuracy[4]: Mean (SD)	0.956 (0.021)	0.956 (0.022)	0.960 (0.035)	0.947 (0.049)	0.956 (0.015)	[illegible] (0.047)	0.963 (0.011)	0.975 (0.021)	0.969 (0.025)
	Rate[5]: Mean (SD)	13.45 (2.64)	13.60 (2.95)	14.50 (3.06)	13.95 (2.48)	13.35 (2.21)	14.70 (1.40)	13.75 (3.05)	14.13 (1.76)	14.94 (1.82)

[1] Pre-exercise (PRE), Midway through exercise (MID), and Post-exercise (POST) performance
[2] Number of correct letters recalled
[3] Standard Deviation (SD)
[4] Ratio of number of correst answers to number of answers attempted
[5] Attempts per minute

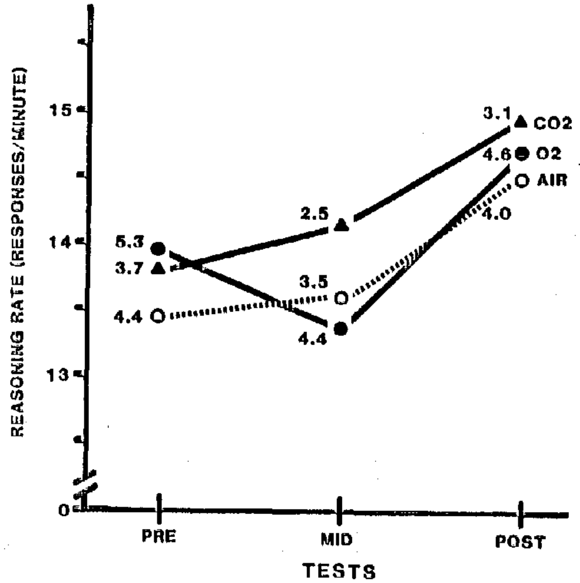

Figure 3. The mean (n = 5) reasoning rate, before, midway through and after exercise, while inhaling room air (AIR), 50% O2 (O2), and 2% CO2 with 50% O2 (CO2). The mean percent errors are included as an index of performance accuracy.

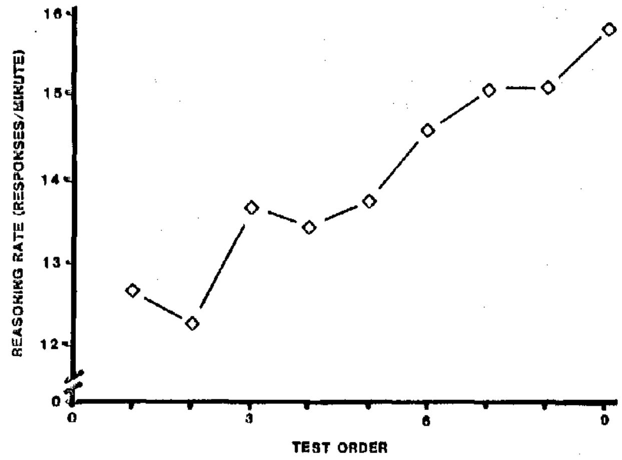

Figure 4. The mean (n = 5) reasoning rates in chronological order.

In a closer look, however, a univariate analysis of these data revealed a significant [$F(1,8) = 5.96$, $p = .011$] practice (learning or sequence) effect which may explain a large portion of the high post-test rates. As shown in Figure 4, the speed of reasoning improved from session to session regardless of the manipulations of the independent variables. Since the accuracy of responding did not differ significantly across conditions, there was no reason to suspect a possible speed-accuracy trade-off. In fact, the obtained trend suggests that, regardless of the gas breathed, accuracy improved concurrently with rate and was consistently better following exercise, than at rest. Exercise in the mid- and post-tests may also account for some of the elevated reasoning rate, but this cannot be determined by the present design.

The most meaningful finding here is that the gas concentrations inspired did not impair cognitive performance. If anything, as unusual as it seems, the trends shown in Figure 3 hint that CO_2 and exercise may even improve reasoning rate. None of the other main or interaction effects tests for reasoning or short-term memory were significant ($p > .05$).

Table 6

Means and Standard Deviations for the Psychomotor Tasks

TEST	AIR PRE[1]	AIR MID[1]	AIR POST[1]	50% O_2 PRE	50% O_2 MID	50% O_2 POST	2% CO_2 & 50% O_2 PRE	2% CO_2 & 50% O_2 MID	2% CO_2 & 50% O_2 POST
STABILOMETER[2] Mean (SD[3])	6.55 (0.78)	7.03 (0.89)	7.34 (0.62)	6.99 (0.82)	7.56 (0.81)	7.64 (0.90)	6.07 (2.45)	7.45 (2.17)	7.02 (2.63)
ROTARY PURSUIT[4] Mean (SD)	16.53 (2.34)	16.39 (2.53)	16.47 (2.58)	17.27 (1.85)	16.50 (2.9[illegible])	16.12 (2.31)	16.26 (3.00)	15.61 (2.83)	15.19 (2.53)
Choice Response TIME[5] Mean (SD)	539 (33)	535 (38)	525 (41)	518 (59)	517 (40)	525 (52)	520 (30)	507 (32)	518 (29)
Choice Response ERRORS[6] Mean (SD)	3.00 (1.87)	3.60 (2.30)	2.80 (0.84)	3.80 (1.79)	3.00 (2.00)	3.40 (1.52)	2.80 (1.30)	2.80 (1.30)	2.20 (1.30)

[1] Pre-exercise (PRE), Midway through exercise (MID), and Post-exercise (POST) performance
[2] Seconds OFF balance
[3] Standard Deviation (SD)
[4] Seconds ON target
[5] Time in msec
[6] Absolute number of errors

Psychomotor Performance Measures

The means and standard deviations for the psychomotor tests are tabulated in Table 6. Neither choice response time nor its error rate showed performance changes due to hyperoxia or hypercapnia. Although these elevated gas concentrations did not significantly affect tracking or balancing performance, each test did possess significant results.

As shown in Figure 5, rotary pursuit tracking was impaired with time. Breathing room air while exercising had no effect on tracking performance, but breathing elevated concentrations of either O_2 or CO_2 while exercising resulted in a significant [$F(2,8) = 5.23$, $p = .035$] decrease in time on target of the post-test conditions ($M = 16.69$ sec) and mid-tests ($M = 16.18$ sec). Although not significant, the impairment trend in tracking due to CO_2 inhalation does look suggestive. It is possible that with a slightly larger

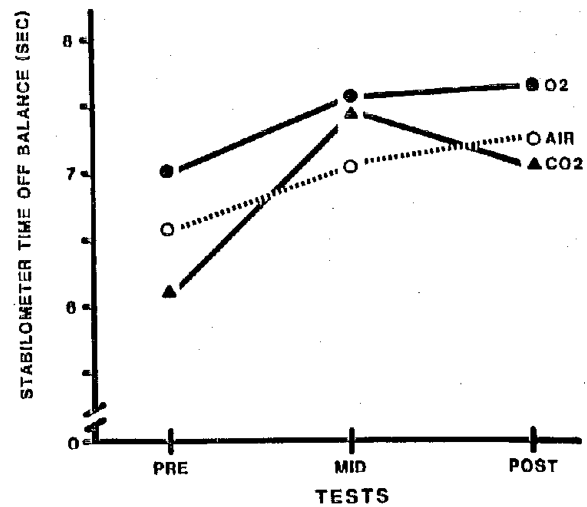

Figure 6. The mean (n = 5) for time off balance during a 20-second stabilometer task performed before, midway through and after exercise while inhaling room air (AIR), 50% O2 (O2), and 2% CO2 with 50% O2 (CO2).

sample size, this test may have shown deleterious effects of CO_2 breathing on pursuit tracking.

Labuc and Withey (1978) and Gibson (1978) found that hyperventilation impaired tracking performance, which suggests that tracking may be sensitive to acute CO_2 changes. However, as these data show, for simple tracking while breathing 2% CO_2 and as Storm and Giannette found for complex tracking during exposure to 4% CO_2, tracking may not be affected by (or sensitive to) chronic hypercapnia.

Hyperoxia and hypercapnia did not affect balancing on a platform stabilometer; however, it appears exercise may cause a decline in performance. As shown in Figure 6, time off balance was significantly greater for the mid-tests ($M = 7.42$ sec) and post-tests ($M = 7.30$ sec) [$F(2,8) = 7.22$, $p = .016$] than for the resting, room air pre-tests ($M = 6.54$ sec).

Because the purpose of this study was to explore the effects of these gas concentrations on performance while simulating the conditions of a mine escape, exercise was not an independent variable and was, therefore, intentionally confounded in the design. Thus, it cannot be concluded that exercise produced these effects because there was not a control condition of breathing the gases without running. Nonetheless, the obtained trend suggests that the stabilometer may be sensitive to the effects of exercise. No other psychomotor contrasts were significant.

Caution. A word of warning is called for when interpreting these results. Just because CO_2 was not found to impair performance does not mean that the CO_2 MACs should be raised. It means that under the conditions specified, these measures failed to show a sensitivity to CO_2. In fact, there remains the possibility that under slightly different circumstances, or with different measures, CO_2 at these levels might produce pronounced effects.

Many stressor experiments are contaminated by uncontrolled (confounding) variables and this study was no exception. Some obvious considerations include age, health, body size and fitness level; however, such factors as volunteer and smoking status, CO_2 sensitivity, gender, and personality characteristics may also contribute unwanted variance and cloud the interpretation of results.

Although a very homogeneous sample population, the subjects in this study may not have been representative of the population of individuals using SCBAs. These subjects were healthy, young, active non-smoking adult male volunteers with fitness levels higher than those of many workers who might don SCBAs. For instance, Kamon, Doyle, and Kovac (1983) collected physiological data on six miners simulating an escape from an underground coal mine following an explosion. Compared with the demographic characteristics of the subjects in this study (see Table 4), the coal miners were older (45.2 vs 26.4 yrs), shorter (172 vs 179.4 cm), heavier (78.6 vs 75.5 kg), and with lower maximum heart rate (176.8 vs 187.2 bpm) and aerobic capacities (34.1 vs 50.3 ml/kg/min). Ayout and Selan (1981) also discuss the unique characteristics of miners.

Furthermore, since the physical performance of smokers is considerably impaired relative to non-smokers (Morgan, 1983) and volunteers may not

possess the same mental or physical characteristics as non-volunteers, the external validity of many laboratory studies, including this one, becomes questionable. Because there are considerable individual differences in tolerances and reactions to CO_2 (e.g., Morgan, 1983), the subjects used in this study may have been insensitive to the CO_2 levels employed. Gender and personality have also been linked to ventilatory responses to CO_2 inhalation (Dempsey, 1979; Lum, 1975; Mora, Grant, Kenyon, and Patel, 1976; Saunders, Heilpern, and Rebuck, 1972; Shershow, King, and Robinson, 1973). Thus, age, body size, gender, degree of lung impairment, personality, volunteer status, experience, aerobic capacity, CO_2 sensitivity, smoking habits and anxiety (trait and state) may certainly be factors which contribute to different results and alternative interpretations. Like many other laboratory studies, carefully controlling various sources of variance in this study may have diminished its ecological validity. Further research of this sort using subjects directly from the populations of interest is nessary to ensure the generalizability of experimental results.

Clinical Symptoms Reported

Each subject experienced two sessions of CO_2 inhalation. The most frequently reported symptom during these exposures was a dry throat (4 of 5 subjects, but two of these also reported dry throats in the air conditions). While one subject appeared very sensitive to CO_2, having a moderate headache with dizziness and weakness throughout the inhalation period, most subjects were not aware of the gas conditions and could not detect changes in their ventilation. During the first work bout, three subjects noticed slight headaches which became most intense when exercise ceased (during the first 3-min of mid-test). For all of these subjects, the headaches disappeared during the cool-down period (while breathing room air and walking on the treadmill). All CO_2 reactions were most intense on the first day of exposure. No headaches were reported during the second exposure to CO_2, only dry throats. These findings hint at the possibility of individual differences in CO_2 intolerance and adaptation (habituation, desensitization, or acclimatization) to CO_2. Further studies should explore these areas.

Conclusions

Working at 75% of $\dot{V}_{O_2}$ max while breathing elevated concentrations of O_2 (50%) or CO_2 (2% with 50% O_2) was not found to affect cognitive and psychomotor performance as measured by the six tests used in this study. A trend in the data implied that hypercapnia may impair tracking performance, but this pattern failed to reach significance. The data also suggested that exercise may have disrupted balance, or viewed another way, that the stabilometer test may have been sensitive to exercise. Consequently, with no performance impairment attributed to breathing elevated levels of O_2 or CO_2, either these gas levels do not influence cognitive and psychomotor performance, or the measures used in this study were not sensitive to such effects.

The design of SCBAs is severely limited by the present MAC of CO_2. Since there is no evidence to suggest these subclinical levels cause physiological dysfunctions, and because there is almost no data available on the effects of CO_2 breathing on cognitive and psychomotor performance, the current standards appear to be based on speculations. Therefore, if studies similar to this one repeatedly show no deterioration in performance, then the existing MACs should be reevaluated.

If higher concentrations of inhaled CO_2 were allowed, considerable improvements could be made in the life-support capacities of SCBAs. For instance, higher permissible CO_2 levels would enable longer usage of the unit. For instance, shallower beds for the scrubbing agents could decrease the size and weight of the SCBA unit. If the weight of the SCBA alone can produce a 20% decrement in both submaximal (Myhre, Holden, Baugardner, and Tucker, 1979) and maximal (Raven, Davis, Shafer, and Linnebur, 1977; Raven, 1983) work capacity, then using a smaller and lighter unit might greatly aid physical performance during escape and rescue activities (also see Morgan, 1983). The size and weight consideration becomes especially important when considering SCBA users who have limited capacities to begin with (due to age, lung disease, low fitness level, etc).

While there is not sufficient data available at this time to make recommendations for raising the MAC of CO_2, evidence is accumulating to suggest the issue be considered in future meetings concerning SCBA standards.

Previous work in our laboratory (Sheehy et al., 1982) found no effects of acute exposure (16 min) of up to 5% CO_2 on behavioral performance measures; this study found no effects of chronic exposure (60 min) of up to 2% CO_2. Continued behavioral studies may someday establish a standard of high utility which does not compromise the safety of the worker.

Acknowledgments

This study was supported by the U.S. Department of the Interior, Bureau of Mines Contract No. JO-100092.

Appreciation is extended to Professors Robert W. Christina, Merrill E. Noble, Elsworth R. Buskirk, and Paul A. Games for sharing their expertise in the areas of motor behavior, cognitive psychology, respiratory physiology, and statistics, respectively. James B. Sheehy conducted preliminary work on the effects of acute exposure to CO_2 and developed the computer programs for this study. N. Scott Deno and Charles F. Ryan provided valuable technical assistance; Donna J. Mah aided in data collection, analysis, and the writing of preliminary reports; and Tina Mihaly helped produce a final copy of the manuscript.

BIBLIOGRAPHY

American Conference of Governmental Industrial Hygienists. (1974). Documentation of the threshold limit values for substances in workroom air with supplements for those substances added or changed since 1971, 3rd edition, Cincinnati, OH: ACGIH, 296-298.

Asmussen, E. and Nielsen, M. (1957). "Ventilatory responses to CO_2 during work of normal and low O_2 tensions," Acta Physiologica Scandinavia, 27-35.

Ayout, M. M. and Selan, J. L. (1981). "Energy expenditures requirement in low coal mines," Proceedings of the Human Factors Society, 426-430.

Baddeley, A. D. (1968). "A three-minute reasoning test based on grammatical transformation," Psychonomic Science, 10, 341-342.

Braddeley, A. D., de Figuerido, J. W., Hawkswell Curtis, J. W., and Williams, A. N. (1968). "Nitrogen narcosis and performance under water," Ergonomics, 11, 157-164.

Calvin, M. and Gozenko, O. G. (1975). "Foundations of space biology and medicine." (Special Publication No. 374). National Aeronautics and Space Administration, Scientific and Technical Information Office, 2, 78-84.

Carter, R. C., Kennedy, R. S., and Bittner, A. C., Jr. (1981). "Grammatical reasoning: A stable performance yardstick." Human Factors, 23, 587-591.

Consolazio, W. V., Fisher, M. B., Pace, N., Pecora, L. J., Pitts, G. C., and Behnke, A. R. (1974). "Effects on man of high concentrations of carbon dioxide in relation to various oxygen pressures during exposures as long as 72 hours. American Journal of Physiology, 151, 479-502.

Craig, F. N. (1955). "Pulmonary ventilation during exercise and inhalation of carbon dioxide.," Journal of Applied Physiology, 7, 467-471.

Craig, F. N., Blevins, W. V., and Cummings, E. G. (1970). "Exhausting work limited by external resistance and inhalation of carbon dioxide," Journal of Applied Physiology, 29, 84--851.

Dempsey, J. A. (1979). "The brain's role in exercise hypernea," Medicine and Science in Sports, 11, 213-220.

Dripps, R. D. and Comroe, J. H. (1947). "The respirator and circulatory response of normal man to inhalation of 7.6 and 10.4 percent CO_2, and maximum voluntary hyperventilation." American Journal of Physiology, 149, 43-51.

Fleishman, E. A. (1960). "Abilities at different stages of practice in rotary pursuit performance," Journal of Experimental Psychology, 60, 162-171.

Friedlander, W. J. and Hill, T. (1954). "EEG changes during administration of carbon dioxide," Diseases of the Nervous System, 15, 71, 75.

Gafafer, W. M. (1943). Manual of Industrial Hygiene and Medical Service in War Industries. Philadelphia: Saunders, 264.

Gibson, T. M. (1978). "Effects of hypocapnia on psychomotor and intellectual performance," Aviation, Space and Environmental Medicine, 49, 943-946.

Glatte, H. A., Motsay, G. J., and Welch, B. E. (1967). "Carbon dioxide tolerance studies." (Report No. SAM-TR-67-77), Brooks Air Force Base, TX: U.S. Air Force, Aerospace Medicine Division (AFSC), USAF School of Aerospace Medicine, 1-22.

Henning, R. A., Sauter, S. L., Reddan, W., and Lanphier, E. H. (1983). "Behavioral impairment with altered ventilatory response to CO_2." Abstracts of 67th Annual Meeting, Chicago, IL, April 10-15, 1983. Federation Proceedings: Federation of American Societies for Experimental Biology, 42, 1013.

Jackson, A. W. and Raven, P. R. (1983). "Statistical and research design considerations concerning industrial respirator research," Journal of the International Society for Respiratory Protection, 1, 31-40.

Kamon, E., Doyle, D., and Kovac, J. (1983). "The oxygen cost of an escape from an underground coal mine," American Industrial Hygiene Association Journal, 44, 552-555.

Kety, S. S. and Schmidt, C. F. (1948). "The effects of altered arterial tension of carbon dioxide and oxygen on cerebral blood flow and cerebral oxygen consumption of normal young men," Journal of Clinical Investigations, 27, 484-492.

Labuc, S. and Withey, W. R. (1978). "Tracking accuracy during mild hyperventilation," Ergonomics, 21, 394-395.

Lum, L. C. (1975). "Hyperventilation: The tip of the iceberg," Journal of Psychosomatic Research, 19, 375-383.

Mora, J. D., Grant, L., Kenyon, P., and Patel, M. K. (1976). "Respiratory ventilation and carbon dioxide levels in syndromes of depression," British Journal of Psychiatry, 129, 457-464.

Morgan, W. P. (1983). "Pyschological problems associated with the wear of industrial respirators," Journal of the International Society for Respiratory Protection, 1, 67-107.

Myhre, L.G., Holden, R. O., Baumgardner, F. W., and Tucker, D. (1979). "Physiological limits of firefighters." (Technical Report No. ESL-TR-79-06), Available from Tyndall AFB, Florida 32403.

National Aeronautics and Space Administration. (1973). Flight Control Division: Skylab Final-Flight Mission Rules, Part I--part SL-2,3,4 basic and Part II--part SL-1 unique. Houston, TX: NASA Flight Control Division Manned Spacecraft Center.

NIOSH. (1976). Criteria for a Recommended Standard . . . Occupational Exposure to Carbon Dioxide. U.S. Department of Health, Education, and Welfare, No. (NIOSH) 76-194. Cincinnati, OH: National Institute for Occupational Safety and Health.

Nunney, D. N. (1963). "Fatique, impairment, and psycho-motor learning," Perceptual and Motor Skills, 16, 369-375.

Poulton, E. C. (1974). "Progressive deterioration in short-term memory while breathing pure oxygen at normal atmospheric pressure," Aerospace Medicine, 45, 482-484.

Raven, P. B. (1983). "Respirator research: Where it needs to go--the man-respiratory interface," Journal of the International Society for Respiratory Protection, 1, 49-55.

Raven, P. B., Davis, C. L., Shafer, C. L., and Linnebur, A. C. (1977). "Maximal stress test performance while wearing self-contained breathing apparatus," Journal of Occupational Medicine, 19, 802-806.

Ryan, E. D. (1962a). "Effects of stress on motor performance and learning," Research Quarterly, 33, 111-119.

Ryan, E. D. (1962b). "Retention of stabilometer and pursuit rotor skills," Research Quarterly, 33, 593-598.

Ryan, E. D. (1965). "Prerest and postrest performance on the stabilometer as a function of distribution of practice," Research Quarterly, 36, 197-204.

Saunders, N. A., Heilpenn, S., and Rebuck, A. S. (1972). "Relation between personality and ventilatory response to carbon dioxide in normal subjects: A role in asthma?" British Medical Journal, 1, 719-721.

Schaefer, K. E. (1963). "The effects of CO_2 and electrolyte shifts on the central nervous system," In: J. P. Schade and W. M. McMeheny (Eds.), Selective Vulnerability of the Brain in Hypoxemia. Oxford: Blackwell Scientific Publications.

Sheehy, J. B., Kamon, E., and Kiser, D. (1982). "Effects of carbon dioxide inhalation on psychomotor and mental performance during exercise and recovery," Human Factors, 24, 581-588.

Shershow, J. C., King, A., and Robinson, S. (1973). "Carbon dioxide sensitivity and personality," Psychosomatic Medicine, 35, 155-160.

Small, H. S., Weitzner, S. W., and Nahas, G. G. (1960). "Cerebrospinal fluid pressures during hypercapnia and hypoxia in dogs," American Journal of Physiology, 198, 704-708.

Storm, W. F. and Giannetta, C. L. (1974). "Effects of hypercapnia and bedrest on psychomotor performance," Aviation, Space and Environmental Medicine, 45, 431-433.

Taskins, D. P. and Simmons, D. H. (1972). "Effects of carbon dioxide breathing on specific airway conductance in normal and asthmatic subjects," American Review of Respiratory Disorders, 106, 729-739.

Wechsler, D. (1958). The Measurement and Appraisal of Adult Intelligence. Baltimore: Williams & Wilkins.

Weitzman, D. O., Kinner, J. S., and Luria, S. M. (1969). "Effects on vision of repeated exposure to carbon dioxide." (Report No. 06-8). New London, CN: U.S. Navy Department, Bureau of Medicine and Surgery, Naval Submarine Medical Center, Submarine Medical Research Laboratory, 1-6.

Weybrew, B. B. (1970). "An exploratory study of the psychological effects of intermittent exposure to elevated carbon dioxide levels." (Report No. 647). Groton, CN: U.S. Navy Department, Bureau of Medicine and Surgery, Naval Submarine Medicine Center, Submarine Medical Research Laboratory, 1-9.

Winer, B. J. (1962). Statistical Principles in Experimental Design. New York: McGraw Hill.

Withey, W. R., Spreight, L. R., Lebuc, S., and Legg, S. R. (1979). "The effect of motivation and mild hyperventilation on tracking accuracy," In: C. Mackay and T. Cox (Eds.), Response to Stress: Occupational Aspects. London: IPC Science and Technology, 156-168.

Womack, G. J. (1961). "Evidence for the cerebral vasoconstrictor effects of breathing on hundred percent oxygen," Aerospace Medicine, 32, 328-332.

APPENDIX B3:

BREATHING 3-4% CO_2: BEHAVIORAL EFFECTS

Max Vercruyssen

The environmental stressor explored in this experiment was breathing elevated, but subclinical, levels of carbon dioxide (CO_2) while running. Simulating an emergency mine escape, six subjects breathed each of three gas mixtures -- room air, 3% CO_2, or 4% CO_2 -- for one hour. Concomitantly, psychomotor and mental performance tests were administered prior to, between, and following two 20-min exercise bouts at 70% of each subject's aerobic capacity. The results showed no effects of these gases on addition, multiplication, grammatical reasoning, and balance on a stabilometer. Combined with previous studies which also failed to find evidence of impaired performance, these findings call for a reevaluation of the existing federal standards for the maximum allowable concentrations of CO_2 for self-contained breathing apparatus (SCBAs), particularly those used for escape during emergencies.

A lack of scientific information pertaining to the effects of breathing elevated, but subclinical, levels of CO_2 on cognitive and psychomotor performance has made it difficult to recommend revision of the federal standards for the maximum allowable concentrations (MACs) of CO_2. A very low limit for the inspired air would initially seem desirable since it would prevent possible psychological and physiological reactions; however, meeting such high standards would greatly increase the size and weight of respiratory devices, making it more difficult for the wearer to use them. The MACs must, therefore, be established with attention given to minimizing the overall difficulties encountered in using such respiratory devices, particularly during emergency escape from mines.

Even though there are no disabling physiological effects or clinical symptoms associated with breathing up to 5% CO_2, there still may be psychological reactions, such as impaired motor control, slowed reactions, disorientation, or diminished mental capacities, which may jeopardize a worker's health and safety. Impaired cognitive and/or motor performance may make the worker susceptible to accidents and may decrease the probability of survival in emergency situations.

Previous research exploring the effects of acute (15 min or less) CO_2 exposures found little evidence of impaired mental performance due to breathing up to 6% CO_2. Sheehy, Kamon and Kiser (1982) exposed their subjects to 4% and 5% CO_2 (with 21 and 50% O_2) for 16 min and found no deterioration in the performance of psychomotor (simple reaction time, pursuit tracking, and choice response time) or mental (short-term memory and reasoning) tasks. Concerned with the risks due to CO_2 retention in diving, Henning, Sauter, Reddan, and Lanphier (1983) found no effects of breathing 6% CO_2 for 10-14 min on simple and choice reaction time, hand steadiness, and postural sway.

A similar picture emerges in quantifying the effects of chronic CO_2 exposures. Storm and Giannetta (1974) exposed six subjects to 4% CO_2 for 14 days and found no effects on complex tracking, eye-hand coordination, and problem solving. Glatte, Motsay, and Welch (1967) found no effects of breathing 3% CO_2 for 5 days on arithmetic, vigilance, hand steadiness, memory, problem solving, and auditory monitoring.

Even when exposures occur during physical work, there is little evidence to support the existing standards. Vercruyssen and Kamon (1984) found no effects of breathing 2% CO_2 for one hour, during and following moderate to strenuous work, on short-term memory, reasoning, balance, choice response time, or pursuit tracking. The purpose of the present experiment was to explore the effects of prolonged breathing (60 min) of elevated but subclinical levels of CO_2 (i.e., 3% and 4%), during and following physical work, on cognitive and motor performance.

All previous research in our lab (Sheehy et al., 1982; Vercruyssen & Kamon, 1984) explored the effects of breathing a toxic gas on the performance of novel experimental tasks. This seemed reasonable since other investigators had found such measures sensitive to other stressors (e.g., nitrogen narcosis, hypoxia, carbon monoxide). However, due to the steep slope of the acquisition trend obtained in previous studies (e.g., Vercruyssen & Kamon, 1984) and the fact that most activities encountered in escaping from mines are well-learned, a different approach was employed for the present experiment. Assuming the effect of an environmental stressor is measured by the deviation from optimal performance produced by exposing the subject to the stressor, the concern of this study was the amount of deviation from a stable best performance state. Learning pilot studies determined the acquisition patterns and the number of trials to a criterion "near asymptotic performance level." All subjects were required to attain this level before starting data collection. The medical support required in these experiments makes them very expensive, and minimizes the number of subjects that could be tested.

Method

Subjects & Design

Six right-handed, beardless, male university graduate students volunteered to serve as paid subjects. Prior to participating in the experiment, all subjects received a medical examination, including exercise tolerance and pulmonary function tests. All were nonsmokers and in good general health. Their demographic characteristics are shown in Table B3-1.

Table B3-1. Subject Demographic Characteristics

Subjects	Age (yrs)	Height (cm)	Body Mass (kg)	Body Fat (%)	HR_{max} (bpm)	$\dot{V}_{O_2}max$ $(ml \cdot kg^{-1} \cdot min^{-1})$
1	27	180.7	77.0	16.3	193	49.5
2	27	182.6	80.0	9.0	178	55.3
3	23	190.3	71.4	12.4	190	58.5
4	33	175.3	62.8	20.1	193	44.4
5	28	177.8	69.6	18.3	190	50.2
6	24	187.5	78.7	10.4	188	51.3
Group Mean =	27	182.4	73.2	14.4	189	51.5
Standard Deviation =	4	5.7	6.5	4.5	6	4.9

Note: HR_{max} = maximum heart rate; $\dot{V}_{O_2}max$ = maximum oxygen consumption (aerobic capacity)

A two-factor, repeated measures 3 X 3 (Gas and Tests) design was employed to analyze data from each of four dependent measures. Three gas concentration conditions were employed: a room air control, 3% CO_2, and 4% CO_2. Performance tests were administered prior to, between, and following two exercise bouts. For each session, each subject breathed one of three different gas mixtures during a one-hour inhalation period from the onset of the first exercise bout to the end of the post-test following the second bout.

The pre-test was always a fully rested, room air control condition while the mid- and post-tests followed exercise and occurred during the gas inhalation period. Subjects were randomly assigned to counterbalanced random combinations of gas conditions. The order of tests within each performance battery was also counterbalanced.

Stressor Conditions

The stressor condition for this study was similar to a miner breathing 3% and 4% CO_2 for one hour, the expected life of a SCBA escape unit, while running slightly over three miles as fast as possible.

Exercise. During the exercise periods, each subject ran for 15 min on a treadmill with the speed and grade adjusted to yield an O_2 uptake of 70% of his VO_2max. Each experimental session consisted of two such work bouts spaced with pre-, mid-, and post-tests, each lasting approximately 15 minutes, during which the dependent measures were collected. Oxygen uptake samples were taken during steady state running while breathing room air in order to record actual exercise intensity. The average intensity for the group was 71.6 ($\pm$ 3% SD) of VO_2max. On the average, the subjects ran slightly over three miles per day at their estimated maximum speeds.

While on the treadmill the subjects were cooled with an electric fan placed directly in front of them. Chest electrodes were connected to a Respironics Digital Exersentry (SN) for monitoring average heart rate. The experiment was conducted in an air-conditioned laboratory where the room temperature ranged from 23 to 25 degrees centigrade. Also, measures were taken to control ambient light and sound.

Carbon Dioxide Inhalation. A 150-liter Douglas bag served as a mixing reservoir into which room air, CO_2, and O_2 were mixed before heating and humidification by passage through warm water enroute to the subject in an open-circuit system. The inspired gas mixture was controlled by continuous monitoring of an Applied Electrochemistry S-3A Oxygen Analyzer and an LB-2 Beckman Medical Gas CO_2 Analyzer. Three gas mixtures were used in this study: (1) room air (0.03% CO_2 and 21% O_2), (2) 3% CO_2 (with 50% O_2), and

(c) 4% CO_2 (with 50% O_2). The prescribed gas mixture (± 0.1% SD) was inhaled for a period of 60 minutes (± 2 min SD) during each of the experimental sessions. Expired air was released into a well ventilated testing room.

Performance Measures

Four performance tasks were administered, each in a pre-, mid-, and post-test format. Grammatical reasoning and arithmetic tasks (addition and multiplication) were considered cognitive tasks which quantified decision-making speed and accuracy; balance was considered a psychomotor task reflecting vestibular integrity and neuromuscular control. Selection of these behavioral measures was based on preliminary pilot studies and results from other investigations using different stressors. These measures were considered representative of certain skills necessary to successfully escape from a mine during an emergency. Any performance degradation due to CO_2 inhalation and/or exercise would provide valuable information in defining the design parameters for escape instructions, emergency apparatus, and mining safeguards.

Six counterbalanced orders of tests were developed with each subject being randomly assigned to one of the orders. Before beginning the experiment, each subject received at least four days of practice with immediate knowledge of results to establish near asymptotic performance levels on each of the performance measures. These near asymptotic levels were reestablished in a practice period prior to each testing session. The amount of practice given was based on learning pilot studies and by results obtained by other investigators (Sheehy et al., 1982; Vercruyssen, 1982; Vercruyssen, & Kamon, 1984).

Grammatical Reasoning. Reasoning, based on grammatical transformations (Baddeley, 1968), has been shown to be a stable (Carter, Kennedy, & Bittner, 1981; Kennedy & Bittner, 1978; Rose, 1974) metric of "higher mental processes" that is sensitive to nitrogen narcosis (Baddeley, de Figuerido, Hawkswell Curtis, & Williams, 1968), age (Webb & Levy, 1982), hypocapnia (Gibson, 1978), oxyhelium diving (Lewis & Baddeley, 1981), and trimix breathing during dives of 660 meters (Logie & Baddeley, 1983). This test consisted of a three-minute task adapted from Baddeley's (1968) grammatical transformation task. Seated in front of a cathode ray terminal (Digital VT52-AE), the subjects read a statement followed by a pair of letters, decided whether or not the statement matched the letter pair, and then entered the appropriate "True" or "False" response on a one of two keys adjacent the return key on a standard alpha-numeric keyboard. Responses were made with the index (false key) or middle finger (true key) and ring finger (return key). The statements were randomly drawn from 64 possible combinations of six binary conditions (see Baddeley, 1968; Baddeley et al., 1968) and were

presented one-at-a-time until the three-minute time interval elapsed.
The following are examples of the statements presented:

True or False. A follows B -- AB
True or False. B precedes A -- BA
True or False. B does not follow A -- AB
True or False. A is not preceded by B -- BA

The stimulus presentation and data collection were completely on-line using a Digital Equipment Corporation (DEC) PDP 11 computer. The criterion measures were the response rate (i.e., the total number performed in each 3-min interval), accuracy (i.e., number of correct responses/total number of responses), and response times for each statement.

<u>Arithmetic Tasks</u>. Tasks similar to the addition and multiplication tests herein described have been shown to be sensitive to sleep deprivation (Webb & Levy, 1982; Williams & Lubin, 1967; Wilkinson, Edwards, & Haines, 1966) abrupt awakening at different times of night (Wilkinson & Stretton, 1971), hyperbaric and cold conditions (Hancock & Milner, 1982; O'Reilly, 1977), elevated body temperature (Wilkinson, Fox, Goldsmith, Hampton, & Lewis, 1964), heat stress (Bateman, 1981), exercise (Gutin & DiGennaro, 1968a, 1968b), oxyhelium diving (Baddeley, & Flemming, 1967; Lewis & Baddeley, 1981), trimix dives to 660 meters (Logie & Baddeley, 1983), repeated diving (Moeller, Chattin, Rogers, Laxar, & Ryack, 1981), and compressed gases (carbon dioxide, oxygen, and nitrogen -- Hesser, Fagraeus, & Adolfson, 1978). Moreover, an arithmetic task has been used by Morgan and Alluisi (1972) as synthetic work in the assessment of human performance. Such tasks have also been shown to be a stable metric in the development of performance evaluation tests for environmental research (Kennedy, and Bittner, 1978; Seales, Kennedy, & Bittner, 1980).

1. <u>Addition Test</u>. This test involved simple vertical addition. The subjects were presented problems, each comprised of five rows of two-digit numbers, to be summed as quickly and accurately as possible. Using the digits 1-9, numbers were randomly generated for each problem. Fifteen problems appeared in three rows of five on each form; 13 equivalent forms were randomly assigned across subjects and conditions. The subjects practiced for 30 sec (a warm-up) before completing as many problems as possible in 2 min. The criterion measures were the number of problems completed (speed) and the percentage of errors (accuracy). To ensure the maximum speed was obtained, the subjects were encouraged to make 5-15% errors.

2. Multiplication Test. In this test, subjects were presented problems which were to be multiplied as quickly and accurately as possible. Each problem consisted of a three-digit multiplicand, a two-digit multiplier, and a five-digit product. Using the digits 1-9, numbers were randomly generated for the multiplicand, the digits 2-9 were used for the multiplier, with the restriction that the product must be a five-digit number. * Fifteen problems appeared in three rows of five on each form; 13 equivalent forms were randomly assigned across subjects and conditions. The subjects were given a 30-sec practice period before beginning the 2-min test. The criterion measures were the number of problems completed (speed) and the percentage of errors (accuracy). To ensure maximum speed, the subjects wre encouraged to make 5-15% errors.

Stabilometer Balancing. Since dizziness and loss of balance are characteristic clinical symptoms associated with CO2 inhalation, the ability of the subject to maintain his balance on a horizontal pivoting platform stabilometer. This measure was also selected because of the information available on its susceptibility to practice (Ryan, 1965) and fatigue (Nunney, 1963) as well as its retention (Ryan, 1962b) and stress reaction (Ryan, 1962a) characteristics. The apparatus consisted of a 37.5 cm X 95 cm X 2.1 cm wooden platform with an axle and bearings positioned directly beneath such that the subject could stand on it, straddling the axle, and attempt to balance -- keep the platform horizontal. Microswitches were positioned on the stabilometer frame to record the amount of time the platform was tilted (off-balance). A Hunter Decade Interval Timer was used to limit the recording period to 20-seconds. A Hunter Model 220C Klockounter was used to record the total time the subject was off balance per 20-sec trial. Rigorous training (more than 150 practice trials) preceded the start of the experiment. In fact, all subjects experienced keeping the platform horizontal (i.e., 0.0 sec off-balance) for the entire 20-sec test; some subjects were able to do this consistently. The subject performed five trials, separated by approximately 30-sec inter-trial rest intervals, during each test.

----

* Because of the ease in computing, multiplication problems used in future studies should not use identical multipliers (e.g., 789 x 66 = ?????).

Procedure

Each subject participated in eight sessions, one per day. Following an exercise tolerance test (Day 1), each subject participated in four 150-minute practice sessions, one each day (Days 2-5), before receiving a counterbalanced random order of experimental sessions (Days 6-8). The first practice session was used to explain the experiment, complete the informed consent documents, introduce the dependent measures and experimental protocol, and provide considerable practice on each of the performance measures. In the course of these practice sessions, the subjects experienced at least 36 3-min grammatical reasoning tests, 150 20-sec stabilometer tests, and 12 2-min addition and multiplication test. Also, the subjects ran on the treadmill while breathing the highest concentration of CO2 (4%) to become familiar with the experimental protocols, the respiratory hoses, treadmill running and the stressor (CO2 inhalation). Thus, these subjects were performing well-learned tasks and had previous experience with all aspects of the experimental procedures, including familiarity with the stressor itself.

Following the practice sessions, the protocol illustrated in Figure B3-1 was used each day. Each experimental session took approximately 135 min to complete and were spaced with at least a 48-hour rest interval.

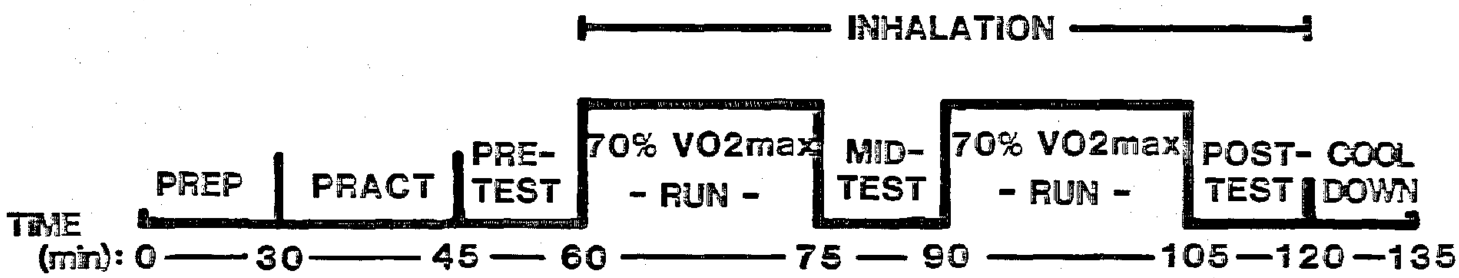

Figure B3-1. Protocol for experimental sessions

Upon arrival to the laboratory each subject was fitted with chest electrodes, given a brief warm-up on each task, and then given the pre-test performance measures which were completed in approximately 15 minutes. Asymptotic performance levels were usually reestablished in one trial for grammatical reasoning, addition, and multiplication. The stabilometer usually required 10 trials. In all, practice and preparation totalled 24.7 min ($\pm$ 4.2 SD).

The pre-test measures (control -- no face mask, no exercise, no gas mixtures) were gathered in 25.2 min ($\pm$ 2.8 SD). The gas inhalation period began with the subject running on a treadmill for two 15-min work bouts at an intensity equivalent to 70% of his aerobic capacity. Between and following these work bouts were the mid- and post-tests, respectively, each also lasting approximately 15 min (mid-test was 16.6 min $\pm$ 1.5 SD; post-test was 15.8 $\pm$ 3.5 SD). The face mask was removed after the post-test, making the total inhalation period 64.4 min ($\pm$ 3.5 SD), and the subject was required to walk on the treadmill at 3 mph for at least 6 min as a "cool-down" before departing the lab. During and following the cool-down, the subject was asked to provide subjective information on his perceived exertion, clinical symptoms (discomforts), performance quality, etc. All eight testing sessions per subject were completed within three weeks.

Treatment of the Data

The dependent measures were analyzed using a multivariate analysis of variance on repeated measures (Games, 1981; Games, Gray, Herron, & Pitz, 1980). All post-hoc follow-up analyses were done using the Tukey Wholly Significant Difference (WSD) technique. In all cases, the level of significance was $p = 0.05$. An additional univariate analysis of the repeated measures was performed on each subject to test for learning (sequence) effects. (See Jackson and Raven, 1983, for a discussion of statistical and research designs for industrial respiratory research.)

Results and Discussion

Performance means and standard deviations for each dependent measure are shown in Table B3-2.

Table B3-2 Performance Means and Standard Deviations

		AIR			3% CO2			4% CO2		
		PRE	MID	POST	PRE	MID	POST	PRE	MID	POST
ADDITION	#	13.8 ±3.1	13.7 ±2.9	14.0 ±2.5	13.3 ±3.6	14.5 ±3.0	13.8 ±4.1	13.8 ±4.0	13.3 ±2.4	13.0 ±4.1
	% ERRORS	12.5 ±10.5	14.7 ±9.4	1.2 ±2.9	6.0 ±4.9	9.0 ±3.2	8.8 ±10.7	12.7 ±15.4	7.8 ±7.5	8.3 ±5.0
MULTIPLICATION	#	30.0 ±7.7	30.2 ±6.4	30.3 ±7.9	28.3 ±7.9	30.7 ±7.3	31.0 ±7.6	29.7 ±6.3	33.0 ±6.2	28.5 ±7.0
	% ERRORS	9.5 ±8.1	7.8 ±12.5	13.3 ±15.5	16.0 ±16.2	11.8 ±9.6	9.0 ±10.0	6.7 ±6.6	6.0 ±4.8	13.2 ±8.0
REASONING	#	98.2 ±17.0	101.8 ±14.0	102.3 ±15.2	98.3 ±15.6	102.3 ±16.3	101.0 ±17.0	107.3 ±29.2	104.8 ±30.6	107.2 ±29.1
	% ERRORS	6.7 ±5.4	5.5 ±3.5	5.5 ±4.0	5.2 ±3.0	5.7 ±3.4	7.0 ±7.7	6.2 ±3.7	7.5 ±3.9	7.3 ±6.5
STABILOMETER	TRIAL 1	2.34 ±2.12	5.00 ±3.23	4.69 ±3.49	1.57 ±1.48	3.25 ±1.96	4.36 ±1.77	1.85 ±1.50	4.07 ±2.85	4.67 ±2.90
	TRIAL 1–3	1.84 ±1.58	4.21 ±2.52	3.62 ±2.38	1.44 ±0.83	3.89 ±2.06	4.00 ±2.10	1.99 ±0.92	4.46 ±2.58	4.26 ±2.82
	TRIAL 1–5	1.96 ±1.61	3.96 ±2.33	3.41 ±2.21	1.30 ±1.01	3.76 ±2.07	3.74 ±2.10	1.62 ±0.99	3.89 ±2.57	3.94 ±2.76
	TRIAL 2–5	1.86 ±1.04	3.70 ±1.87	3.07 ±1.54	1.18 ±0.55	3.61 ±1.49	3.40 ±1.71	1.57 ±0.45	3.84 ±2.20	4.15 ±2.62

Note: ± = standard deviation; # = number of items completed; % error = relative number of errors; AIR = 0.03% CO_2, 21% O_2; 3% CO_2 = 3% CO_2, 50% O_2; 4% CO_2 = 4% CO_2, 50% O_2; PRE = pre-exercise test; MID = mid-exercise test; POST = post-exercise test.

Only two measures produced significant results ($\underline{p} < .05$): multiplication rate and time off-balance on the stabilometer. The mean multiplication rates as a function of inspired gases and tests are illustrated in Figure B3-2. Next to each mean rate value is the mean percentage errors for that condition. Multiplication rate was significantly faster [$\underline{F}$ (2,10) = 7.57; $\underline{p}$ = .001], with the lowest percentage of errors, on the mid-test while breathing 4% CO2 than when breathing other gas mixtures. This finding is difficult to interpret, however, since breathing 4% CO2 also produced the slowest multiplication rate on the post-test. It is not clear why such mid- and post-test differences occurred.

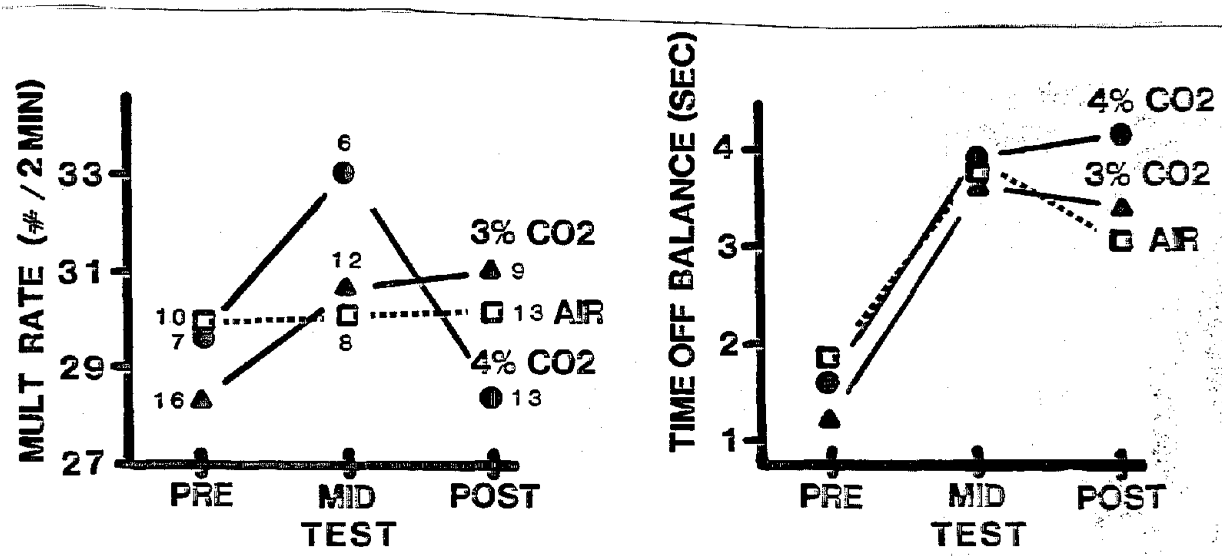

Figure B3-2. Mean multiplication rate and time off-balance as a function of gases inhaled and tests. Percentage errors per condition are indicated next to each multiplication rate.

Mean time off-balance during the platform stabilometer testing is also shown in Figure B3-2 as a function of inspired gases and tests. Balance was significantly impaired [$\underline{F}$ (2,10) = 14.59; $\underline{p}$ = .001] on the mid-test ($\underline{M}$ = 3.72 sec) and post-tests ($\underline{M}$ = 3.54 sec) compared to the pre-test ($\underline{M}$ = 1.54 sec) -- presumably due to exercise and the added respiratory hoses. However, because the purpose of this study was to explore the effects of these gas concentrations on performance while simulating the conditions of a mine escape, exercise was not an independent variable and was therefore intentionally confounded in the design. Thus, it cannot be concluded that exercise produced these effects because there was not a control condition of breathing the gases without running. Despite the fact that the values obtained on the pre-tests were very similar -- suggesting high inter-test reliability -- the gas trend shown on the post-test was not significant (p > .05).

The most meaningful finding is that the gas concentrations inspired did not impair cognitive or psychomotor performance. If anything, as unusual as it seems, the trends shown in Figure B3-2 hint that CO2 and exercise may even improve multiplication rate under certain conditions. Other than the two effects herein mentioned, none of the other main or interaction effects tests were significant (p > .05).

Vercruyssen and Kamon (1984) warn against the misinterpretation of null results in stress studies similar to this one. Affirming the null hypothesis -- that there is no effect due to the stressor conditions -- is not grounds for raising the MAC for CO2 It simply means that under the conditions specified, these dependent measures failed to show a sensitivity to CO2 There still remains the possibility that under slightly different circumstances, or with different dependent measures, CO2 at these levels might have produced significant effects. If numerous other dependent measures were employed and all failed to reveal CO2 effects then there might be evidence supporting the notion that humans can tolerate these subclinical levels of CO2 without suffering from impairments in cognitive and motor performance.

Vercruyssen and Kamon (1984) also identify potential confounding variables to be considered in evaluating the external validity of such studies. Most important were age, health, body size, fitness level, volunteer and smoking status, CO2 sensitivity, degree of lung impairment, experience, gender, and personality characteristics. The subjects in this study may not have been representative of the population of individuals using SCBAs. To maximize statistical power, these subjects comprised a homogeneous population of healthy, young, active, nonsmoking, adult male volunteers with relatively high fitness levels. Each demographic characteristic provides a possible source of systematic variance and, therefore, must be given careful consideration when interpreting the results of this investigation (also see Ayoub & Selan, 1981; Dempsey, 1979; Kamon, Doyle, & Kovac, 1983; Morgan, 1983; Vercruyssen & Kamon, 1984).

Each subject experienced two sessions of CO2 inhalation. The most frequently reported symptom during these exposures was a dry throat (4 of 5 subjects, but two of these also reported dry throats in the air conditions). While one subject appeared very sensitive to CO2 having a moderate headache with dizziness and weakness throughout the inhalation period, most subjects were not aware of the gas conditions and could not detect changes in their ventilation. During the first work bout, three subjects noticed slight headaches which became most intense when exercise ceased (during the first 3-min of mid-test). For all of these subjects, the headaches disappeared during the cool-down period (while breathing room air and walking on the treadmill). All CO_2 reactions were most intense on the first day of exposure. No headaches were reported during the second exposure to CO_2 only dry throats. These findings hint at the possibility of individual differences in CO_2 tolerance and adaptation (habituation, desensitization, or acclimatization) to CO_2 Further studies should explore these areas.

Emergency breathing systems, e.g., SCBAs, must be able to sustain life and maximize the probability of successful escape from a hazardous environment without constraining the escape activities of the user. Since there is no evidence to suggest these subclinical levels cause physiological dysfunctions and because there is almost no data available on the effects of CO_2 breathing on cognitive and psychomotor performance, the current standards appear to be based on speculations. Therefore, if studies similar to this one repeatedly show no deterioration in performance, then the existing MACs should be reevaluated. If higher concentrations of inhaled CO_2 were allowed, considerable improvements could be made in the life-support capacities of SCBAs (see Vercruyssen & Kamon, 1984).

Conclusions

Breathing as high as 4% CO_2 for one hour, during and following physical work, did not impair cognitive and motor performance (i.e., addition speed or accuracy, multiplication accuracy, reasoning speed or accuracy, or stabilometer balance). Breathing 4% CO_2 caused an unexplained improvement in multiplication but this finding is difficult to interpret and the authors are reluctant to suggest that breathing CO_2 improves mental performance. The data also suggested that exercise may have disrupted balance, or viewed another way, that the stabilometer test may have been sensitive to exercise. Finding no performance impairment attributed to breathing elevated levels of CO_2 may be explained in one of three ways: (1) the cognitive processes required to perform the experimental tasks are flexible enough to mitigate the effects of the stressor, (2) the dependent measures employed were not sensitive to the type of degradation effects encountered, or (3) breathing up to 4% CO_2 does not significantly impair cognitive and psychomotor performance essential to mine escape. The authors are inclined to believe the latter.

Acknowledgments

This study was supported by the U.S. Department of the Interior, Bureau of Mines Contract No. J0 100092.

Appreciation is extended to Professors Merrill E. Noble, Robert W. Christina, Elsworth R. Buskirk, and Paul A. Games for sharing their expertise in the areas of cognitive psychology, motor behavior, respiratory physiology, and statistics, respectively. James B. Sheehy conducted preliminary work on the effects of acute exposure to CO2 and developed the computer programs for the reasoning task. N. Scott Deno and Charles F. Ryan provided valuable technical assistance, Donna J. Mah aided in data collection and analysis, and Tina Mihaly helped produce a final copy of this manuscript.

References

Ayoub, M.M., & Selan, J.L. Energy expenditures requirement in low coal mines. Proceedings of the Human Factors Society, 1981, 426-430.

Baddeley, A.D. A three minute reasoning test based on grammatical transformation. Psychonomic Science, 1968, 10(10), 341-342.

Baddeley, A.D., de Figuerido, J.W., Hawkswell Curtis, J.W., & Williams, A.N. Nitrogen narcosis and performance under water. Ergonomics, 1968, 11(2), 157-164.

Baddeley, A.D., & Flemming, N.C. The efficiency of divers breathing oxy-helium. Ergonomics, 1967, 10(3), 311-319.

Bateman, R.P. The effects of increased ambient temperature on dual task performance. Proceedings of the Human Factors Society, 1981, 379-383.

Carter, R.C., Kennedy, R.S., & Bittner, A.C., Jr. Grammatical reasoning: A stable performance yardstick. Human Factors, 1981, 23(5), 587-591.

Dempsey, J.A. The brain's role in exercise hypernea. Medicine and Science in Sports, 1979, 11, 213-220.

Games, P.A. The ANOVR series: Analyses of repeated measures designs with optimal robust procedures when assumptions are violated. The American Statistician, 1981, 35, 109-110.

Games, P.A., Gray, G.S., Herron, W.L., & Pitz, G.F. ANOVR: Analysis of variance with repeated measures. Behavior Research Methods and Instrumentation, 1980, 112, 467.

Gibson, T.M. Effects of hypocapnia on psychomotor and intellectual performance. Aviation, Space and Environmental Medicine, 1978, 49(8), 943-946.

Glatte, H.A., Motsay, G.J., & Welch, B.E. Carbon dioxide tolerance studies. (Report No. SAM-TR-67-77), Brooks Air Force Base, Tx: U.S. Air Force, Aerospace Medicine Division (AFSC), USAF School of Aerospace Medicine, 1967, 1-22.

Gutin B., & DiGennaro. Effect of one-minute and five-minute step-ups on performance of simple addition. Research Quarterly, 1968, 39(1), 81-85. (a)

Gutin B., & DiGennaro. Effect of a treadmill run to exhaustion on performance of long addition. Research Quarterly, 1968, 39(4), 958-964. (b)

Hancock, P.A., & Milner, E.K. Mental and psychomotor task performance in an open ocean underwater environment. Research Quarterly for Exercise and Sport, 1982, 53(3), 247-251.

Henning, R.A., Sauter, S.L., Reddan, W., & Lanphier, E.H. Behavioral impairment with altered ventilatory response to CO2 Abstracts of 67th Annual Meeting, Chicago, ILL, April 10-15, 1983. Federation Proceedings: Federation of American Societies for Experimental Biology, 1983, 42(4), 1013.

Hesser, C.M., Fagraeus, L., & Adolfson, J. Roles of nitrogen, Oxygen, and carbon dioxide in compressed-air narcosis. Undersea Biomedical Research, 1978, 5(4), 391-200.

Jackson, A.W., & Raven, P.B. Statistical and research design considerations concerning industrial respirator research. Journal of the International Society for Respiratory Protection, 1983, 1,(2), 31-40.

Kamon, E., Doyle, D., & Kovac, J. The oxygen cost of an escape from an underground coal mine. American Industrial Hygiene Association Journal, 1983, 44, 552-555.

Kennedy, R.S., & Bittner, A.C., Jr. Progress in the analysis of a performance evaluation test for environmental research (PETER). Proceedings of the 22nd Annual Meeting of the Human Factors Society, 1978, 29-35. (NTIS No. AD A060676) Also in: R.S. Kennedy, A.C. Bittner, Jr., M.M. Harbeson, & M.B. Jones, Perspectives in performance evaluation tests for environmental research (PETER): Collected papers. (Research Report No. NBDL -- 80R004, NTIS No. AD A111180) New Orleans: Naval Biodynamics Laboratory, 1981, November, 14-17.

Lewis, V.J., & Baddeley, A.D. Cognitive performance, sleep quality and mood during deep oxyhelium diving. Ergonomics, 1981, 24(10), 773-793.

Logie, R.H., & Baddeley, A.D. A trimix saturation dive to 660 m: Studies of cognitive performance, mood and sleep quality. Ergonomics, 1983, 26(4), 359-374.

Moeller, G., Chattin, C., Rogers, W., Laxar, K., & Ryack, B. Performance effects with repeated exposure to the diving environment. Journal of Applied Psychology, 1981, 66(4), 502-510.

Morgan, W.P. Pyschological problems associated with the wear of industrial respirators. Journal of the International Society for Respiratory Protection, 1983, 1(3), 67-107.

Morgan, B.B., & Alluisi, E.A. Synthetic work: Methodology for assessment of human performance. Perceptual and Motor Skills, 1972, 35, 835-845.

Nunney, D.N. Fatigue, impairment, and psycho-motor learning. Perceptual and Motor Skills, 1963, 16, 369-375.

O'Reilly, J.P. Hana Kai II: A 17-day dry saturation dive at 18.6 ATA. VI: Cognitive performance, reaction time, and personality changes. Undersea Biomedical Research, 1977, 4(3), 297-305.

Rose, A.M. Human information processing: An assessment and research battery. Human Performance Center -- Technical Report No. 45, Department of Psychology, University of Michigan, 1974, January.

Ryan, E.D. Effects of stress on motor performance and learning. Research Quarterly, 1962, 33(1), 111-119. (a)

Ryan, E.D. Retention of stabilometer and pursuit rotor skills. Research Quarterly, 1962, 33(4), 593-598. (b)

Ryan, E.D. Prerest and postrest performance on the stabilometer as a function of distribution of practice. Research Quarterly, 1965, 36(2), 197-204.

Sheehy, J.B., Kamon, E., & Kiser, D. Effects of carbon dioxide inhalation on psychomotor and mental performance during exercise and recovery. Human Factors, 1982, 24(5), 581-588.

Storm, W.F., & Giannetta, C.L. Effects of hypercapnia and bedrest on psychomotor performance. Aviation, Space and Environmental Medicine, 1974, 45, 431-433.

Vercruyssen, M. [CO2 Experiment 4 Dependent Measures: Pilot Studies]. Unpublished raw data, 1982.

Vercruyssen, M., & Kamon, E. Behavioral effects of one-hour breathing of high concentrations of CO2 and O2 while doing physical work. Journal of the International Society for Respiratory Protection, 1984, 2(1), 63-89.

Webb, W.B., & Levy, C.M. Age, sleep deprivation, and performance. Psychophysiology, 1982, 19(3), 272-276.

Wilkinson, R.T., Edwards, R.S., & Haines, E. Performance following a night of reduced sleep. Psychonomic Science, 1966, 5(12), 471-472.

Wilkinson, R.T., Fox, R.H., Goldsmith, R., Hampton, I.F.G., & Lewis, H.E. Psychological and physiological responses to raised body temperature. Journal of Applied Physiology, 1964, 19(20), 287-291.

Wilkinson, R.T., & Stretton, M. Performance after awakening at different times of night. Psychonomic Science, 1971, 23(4), 283-285.

Williams, H.L, & Lubin, A. Speeded addition and sleep loss. Journal of Experimental Psychology, 1967, 73(2), 313-317.

BEHAVIORAL EFFECTS OF BREATHING 3% AND 4% CARBON DIOXIDE DURING AND FOLLOWING PHYSICAL WORK*

Max Vercruyssen and Eliezer Kamon

Ergonomics Unit
Laboratory for Human Performance Research
The Pennsylvania State University
University Park, PA 16802

U.S.A.

The environmental stressor explored in this experiment was breathing elevated but subclinical levels of carbon dioxide (CO_2) while running on a treadmill. Simulating an emergency mine escape, six subjects breathed, for one hour, each of three gas mixtures: room air, 3% CO_2, or 4% CO_2. Concomitantly, psychomotor and mental performance tests were administered prior to, between, and following two 20-min exercise bouts at 70% of each subject's aerobic capacity. The results showed no effects of these gases on performance, as measured by addition, multiplication, grammatical reasoning, and balance on a stabilometer. These findings call for a reevaluation of the existing federal standards for the maximum allowable concentrations of CO_2 for self-contained breathing apparatuses (SCBAs), particularly those used for escape during emergencies.

Although there are no disabling physiological effects or clinical symptoms associated with one-hour breathing of up to 5% CO_2, there still may be psychological reactions, such as impaired motor control, slowed reactions, disorientation, or diminished mental capacities, which may jeopardize a worker's health and safety. Impaired cognitive and/or motor performance may make the worker susceptible to accidents and may decrease the probability of survival in emergency situations. Therefore, it is important for applied as well as theoretical reasons to study CO_2 inhalation as an environmental stressor.

Previous research exploring the effects of breathing elevated but subclinical levels of CO_2 have consistently failed to demonstrate degradation in performance. Sheehy, Kamon and Kiser (1982) exposed their subjects to 4% and 5% CO_2 (with 21 and 50% O_2) for 16 min during which the subjects ran on a treadmill at 80% $\dot{V}_{O_2}$max for 10 min. Up to 5% CO_2, they found no deterioration in the performance of psychomotor tasks (simple reaction time, pursuit tracking, and choice response time) or mental tasks (short-term memory and reasoning). Concerned with the risks due to CO_2 retention in diving, Henning, Sauter, Reddan, and Lanphier (1983) found no effects of breathing 6% CO_2 for 10-14 min on simple and choice reaction time, hand steadiness, and postural sway. Storm and Giannetta (1974) exposed six subjects to 4% CO_2 for 14 days and found no effects on complex tracking, eye-hand coordination, and problem solving. Glatte, Motsay, and Welch (1967) found no effects of breathing 3% CO_2 for 5 days on arithmetic, vigilance, hand steadiness, memory, problem solving and auditory monitoring. Recently, an experiment was conducted by Vercruyssen and Kamon (in press) which found no effects of breathing 2% CO_2 for one hour, during and following moderate-to-strenuous work, on short-term memory, reasoning, balance, choice response time, or pursuit tracking. The purpose of the present experiment was to increase the gas concentration used in the previous experiment to explore the effects of breathing 3% and 4% CO_2, during and following physical work, on cognitive and motor performance.

METHOD

Subjects and Design

Six right-handed, beardless, male university graduate students volunteered to serve as paid subjects. All were nonsmokers and in good general health. Their mean age was 27 years; their mean aerobic capacity was 51.5 $ml \cdot kg^{-1} \cdot min^{-1}$. Prior to participating in the experiment, all subjects received a medical examination, including exercise tolerance and pulmonary function tests.

A two-factor, repeated measures 3 x 3 (Gas x Tests) design was employed to analyze data from each of four dependent measures: reasoning, addition, multiplication, and balance. Three gas concentration conditions were employed: a room air control, 3% CO_2 and 4% CO_2. Subjects were randomly assigned to counterbalanced random combinations of gas conditions. Six counterbalanced orders of tests were developed with each subject being randomly assigned to one of the orders.

Stressor Conditions

The environmental stressor imposed in this study was breathing 3% and 4% CO_2 for one hour--the expected life of a SCBA escape unit--while running slightly over three miles as fast as possible. During the exercise periods, each subject ran for 15 min on a treadmill with the speed and grade adjusted to yield an O_2 uptake of 70% of his $\dot{V}_{O_2}$max. Each experimental session consisted of two such work bouts spaced with pre-, mid-, and post-tests, each lasting approximately 15 min, during which the dependent measures were collected. For each session, each subject breathed one of three different gas mixtures during a one-hour inhalation period from the onset of the first exercise bout to the end of the post-test following the second bout. The pre-test was always a full rested, room

*This is a condensed version of a contract report for the U.S. Department of Interior, Bureau of Mines. For further details, see Vercruyssen (Note 1).

air control condition, while the mid- and post-tests followed exercise and occurred during the gas inhalation period. Three gas mixtures were delivered in an open-circuit system: (1) room air (0.03% CO_2 and 21% O_2), (2) 3% CO_2 (with 50% O_2), and (c) 4% CO_2 (with 50% O_2).

Performance Measures

Four performance tasks were administered, each in a pre-, mid-, and post-test format. Grammatical reasoning and arithmetic tasks (addition and multiplication) were considered cognitive tasks which quantified decision-making speed and accuracy; balance was considered a psychomotor task reflecting vestibular integrity and neuromuscular control. Selection of these behavioral measures was based on preliminary pilot studies and results from other investigations using different stressors. These measures were considered representative of certain skills necessary to successfully escape from a mine during an emergency. Any performance degradation due to CO_2 inhalation and/or exercise would provide valuable information in defining the design parameters for escape instructions, emergency apparatus, and mining safeguards.

Before beginning the experiment, each subject received at least four days of practice with immediate knowledge of results to establish near asymptotic performance levels on each of the performance measures. These near asymptotic levels were reestablished in a practice period prior to each testing session. Following are brief descriptions of the performance tasks, details are available elsewhere (Sheehy et al., 1982; Vercruyssen, Note 1; Vercruyssen & Kamon, in press).

Grammatical Reasoning. Reasoning, based on grammatical transformations (Baddeley, 1968), has been shown to be a stable metric (Carter, Kennedy, & Bittner, 1981) of "higher mental processes" that is sensitive to nitrogen narcosis (Baddeley, de Figuerido, Hawkswell Curtis, & Williams, 1968), age (Webb & Levy, 1982), hypocapnia (Gibson, 1978), oxyhelium diving (Lewis & Baddeley, 1981), and trimix breathing during dives of 660 meters (Logie & Baddeley, 1983). Criterion measures were response rate (i.e., the total number performed in each 3-min interval), accuracy (i.e., number of correct responses/total number of responses), and response times for each statement.

Arithmetic Tasks. Tasks similar to the addition and multiplication tests herein described have been shown to be sensitive to sleep deprivation (Webb & Levy, 1982) abrupt awakening at different times of night (Wilinson & Stretton, 1971), hyperbaric and cold conditions (Hancock & Milner, 1982), elevated body temperature (Wilkinson, Fox, Goldsmith, Hampton, & Lewis, 1964), heat stress (Bateman, 1981), exercise (Gutin & DiGennaro, 1968a, 1968b), oxyhelium diving (Lewis & Baddeley, 1981), trimix dives to 660 meters (Logie & Baddeley, 1983), repeated diving (Moeller, Chattin, Rogers, Laxar, & Ryack, 1981), and compressed gases (carbon dioxide, oxygen, and nitrogen (Hesser, Fagraeus, & Adolfson, 1978). Moreover, an arithmetic task has been used by Morgan and Alluisi (1972) as synthetic work in the assessment of human performance. Such tasks appear to be suitable performance evaluation tests for environmental stressor research (Seales, Kennedy, & Bittner, 1980).

The addition test involved simple vertical addition. The subjects were presented problems, each comprised of five rows of two-digit numbers, to be summed as quickly and accurately as possible. The subjects practiced for 30 sec (a warm-up) before completing as many problems as possible in 2 min. Criterion measures were the number of problems completed (speed) and the percentage of errors (accuracy). To avoid speed-accuracy tradeoffs in responding and to ensure maximum speed of response execution, the subjects were encouraged to make 5-15% errors.

In the multiplication test, subjects were presented problems which were to be multiplied as quickly and accurately as possible. Each problem consisted of a three-digit multiplicant, a two-digit multiplier, and a five-digit product. The subjects were given a 30-sec practice period before beginning the 2-min test. Criterion measures were the number of problems completed (speed) and the percentage of errors (accuracy). The subjects were encouraged to make 5-15% errors.

Stabilometer Balancing. Since dizziness and loss of balance are characteristic clinical symptoms associated with CO_2 inhalation, the ability of the subject to maintain his balance on a horizontal pivoting platform stabilometer was measured. This task was also selected because of the information available on its susceptibility to practice (Ryan, 1965) and fatigue (Nunney, 1963) as well as its retention (Ryan, 1962b) and stress reaction (Ryan, 1962a) characteristics. The criterion measure was the total time the subject was off balance per 20-sec trial. The subject performed five trials, separated by approximately 30-sec inter-trial rest intervals, during each test.

Procedure

Each subject participated in eight sessions, one per day, all within a three-week period. Following an exercise tolerance test (Day 1), each subject participated in four 150-minute pracice sessions, one each day (Days 2-5), before receiving a counterbalanced random order of experimental sessions (Days 6-8). During the practice sessions, subjects experienced at least 36 3-min grammatical reasoning tests, 150 20-sec stabilometer tests, and 12 2-min addition and multiplication tests. Also, subjects ran on the treadmill while breathing the highest concentration of CO_2 (4%) to become familiar with the experimental protocols, the respiratory hoses, treadmill running, and the stressor (CO_2 inhalation). In short, these subjects were performing well-learned tasks and had previous experience with all aspects of the experimental procedures, including familiarity with the stressor itself. Each experimental session took approximately 135 min to complete and all were spaced with at least a 48-hour rest interval.

Treatment of the Data

The dependent measures were analyzed using a multivariate analysis of variance on repeated measures (Games, 1981; Games, Gray, Herron, & Pitz, 1980). All post-hoc analyses were done using the Tukey Wholly Significant Difference (WSD) technique.

For all contrasts, the level of significance was $p = 0.05$. An additional univariate analysis of the repeated measures was performed to test for learning (sequence) effects. Data were treated in accordance with the recommendations of Jackson and Raven (1983).

RESULTS AND DISCUSSION

Performance means and standard deviations for each dependent measure are shown in Table 1.

Only two measures produced significant results ($p < .05$): multiplication rate and time off-balance on the stabilometer. Mean multiplication rate as a function of inspired gases and tests is illustrated in Figure 1. Next to each mean rate value is the mean percentage errors for that condition. Multiplication rate was significantly faster (F (2,10) = 7.57; p = .010), with the lowest percentage of errors, on the mid-test while breathing 4% CO_2 than when breathing other gas mixtures. This finding is difficult to interpret, however, since breathing 4% CO_2 also produced the slowest multiplication rate on the post-test. It is not clear why such mid- and post-test differences occurred.

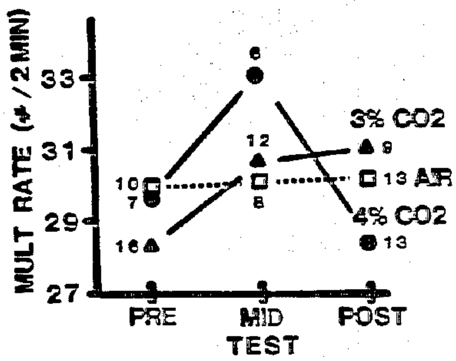

Figure 1. Multiplication rate and % errors

Table 1. Performance Means and Standard Deviations

		AIR			3% CO2			4% CO2		
		PRE	MID	POST	PRE	MID	POST	PRE	MID	POST
ADDITION	#	13.8 ±3.1	13.7 ±2.9	14.0 ±2.5	13.3 ±3.6	14.5 ±3.0	13.8 ±4.1	13.8 ±4.0	13.3 ±2.4	13.0 ±4.1
	% ERRORS	12.5 ±10.5	14.7 ±9.4	1.2 ±2.9	6.0 ±4.9	9.0 ±8.2	8.8 ±10.7	12.7 ±15.4	7.8 ±7.5	8.3 ±5.0
MULTIPLICATION	#	30.0 ±7.7	30.2 ±6.4	30.3 ±7.9	28.3 ±7.9	30.7 ±7.3	31.0 ±7.6	29.7 ±6.3	33.0 ±6.2	28.5 ±7.0
	% ERRORS	9.5 ±8.1	7.8 ±12.5	13.3 ±15.5	16.0 ±16.2	11.8 ±9.6	9.0 ±10.0	6.7 ±6.6	6.0 ±4.8	13.2 ±8.0
REASONING	#	98.2 ±17.0	101.8 ±14.0	102.3 ±15.2	98.3 ±15.6	102.3 ±16.3	101.0 ±17.0	107.3 ±29.2	104.8 ±30.6	107.2 ±29.1
	% ERRORS	6.7 ±5.4	5.5 ±3.5	5.5 ±4.0	5.2 ±3.0	5.7 ±3.4	7.8 ±7.7	6.2 ±3.7	7.5 ±3.9	7.3 ±6.5
STABILOMETER	TRIAL 1	2.34 ±2.12	5.00 ±3.23	4.69 ±3.49	1.57 ±1.48	3.25 ±1.96	4.36 ±1.77	1.85 ±1.50	4.07 ±2.85	4.67 ±2.90
	TRIAL 1-3	1.84 ±1.58	4.21 ±2.52	3.62 ±2.38	1.44 ±0.83	3.89 ±2.06	4.00 ±2.10	1.99 ±0.92	4.46 ±2.59	4.26 ±2.82
	TRIAL 1-5	1.96 ±1.61	3.96 ±2.33	3.41 ±2.21	1.30 ±1.01	3.76 ±2.07	3.74 ±2.10	1.62 ±0.99	3.89 ±2.57	3.94 ±2.76
	TRIAL 2-5	1.86 ±1.04	3.70 ±1.87	3.07 ±1.54	1.18 ±0.55	3.61 ±1.49	3.40 ±1.71	1.57 ±0.45	3.84 ±2.20	4.15 ±2.62

Note: ± = standard deviation; # = number of items completed; % error = relative number of errors; AIR = 0.03% CO_2, 21% O_2; 3% CO_2 = 3% CO_2, 50% O_2; 4% CO_2 = 4% CO_2, 50% O_2; PRE = pre-exercise test; MID = mid-exercise test; POST = post-exercise test.

Mean time off-balance is shown in Figure 2 as a function of inspired gases and tests. Balance was significantly impaired [F (2,10) = 14.59; p = .001] on the mid-test (M = 3.72 sec) and post-test (M = 3.54 sec) compared to the pre-test (M = 1.54 sec)--presumably due to exercise and the added respiratory hoses. These data suggests that exercise may impair balance on the platform stabilometer, but that breathing CO_2 does not. However, since exercise was not an independent variable and was intentionally confounded in the design, it cannot be concluded that exercise produced these effects. A control condition of breathing the gases without running would be necessary to determine the effects of exercise on performance. The apparent gas trend shown on the post-test was not significant ($p > .05$).

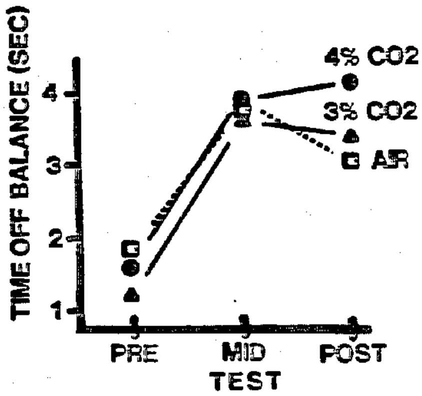

Figure 2. Balance on stabilometer

The most meaningful finding is that the gas concentrations inspired did not impair cognitive or psychomotor performance. However, Vercruyssen and Kamon (in press) identify potential confounding variables to be considered in evaluating the external validity of such studies. Most important are subject demographics: age, health, body size, fitness, volunteer and smoking status, CO_2 sensitivity, degree of lung impairment, experience, gender, and personality characteristics. To maximize statistical power, the subjects used in this experiment comprised a homogeneous population of healthy, young, active, nonsmoking, adult male volunteers with relatively high fitness and, therefore, may not have been representative of populations of miners or others using SCBAs. Thus, care must be taken when interpreting the results of this investigation since each demographic characteristic provides a possible source of systematic variance (also see Kamon, Doyle, & Kovac, 1983; Morgan, 1983; Vercruyssen & Kamon, in press).

Since there is no evidence to suggest these subclinical levels cause physiological dysfunctions or impairment of cognitive and psychomotor performance, the existing federal standards for the maximum allowable concentrations of CO_2 should be reevaluated. If higher concentrations of inhaled CO_2 were allowed, considerable improvements could be made in the life-support capacities of SCBAs (see Vercruyssen & Kamon, in press).

CONCLUSIONS

Breathing as high as 4% CO_2 for one hour, during and following treadmill running, did not impair cognitive and motor performance (i.e., addition speed or accuracy, multiplication accuracy, reasoning speed or accuracy, or stabilometer balance). Three explanations account for these results: (1) the cognitive processes required to perform the experimental tasks are flexible enough to mitigate the effects of the stressor, (2) the dependent measures employed were not sensitive to the type of degradation effects encountered, or (3) breathing up to 4% CO_2 does not significantly impair cognitive and psychomotor performance essential to mine escape. The authors are inclined to believe the last explanation.

ACKNOWLEDGMENTS

This study was supported by the U.S. Department of the Interior, Bureau of Mines Contract No. J0-100092.

Appreciation is extended to Professors Merrill E. Noble, Robert W. Christina, Elsworth R. Buskirk, and Paul A. Games for sharing their expertise in the areas of cognitive psychology, motor behavior, respiratory physiology, and statistics, respectively. James B. Sheehy conducted preliminary work on the effects of acute exposure to CO_2 and developed the computer programs for the reasoning task. N. Scott Deno and Charles F. Ryan provided valuable technical assistance; Donna J. Mah aided in data collection and analysis; Tina Mihaly and Becky Nilson helped produce a final copy of this manuscript.

REFERENCES

Reference Note

1. Vercruyssen, M. Breathing 3-4% CO_2: Behavioral effects. In E. Kamon, N. S. Deno, & M. Vercruyssen, Physiological Response of Miners to Emergencies. End of contract report, U.S. Department of the Interior, Bureau of Mines (No. J0-100092). In preparation.

Published References

Baddeley, A. D. A three-minute reasoning test based on grammatical transformation. Psychonomic Science, 1968, 10(10), 341-342.

Baddeley, A. D., de Figuerido, J. W., Hawkswell Curtis, J. W., & Williams, A. N. Nitrogen narcosis and performance under water. Ergonomics, 1968, 11(2), 157-164.

Bateman, R. P. The effects of increased ambient temperature on dual task performance. Proceedings of the Human Factors Society, 1981, 379-383.

Carter, R. C., Kennedy, R. S., & Bittner, A. C., Jr. Grammatical reasoning: A stable performance yardstick. Human Factors, 1981, 23(5), 587-591.

Games, P. A. The ANOVR series: Analyses of repeated measures designed with optimal robust procedures when assumptions are violated. The American Statistician, 1981, 35, 109-110.

Games, P. A., Gray, G. S., Herron, W. L., & Pitz, G. F. ANOVR: Analysis of variance with repeated measures. Behavior Research Methods and Instrumentation, 1980, 112, 467.

Gibson, T. R. Effects of hypocapnia on psychomotor and intellectual performance. Aviation, Space and Environmental Medicine, 1978, 49(8), 943-946.

Glatte, H. A., Motsay, G. J., & Welch, B. E. Carbon dioxide tolerance studies. (Report No. SAM-TR-67-77), Brooks Air Force Base, Tx: U.S. Air Force, Aerospace Medicine Division (AFSC), USAF School of Aerospace Medicine, 1967, 1-22.

Gutin, B., & DiGennaro. Effect of one-minute and Five-minute step-ups on performance of simple addition. Research Quarterly, 1968, 39(1), 81-85. (a)

Gutlin, B., & DiGennaro. Effect of a treadmill run to exhaustion on performance of long addition. Research Quarterly, 1968, 39(4), 959-964. (b)

Hancock, P. A., & Milner, E. K. Mental and psychomotor task performance in an open ocean underwater environment. Research Quarterly for Exercise and Sport, 1982, 53(3), 247-251.

Henning, R. A., Sauter, S. L., Reddan, W., & Lanphier, E. H. Behavioral impairment with altered ventilatory response to CO_2. Abstracts of 67th Annual Meeting, Chicago, IL, April 10-15, 1983. Federation Proceedings: Federation of American Societies for Experimental Biology, 1983, 42(4), 1013.

Hesser, C. M., Fagraeus, L., & Adolfson, J. Roles of nitrogen, oxygen, and carbon dioxide in compressed-air narcosis. Undersea Biomedical Research, 1978, 5(4), 391-200.

Jackson, A. W., & Raven, P. B. Statistical and research design considerations concerning industrial respirator research. Journal of the International Society for Respiratory Protection, 1983, 1(2), 31-40.

Kamon, E., Doyle, D., & Kovac, J. The oxygen cost of an escape from an underground coal mine. American Industrial Hygiene Association Journal, 1983, 44, 552-555.

Kennedy, R. S., & Bittner, A. C., Jr. Progress in the analysis of a performance evaluation test for environmental research (PETER). Proceedings of the 22nd Annual Meeting of the Human Factors Society, 1978, 29-35. (NTIS No. AD A060676)

Lewis, V. J., & Baddeley, A. D. Cognitive performance, sleep quality and mood during deep oxyhelium diving. Ergonomics, 1981, 24(10), 773-793.

Logie, R. H., & Baddeley, A. D. A trimix saturation dive to 660 m: Studies of cognitive performance, mood and sleep quality. Ergonomics, 1983, 26(4), 359-374.

Moeller, G., Chattin, C., Rogers, W., Laxar, K., and Ryack, B. Performance effects with repeated exposure to the diving environment. Journal of Applied Psychology, 1981, 66(4), 502-510.

Morgan, B. B., & Alluisi, E. A. Synthetic work: Methodology for assessment of human performance. Perceptual and Motor Skills, 1972, 35, 835-845.

Morgan, W. P. Pyschological problems associated with the wear of industrial respirators. Journal of the International Society for Respiratory Protection, 1983, 1(3), 67-107.

Nunney, D. N. Fatigue, impairment, and psychomotor learning. Perceptual and Motor Skills, 1963, 16, 369-375.

Ryan, E. D. Effects of stress on motor performance and learning. Research Quarterly, 1962, 33(1), 111-119. (a)

Ryan, E. D. Retention of stabilometer and pursuit rotor skills. Research Quarterly, 1962, 33(4), 593-598. (b)

Ryan, E. D. Prerest and postrest performance on the stabilometer as a function of distribution of practice. Research Quarterly, 1965, 36(2) 197-204.

Seales, D. M., Kennedy, R. S., & Bittner, A. C., Jr. Development of performance evaluation tests for environmental research (PETER): Arithmetic computation, Perceptual and Motor Skills, 1980, 51, 1023-1031.

Sheehy, J. B., Kamon, E., & Kiser, D. Effects of carbon dioxide inhalation on psychomotor and mental performance during exercise and recovery. Human Factors, 1982, 24(5), 581-588.

Storm, W. F., & Giannetta, C. L. Effects of hypercapnia and bedrest on psychomotor performance. Aviation, Space and Environmental Medicine, 1974, 45, 431-433.

Vercruyssen, M., & Kamon, E. Behavioral effects of one-hour breathing of high concentrations of CO_2 and O_2 while doing physical work. Journal of the International Society for Respiratory Protection, in press.

Webb, W. B., & Levy, C. M. Age, sleep deprivation, and performance. Psychophysiology, 1982, 19(3), 272-276.

Wilkinson, R. T., Fox, R. H., Goldsmith, R., Hampton, I. F. G., & Lewis, H. E. Psychological and physiological responses to raised body temperature. Journal of Applied Physiology, 1964, 19 (20), 287-291.

Wilkinson, R. T., & Stretton, M. Performance after awakening at different times of night. Psychonomic Science, 1971, 23(4), 283-285.

COMPUTER TASK FOR ASSESSING THE EFFECTS OF ENVIRONMENTAL STRESSORS ON MENTAL PERFORMANCE

Max Vercruyssen and Merrill E. Noble

The Pennsylvania State University
University Park, PA 16802
U.S.A.

Presented is a research strategy for quantifying the effects of environmental stressors on mental performance and the development of a computer-operated information processing task which uses serial choice reaction time (SCRT) as the principal dependent measure. The proposed research strategy advocates the use of batteries of exploratory tests during the early phases of a research project to isolate the general type(s) of performance impaired by the stressor. In subsequent phases, it is recommended that tests be designed to investigate fundamental psychological processes by using unidimensional tasks, like the SCRT task, with multiple intra-task variables.

An environmental stressor may be any condition or aspect of a physical environment which in some way impairs human sensory or motor functions or poses a threat to personal health and safety. Examples include inhalation of toxic gases and particulates, consumption of drugs and alcohol, ambient noise, and atmospheric conditions (also see Vercruyssen, 1984; Vercruyssen & Noble, Note 1). These stressors are particularly hazardous when performance is impaired without the person being consciously aware of the presence of the stressor, the imbalance created between demands of the task and the person's response capabilities, or the degree of performance degradation.

This paper briefly discusses some research considerations in quantifying the effects of environmental stressors on human performance and then highlights the development of a computer task, based on serial choice reaction time, which may be useful as a stressor research metric. Several segments of material presented were extracted from a dissertation by Vercruyssen (1984).

QUANTIFYING THE EFFECTS OF STRESSORS

In environmental stressor experimentation, a systematic research strategy is essential. In preliminary explorations, it is suggested that one first identify a performance parameter to examine and then construct a battery of tests designed to sample many different general types of performance. If it is determined that a stressor impairs a certain type of performance, i.e., if a dependent measure from the battery of tests is found to be sensitive to the stressor, secondary exploration should focus on examining the basic processes which produce that type of performance. Understanding these basic psychological processes in turn permits definitive applied research.

Preliminary Explorations

Ascertaining the effects of environmental stressors on mental performance is often a perplexing problem. Stressors can affect performance in many different ways depending on the state of the organism, the characteristics of the stress condition, the nature of the task performed, and the experimental methodology employed (Alluisi, 1975; Vercruyssen, 1984; Welford, 1973; Wilkinson, 1969). For this reason, results in stressor research are often uninterpretable. Absence of an effect, for instance, may be due simply to characteristics of the subjects used in the study, selection of an insensitive performance task, or inappropriate experimental procedures. In other words, there might have been significant effects if another sample population, performance task, or research method had been employed. Therefore, a stressor research project should include multiple experiments and employ methods which systematically manipulate characteristics of the stressor and demands of the performance task while controlling organismic variables.

Usually stressors produce changes in one or more of four performance parameters: (1) physical work output, (2) mental performance, (3) physiological reactions, and (4) emotional reactions (Vercruyssen, Note 2). However, even when concerned with only mental performance, a major problem confronting scientists embarking on stressor research projects is identifying the general type of mental performance impaired by the stressor (e.g., memory, motor control, decision-making, perception). Alcohol in moderate doses, for instance, seems to have its greatest effects on motor control, e.g., speech, balance, coordination, and movement time. Amphetamines seem to speed movement time (MT) without having major effects on reaction time (RT); whereas, barbiturates work in reverse (Frowein, 1981). Thus, to improve ecological validity and increase the probability of identifying a particular type of performance impaired by the stressor, it has become common practice during exploratory studies for stress researchers to use a battery of performance tasks which samples distinctly different general types of performance. Scores of applied studies have explored the effects of environmental stressors using such test batteries. In fact, the most common approach taken in 97 stressor studies reviewed by Poulton (1970) was the use of test batteries which employed many different tasks. Hence, within each stressor experiment, a battery of tasks may be useful in identifying the general type(s) of performance affected by stressors.

Threshold for Emergence of Effects

Once a stressor has been shown to affect performance, it may be useful to determine threshold level which reliably produces effects. This threshold may also be viewed as the maximum safe level, above which stressor effects occur. Usually stressor research studies begin with relatively low levels of the stressor and increment the intensity from study-to-study until effects are found. Since stressor effects may not become apparent until the subject has been engaged for a long time on the task, time spent performing the task (i.e., time-on-task) may also be systematically manipulated. During the search for effects, the dependent measures also evolve and become increasingly more sensitive. Therefore, after effects are documented, and specific types of performance tasks are determined to be sensitive to the stressor, stressor levels may be gradually reduced until the effect disappears. In this way a threshold point can be established above which effects emerge.

Secondary Exploration

A major limitation of the test battery approach is that it is neither designed for, nor very capable of, making inferences about the effects of stressors on fundamental processes underlying information processing (see Frowein, 1981). Therefore, once a general type of performance impairment is discovered, a performance measure is needed to identify the underlying processes affected by the stressor. In such cases, a unidimentional approach, involving a single task, may be implemented to explore the effects of a stressor on several well-defined task variables (e.g., Frowein, 1981; Moraal, 1982; Rabbitt, 1979; Sanders, 1977, 1980, 1981, 1983; Sanders & Bunt, 1971; Sanders, Wijnen, & von Arkel, 1982; Vercruyssen, 1984). Intra-task variables place demands on and reflect activity of certain cognitive processes. The additive factors method (Sanders, 1980, 1983; Sternberg, 1969) is one means of investigating such processes (processing stages). Thus, to determine which fundamental processes are affected, use of a single task with multiple intra-task variables is recommended.

Research Strategy Applied

An example which applies the proposed research strategy task might be helpful at this point. The Ergonomics Unit at The Pennsylvania State University (PSU) has been interested in the effects of breathing a toxic gas (carbon dioxide) on cognitive and psychomotor performance. To date, five experiments have been performed over a five-year period. As previously recommended, these studies began with a battery of tasks to identify sensitive performance measures after which a single task, involving multiple intra-task factors, was developed (Sheehy, Kamon, & Kiser, 1982; Vercruyssen, 1984, Note 3; Vercruyssen & Kamon, in press, Note 4). The elevated but subclinical gas concentration and exposure durations employed in these studies were progressively increased until it was determined that choice responding was susceptible to impairment. Choice response time was the only task to be influenced by carbon dioxide (CO_2) inhalation. Tasks which produced null results at numerous stressor intensities included short-term memory (forward and backward serial recall of letters and numbers), reasoning (grammatical transformations), arithmetic problems (addition and multiplication), balance on a platform stabilometer, rotary pursuit tracking, simple reaction time, and critical flicker fusion.

Since choice response time was the only performance task found susceptible to performance degradation, subsequent research focused on response latencies and information processing. The remaining portion of this paper will be restricted to discussion of the technique used at PSU to investigate basic psychological processes affected by a stressor (CO_2). It is important to note that if the preliminary test battery approach had identified some other task, e.g., tracking, memory, or balance, as being sensitive to the stressor, an entirely different follow-up technique would have been employed.

SERIAL CHOICE RESPONDING

If it can be determined that the ability to quickly react to stimulation is impaired by exposure to an environmental stressor, information processing, as measured by serial choice responding, may be an appropriate dependent measure. Serial choice response tasks are self-paced, i.e., each stimulus is activated by the subject's previous response, and involve the repeated performance of discrete responses, e.g., pushing a button or tapping a disc, without intertrial rest intervals. The most common serial responding instrumentation employed in stress research has been the 5-Choice Task developed in England's Medical Research Council, Applied Psychology Unit, by Leonard (1959). This task was adapted from the apparatus used by Bills (1931, 1937). Alternative forms of the 5-Choice Task were also used by Broadbent (1953, 1957), Pepler (1959), and Wilkinson (1959, 1975). These tasks require the subject to tap one of five metal discs with a hand-held stylus in response to the illumination of one of five lights. Responding to one bulb darkened that bulb and illuminated another, to which the subject responds by tapping the corresponding disc, and so on. Typically, the subject works at the task continually, without rest, for 30 min, without knowledge of results (see Poulton, 1970). A series of clocks and counters provide the dependent measures. Tapping the correct disc trips the correct response counter, while tapping the wrong disc advances the error counter. A "gap" or "block" occurs if the subject failed to tap a disc within a 1.5-sec interval. A clock measured the interval between two responses and triggered a gap counter every 1.5 sec. The gap time interval was arbitrarily established, but it represents approximately twice the average inter-trial response interval. At the end of each 5-min interval, the experimenter records readings on the counters.

Employing serial performance measures, similar to the 5-Choice Task, in stressor research has several advantages which merit consideration. First, serial responding is appealing because of its long history in successfully demonstrating the effect of a multitude of stressors on performance (see Poulton, 1970). Second, serial RT tasks generate a larger number of trials per condition than discrete RT tasks and this is beneficial statistically. Where many studies report using blocks of 20 to 300 discrete RT trials collected in a 20-min session, SCRT tasks may result in as many as 2000 serial trials during this same collection interval. According to the central limit theorem, the large number of trials per condition will make the RT data more normally distributed and, therefore, better suited for analysis of variance tests than discrete data with a relatively small number of trials, and positively skewed RT distributions. Third, since responding continues without rest breaks, there is no time to recover from or compensate for the effects of the stressor, which places additional demands on the information processing system. Length of the response-stimulus interval is important since, there may be sufficient recovery time between discrete trials to counteract the effects of the stressor. Finally, serial responding samples performance over the entire testing session. Where discrete measures represent activity taking place in about 10% of the data collection period, serial measures (RT & MT) account for nearly 100% of the subject's activity during this period. This capability becomes especially valuable when exploring the effects of a stress relative to time-on-task and duration of exposure.

SCRT COMPUTER TASK

All serial responding tasks function essentially the same with regard to stimulus delivery, however, recent systems deviate considerably from the original 5-Choice Task description in that they are capable of digital storage of responses. Computer assistance has permitted automated data collection and the recording of considerably more detailed information about the responses, which in turn has provided greater methodological capabilities.

The use of computers and digital storage devices for psychological data collection is not a new idea (e.g., Doorne & Sanders, 1968; Houghton & Wilkinson, 1973, 1982; Kvalseth & Mohn, 1983; White et al., 1980; Wilkinson, 1975; Wilkinson & Houghton, 1975, 1982). Neither is the use of serial choice responding a recent discovery (e.g., Bills, 1931, 1973; Leonard, 1959; Wilkinson, 1959). However, it has only been in recent years that computer-driven serial responding systems have been used in environmental stressor research (e.g., Ellis, 1982; Fowler, White, Wright, & Ackles, 1982; Frowein & Sanders, 1978; Vercruyssen, 1984). Doorne and Sanders (1968) developed one of the first computer-assisted reaction time systems capable of a variety of applications, including serial responding. Their Digital Equipment Corporation (DEC) PDP 7 computer-supported system was named PSARP--Programmable Signal and Response Processor. Wilkinson and Houghton (1975; also Wilkinson, 1975) converted a cassette tape recorder into a portable four-choice serial reaction time testing unit for field testing. White et al. (1980) developed a serial choice reaction timer which used a DEC PDP 11/04 computer. Using a DEC PDP 11 computer, an All-Purpose Experimental System--APES--was created by Ternes, Ehrman and O'Brien (1982) for behavioral pharmacology studies. These are only a few of the computer-based SCRT systems which have evolved from Leonard's 5-Choice Task.

The PSU SCRT Apparatus

The SCRT apparatus developed at The Pennsylvania State University was intended to quantify the rate and quality of information processing in human subjects during exposure to various environmental stressors. Connected to the real-time clock on any DEC PDP11 computer, this 4-key SCRT apparatus serially presents stimuli--a digit in a light emitting diode (LED) display--and collects several descriptive measures of information processing behavior. To be more specific, for each response, information stored on disk for subsequent analysis includes response latencies (reaction, movement and response times) and elapsed time, as well as measures of response rate (total number of trials performed) and accuracy (stimulus LED presented, response key struck, and error status of trial). Reaction time, in this case, refers to the interval from the onset of a stimulus to the initiation of a response. Movement time is measured from the initiation of a response to its completion. Response time is the sum of RT and MT. Elapsed time begins with the first stimulus in an experimental session and ends with the last response.

The PSU SCRT apparatus was constucted in such a way as to permit collection of simple, discrete choice, or serial reaction/response times, with all latencies accurate to 1 msec. It was also designed to permit manipulations of such intra-task factors as stimulus intensity, stimulus degradation, stimulus-response compatibility, number of stimulus and response alternatives, response and stimulus probabilities, movement amplitude and duration, and response-stimulus or stimulus-stimulus intervals. In all cases, entire testing sessions can be programmed and data collection is fully automated (on-line). Further details of this SCRT apparatus are available elsewhere (Vercruyssen, Deno, & Brennan, Note 5).

Recently, this SCRT computer task was used to examine fundamental processes and determine which of two stages of information processing were affected by breathing CO_2 (Vercruyssen, 1984).

This research determined that the inhalation of CO_2 severely impairs the rate of information processing. By manipulating such intra-task variables as stimulus degradation and stimulus-response compatibility, it was also determined that the locus of this effect is in the response selection stage of processing, rather than an early, encoding stage.

There are no panacreas available for stress research scientists. However, the research strategy and SCRT apparatus herein described was helpful in quantifying the effects of carbon dioxide on mental performance and may have utility in other applications as well.

CONCLUSIONS

Environmental stressor research should begin by employing multiple experiments, each with several different tasks, to determine the stressor's influence on various general types of performance. If response latencies are susceptible to impairment, computer-assisted SCRT tasks may be useful in assessing the effects of such stressors on basic cognitive processes.

ACKNOWLEDGMENTS

The SCRT task evolved from the cooperative efforts of the Ergonomics Unit of the Laboratory for Human Performance Research, Department of Psychology, and Motor Behavior Laboratory at The Pennsylvania State University. Funding was provided by the U.S. Department of the Interior, Bureau of Mines Contract No. JO-100092 (Eliezer Kamon, Principal Investigator). The SCRT apparatus design and computer interface was developed by bioengineers, N. S. Deno and T. J. Brennan, with assistance from C. F. Ryan. Appreciation is extended to R. W. Christina and M. Harada for their theoretical contributions, and to B. Nilson, the typist.

REFERENCES

Reference Notes

1 Vercruyssen, M., & Noble, M.E. Factors influencing perceptual and psychomotor performance: Effects of environmental stressors. In: J.M. Shemick (Ed.), 1984 American Council of Industrial Arts Teachers in Education Yearbook. Chapter in preparation, The Pennsylvania State University.

2 Vercruyssen, M. Multi-stressor research. In: E. Kamon, N.S. Deno, & M. Vercruyssen, Physiological Responses of Miners to Emergencies. Research continuation proposal for the U.S. Department of the Interior, Bureau of Mines, Contract No. JO-100092, Manuscript in review, The Pennsylvania State University, 1983.

3 Vercruyssen, M. Breathing 3-4% CO_2: Behavioral effects. In: E. Kamon, N.S. Deno, & M. Vercruyssen, Physiological Response of Miners to Emergencies. U.S. Department of Interior, Bureau of Mines, End of contract report (No. JO-100092). In preparation, The Pennsylvania State University.

4 Vercruyssen, M., & Kamon, E. Behavioral effects of breathing 3% and 4% carbon dioxide, during and following physical work. Appears elsewhere in these Proceedings.

5 Vercruyssen, M., Deno, N.S., & Brennan, T.J. A human performance assessment system for stress research. Manuscript in preparation, The Pennsylvania State University.

Published References

Alluisi, E.A. Optimum uses of psychobiological sensorimotor, and performance measurement strategies. Human Factors, 1975, 17(4), 309-320.

Bills, A.G. Blocking: A new principle in mental fatigue. American Journal of Psychology, 1931, 43, 230-245.

Bills, A.G. Blocking in mental fatigue and anoxemia compared. Journal of Experimental Psychology, 1937, 10, 437-452.

Broadbent, D.E. Noise, paced performance and vigilance tasks. British Journal of Psychology, 1953, 44, 295-303.

Broadbent, D.E. Effects of noises of high and low frequency on behaviour. Ergonomics, 1957, 1, 21-29.

Doorne, H.V., & Sanders, A.F. PSARP, a programmable signal and response processor. Behavior Research Methods & Instrumentation, 1968, 1, 29-32.

Ellis, H.D. The effects of cold on the performance of serial choice reaction time and various discrete tasks. Human Factors, 1982, 24(5), 589-598.

Fowler, B., White, P.L., Wright, G.R., & Ackles, K.N. The effects of hypoxia on serial response time. Ergonomics, 1982, 25(3), 189-201.

Frowein, H.W. Selective drug effects on information processing. Thesis for doctor in de sociale wetenschappen (Ph.D. in Social Sciences), at de Katholieke Hogeschool (Catholic High School, a university), Tilburg, The Netherlands. Druk: Sneldruck Boulevard Enschede, 4 September 1981.

Frowein, H.W., & Sanders, A.F. Effects of amphetamine and barbiturate in a serial reaction task under paced and self-paced conditions. Acta Psychologica, 1978, 42, 263-276.

Houghton, D., & Wilkinson, R.T. Miniature reaction timer with memory. Behavior Research Methods & Instrumentation, 1973, 5(3), 273-276.

Houghton, D., & Wilkinson, R.T. Microreaction timer. Behavior Research Methods & Instrumentation, 1982, 14(5), 455-458.

Kvalseth, T.O., & Mohn, S.W. Digitech: a microcomputer-digitizer facility for automated testing of motor performance during discrete positioning movements. Ergonomics, 1983, 26(4), 401-407.

Leonard, J.A. Five choice serial reaction apparatus. Cambridge, England: Medical Research Council, MRC Applied Psychology Unit Report 326, 1959.

Moraal, J. Age and information processing. Proceedings of the Human Factors Society, 1982, 184-188.

Pepler, R.D. Warmth and lack of sleep: Accuracy or activity reduced? Journal of Comparative and Physiological Psychology, 1959, 52, 446-450.

Poulton, E.C. Environment and human efficiency. Springfield, IL: Charles C. Thomas, Publisher, 1970.

Rabbitt, P. Current paradigms and models in human information processing. In: V. Hamilton & D.M. Warburton (eds.), Human Stress and Cognition. Chicester: Wiley 1979, 115-140.

Sanders, A.F. Structural and functional aspects of the reaction process. In: S. Dornic (ed.), Attention and Performance VI, Hillsdale: Erlbaum, 1977, 3-25.

Sanders, A.F. Stage analysis of reaction processes. In: G. Stelmach & J. Requin (eds.), Tutorials on Motor Behavior. Amsterdam: North Holland, 1980.

Sanders, A.F. Stress and human performance: A working model and some applications. In: G. Salvendi & M.J. Smith (eds.), Machine Pacing and Occupational Stress. London: Taylor and Francis, 1981.

Sanders, A.F. Toward a model of stress and human performance. Acta Psychologica, 1983, 53, 61-97.

Sanders, A.F., & Bunt, A.A. Some remarks on the effect of drugs, lack of sleep, and loud noise on human performance. Nederlands Tijdschrift voor Psychologie, 1971, 26, 670-684.

Sanders, A.F., Wijnen, J.L.C., & von Arkel, A.E. An additive factor analysis of the effects of sleep loss on reaction processes. Acta Psychologica, 1982, 51, 41-59.

Sheehy, J.B., Kamon, E., & Kiser, D. Effects of carbon dioxide inhalation on psychomotor and mental performance during exercise and recovery. Human Factors, 1982, 24(5), 581-588.

Sternberg, S. The discovery of processing stages: Extensions of Donders' method. Acta Psychologica, 1969, 30, 276-315.

Ternes, J.W., Ehrman, R., & O'Brien, C.P. A software system for real-time control of psychological experiments. Behavior Research Methods & Instrumentation, 1982, 14(2), 160-164

Vercruyssen, M. Carbon dioxide and information processing: Effects of an environmental stressor on cognition. Dissertation for Ph.D., College of Health, Physical Education, and Recreation, University Park, PA: The Pennsylvania State University, May 1984.

Vercruyssen, M., & Kamon, E. Behavioral effects of one-hour breathing of high concentrations of CO_2 and O_2 while doing physical work. Journal of the International Society for Respiratory Protection, in press.

Welford, A.T. Stress and performance. Ergonomics, 1973, 16(5), 567-580.

White, P.L., Fowler, B.H., Sweeney, D.M., Chillcott, G.T., Wright, G.R., Eastman, D.E., Ackles, K.N., & Holness, D.E. The DCIEM "on line" serial choice reaction timer (SCRT). Defence and Civil Institute of Environmental Medicine Report No. 80-R-17, Department of National Defence, Ottawa, Canada, March 1980.

Wilkinson, R.T. Rest pauses in a task affected by lack of sleep. Ergonomics, 1959, 2, 373-380.

Wilkinson, R.T. Some factors influencing the effect of environmental stressors upon performance. Psychological Bulletin, 1969, 72, 260-272.

Wilkinson, R.T. Performance under stress. Proceedings of the Royal Society of Medicine, 1975, 68(7), 425-427 (Section of Comparative Medicine, 23-25).

Wilkinson, R.T., & Houghton, D. Portable four-choice reaction time test with magnetic tape memory. Behavior Research Methods & Instrumentation, 1975, 7(5), 441-446.

Wilkinson, R.T., & Houghton, D. Field test of arousal: A portable reaction timer with data storage. Human Factors, 1982, 24(4), 487-493.

APPENDIX B6: Dissertation Abstract

CARBON DIOXIDE INHALATION AND INFORMATION PROCESSING: EFFECTS OF AN ENVIRONMENTAL STRESSOR ON COGNITION

Max Vercruyssen

This experiment was undertaken to determine whether breathing carbon dioxide (CO_2) a toxic environmental stressor, slows information processing and, if it does, whether the locus of this effect is in the encoding or response selection stage, or both. In a 2 X 2 X 2 X 4 (Gas X Degradation X Compatibility X Time-on-Task) within-subjects design, six highly practiced (more than 10,000 trials) healthy young male subjects performed a serial choice reaction time (SCRT) task while breathing either 4% CO_2 or room air (0.03% CO_2). Task variables manipulated were stimulus degradation (intact vs. degraded) and stimulus-response compatibility (high vs. low). Data from each 20-min SCRT test were subdivided into four 5-min intervals to determine the effects of time-on-task.

Unidirectional t-tests obtained from analyses of variance on the means of correct SCRT trials revealed significant increases in SCRT from breathing CO_2 ($p = .004$), degrading the stimulus ($p < .001$), lowering compatibility ($p = .004$), and increasing time-on-task ($p = .020$). Lowering compatibility served to exaggerate the impairment produced by CO_2 inhalation ($p = .038$). Time-on-task, however, did not interact with gas, degradation, or compatibility. According to the logic of the Additive Factors Method (Sternberg, 1969), these findings support the following conclusions: (1) breathing 4% CO_2 slows information processing, (2) the locus of this effect is associated with the response selection stage of processing, and (3) the progressive deterioration in performance due to increases in time-on-task affects both the encoding and response selection stages in a similar manner.

Serial Choice Reaction Time, analyzed according to the Additive Factors Method, was sensitive to the degrading effects of breathing CO_2 and the procedures employed in this experiment were useful in determining the effects of this environmental stressor on two stages of information processing. This same methodology may be also appropriate for investigating the effects of other stressors on tasks which involve the processing of information via linear stages.

NOTE: For complete details of this study, see the dissertation:

Vercruyssen, M. (1984). Carbon dioxide inhalation and information processing: Effects of an enviromental stressor on cognition. Doctoral dissertation, College of HPER, The Pennsylvania State University, University Park, PA.

APPENDIX C1:

POSITIVE PRESSURE BREATHING

Introduction

Current interest in PPB is due to its growing application to emergency respirators as used by miners and rescue workers. A major advantage of a positive pressure air supply is the exclusion of toxic gases that are sometimes present in the workers' immediate environment. Any air leaks around the facemask are forced to flow outwards, preventing the entry of environmental gases.

However, currently available respirators cannot maintain the positive pressure under conditions of moderate to high ventilatory demand, as occurs during heavy physical labor. In these situations, the worker risks exposure to toxic gases when the mask pressure goes negative during inspiration. To maintain positive pressure under all conditions the respirators must operate at a higher average pressure, or be designed with less internal flow resistance. While reducing the flow resistance is strictly a design problem, increasing the pressure presents potential physiological problems.

The general response among unanesthetized resting humans is for PPB to cause an increase in tidal volume (VT) and minute ventilation (VE), and a decrease in stroke volume (SV) and cardiac output (Q). When exercise is introduced as an added input, the picture is even more complex. Only Bjurstedt, Rosenhamer, Lindborg, and Hesser (1979) and Kiser (1982) have examined PPB effects during exercise. These researchers generally found that the PPB effects noted at rest, are diminished, but not eliminated, by bicycle exercise at 50%VO2 max.

The purpose of this study was to evaluate the effects on ventilation and oxygen consumption from PPB. These parameters were analyzed in terms of steady-state and transient characteristics.

Method

Subjects

Six males, age 22 to 34, participated as paid volunteer subjects. Each was medically screened, receiving a physical examination, resting 12-lead electrocardiogram, pulmonary function test, and a graded exercise tolerance test. As determined by testing in the Ergonomics Lab with a protocol describe later, maximal oxygen uptake ranged from 49.5 to 74.8 mlO2 min-1 kg-1, Five were engaged in regular aerobic training. Physical data of the subjects are presented in Table C1-1.

Table C1-1. Physical Characteristics of the Subjects

Subject	Age (yrs)	Height (cm)	Weight (kg)	VO2max ml02 min-1 kg-1
A	22	184	72.6	74.8
B	22	180	70.2	50.3
C	22	187	73.2	57.5
D	24	190	77.5	62.5
E	34	172	60.2	52.5
F	24	178	72.7	49.5
$\bar{X}$	25	182	71.0	57.8
SD	5	6	5.8	9.6

$\bar{X}$ = Mean
SD = Standard Deviation

Pressurization System

Figure C1-1 shows a schematic diagram of the pressurization system. Pressure level was controlled by adjusting the blower speed and the flow resistance at the air dump port. As measured by a water column manometer, the desired pressure level could be set to within 0.2 cmH2O under zero flow conditions. Flow through the manifold from the blower inlet to the dump port was sufficient to prevent recirculation of expired gas to the inspired line.

Because of flow resistance through the air lines, pressure fluctuated at the mouthpiece over each breathing cycle. Large balloons of about 900 liters, acting as capacitance elements, helped stabilize mouthpiece pressures.

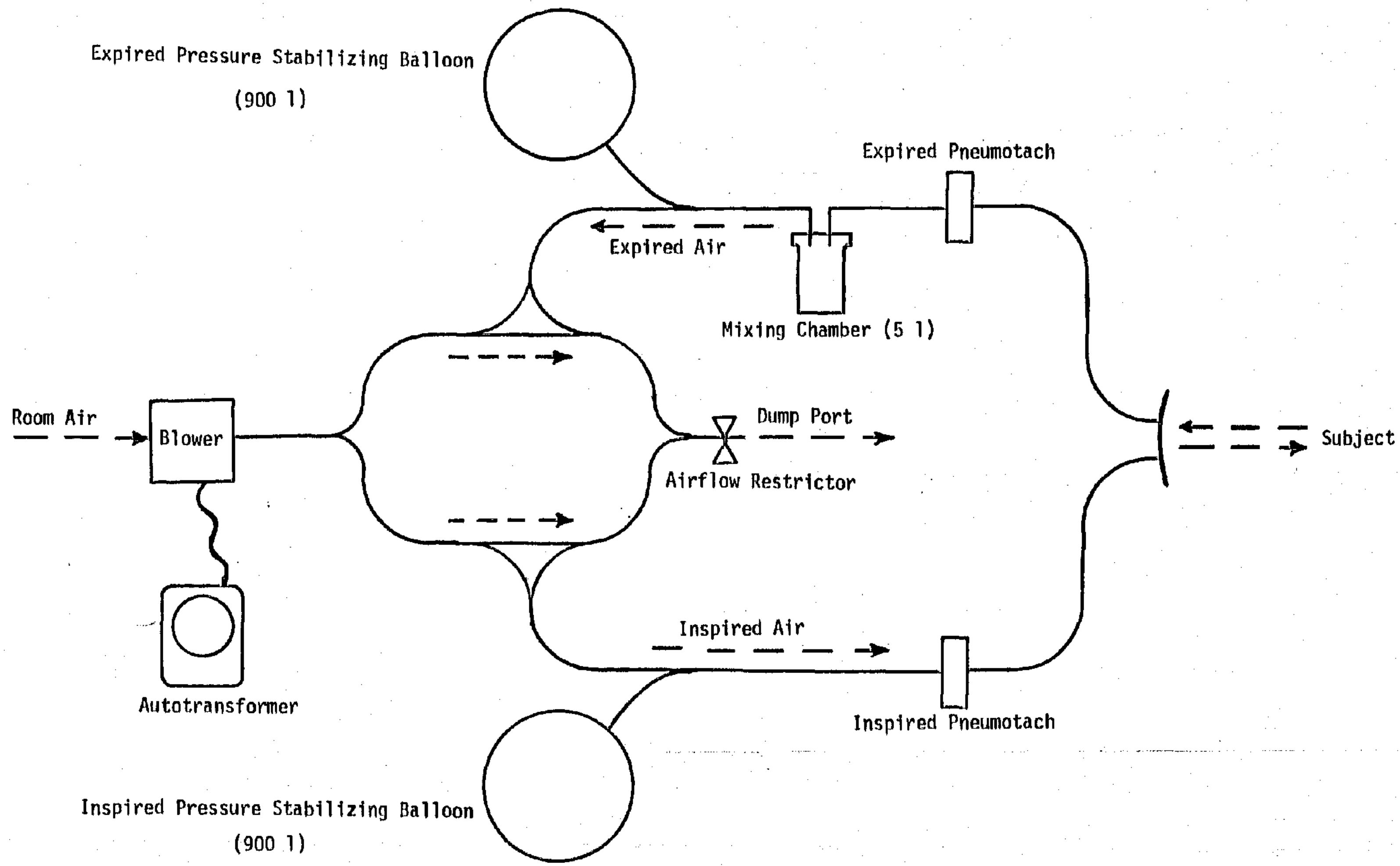

Figure C1-1 Pressurization System

At VE's of 28, 82, and 125 l*min-1, mouthpiece pressure fluctuation was 2, 4, and 7 cmH2O respectively, independent of average system pressure. Thus at 8 and 16 cmH2O average pressure, mouthpiece pressure never became negative. Pressure of the mixing chamber, from which gas was drawn for analysis, was very stable. At a VE of 90 l*min-1, mixing chamber pressure fluctuation was less than 0.75 cmH2O.

Data Collection System

Tidal volume was determined by computer integration of the flow signal over inspiration and expiration. Fleish No.2 Pneumotachographs (pneumotachs) were mounted in the inspiratory and expiratory air lines to measure instantaneous flow.

Gas analysis was continuous, with the gas sampling from a 5 liter mixing chamber, located downstream from the expired pneumotach.

Procedures

Each subject came to the lab for a familarization session. Electrodes for heart rate were attached and each of the experimental conditions that would later be tested was experienced for several minutes, except the maximal aerobic exercise condition. At each of the execise intensities the pressure was varied from 0 to 16 cmH2O.

Maximal testing is done in three trials, with at least two days between trials. Maximum oxygen uptake was measured at pressure levels of 0 (control), 8, and 16 cmH2O. Increasing pressure levels were used rather than randomization to maximize protection for the subjects. If any problem was encountered at 8 cmH2O, the 16 cmH2O trial would have been cancelled.

A submaximal exercise protocol was used. Each subject ran a total of six submaximal trials, with at least one rest day between trials. Two trials were run at each pressure level. In one trial the subject recovered from running exercise (80% VO2max) while walking (25% VO2max). In the other trial, the subject recovered while standing stationary. In the case of standing recovery, the treadmill was stopped abruptly at the end of the running interval. For the walking recovery, the treadmill was slowed as quickly as possible, the deceleration taking about 20 seconds.

Data Analysis

Maximal Performance. During each trial, the computer averaged and printed data over 30-second intervals. After the trial, all variables were averaged over two consecutive intervals in which VO2 was the highest. If VO2 values were stable for three intervals, then three intervals were averaged. Multiple dependent t-tests were performed between each pressure level for each variable. To maximize the chance of observing any adverse effect at maximum, family-wise error rate was not controlled.

Submaximal Performance. Averages were calculated for each variable over the last 5-minutes of each of the initial 10 minutes standing and walking intervals. That is, standing was averaged from minute 5.0 to 10.0, and walking was averaged from minute 15.0 to 20.0. Because steady state was only being approached towards the end of the 5 minute running interval, a linear regression was run on each variable from minute 23.0 to 25.0. A regression predicted value at the end of minute 24 was used as the steady state value.

For each variable, the steady state values were analysed by a repeated measures three-factor (pressure, exercise intensity, trial) AOV.

Results

Results will be presented in several sections: maximal performance, submaximal steady state, and prerunning-postrunning comparison.

Maximum Performance

No significant difference between any pressure levels was found for any variable. Because of the natural progression in exercise intensity and the lack of significance, data are presented in the appropriate tables in the following section with submaximal steady state data.

Trends though were seen in fb and VT. Between control and 16 cmH2O, fb declined from 52.0 to 49.0 bpm (breaths per minute). Between control and 8 and 16 cmH2O, group mean VT's increased from 2.19 to 2.29 and 2.34 liters, respectively. Rather than reinforcing, the trends in fb and VT were offsetting, so no changes due to pressure were seen in VE. Data are presented in the following section.

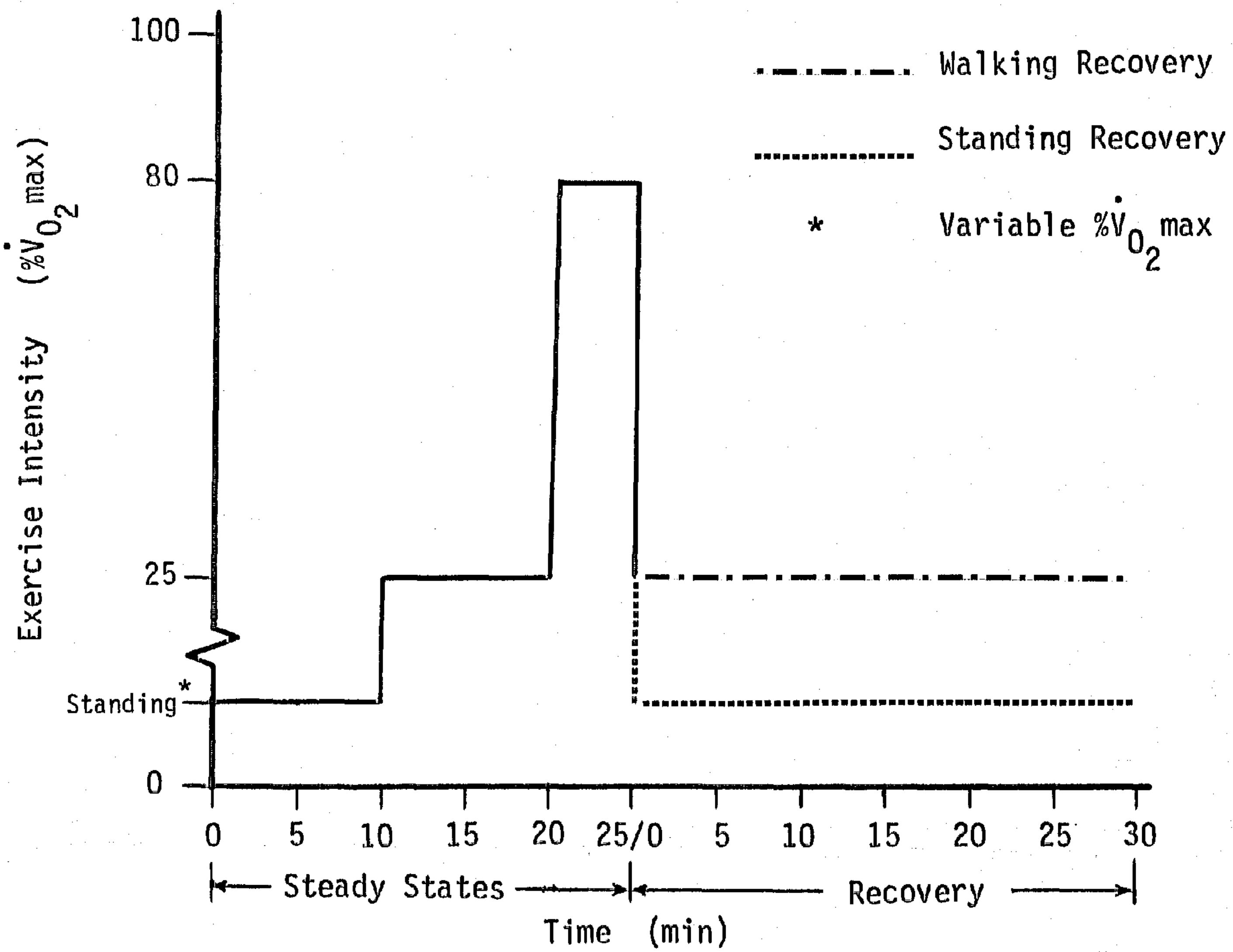

Figure C1-2 Submaximal Protocols

Submaximal Steady State

Each variable will be considered in turn. Significant effects due to pressure or interaction of pressure and intensity will be noted. Variables with significant effects will be presented in Figures and Tables.

Respiration Rate

No significant pressure main effects or interactions were found, and hence no follow-up tests were conducted. Data are presented in Table C1-2.

Tidal Volume

A highly significant ($p < .001$) interaction of pressure and intensity was noted. Pressure effects were analyzed at each level of exercise independently (simple effects follow-up). Data are presented in Table C1-3 and Figure C1-3. Significant increases were noted only in the standing exercise intensity. But VT showed a trend increase in the running and maximum intensities. Examination of Figure C1-3 suggests that the interaction occurs primarily at the walking conditions.

Table C1-2. Respiration Rate (breaths per min).
Group Means and Standard Deviations for each Exercise Intensity and Pressure Level (cmH2O).

Exercise Intensity	Pressure 0	8	16
Maximum	52.0 ± 8.5	50.8 ± 7.7	49.0 ± 8.8 p0 < .10
Running	41.7 ± 7.5	40.6 ± 7.7	40.8 ± 7.9
Walking	25.3 ± 5.5	26.8 ± 7.0	26.6 ± 7.8
Standing	18.6 ± 3.8	17.8 ± 4.2	18.5 ± 4.9

When listed, p0 is probability of difference from 0 cmH2O. p8 is probability of difference from 8 cmH2O. No listed probability indicates no significance (p < .05) and no trend (p < .10).

Table C1-3. Tidal Volume (liters).
Group Means and Standard Deviations for each Exercise Intensity and Pressure Level (cmH2O).

Exercise Intensity	Pressure 0	8	16
Maximum	2.19 ± .20	2.29 ± .24 p0 < .10	2.34 ± .27 p0 < .10
Running	1.79 ± .28	1.86 ± .30 p0 = .069	1.92 ± .31 p0 = .072 p8 = .098
Walking	.93 ± .18	.94 ± .23	1.01 ± .26
Standing	.55 ± .07	.70 ± .21 p0 = .039	.86 ± .30 p0 = .031 p8 = .024

When listed, p0 is probability of difference from 0 cmH2O. p8 is probability of difference from 8 cmH2O. No listed probability indicates no significance (p < .05) and no trend (p < .10).

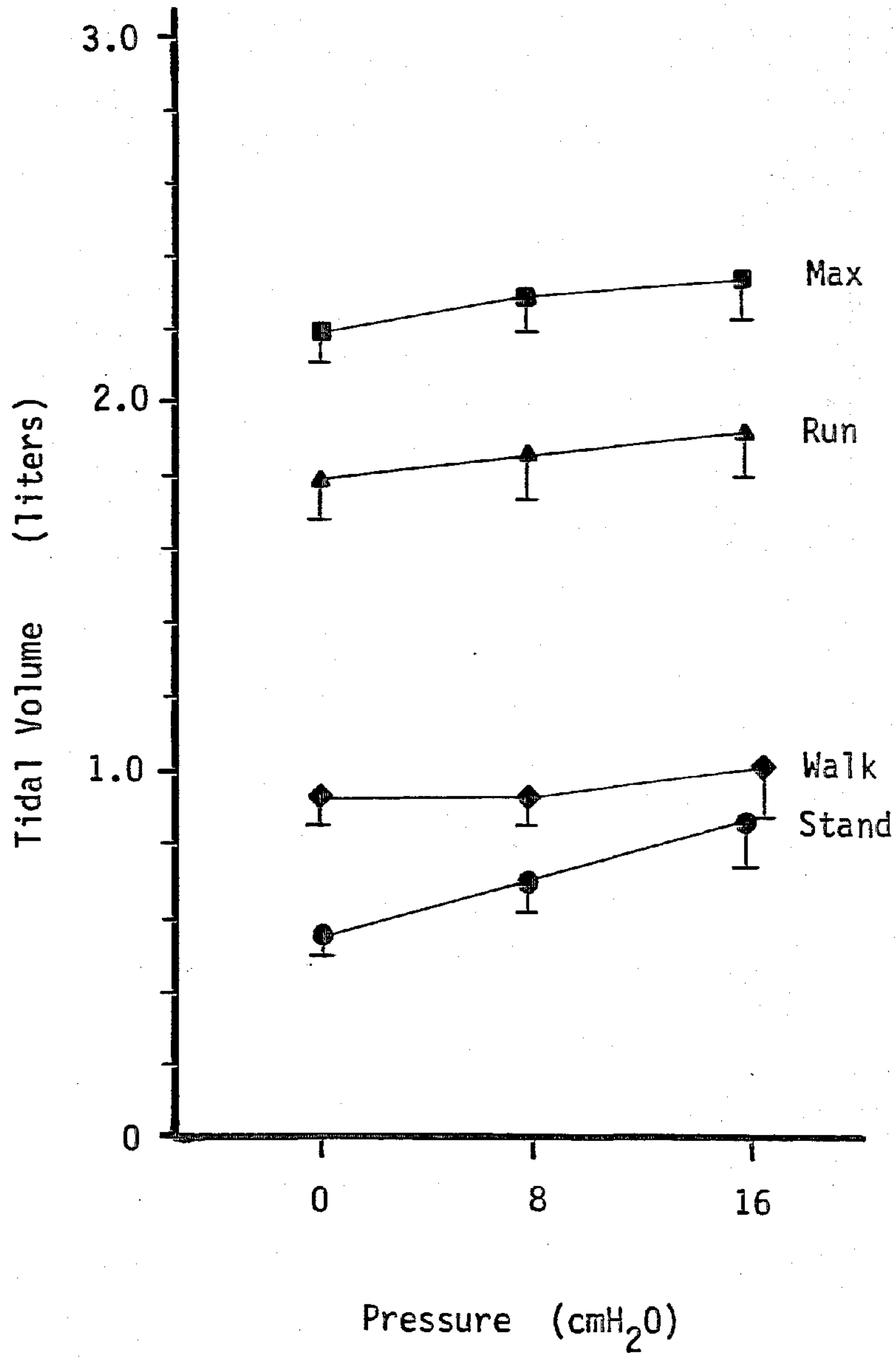

Figure C1-3 Steady State Tidal Volumes (liters) at Each Exercise Intensity and Pressure.

Minute Ventilation

A very significant ($p = .002$) pressure main effect was found, with no significant interaction of pressure and intensity. Data were combined over all submaximal intensities, and main effects follow-up indicated a significant increase in ventilation between 0 and 16 cmH2O, and between 8 and 16 cmH2O, but not between 0 and 8 cmH2O. Data are presented in Table C1-4 and Figure C1-4.

Oxygen Uptake and Carbon Dioxide Elimination

No significant effects were seen in either VO2 or in VCO2.

Table C1-4. Minute Ventilation (liters per min). Group Means and Standard Deviations for each Exercise Intensity and Pressure Level (cmH2O).

Exercise Intensity	Pressure 0	Pressure 8	Pressure 16
Maximum	113.3 ± 20.3	115.6 ± 16.3	113.7 ± 15.2
Running	74.5 ± 16.4	74.4 ± 17.0	77.1 ± 16.3
Walking	23.0 ± 4.1	24.1 ± 5.1	25.8 ± 4.6
Standing	10.0 ± 1.4	12.5 ± 1.4	15.0 ± 3.5
Combined Submaximum	35.8	37.2	39.3 p0 < .001 p8 = .046

When listed, p0 is probability of difference from 0 cmH2O. p8 is probability of difference from 8 cmH2O. No listed probability indicates no significance ($p < .05$) and no trend ($p < .10$).

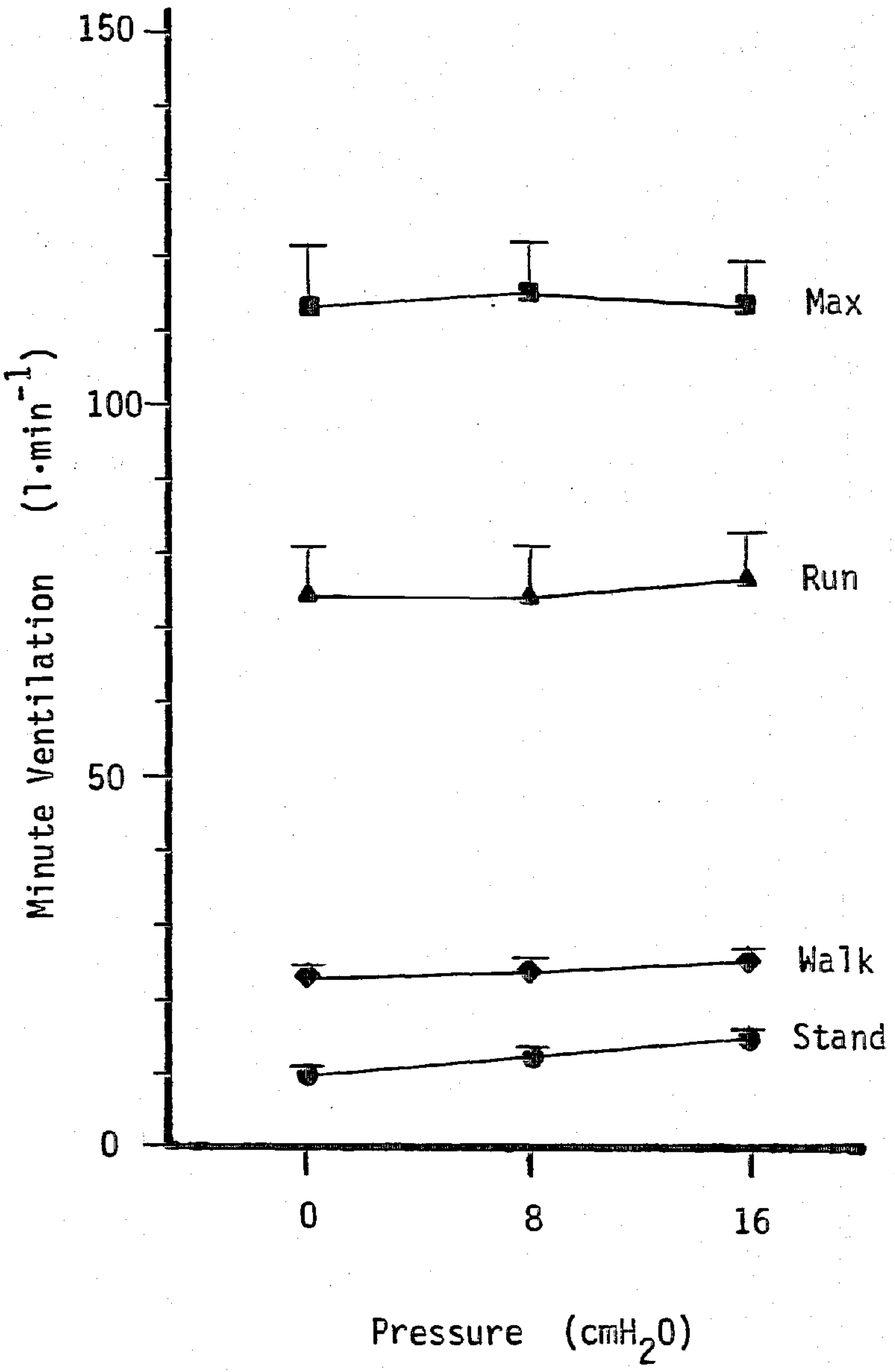

Figure C1-4 Steady State Minute Ventilation ($l \cdot min^{-1}$) at Each Exercise Intensity and Pressure.

Respiratory Exchange Ratio

Despite the lack of significance in VO2 and VCO2, R showed a very significant ($p = .002$) interaction of pressure and intensity. Data are presented in Table C1-5. Figure C1-5 clearly indicates the strong interaction. The only significant pressure effect occurs under the resting condition.

Table C1-5. Respiratory Exchange Ratio.
Group Means and Standard Deviations for each Exercise Intensity and Pressure Level (cmH2O).

Exercise Intensity	Pressure 0	8	16
Maximum	1.12 ± .04	1.10 ± .06	1.09 ± .05
Running	1.03 ± .06	1.04 ± .05	1.04 ± .07
Walking	.91 ± .05	.92 ± .05	.91 ± .04
Standing	.89 ± .06	.95 ± .08 p0 = .035	.99 ± .10 p0 = .005 p8 = .083

When listed, p0 is probability of difference from 0 cmH2O. p8 is probability of difference from 8 cmH2O. No listed probability indicates no significance ($p < .05$) and no trend ($p < .10$).

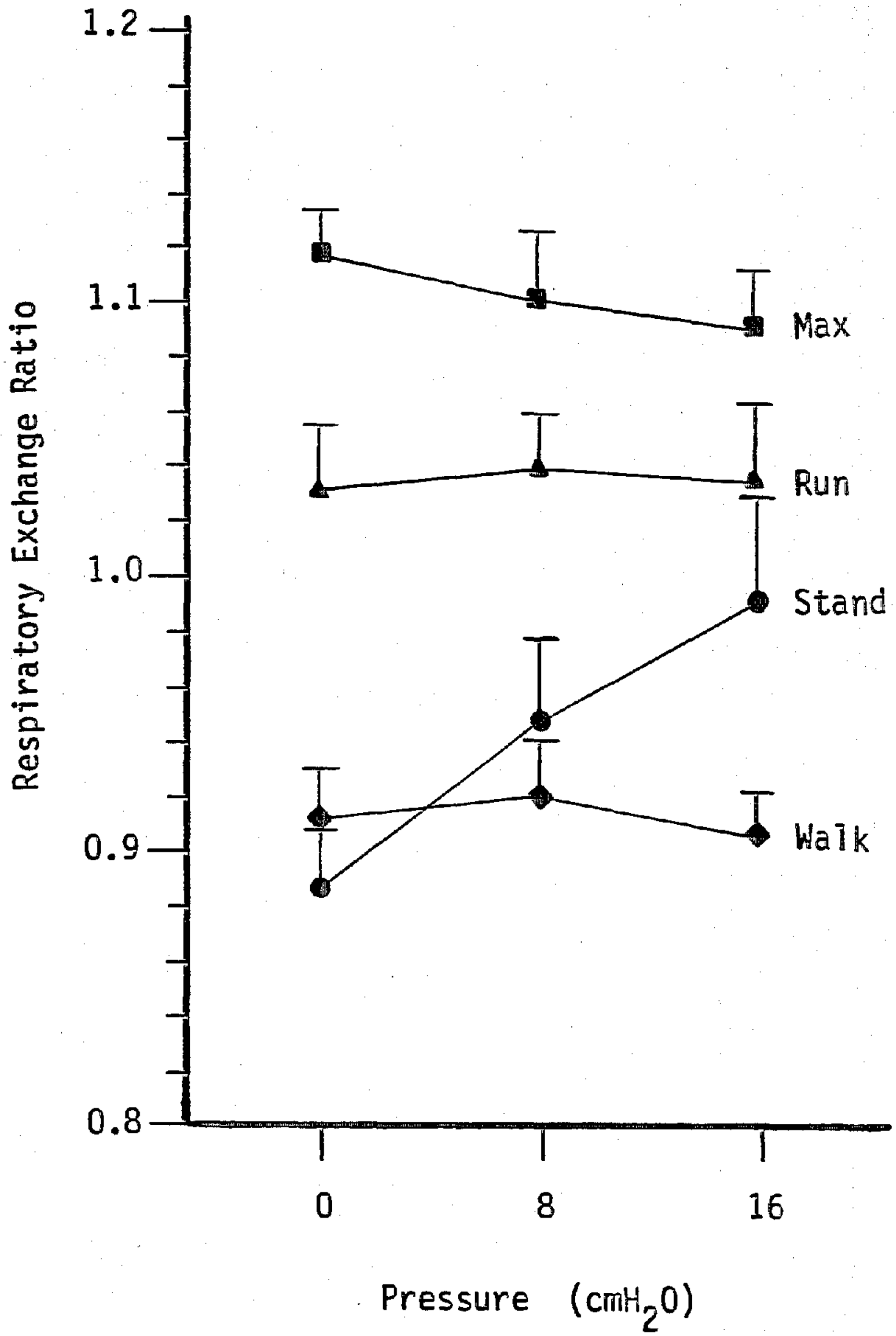

Figure C1-5 Respiratory Exchange Ratios at Each Exercise Intensity and Pressure

Discussion

Maximum Performance

The only effects, due to PPB, were a trend decrease in fb and a trend increase in VT. The VT increase is further supported by similar increases seen at the submaximal intensities. While fb and VT each change, the effects are cancelling, so that VE at maximum is unchanged, and the possibility exists for the maintainance of normal VO2max.

More importantly, no decrement was actually measured in VO2max, or VCO2max, under PPB. The slightly (less than 5%) increase in VO2max was nonsignificant ($p > .10$).

That no effect is observed is indicative that any circulatory impairments existing at lower intensities are eliminated when running at maximum, or that they are at least non-limiting in their performance effect (Saltin and Rowell, 1980). Likewise, any possible changes in pulmonary function are shown to be non-limiting. As described before, at high ventilation, mouthpiece pressure fluctuated because of flow resistance. If abdominal pumping during breathing supports Q by causing a cyclic decrease in the venous return pressure gradient (Cruz et al., 1967; Vuori et al., 1979), this periodic breathing pressure fluctuation may also help support Q in a similar manner.

Submaximum Performance

Prerunning-Postrunning. No significant difference in responses of VT, VE or R due to PPB was found when the same exercise conditions were compared before and after the running interval. This indicates that during a given trial, the subjects, as a group, responded consistently to the PPB at walking or resting intensities despite intervening high intensity exercise. Other variables, fb, VO2, and VCO2, which were nonsignificant in the steady state, were not compared pre- and post- running.

Steady State

The significant effects of PPB can best been seen by considering together fb, VT, VE, and R. The prime indicator is R. At standing rest, R increases linearly and significantly from 0 to 16 cmH2O (Figure C1-5). This increase is indicative of PPB induced hyperventilation. At walking and running intensities, R is unchanged by pressure, indicating proper alveolar ventilation.

However, VE is significantly elevated by PPB at all submaximum intensities (Table C1-4 and Figure C1-4). Also, VT (Table C1-3 and Figure C1-3) shows an increase at standing, walking, running, and maximum (trend level at running and maximum). The fb is virtually constant in response to PPB, so VE increases are almost entirely caused by VT increases. Because R indicates proper alveolar ventilation at intensities above resting, the increased ventilation must be accounted for by deadspace. Kiser (1982) reported that 16 cmH2O PPB increased physiological deadspace 70 ml at rest, and 50 ml at 50% VO2max. Except for the resting conditions, average submaximal VT increase in this study is about 100 ml at 16 cmH2O. Considering the different subject samples and measurement errors, this is reasonably good agreement.

The lack of PPB effects on VO2 and VCO2 and on R, at intensities above resting, are very encouraging from respirator applications viewpoint. No impairment of working capacity should be anticipated at pressures up to 16 cmH2O.

APPENDIX D1:

EFFECTS OF HOT INHALED AIR

Introduction

This experiment was undertaken in order to study the effects of inspiring air with elevated wet bulb temperatures on tissue temperatures of the tongue and hard palate. Many breathing devices used in escape or rescue situations create air which is very hot and almost completely saturated with water vapor during the process of scrubbing CO2 out of the expired air. Under these hot and humid conditions the tissues of the upper respiratory tract are no longer able to rely on evaporation as a device to dissipate heat. In addition, the latent heat of hot air saturated with water vapor is much greater than the heat energy contained in hot, dry air. In practical terms, these factors point towards a need for a better understanding of the respiratory heat gain that will occur when using a self-contained breathing apparatus (SCBA) for protection against burns of the mouth which may jeopardize a worker's life in an emergency situation. Previous work in the Ergonomics Unit of the Laboratory for Human Performance Research has investigated the effects of inhaling dry hot air. The present investigation was undertaken to study the additional thermal stresses created when hot inspired air is saturated with water vapor.

Both the humidity and the temperature of inspired gas have an important effect on the SCBA wearer's comfort and ability to perform heavy work, particularly in unfavorable environments. The water vapor content is by far more important because of the relatively large thermal exchanges involved in the evaporative process in the respiratory tract. Rapid changes of air temperature take place within a short distance in the upper respiratory tract. The resultant heat exchange when cool, reasonably dry air is breathed is small but becomes increasingly important in hot and humid environments. When the inspired air exceeds body temperature and is saturated with water vapor there is a net gain of heat by the respiratory tract (Hartwell and Senneck, 1956).

According to results obtained by McCutchan and Taylor (1951), wet bulb temperatures below 35.2 degrees Centigrade should not cause a respiratory heat gain, while wet bulb temperatures above this level should cause a gain of heat to the respiratory tract. However, this study dealt with low relative humidity conditions when inspiring hot air and their findings may not be applicable to high humidity conditions. When breathing hot dry air, the ability of the respiratory tract to dissipate the heat presented to it is extremely effective. Increasing the water vapor content of this air seems to have a great impact on the ability of the respiratory tract to dissipate this heat, but the relative contributions of dry bulb temperature and relative humidity level on respiratory heat gain have yet to be determined. Despite the number of studies which have been done studying the conditioning of air and heat and water exchanges that occur during respiration, a literature search found no study which demonstrates the effect of breathing hot air saturated with water vapor on tissue temperatures inside the mouth.

In hot climates the respiratory tract is generally able to increase its heat losses so that body thermoregulation is aided by the elimination of greater amounts of heat. In these climates the humidity of the environment is of particular importance.

If inspired air is hot and dry some evaporation of water from the mucosa will occur during inspiration. This evaporation cools the mucosa despite the fact that the temperature might be extremely high. The reason for this is that the cooling produced by evaporation of water is highly efficient (the latent heat of evaporation is 538 calories per gram). The fact that evaporative cooling is efficient, coupled with the fact that air having a low specific heat warms the mucosa very little, results in a cooling of the mucosa during inspiration of hot dry air. Under these conditions the cooler mucosa is able to recover a portion of its water losses during expiration, and the total water loss to the body in a hot climate is diminished.

If, on the other hand, the inspired air is both hot and humid no significant evaporative cooling of the respiratory tract mucosa occurs during inspiration. In fact, if the air is saturated and above body temperature the mucosa may gain heat both from the inspired air and from the water vapor in the inspired air which will condense on the mucosa to release its latent heat. This heat gain can raise mucosal temperatures to 37 degrees Centigrade or higher. Under these conditions the respiratory tract is eliminating as much heat as possible but in net value is gaining both heat and water (Walker and Wells, 1961).

Comroe (1974) discusses briefly the effects of breathing air saturated with water vapor at temperatures greater than body temperature. He states that tissue temperature will rise if a person exposed to hot air hyperventilates, due to the fact that more calories will be presented to the tissues each minute. Comroe (1974) also states that very hot air or steam that reaches the alveolar ducts and alveoli is apt to produce little heat damage there because of the fact that the huge flow of pulmonary capillary blood at 37 degrees Centigrade will limit the increase in temperature of these tissues. However, this air may cause burns of the conducting air passages.

The most complete study of the biothermal processes involved during respiration, carried out by McCutchan and Taylor (1951), showed that the temperature, mass, and heat properties of the respiratory exchange correlates closely with the wet bulb. In this experiment subjects were subjected to inspired air temperatures up to 115.5 deg C but with low relative humidities and found no intolerable heating of the respiratory passages, though the exposure times were somewhat brief (i.e. less than 5 minutes). It became apparent that, like sweat evaporation in its effect on the skin, the evaporative cooling mechanism of the respiratory tract has great capacity to absorb sensible heat through humidification. McCutchan and Taylor developed an equation which expresses the heat exchange in the respiratory tract solely as a function of the wet bulb temperature of the inspired gas. This equation solves for zero at approximately 35.2 degrees C. Inspired wet bulb temperatures above this will presumably cause a respiratory heat gain, while inspired wet bulb temperatures below this temperature would result in a respiratory heat loss.

The subjective reports of heat sensations experienced by subjects in the experiment by McCutchan and Taylor (1951) agree with previously done investigations where despite heat exposures of up to 240 deg F there were found no critical sensations of heat or burning referred to the respiratory tract. McCutchan and Taylor (1951) included only one condition which was designed to produce a heat gain in the respiratory tract, 200 deg F and 1.18 inches Hg. of vapor pressure. This condition caused three of the five subjects to report that the inspired air 'set the teeth on edge.' The comments on the 160 deg F tests were that the air was 'warm' or 'dry,' and 120 deg F air was not sensed as being different from room air. The authors also point out that while the total body heat balance does not obey the heat and mass transfer laws of the wet bulb but the respiratory heat balance does so very closely.

A study by Seeley (1940) involved sampling of air at three different depths within the nose (at the anterior end of the inferior turbinate, in the midportion of the inferior meatus, and at the posterior tip of the inferior turbinate). A rise in water vapor content was found at each location. Over wide ranges of relative humidity of inspired air most of the addition of water vapor had occurred by the time the air reached the midpoint. In each instance some water was added beyond the third position, as indicated by sampling of expired air.

In the same study there were similar findings regarding temperature range. Inspired air at temperatures ranging from -8 to 55 degrees C (18 to 131 degrees F) were adjusted to 10 to 39 degrees C at the first position, 24 to 38 degrees C at the second, and 27 to 37 degrees C in the third position. In each instance the temperature of the air had risen by the time expired air reached the nose and fell somewhat during its passage back through the nasal passages. The nose was able to adjust to very rapid changes in the character of the inspired air. This exchange function is performed nearly as well during mouth breathing as during nasal breathing.

Experimental studies in animals reveal the air delivered to the larynx or trachea at temperatures up to 550 degrees C is still adjusted toward body temperature in the tracheobronchial tree and produces remarkably little lung damage (Moritz et al., 1944). These investigators studied the effects of breathing several types of hot air on the respiratory tracts of dogs. The dogs were either exposed to oven-heated air, flame, or live steam. They designed their experiment to expose the air passages to heat without causing concomitant injury of the skin so that any pathological changes that occurred could be attributed to the inhaled heat independent of any secondary effects that might result from thermal injury of the surface of the body. The mildest thermal exposures in these experiments was in fact more than sufficient to cause severe injury to the skin.

In their discussion of the ability of the respiratory tract to inhale air which, if it were in contact with the skin, would cause burns, Moritz et al. speculated that the reason for this was due to the fact that the quantity of heat that can be stored in the volume of gas that constitutes a breath is remarkably small. They calculated the heat transfer that would take place with inhalation of a mixture of equal parts of air and steam at 125 deg C. Such an atmosphere would cause severe burns of the skin within one second. If an amount of such a mixture sufficient to increase the lung volume by 500 cc. were inhaled and if it were cooled to 38 deg C before being exhaled, approximately 300 mg. of water would be condensed in the respiratory tract. The heat energy liberated, incident to the condensation of this amount of water, would be approximately 175 calories. In addition to this, approximately 12 calories would be liberated incident to the cooling of the gases and 26 calories incident to the cooling of the condensed water, bringing the total transfer of heat to the respiratory tract in excess of 200 calories.

Moritz et al. (1944) concluded that: 1) At any given temperature moist air has more heat to give up than does an equal volume of dry air and is accordingly more likely to cause thermal injury of the respiratory tract; 2) Inhalation of dry or moist hot air may destroy the upper tracheal mucosa without causing primary thermal injury of the lungs; 3) The most vulnerable part of the lung to thermal injury is the central parenchyma where the respiratory bronchioles and alveoli have the shortest and most direct connection with the primary bronchi; and 4) In instances of mild thermal injury of the lungs the centrally located alveoli were the seat of hemorrhagic edema even though there had been insufficient heat to cause recognizable injury of the bronchial mucosa or of the more peripherally located air sacs.

Method

The purpose of this investigation was to examine the effects of inspiration of air with high wet bulb temperatures on tissue temperatures of the tongue and of the hard palate. This section deals with subjects, methods of measurement, experimental procedures, equipment used in the tests, experimental design, protocol, and statistical treatment of the data.

Subjects

The subjects were 6 men between the ages of 21 and 28 years of age with a mean age of 23.7 years. All subjects were paid volunteers and were physically active. All subjects received a physical examination prior to any testing, and a graded exercise tolerance test was utilized to determine the subjects maximum workrate. Other than one subject who had an occasional wandering pacemaker, all subjects had normal resting and exercise ECGs. The subjects V(dot)O2max values ranged from 43.6 to 72.0 ml*kg-1*min-1 with a mean of 59.6 ml*kg-1*min-1. Individual characteristics of the subjects are reported Table D1-1. Estimated V(dot)E values for the exercise workload undertaken by the subjects are included in this table using a predictive equation developed by Bernard, Kamon & Stein (1979).

Table D1-1 Individual subject characteristics

Subject	Age	Height (cm)	Weight (kg)	$\dot{V}_{O_2}$max ($ml \cdot kg^{-1} \cdot min^{-1}$)	Estimated $\dot{V}_E$ at 40% $\dot{V}_{O_2}$max (l/min)
TC	28	171.5	66.6	61.4	38.9
SG	27	182.5	74.8	54.9	39.0
GH	21	171.5	77.8	43.6	32.0
JP	23	187.0	73.2	64.9	45.8
DS	22	184.4	72.6	72.0	50.8
PS	21	181.0	68.1	60.5	39.2
Mean	23.67	179.65	72.18	59.55	40.95
SD	3.8	6.62	4.18	9.63	6.51

Equipment

Air was delivered at approximately 125 liters*min.-1 into a vapor generator. Within the vapor generator, humidification occurred by passing water at a known temperature into the generator. This water was dispersed through a large number of glass beads causing a great deal of water to be liberated into the air, virtually saturating the air at that point. The saturated air then travelled from the vapor generator through insulated tubing to a heat gun which heated the air to the desired temperature and relative humidity conditions. The final temperature and relative humidity conditions were determined by means of dry bulb and wet bulb readings taken in the line about six inches proximal to the subject's mouth. Expired air was dumped into the room. All temperature data was recorded by a Doric Datalogger at five minute intervals. Figure D1-1 shows a schematic of the experimental equipment used in this experiment.

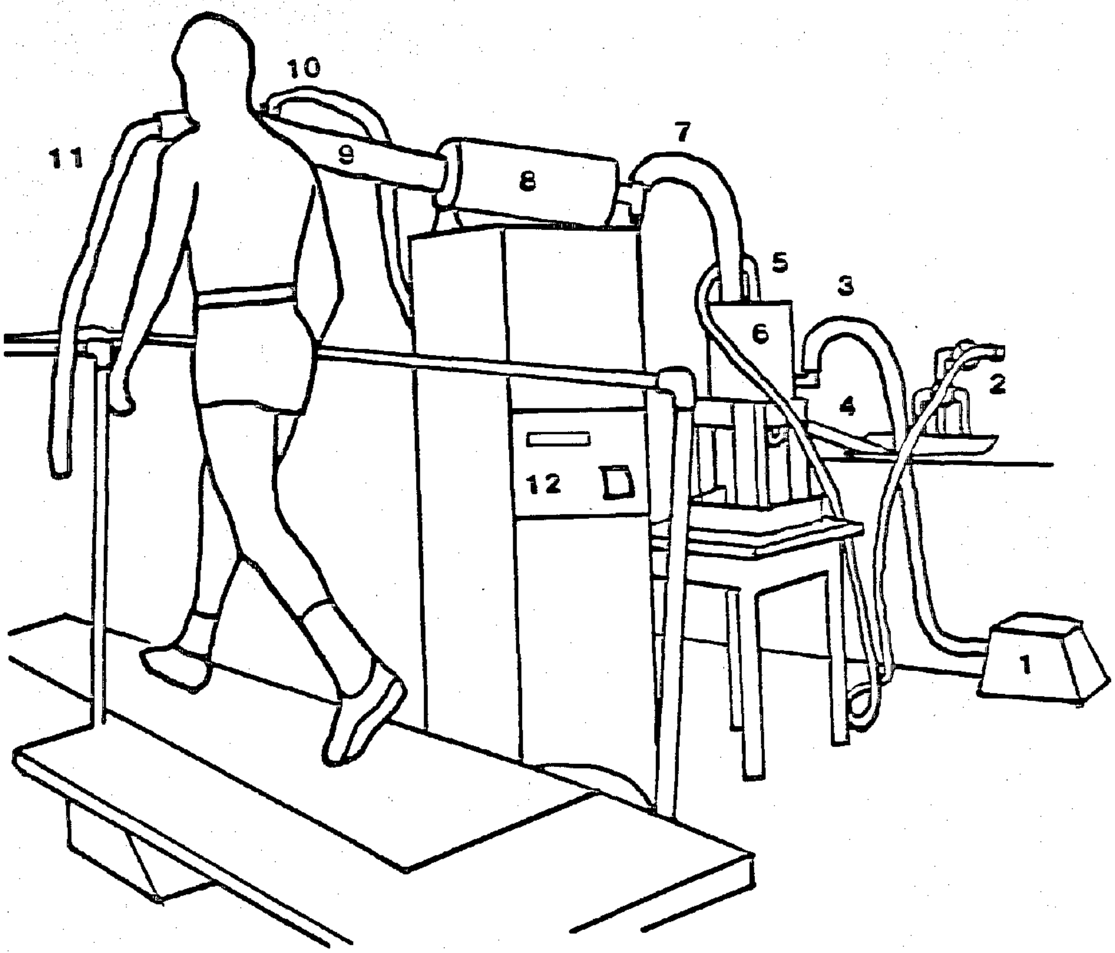

Figure D1-1 Schematic diagram of apparatus used in hot humid air inhalation experiment

Note: 1 = High velocity positive pressure air pump; 2 = Input water temperature regulator; 3 = Input air hose; 4 = Drain pipe; 5 = Input water hose; 6 = Vapor generator; 7 = Insulated tubing to heat gun; 8 = Heat gun; 9 = Insulated tubing to mouthpiece; 10 = Dry bulb and wet bulb thermocouples; 11 = Expired air hose; and 12 = Doric datalogger.

To insure that a proper wet bulb temperature was obtained at the airflow used in this study, wet bulb temperatures were measured at increasing airflows (controlled by a variac) to show that the air flow was great enough to cause the proper amount of evaporation to take place from the wick of the wet bulb. Tissue temperatures on the tongue and hard palate were taken by means of thermocouples held in place by a football-style mouth protector which was form-fitted to each subject's mouth. This allowed temperature sampling at fixed locations. A rectal thermistor was used to record the subject's core temperature. Heart rate was displayed on a digital monitor (Respironics Exersentry SN) in beats per minute or a Hewlett-Packard Electrocardiograph and was recorded in beats per minute.

Design

Mouth temperatures were measured on the hard palate and on the top of the tongue. The hot inspired air temperatures were 41, 46, and 51 deg C. At the three hot air conditions, three relative humidities were studied: 65%, 80%, and 95%. Subjects ran on a treadmill for 60 minutes at 40% of their V(dot)O2max under each of the test conditions. The first four subjects were tested in a step-wise fashion, i.e. subjected to the 41 deg C air with increasing relative humidity (i.e. 65%, 80%, and 95%), then were tested at 46 deg C with increasing relative humidities levels, etc. For the final two subjects test conditions were randomized and subjects were not aware of the dry bulb or relative humidity conditions they were experiencing. This was done in order to control for possible learning effects from the stepwise testing procedure and for any psychological effects from the subjects awareness of the test conditions. A control test was done for all subjects at room air conditions (approximately 25 C). The relative humidity for the control test was 50%.

Protocol

The desired input water temperature for the vapor generator and the temperature of the heat gun for the specific inspired air conditions was calculated using a program developed in the Ergonomics Unit of the Laboratory for Human Performance Research. The temperatures of the input water and heat gun were set at least 45 minutes prior to the start of the test in order to achieve a reasonably stable air condition. A constant check was made of the air conditions before the experiment by the use of a computer program which calculated relative humidity when given dry bulb and wet bulb temperatures.

Upon entering the laboratory the subjects were fitted with chest electrodes, and then the subject inserted the rectal thermistor. Resting tongue and palate temperatures, resting core temperature, and a resting heart rate were obtained just prior to the start of the test. The treadmill was then set at the conditions required to exercise the subject at 40% of his V(dot)O2max and the subject started the test. Measurements of the input water temperature, heat gun temperature, dry bulb and wet bulb temperatures, core temperature, palate temperature, tongue temperature, and heart rate were taken every five minutes during the 60 minutes of the test using a Doric Datalogger. These data were then entered into computer files for later analysis.

<u>Statistical Treatment of the Data</u>

In a univariate analysis of variance of repeated measures (ANOVR) design, data from the ten wet bulb temperatures were analyzed by a statistical package developed by Paul Games (Games, 1981; Games, Gray, Herron, and Pitz, 1980). A two-factor 3 x 3 (temperature x humidity) ANOVR was employed to examine the effects of increasing dry bulb temperatures and relative humidities on tissue temperatures of the tongue and hard palate for the elevated wet bulb conditions. Linear regressions were calculated to describe the tongue and hard palate temperatures and inspired wet bulb relationship. The secondary measures, heart rate and core temperature, were also analyzed in a univariate and multivariate ANOVR. Critical alpha levels were .05 in all cases.

<u>Results and Discussion</u>

The purpose of this investigation was to determine the effects of elevated wet bulb temperatures of inspired air on tissue temperatures measured on the tongue and hard palate. This section presents the data collected during the investigation and an interpretation of the results is offered in the following sections: (1) tongue temperature, (2) palate temperature, (3) core temperature, and (4) heart rate.

<u>Tongue Temperature</u>

Table D1-2 shows the mean tongue and palate temperatures for the control and experimental conditions and also gives the mean wet bulb temperature for each of the test conditions. The conditions are arranged in ascending wet bulb order.

Table D1-2 Mean tongue and palate temperatures during the various experimental conditions (in order of increasing inspired wet bulb temperature).

$\bar{T}_{wb}$ (°C)	18.9	34.7	37.8	39.0	40.1	42.3	43.6	44.9	46.9	49.3
s.d.	2.83	0.48	0.52	0.50	0.43	0.28	0.39	0.55	0.29	0.49
$\bar{T}_{db}$ (°C)	24.8	41.3	41.1	45.9	41.3	46.2	51.1	45.8	51.0	50.7
s.d.	2.28	0.12	0.17	0.30	0.23	0.18	0.45	0.31	0.36	0.15
$\%\overline{RH}$	57.5	64.5	81.1	65.6	93.3	79.2	65.0	94.4	79.7	92.6
s.d.	6.12	1.93	2.10	1.81	2.20	1.04	1.70	2.72	2.04	2.43
$\bar{T}_{tongue}$ (°C)	30.7	35.8	37.2	37.4	38.4	39.0	39.2	40.4	41.4	42.2
s.d.	1.50	0.36	0.36	0.42	0.26	0.57	0.47	0.83	0.67	0.96
$\bar{T}_{palate}$ (°C)	31.1	36.0	37.6	37.7	38.4	39.1	39.3	40.3	41.4	42.4
s.d.	1.26	0.37	0.56	0.35	0.48	0.43	0.33	0.74	0.38	0.42

The mean tongue temperature of the control condition (i. e., 25 deg C and 50% RH; Twb = 18.9 deg C) was 30.7 degrees and was significantly lower than all of the experimental conditions [$F(1,9) = 120.160$; $p < .001$]. Throughout the experimental conditions, as the wet bulb temperature increased, the tissue temperature of the tongue also increased.

There were also significant differences found among the experimental conditions. A Duncan underline procedure summarizes these differences in Table D1-3.

Table D1-3 Duncan underline procedure summarizing significant differences in tongue temperature among the various test conditions (WSD = 1.43).

$\bar{T}_{wb}$ (°C)	18.9	34.7	37.8	39.0	40.1	42.3	43.6	44.9	46.9	49.3
$\bar{T}_{tongue}$ (°C)	30.7	35.8	37.2	37.4	38.4	39.0	39.2	40.4	41.4	42.2
			———	———	———					
					———	———	———			
							———	———		
								———	———	
									———	———

Note: ____ = not statistically different ($p < .05$).

Figure D1-Z shows the mean tongue temperatures as a function of the inspired wet bulb temperature. The correlation of tongue temperature to inspired wet bulb temperature was .968.

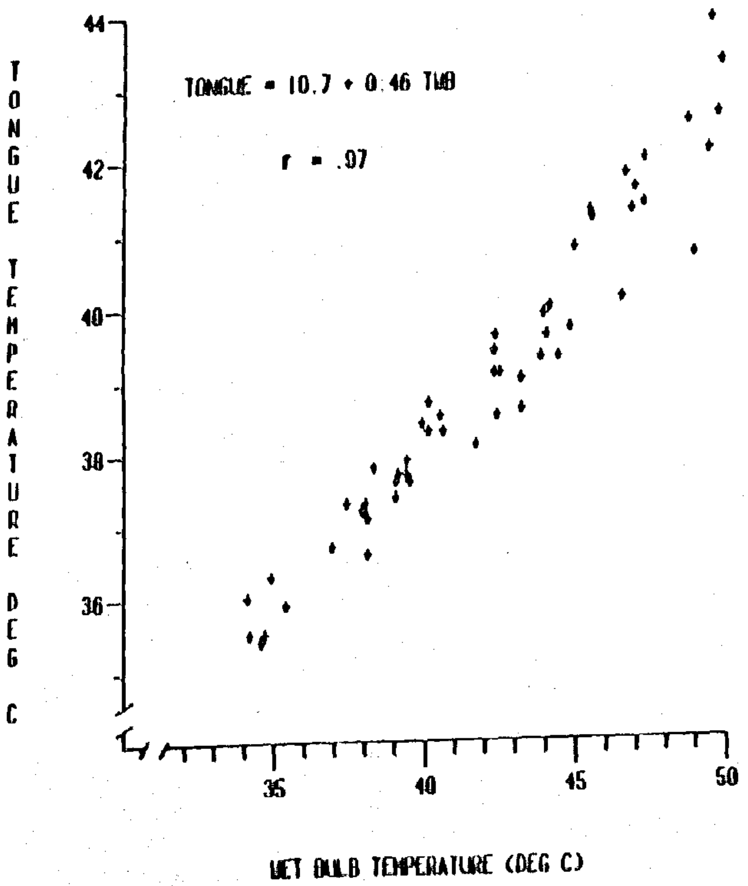

Figure D1-2 Mean tongue temperature versus inspired wet bulb temperature

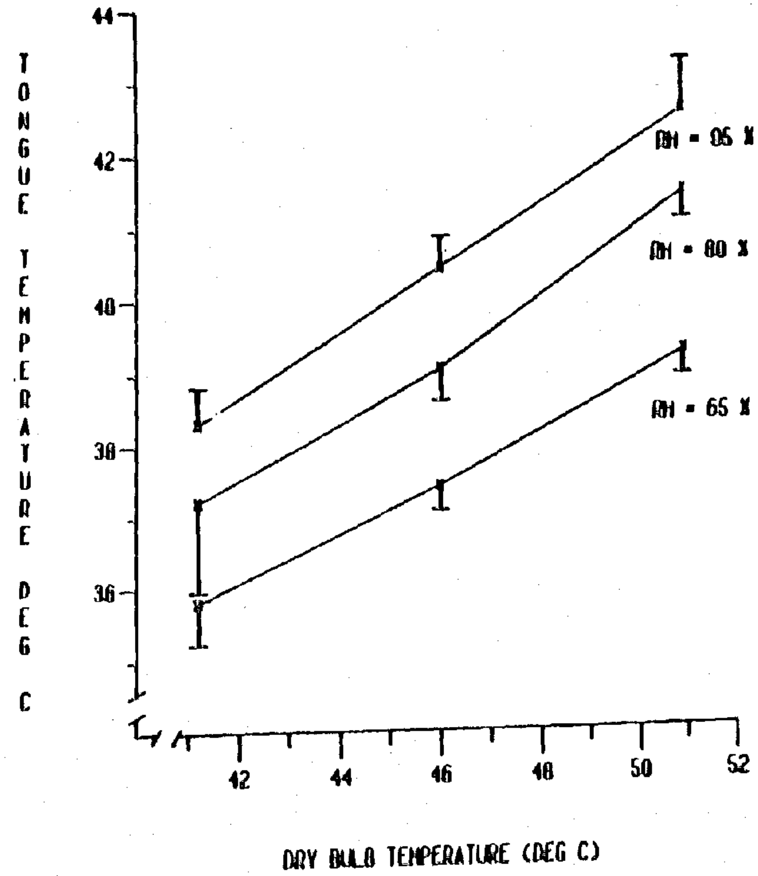

Figure D1-3 Mean tongue temperatures at different relative humidities versus increasing dry bulb temperatures

A least squares regression equation for this data is:

$$T_{tongue}\ (deg\ C) = 19.7\ (deg\ C) + 0.46\ T_{wb}\ (deg\ C)$$

(Standard error of estimate = .53)

This equation had an R-squared value of .937 adjusted for the degrees of freedom.

Influence of Dry Bulb Temperature and Relative Humidity

The two-factor ANOVR showed significant main increases in tongue temperature due to dry bulb temperature [$F(1,5) = 124.009$; $p < .001$] and relative humidity [$F(1,5) = 195.111$; $p < .001$]. The interaction of dry bulb temperature and relative humidity was not significant ($p = .254$). Figure D1-3 shows mean tongue temperatures at different relative humidities versus increasing dry bulb temepratures. Note that the lines describing relative humidities are basically parallel. If there had been a significant interaction between the dry bulb temperature and relative humidity these lines would converge.

Palate temperatures reacted in very much the same fashion as did the tongue temperatures.

Core Temperature

Since the experimental conditions should cause a respiratory heat gain it was of interest to see if inspired wet bulb temperatures might affect core temperature as measured with a rectal probe. This was not the case, however, since core temperatures were not affected by the heat gain incurred by the respiratory tract due to the breathing of air at elevated wet bulb temperatures ($p > .05$). Figure D1-4 shows a typical time course for core temperature during inhalation of hot humid air. Differences in core temperature due to increasing dry bulb temperatures and relative humidities were not significant ($p > .05$).

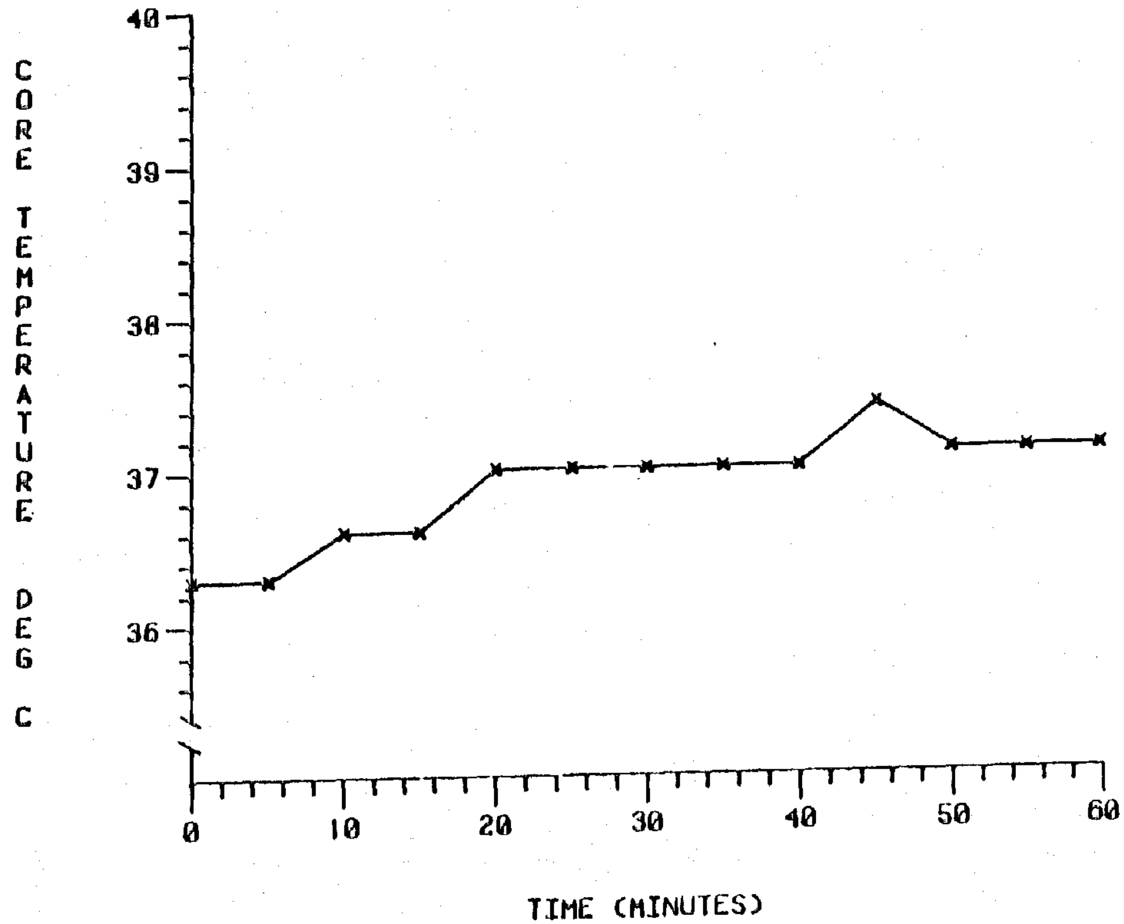

Figure D1-4 Typical time course of core temperature during a 60-minute hot humid air inhalation session

Heart Rate

It was also of interest to determine whether heart rate was affected by inspiration of air with elevated wet bulb temperatures. There were no significance increases found when comparing heart rate to increasing wet bulb temperatures of inspired air ($p > .05$). There were also no significant increases in heart rate due to increasing dry bulb temperatures ($p > .05$) or due to increasing levels of relative humidity ($p > .05$).

General Discussion

The most important finding of this investigation is that wet bulb temperature of the inspired air seems to be a better descriptor of heat stress to the tissues of the mouth than either dry bulb temperature, relative humidity, or both of these combined. The process of heat transfer in the mouth seems to be very much like the heat exchange which occurs with a wet bulb thermometer. This finding is in agreement with the results of a similar study by McCutchan and Taylor (1951), who were studying the effects of the inspired air temperature and relative humidity on the temperature and relative humidity of the expired air. They found that their results were extremely well described solely in terms of wet bulb temperature. They further suggested that the heat transfer that takes place in the mouth is fully analogous to the process that takes place with a wet bulb.

Estimations of respiratory heat gain were made by calculating the difference between enthalpy contained in the inspired air and enthalpy of expired air. The assumption was made that expired air was in equilibrium with the tissue temperatures of the mouth and was fully saturated with water vapor. The results of these calculations are presented in Table D1-4.

Table D1-4 Estimates of respiratory heat exchange in test conditions assuming expired air is in equilibrium with tissue temperatures in the mouth and is fully saturated with water vapor.

T_{wb} of Inspired Air (°C)	Kcals/Liter of Inspired Air	Estimated Expired Air Temperature (°C)	Estimated Kcal/Liter Expired Air	Estimated Respiratory Heat Gain (Kcals/Liter)
18.9	0.0191	30.7	0.0328	- 0.0137
34.7	0.0394	35.8	0.0397	- 0.0003
37.8	0.0422	37.2	0.0415	+ 0.0007
39.0	0.0450	37.4	0.0418	+ 0.0032
40.1	0.0467	38.3	0.0433	+ 0.0034
42.3	0.0510	39.0	0.0041	+ 0.0069
43.6	0.0534	39.2	0.0449	+ 0.0085
44.9	0.0570	40.4	0.0469	+ 0.0101
46.9	0.0607	41.4	0.0491	+ 0.0116
49.3	0.0672	42.2	0.0510	+ 0.0162

As you can see from Table D1-4 the two lowest wet bulb conditions (i. e. Twb of 34.3 deg C or lower) would result in a respiratory heat loss. Inspired air wet bulb conditions of 37.5 deg C or higher result in a respiratory heat gain. At the most severely elevated wet bulb condition the respiratory heat gain incurred by the subject over the hour-long test at an average V(dot)E of 41 L/min would be 39.85 kcals. These calculations are in agreement with the findings of McCutchan and Taylor (1951) who found in their study that respiratory heat gain started when the inspired wet bulb temperature exceeded 35.2 deg C.

The subjective feelings elicited from the subjects also bear reporting. There were two conditions which tended to be percieved as very difficult for the subjects to endure. These were the two conditions with the highest wet bulb temperatures; 51 deg C and 80% RH and 51 deg C and 95% RH (TWB = 44.5 deg C and 48.8 deg C respectively). During and after these tests there were frequent complaints that the subject's gums, tongue or back of the mouth hurt, though not severely. Redness of the subjects gums and tongue were also noted following these tests. Interestingly, the gums were often the first area which became a concern with regard to tissue sensitivity inside the mouth. This is perhaps because they are the first tissues to come into contact with the heat load being presented to the mouth, before sufficient conditioning of the inspired air is possible.

Though the gums were usually the first tissues affected by the inhalation of hot humid air, the tongue, hard palate and posterior wall of the pharynx were often a bit sore after tests at the most extreme hot air levels. Redness of the tissues were also noted in these regions. One subject elected not to finish the test at the 51 deg C and 95% RH level after 25 minutes of the inhalation of this air.

It was noted that often during the two most extremely stressful test conditions that ventilation by the subjects was rapid and very shallow. This is perhaps a protective mechanism mediated by neural respiratory control centers as a final defense mechanism designed to protect the sensitive tissues of the respiratory tract during inhalation of air with elevated wet bulb temperatures.

AUTOMATIC BREATHING AND METABOLIC SIMULATOR: THE RESPIRING ROBOT

N. Scott Deno
The Pennsylvania State University
Noll Laboratory
University Park, PA 16802

ABSTRACT

Automatic breathing and metabolic simulator (ABMS) systems were first developed in the early 1940s and work continues today on a simulator of the human at work as a replacement for the human subject during respirator "man-testing." The systems' responsiveness to dynamically changing gas compositions and changes in simulated work rates have constituted the most complex design problems. The responsiveness requirement dictated the incorporation of a minicomputer. Our ABMS system is a "pendulum" ventilated lung with continuous gas-exchange metabolism simulation (no cyclic injection or withdrawal pumps and no combustion furnace) monitored by a complete breath-by-breath, on-line metabolism measurement system. Any desired protocol can be programmed by specifying, for each period of the protocol, the oxygen consumption ($\dot{V}_{O_2}$), carbon dioxide elimination ($\dot{V}_{CO_2}$), respiratory frequency (f_r), ventilation rate ($\dot{V}_E$), and the breathing waveform shape. All metabolic states from rest to supermaximal can be simulated: $\dot{V}_{O_2}$ from 0-6 l/min, $\dot{V}_{CO_2}$ from 0-7 l/min, and $\dot{V}_E$ from 0-130 l/min. The time constant for requested changes in metabolic state is nominally 1 minute. Corrections for changes in inspired gas composition are made immediately after every respiratory cycle. Results are monitored continuously. Our ABMS system meets all of the requirements as a candidate for complete "man-test" simulation for testing self-contained breathing apparatus using testing guidelines such as 30 CFR 11.

INTRODUCTION

Simulation of human respiration has proven over the years to be a greater challenge than many researchers' original expectations. This research effort has spanned nearly fifty years, since the early work using crankshaft-driven diaphragms with variable fulcrums to vary the stroke of the diaphragms. One large diaphragm produced the ventilation ($\dot{V}_E$), one smaller diaphragm injected CO_2 to simulate CO_2 elimination ($\dot{V}_{CO_2}$), and one smaller diaphragm withdrew gas to simulate oxygen consumption ($\dot{V}_{O_2}$). These early systems were very durable but produced poor simulations in many situations. For example,

$\dot{V}_{O_2}$ with the early systems was directly proportional to inspired oxygen concentration (FI_{O_2}), when a constant $\dot{V}_{O_2}$ was desired. Changes in simulated exercise protocol were all performed manually. Also, no monitoring of gas concentrations, pressure or temperature were integrated into the system. Improving the performance of automated breathing and metabolic simulator (ABMS) systems beyond these early systems has revealed a large number of significant technical problems. Several of these problems could not be solved until recent gas analyzer and computer technology became available.

Historically, the major problem in ABMS development has been incorporating ABMS-system responsiveness and computer intelligence. This responsiveness characteristics applies to monitoring subsystems, control subsystems, and the feedback from the ABMS brain (the computer). The human body's reaction to superimposed changes in exercise intensity and inspired gas concentrations is too dynamic to simulate without responsive monitoring, decision-making and control. For example, an adequate ABMS system, like the human body, must exhibit a $\dot{V}_{O_2}$ which is indepdendent of FI_{O_2}. But, the ABMS system must do this without the benefit of numerous biochemical regulation mechanisms of the human, such as the blood's oxygen dissociation characteristics. Since practical considerations have forced ABMS designers to simulate $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ by withdrawal and injection of gases, a fast response control loop must exist from the monitoring of gas concentrations at the mouth, to verifying desired simulation conditions, and finally, to controling adjustements of gas injection and withdrawal. Clearly, a responsive ABMS system must be defined as a system which will make the correct control adjustments within several breaths after a change in the environment of the ABMS system. Also, these control changes initiated by the ABMS system should be reflected as a correction observed at the mouth within several breaths. This implies, among other constraints, breath-by-breath monitoring of gas exchange.

Previously constructed ABMS systems have contributed significantly to the knowledge about ABMS system techniques. The early diaphragm systems described previously demonstrated the need for better monitoring and control, and also the necessity for injection of nitrogen during conditions of less than 100% oxygen and/or exchange ratios less than 1.0. ABMS systems which burned combustible gases to partly simulate metabolism revealed the hazards, significant maintenance requirements and near impracticality of such systems.

ABMS systems with separate inspired and expired ventilation flow pathways have shown undesirably long response times to changes in inhaled gas concentrations when the internal dead space of the ABMS system is several times larger than a human's lung volume. ABMS systems which use compliant elements for injection and withdrawal of gases have shown sensitivities to pressures developed at the mouth resulting in metabolism errors. The practicality of most former ABMS systems was minimal without automatic and dynamic protocol control. Typically, in the past, a single metabolic condition was time-consuming to set, verify, and maintain. Former systems lacked a set of measurements to completely profile the performances of a self-contained breathing apparatus (SCBA).

In summary, upon embarking on the concepts and design of the ABMS system described, past research clearly indicated a need for a radical change in design. Using the old design concepts, which were produced at considerable cost per system, undesirable shortcomings in the system were inevitable. Our system is radically different and solves all the classical ABMS system problems. It is responsive with respect to all necessary parameters; system dead space, measurement, intelligence, and control. The system does not burn combustible gases to simulate metabolism. Nitrogen injection is used to provide proper simulation under all conditions of O_2 concentration and desired exchange ratio. All variables which are currently required to establish a pass or fail decision after testing a SCBA are measured using true breath-by-breath monitoring techniques. All the injection and withdrawal techniques display no compliant characteristics. The design of the ABMS system is very similar to the human anatomy and dead-space compartments have volumes which are equal to a human. All dynamic protocols which are humanly possible are easily programmed/executed.

SYSTEM DESCRIPTION

This revolutionary concept in automated breathing and metabolic simulators has been constructed for a totally automated exercise protocol, such as the required "man-test" for respiratory protection device certification by the National Institute for Occupational Safety and Health. The flexibility and capability of this system can be appreciated when one understands the immense power of current mini-computers, the heart of the measurement and control functions. All of the simulator's intelligence, enabling it to perform as a human subject, the desired exercise protocol, and the recorded history of performance (resulting data) are stored on disk files in the computer. Almost no constraints on behavior are built into the physical sub-assemblies of the simulator (such as crankshaft breathing drive which can produce only sinewave patterns). This simulator can actually record, summarize, and write reports on the results of a test as the test is conducted. This includes high speed processes such as the instantaneous control of the lung waveform and the breath-by-breath, on-line calculations.

Computer Controls

The computer directly and completely controls three sub-systems which are shown in Figure 1. The lung, which is a stepper-motor-driven piston design, is controlled to simulate any breathing waveform which is humanly possible. The second sub-system is a group of three valves which determine metabolism through adjustment of flow rates of N_2 and CO_2 into the lung and inhaled gas mixture of N_2, CO_2, and O_2 out of the lung. The third sub-system (Valve D) is an on-off isolation valve at the mouth of the simulator.

Breathing Simulation

The breathing is simulated by a large piston driven by a high-torque stepper motor. All breathing waveforms with ventilations ranging from 0 to 130 l/min STPD are programmable where the waveform can change nearly every breath. Sinewave, trapezoidal wave, triangle wave, and any other non-symmetrical waveforms are possible. Also, the inspired and expired times can be unequal. The piston design is gas-tight, if fitted properly, and has no undesirable complaint characteristics.

Metabolism Simulator

Carbon dioxide elimination ($\dot{V}_{CO_2}$) is simulated by CO_2 injection where $\dot{V}_{CO_2}$ is equal to the CO_2 injection rate minus the CO_2 lost through the exhaust flow. The oxygen consumption ($\dot{V}_{O_2}$) is simulated by O_2 withdrawal where $\dot{V}_{O_2}$ is equal to the O_2 lost through the exhaust flow. The N_2 injection is then used to balance the net flow rate into or from the lung which is not produced directly by piston movement. These flow rates are constant and enable simulation of all metabolic conditions ($\dot{V}_{CO_2}$, $\dot{V}_{O_2}$, and/or exchange ratio). The continuous-flow concept also performs a better inter-breath simulation of the progressive increase in expired CO_2 and progressive decrease in O_2 expired as with actual human subjects. Other ABMS systems display constant expired gas concentrations, which is a poor simulation and may affect results obtained when testing respirators.

This continuous flow concept is simple in concept; however, it requires a dynamic and intelligent monitor (the computer) to rapidly readjust the valve settings if inspired concentrations are changing. All ABMS systems are prone to errors if the system cannot respond to changes in inspired gas composition. A breath-by-breath analysis of mixed inspired gas composition is really required for any ABMS system because inspired gas composition can change dramatically in only seconds when testing respirators with pure O_2 supplies. The respiring robot system uses breath-by-breath analysis.

The final redundant check on the metabolism is an actual breath-by-breath analysis, which is independent of the actual control functions. The respiring robot system uses the information to "fine tune" the actual valve settings to achieve exact values of desired metabolism.

Measurements

All the measurements are effectively instantaneous and continuous; no slow speed multiplexing of electronics or mechanical valves limits the respiring robot system from continuous monitoring of all measured variables. All measurements are made with fast response sensors and most measurements are made at the mouth: O_2 and CO_2 concentration, flow rate (ventilation), pressure and temperature. These signals are processed digitally, primarily through numerous integration operations throughout inspiratory and expiratory cycles to calculate the desired parameters. Even though any conceivable parameter can be calculated, the following are currently calculated breath-by-breath and are also available as an average over any desired interval (typically one minute): oxygen consumption ($\dot{V}_{O_2}$), carbon dioxide elimination ($\dot{V}_{CO_2}$), expired ventilation ($\dot{V}_E$), inspired ventilation ($\dot{V}_I$), frequency of breathing (f_r), expired tidal volume (V_{ET}), inspired tidal volume (V_{IT}), inspired O_2 fraction (FI_{O_2}), inspired CO_2 fraction (FI_{CO_2}), expired O_2 fraction (FE_{O_2}), expired CO_2 fraction (FE_{CO_2}), peak inspired pressure (P_{PI}), peak expired pressure (P_{PE}), end tidal CO_2 (PET_{CO_2}), minimum inspired CO_2 (PMN_{CO_2}), minimum mouth temperature (TE_{MN}), maximum mouth temperature (TI_{MX}), expired time (t_E), and inspired time (t_I). All results are stored in standard units.

This breath-by-breath data is averaged and stored on disks for later reference and/or report writing and/or statistical analysis with other tests.

Temperature and Humidity

Temperature and humidity simulation with the respiring robot system is simplified by the similarity between the physical layout of the system and the human anatomy. Two thermal reservoirs, the lung and the upper airway heat exchanger, are maintained at 37 degrees centigrade. Since the respiring robot system has a bidirectional airway flow in an identical manner as a human subject, the dynamics of expired and inspired air temperature changes will be closely simulated by maintaining only two thermal reservoirs at a constant temperature. The initial humidification is provided by pre-heating and pre-humidifying the injected air in the mixing chamber. Final humidification takes place in the lung. The water wets the entire mixing chamber and lung. Pump A in Figure 1 circulates the water to maintain a water film in the mixing chamber and lung. The respiring robot and human anatomy differ only in that the alveolar and branchi volume in the human are simulated as a single lumped volume above the piston.

Protocol

The protocol of a particular test is defined by a data file on the computer's disk. Any number of protocols can be written into any number of data files. New protocols can be written in minutes and old protocol data files are always retained for future selection. The 30CFR11 "Man-Tests" are a subset of the library of protocol data files. Protocols have no limits as to test time duration or the frequency at which requested metabolisms or breathing waveforms are changed. A practical maximum frequency of protocol change is 4 times/minute or every 15 seconds.

Maintenance

Daily maintenance involves very few items; checking the humidity water reservoir, dump the water accumulated in water traps and calibration of the gas analyzers. The lung piston should be greased bimonthly and the lung motor greased annually.

RESULTS

Performance during the last year of routine use has been very encouraging. A sophisticated system like the respiring robot requires many hours of testing under numerous conditions to verify its accuracy, proper operating procedures, and long-term reliability. The respiring robot operation has included constant metabolism tests, 30CFR11 "Man-Tests," and special transient exercise simulations at both room air and high oxygen environments. Tests have been performed with chemical and bottled SCBAs. Single SCBA test durations have been up to 120 minutes and actual testing of up to six hours in an eight-hour day.

Respiring robot metabolism and ventilation were measured using total collection of the expired gases in a 200 liter collection bag during a steady-state metabolism (Consolazio et al., 1963). Accuracy of the respiring robot depends primarily on the calibration of the gas analysis system and the maintenance of the response characteristics of the gas analyzers. Comparisons between the respiring robot and the collections for $\dot{V}_{O_2}$s from rest to 3.0 l/min have been with 5%. The upper $\dot{V}_{O_2}$ range of the respiring robot extends to 6 l/min, but has not been validated. During an established steady-state work rate, variations in 30 second averages of $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ are less than 10%, and overall averages differ less than 5% from the desired condition. Sudden changes in environmental conditions, such as when the SCBA is first connected to the respiring robot and the oxygen levels rise from 21 to 70% in a minute, produce temporary pertubations in $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ are typically 20% over 90 seconds; however, the overall average over the same period deviates less than 5%. Perturbations of $\dot{V}_{O_2}$ are typically 100% which seem high; however, this is predominantly due to the washout of the lungs of the respiring robot in a manner identical to that of a human subject.

Transient metabolism control characteristics are dependent on the magnitude of the change requested. The time constant for changes in metabolism of 0.1 l/min is 10 to 20 seconds. The time constant for changes in metabolism of 1.0 l/min is one minute. These are the maximum rates of change; slower rates of change are implemented by computer software. These maximum rates of change for the respiring robot are only slightly faster than the human (Whipp and Wasserman, 1972). Typically transient characteristics are shown in Figure 2. Final programmed respiring robot transient characteristics are based on previously published and unpublished human subject testing by our laboratory (Bernard et al., 1977). Transient performance of an ABMS system ultimately has a very significant effect on the total average metabolism during an exercise protocol, because many protocol activities, such as most 30CFR11 "Man-Tests," are too short to achieve steady-state. This means that the subject or ABMS is a transient state the majority of the time. For example, laddermill activities during 30CFR11 "Man-Tests" achieve only 60% of the metabolic rate which would be achieved if the activity were continued.

Simulator performance compared to that of a human subject is shown in Figures 3 and 4. Plotted data are of 0.5 minute averages for a 30CFR11 30-minute "Man-Test" No. 2. Both $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ for the human show more variability than those of the ABMS which is expected due to the variability in human subject breathing. These comparisons show good agreement with the exception of a slight phase shift between the human and the respiring robot. This phase shift can be removed; however, its effect is very small in terms of overall SCBA performance testing. Data in Figures 3 and 4 were collected under room air conditions. Tests using the respiring robot with SCBAs show similar results as shown in Figures 5 and 6 for a 30CFR11 10-minute "Man-Test" No. 2. Major differences in results between room air and SCBA conditions occur when donning and removing the SCBA. The sudden changes in oxygen concentration cause perturbations of the metabolism (primarily $\dot{V}_{O_2}$) for both the human subject and the respiring robot. This can be observed in Figure 5 at the beginning of the test using the simulator. Human data shown in Figures 5 and 6 were measured at room air conditions for practical considerations. Respiring robot results in Figures 5 and 6 were measured using a chemical oxygen SCBA. The differences in transitions between the human and the simulator are caused primarily by human variability between tests and slightly inappropriate protocol requests to the simulator with regard to a specific subject's response.

Repeatability has been a major performance goal. Two methods have been used to evaluate repeatability; comparisons with human test durations using SCBAs, and comparisons between total gas exchange throughout a test protocol. A one-hour protocol was used where the work rate cycled from rest to 1.0 l/min oxygen consumption. The mean SCBA duration of more than 20 tests using human subjects was 68 minutes. Based on the same failure criteria, the mean duration of 27 tests using the respiring robot was 83.6 minutes with a standard deviation of 12.2 minutes. For these 27 tests, the measured total mean volume of CO_2 delivered to the respirator was 45.8 liters with a standard deviation of 2.1 liters. Total mean volume of O_2 consumed was 52.0 liters, with a standard deviation of 4.8 liters.

Instantaneous recordings of expired gases show similar waveforms when comparing human subjects and the simulator. At 1.0 l/min, $\dot{V}_{O_2}$ and conditions of normal breathing and hyperventilation, Figure 7 shows the instantaneous CO_2 during an expiration for the simulator and the human subject.

Nearly daily operation for two years has produced a maintenance record including a total of two days of down time. This service record includes all sub-systems, such as computer, lung, control, and measurement.

DISCUSSION

The respiring robot is an ABMS system which overcomes all the traditional limitations which former ABMS systems have had with respect to the ultimate

goal of accurate simulation of dynamic exercise protocols like 30 CFR 11 certification "Man-Tests." No limitations have been observed in one year of operation involving SCBAs which would preclude the respiring robot from becoming a total replacement for evaluating human subjects' metabolism and breathing effects on SCBAs. Of course, the biomechanical aspects of SCBAs will always require human subjects for a thorough evaluation.

Routine maintenance is minimal. Calibration of the gas analyzers, checking levels of the water reservoirs, and checking CO_2 and N_2 gas supplies are the extent of preoperational procedures. No mandatory overhaul or replacement is required of any component. Periodic inspections have revealed no noticeable wear on moving parts after hundreds of hours of operation.

Operational precautions which have been observed are minimal. Checks for leaks caused by defective tubing and fittings must be done periodically. Even seemingly minor leakage at certain locations within the system can cause significant errors. To identify these problems immediately, the respiring robot has an automatic means to do a total system leak check using a mouth isolation valve. In practice only several tests have been disrupted due to leaks. A more potentially serious problem comes from prolonged conditions of inspired gas at high temperature and humidity. Condensation of water vapor must be prevented when possible, or trapped where condensation does occur. Bottled oxygen SCBAs can produce inspired gases which have high water vapor saturations at temperatures of as high as 50 degrees centigrade. Proper locations of heating and water traps will control the problem; however, frequent checking of water traps and heaters is judicious during high humidity environments.

The heart of the respiring robot is the computer software, which is beyond the scope of this paper. The size and complexity of the software required can be appreciated when considering that one computer performs all protocol control, metabolism control, breathing control, and measurement functions simultaneously. These functions include everything from the simple operator-computer interaction to the most complex mass balance calculations. The software dependence enables the system performance, simplicity of mechanical design, and flexibility.

The total software dependence of the respiring robot allows a complete change in the operational objective by simply changing the current running program in the respiring robot computer. This is a powerful feature when future requirements change and new knowledge mandates changes in the respiring robot's operating characteristics. This also enables certain "bench tests" to be performed on the respiring robot without changing the mechanical configuration.

BIBLIOGRAPHY

Bernard, T. E., Stein, R. L., and Kamon, E. (1977). Evaluation of federal man test for self-contained breathing apparatus. Am. Ind. Hyg. 38:689-695.

Consolazio, C. F., Johnson, R. E., and Pecora, L. J. (1963). Physiological measurements of metabolic function in man. New York: McGraw-Hill.

Whipp, B. J., Wasserman, K. (1972). Oxygen uptake kinetics for various intensities of constant-load work. J. Appl. Physiol. 33:351-356.

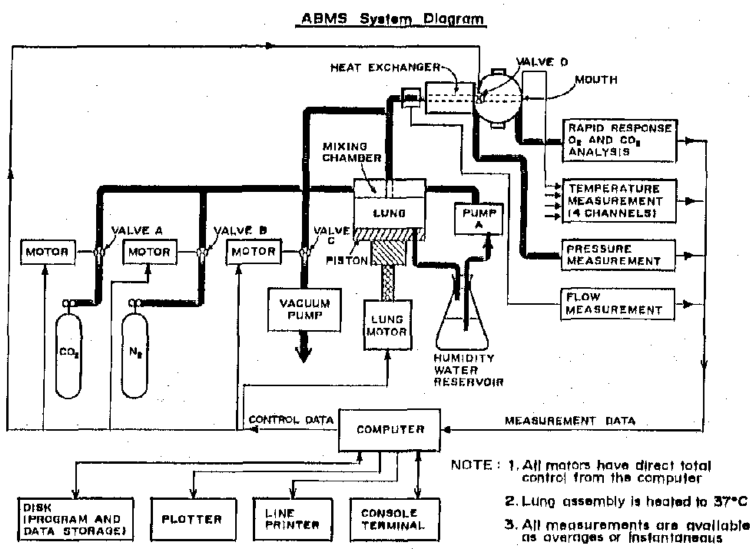

Figure 1. Diagrammatic representation of all the ABMS system components.

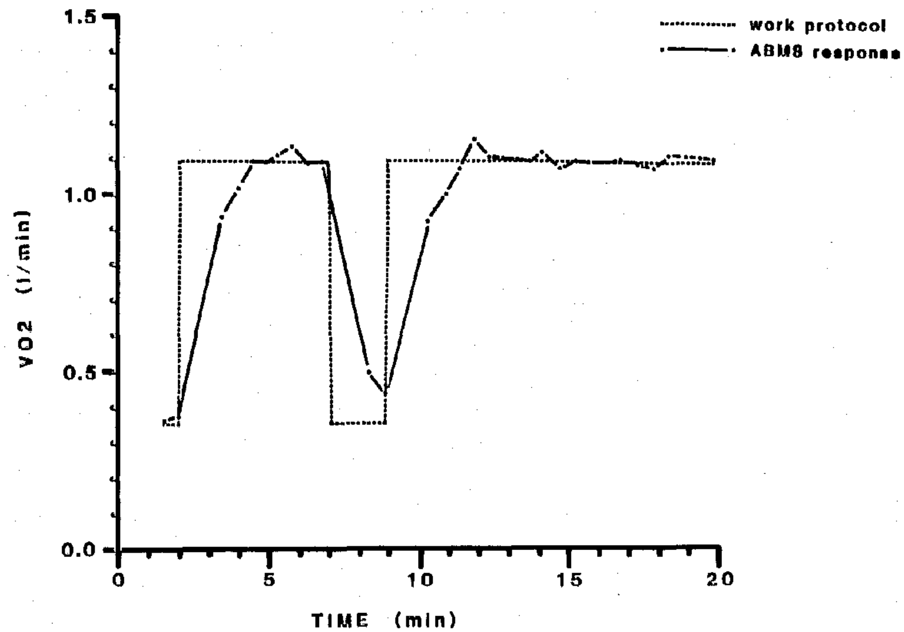

Figure 2. Response characteristics of the ABMS are compared to the actual requested work protocol.

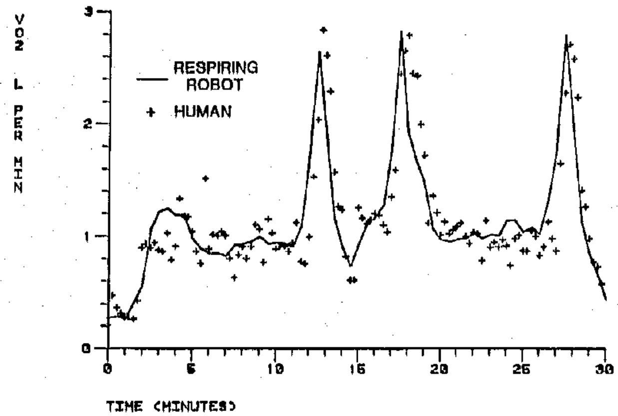

Figure 3. Oxygen consumption ($\dot{V}_{O_2}$) is compared between the human subject and the ABMS system for a 30-minute 30 CFR 11 man-test #2.

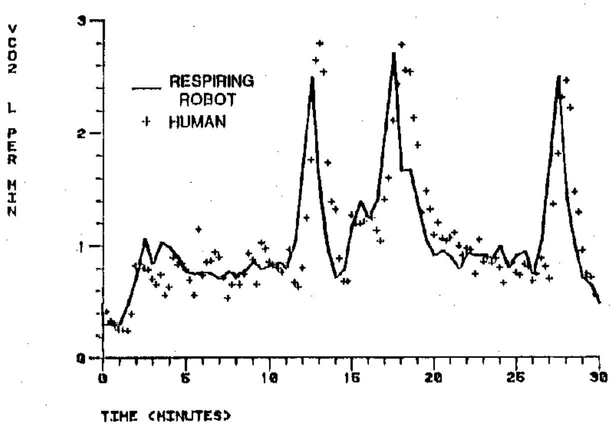

Figure 4. Carbon dioxide elimination ($\dot{V}_{CO_2}$) is compared between the human subject and the ABMS system for a 30-minute 30 CFR 11 man-test #2.

Journal of the ISRP

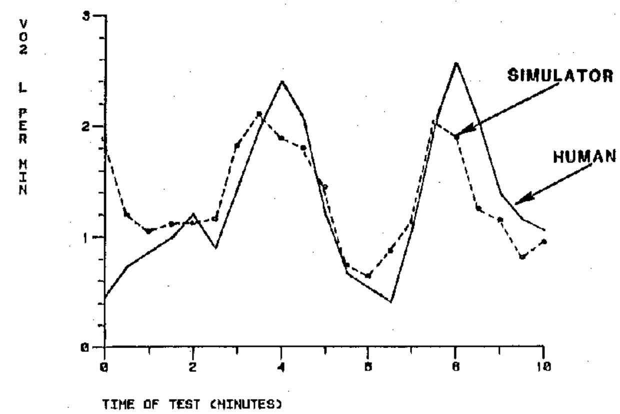

Figure 5. Oxygen consumption ($\dot{V}_{O_2}$) is compared between the human subject and the ABMS system for a 10-minute 30 CFR 11 man-test #2.

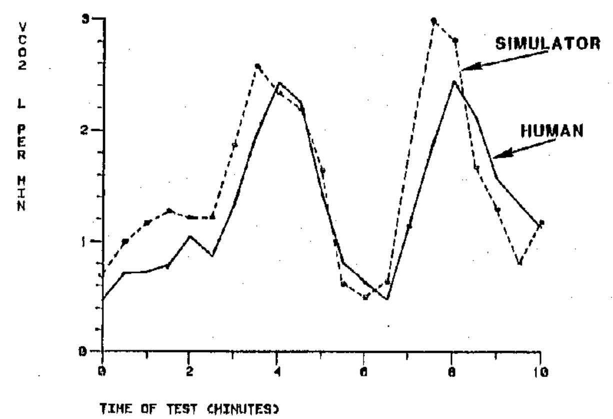

Figure 6. Carbon dioxide elimination ($\dot{V}_{CO_2}$) is compared between the human subject and the ABMS system for a 10-minute 30 CFR 11 man-test #2.

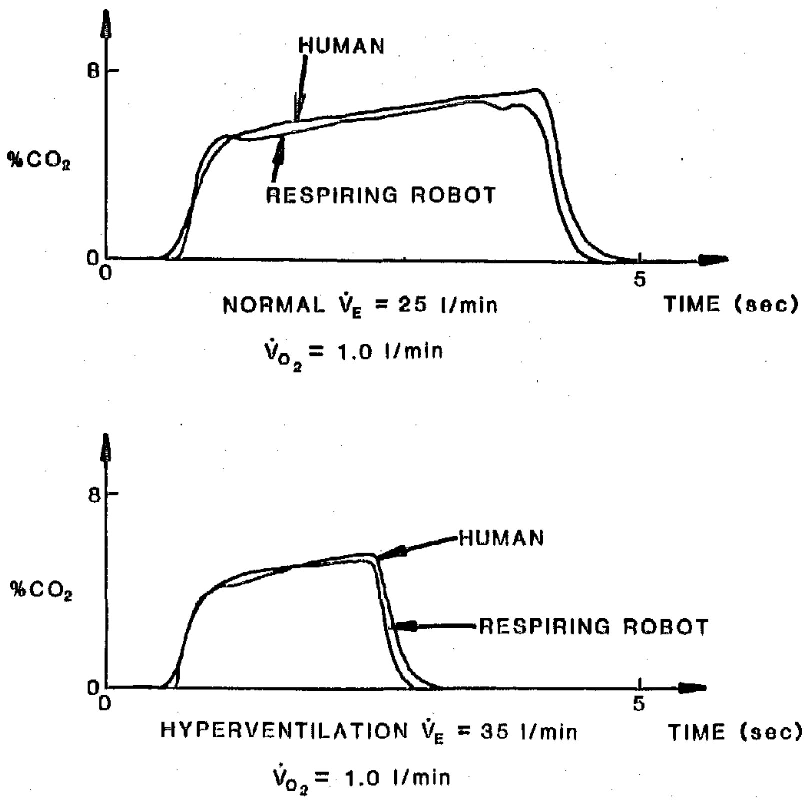

Figure 7. Instantaneous carbon dioxide concentration during an expiration is compared between the human and the ABMS system. Results are shown for both normal and hyperventilation conditions.

APPENDIX F1:

A MATHEMATICAL COMPUTER SIMULATION OF BOTTLED OXYGEN-TYPE RESPIRATORS AND HUMAN SUBJECTS

This chapter gives a complete description of the model simulating a human breathing with a bottled oxygen type respirator. The description is divided into two distinct parts. The first part is a general overview of the entire model along with a description of the man tests that will be used as the human input parameters. The second half is a description of the CO2 scrubbing unit. The results of the validation study for this portion of the model will also be presented.

This first section is a general overview of the REspirator MODel (REMOD) system written in the form of a flow chart of the actual program. The model is set up so that the simulation can begin when the respirator is donned either at the beginning of an inspiration or an expiration. However, most manufacturers recommend that an inspiration should occur first. Therefore this discussion of the program is written in that mode. An important fact to keep in mind is that the model iterates on a breath-by-breath basis as opposed to the more conventional method of time iteration in which each breath is divided up into many small time increments (Dickinson, 1977). This allows the model to run much faster than real time even on a small computer.

The diagram of a human and respirator simulation (Figure F1-1) shows the relationships between the various parts of the model. All of the items drawn are easily changed within the model to accomodate different types of respirators, as well as the wide variety of humans possible. The three triangles surrounding the two large boxes (labeled HUMAN LUNG VOLUME and RESPIRATOR BAG VOLUME) represent summers which keep track of the individual gas volume assigned. As the diagram shows, the gas volumes are composed of the gas inhaled or exhaled plus or minus any gas that either the respirator or the human produces or consumes. An important difference between the two halves of the model is the diamond shaped block below the respirator bag volume block. This block shows the bag volume being tested continuously with gas being vented if the volume is too large or oxygen being injected by the demand valve if the volume is too small.

The model is written as a short main program which calls various subroutines, in turn, to perform the actual calculations. This set-up was chosen to allow the user to quickly and easily change the respirator's characteristics to accommodate different manufacturer's specifications (Deno, 1983). There are several subroutines at the beginning of the program that are called only once in order to set up the initial conditions of the human subject and the respirator.

DIAGRAM OF A RESPIRATOR AND HUMAN SIMULATION

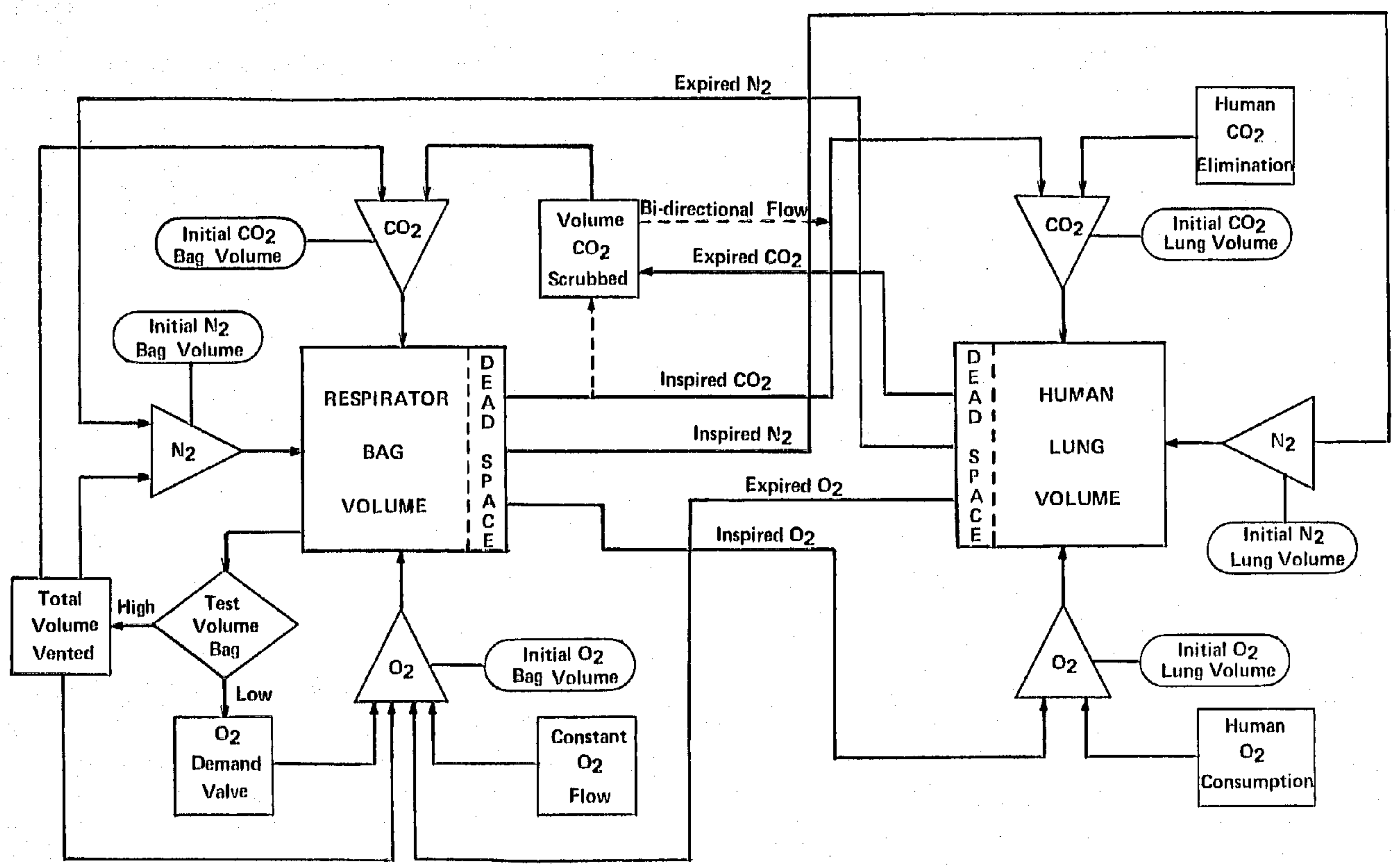

Figure F1.1. Block diagram of the respirator and human subject computer simulation

After the respirator and the human have been set up, the model calls the PROTOCOL subroutine which establishes the human work rate. The work rates were chosen from actual tests of people working under the MSHA/NIOSH, 30 CFR Part 11, work protocols. The values that the simulation obtains from this subroutine consist of: (a) VO2, a measure of the rate at which the body is consuming oxygen (O2); (b) VCO2, a measure of the rate at which the body is producing carbon dioxide (CO2); (c) FB, the frequency at which the wearer is breathing; (d) VE, the total volume of air moved past the mouth in one minute; and (e) TIME, the length of time this level of work must be continued. Different work rates are specified in an attempt to simulate the actual rescue or escape experience in the mine.

The first subroutine the main program calls is responsible for producing the desired characteristics of any brand of respirator. Basic variables include (a) maximum bag volumes, (b) volume of O2 available, (c) dead space within the breathing hoses, and (d) type of CO2 scrubber. The scrubber can be changed from a uni-directional flow type canister to a bi-directional flow model. Once the overall scrubber's characteristics have been determined (including diameter, length and weight of LiOH present in the bed of the canister) the characteristics of the shrinking pore model are set, based on the size of the granules. A more detailed description of the workings of this shrinking pore model follows, including its validation based on experimental data presented by Bernard (1979), Boryta and Maas (1982), and Kyriazi (1984).

Human characteristics that need to be established include: (a) functional residual capacity of the lung, which is a measure of the volume of the lung following a normal expiration; (b) dead space made up of the trachea, bronchia, mouth and nose; and (c) alveolar O2 and CO2 concentrations, which are measured within the lung. Values for the average alveolar O2 and CO2 concentrations were taken from an article by Murphy (1969). He obtained his data from actual measurements on humans. Values for the other two characteristics were set at average values for normal, healthy humans (Bannister, Cunningham, & Douglas, 1954).

Everything is now set for the first inspiration of the test simulation to begin. A minor error is made here in assuming that the dead space of both the respirator and the human are filled with gas of the same concentration as that of "normal" room air. If the respirator were actually being donned during an escape attempt in a mine, chances are the ambient conditions would not be "normal" room air.

The first calculation the model makes is an estimation of the fractional concentration of the gases passing by the mouth. Next it determines new lung volumes based on the air in the lung. It is assumed throughout the model that the lung, as well as the respirator, contain completely mixed gas. This assumption is based on the paper by Murphy, describing a model of lung gas exchange. In it he calculates "that the oxygen partial pressure fluctuates approximately 2 mmHg on either side of the mean value" in the lung during both inspiration and expiration. This corresponds to a fluctuation in O_2 fractional concentration of 0.27 percent. Considering the accuracy of this model, we concluded that our assumption of a lung's containing perfectly mixed gas was not a significant error. Also, since the model iterates on a breath-by-breath basis and only reports values on the the half minute, we ignored the fluctuation in fractional concentrations at the mouth due to mixing within the lung and the respirator's breathing bag.

Two separate measurements (calculations) of inspired CO_2 concentration are made and recorded during the inspiratory phase of the breathing cycle. The first measurement is the average CO_2 concentration taken over an entire breath. The second measurement is the concentration of CO_2 at the distal end of the respirator breathing hose. This measurement is the one that best approximates the measurement MSHA/NIOSH would make during an actual human test of a respirator. The average CO_2 concentration, measured at the mouth over an entire breath, however, will be significantly higher than that in the breathing bag due to the volume of CO_2 in the respirator's dead space that does not reach the scrubbing unit.

A major assumption of the model is that all of a person's metabolism occurs during the inspiratory phase of the breathing cycle (Deno, 1983). This is a major simplification since the cells are continuously consuming and producing O_2 and CO_2. This simplification was necessary if the breath-by-breath time incremental system is to be implemented.

Most bottled oxygen respirators are equipped with a demand valve which is activated when the pressure in the breathing bag drops below a set point. This drop in pressure corresponds to an empty breathing bag. Our model works on the basis of volumes, hence the demand valve is activated when the inspired volume exceeds the volume of gas within the breathing bag. Respirators that are not equipped with a demand valve of this type must have a greatly increased constant flow rate. The MSHA/NIOSH standard for constant flow rate in a respirator with a demand valve is set at 1.5 liters/minute and without a demand valve at 3.0 liters/minute (30 CFR Part 11.85b).

When the inspiratory phase is complete, the model begins the calculations for the expiratory phase. An important parameter that must be calculated is the change in the expired tidal volume due to the respiratory exchange ratio of the human subject. During sub-maximal work the volume of CO_2 produced is less than the volume of O_2 consumed. This means the volume of the human lung would continually decrease if both the inspired and expired tidal volumes were equal. On the other hand, at maximal work loads in an anaerobic condition, the lung volume would increase due to the respiratory exchange ratio. Both of these conditions must be accounted for if the model's total gas volume is to stay constant throughout the changing work loads. This is done by modifiying the expired tidal volume by the respiratory exchange ratio.

The model always assumes that the volume of nitrogen (N_2) in the lung is constant. Otis, Rahn, and Fenn (1948) show that the change in N_2 concentration during breath holding (50 seconds) is less than 1 percent. Since we are not prolonging the residence time of the gases in the lung, the actual change in N_2 volume, due to absorption by the body, should be far less than 1 percent.

After the modification of expired tidal volume has been taken into consideration, the model determines the fraction of gases passing by the mouth. After the gas passes the mouth it enters the CO_2 scrubbing unit, which is represented by a shrinking pore model described in more detail later. This model gives the concentration of CO_2 coming out of the LiOH bed. Then it calculates and records the scrubbing efficiency and total moles scrubbed. Finally it figures the new volume of gas in the breathing bag, which is due to the influx (expiration) of gas from the human.

Most respirator breathing bags are equipped with a relief valve to prevent the bag from over filling. This model is no exception. It compares the new bag volume to the maximum bag volume, which is an input variable of the respirator characteristics subroutine, and then finds the volume that needs to be vented. This value, along with the total volume of O_2 produced and CO_2 scrubbed, is recorded and printed along with the rest of the test data.

The model increments on a breath-by-breath basis. It sends data to an averaging routine after every breath, from which half minute averages are calculated and written to an output file, as well as being presented on the CRT screen. This output file contains the work rate; all of the human breathing characteristics; the inspired and expired gas fractions of O_2, CO_2, and N_2; and the previously mentioned values of O_2 produced and CO_2 consumed. The model also includes in its half minute reports the amount of O_2 received via the demand valve, the amount of gas vented and the scrubbing efficiency of the canister (Figure F1-2).

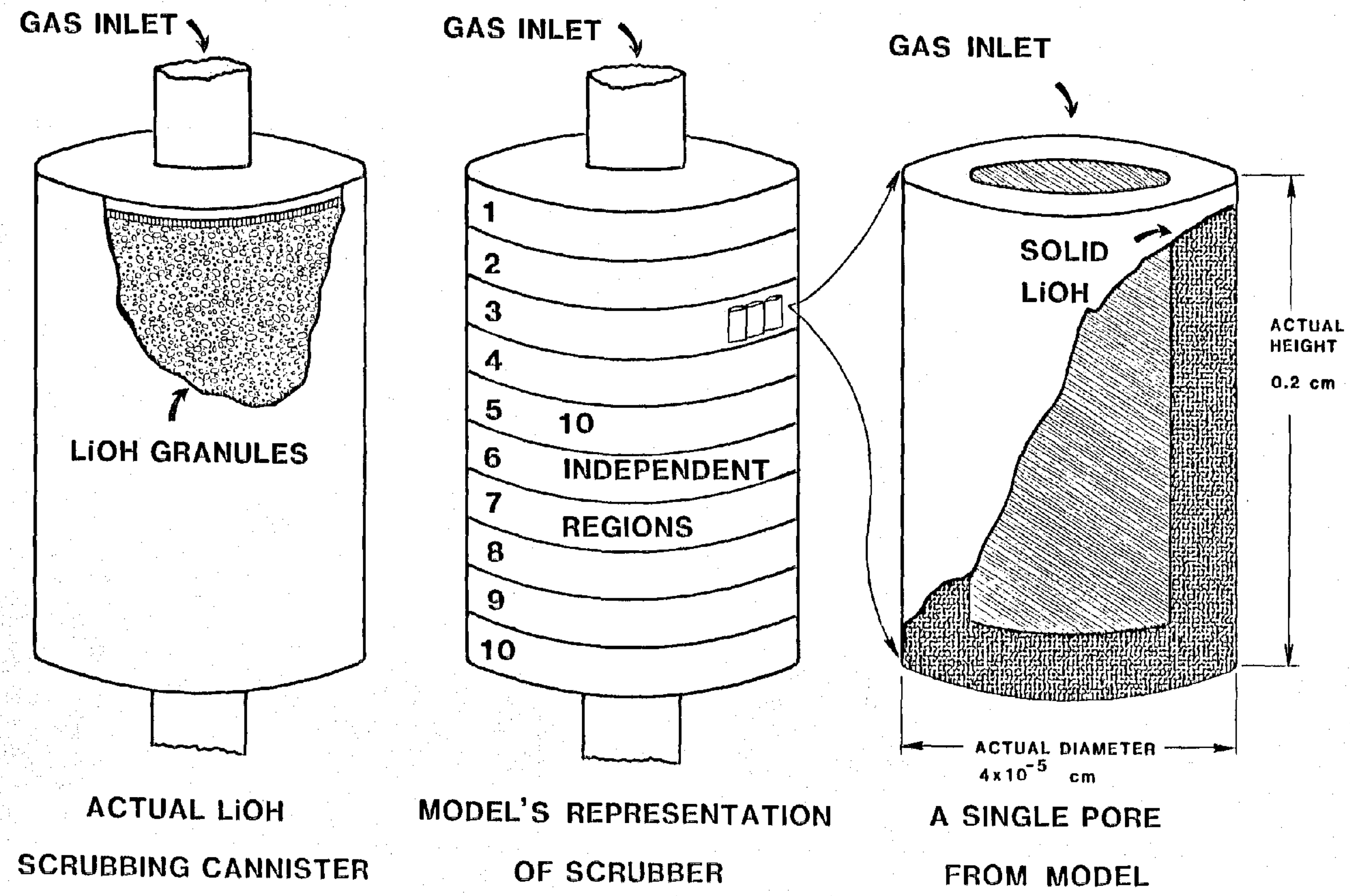

Figure F1.2. Diagram showing progression from actual respirator CO_2 scrubber to a single pore within the CO_2 scrubbing subroutine

The model has now completed one entire breath. The protocol must be checked at this point to determine whether a new work rate is required. If it is, the model reads in a new set of data and continues to breathe. If a new work load is not required, the model goes to the next phase of a breath and continues until the total time of the test is exceeded or until it is determined that the respirator has failed the test for any reason set forth in the MSHA/NIOSH rules and regulations.

Obviously the REMOD system cannot run or climb a ladder. Therefore the exercise is performed by human subjects and the intensity levels are recorded. Kamon, Bernard and Stein (1975) measured the steady state response to each of the activities required in the MSHA/NIOSH 30 CFR Part 11 regulations for humans. In another paper Bernard, Kamon, and Stein (1979) give equations describing the relationship between VO2 and VE with the rate of CO2 production (VCO2) and the frequency of breathing (FB). The equations are based on an average (50th percentile) miner's body weight and fitness level. A 95th percentile man can be approximated by adding 1.65 to the mean value of VO2 or VE and multiplying by the standard deviation. The other values can then be recalculated based upon the higher VO2 and VE values. These values for the steady state responses to the activities required in the man tests are calculated and input as variables into the human side of the simulation.

The respiratory and circulatory systems' ability to provide O2 during these tests lags behind the start of exercise, causing the human subject to accrue an O2 deficit as the muscles resort to anerobic processes to produce the necessary energy during the transient period between the beginning of exercise and the steady state value. This O2 deficit must be repaid as soon as the exercise ceases. During this transient "repayment" period the body's aerobic activity remains elevated.

Estimation of the human's aerobic activity, i.e., oxygen consumption and carbon dioxide production, during this transient period is more difficult to predict than the steady state responses. We calculated the values for the transition periods from regression equations presented by Linnarsson (1974). He measured the response of eight subjects to step changes in work load and fit first and second order exponentials to the output waveforms. He presents equations for both the step up to exercise and the step down from exercise for VO2, VCO2, VE, tidal volume (TV), and functional residual capacity (FRC).

The CO2 Scrubbing Unit Model:

The second half of this chapter concerns the shrinking pore model used in conjunction with the REspiration MODel (REMOD) program. This pore model simulates the scrubbing action of the lithium hydroxide (LiOH) in the respirator's absorbing canister. The basic idea for the model was taken from two papers, one by

Ramachandran and Smith (1977) and the other by Chrostowski and Georgakis (1978).

Boryta and Maas (1982) state in their paper that "The absorption of CO_2 by LiOH is apparently a diffusion controlled process". With this in mind we decided to implement a kinetic reaction model based entirely on diffusion. The aforementioned papers described models of this type. We decided to use a modification of these models for several reasons:

1. "...the effect of chemical kinetics on the absorption process is not as important as the dynamics (dimensions) of bed configuration" (Boryta & Maas, 1982).

2. The physical properties required of the reactant and the product are not all known. This problem was faced by the other authors when trying to validate their models.

3. The methods for solving the differential equations involved are complex and time consuming. One of the main goals of the model was to have it run faster than real-time on a small computer. The models described in the published papers could not be solved within this time constraint.

4. Representing the functional characteristics of the CO_2 scrubber was more important to the overall study than requiring that the scrubber characteristics be determined from the most rigorous absorption models.

After considering this information, we decided to create a simplified version of a shrinking pore model as the CO_2 scrubber portion of the overall model. The equations describing the initial pore dimensions were taken from the paper by Ramachandran and Smith (1977). These equations determine the initial pore radius, initial wall thickness and the overall depth of the pore, based on macroscopic properties of the LiOH granules. The total chemical bed is divided into ten equal regions, by volume, representing the actual scrubbing bed within the respirator. The regions are divided along the axis of flow through the bed. Each region's pores are independent of the other nine regions of the bed. Each region contains a large number of "small" pores assumed to be homogeneously distributed (Figure F1-2). This allows plotting of the pore radius as a function of bed length. Also, the concentration of the outlet gas from each layer, or region, of the bed can be plotted, detailing exactly the concentration profile within the scrubber.

The equation governing the absorption rate or reaction rate of the CO_2 is divided into 2 distinct terms. The first term:

K1 * (rad)**2 * pi * conc / pore depth (1)

where: rad = the radius of pore mouth
pi = 3.14159
conc = the concentration of CO_2 entering
pore depth = depth of pore
K1 = diffusion coefficient (cm**2/min)

The first term models the diffusion of the gas into the pore, taking into account the cross-sectional area of the pore, the concentration of the gas, and the depth of the pore. A single diffusivity constant (K1: cm**2/min) from this term (1) is varied to improve the fit of the model data to empirical data, as Ramachandran and Smith did in their study. This constant is related to the diffusion coefficient of the gas within the pore and/or the reaction rate constant. We assume that the reaction occurs so rapidly that for practical purposes the constant can be reduced to a basic diffusion rate constant. It is assumed that the absorption rate is proportional to the concentration of gas at the pores opening.

The second term of the equation accounts for the decrease in diffusion rate through the reaction product as the product layer thickness increases. The second term:

K4 * (fractional change in pore radius)   (2)

where: K4 = diffusion constant (cm**2 x Vol%)/min

The decrease in diffusion is proportional to the fractional change in the pore radius. Chrostowski and Georgakis (1978) make a similar adjustment in the diffusion constant in their model.

The overall equation, combining the first and second terms, predicts the number of moles of CO_2 absorbed in each region:

(1st - 2nd) * (Num pores/Mol vol) * Res time   (3)

where: 1st = the first term (1)
2nd = the second term (2)
Num pores = number of pores in each region
Mol vol = molecular volume of an ideal gas
Res time = residence time of gas in each layer

In terms of an electronic analog, the first term (1) of the overall equation can be thought of as a conductance (A) and resistance (B) in series (Deno, 1983).

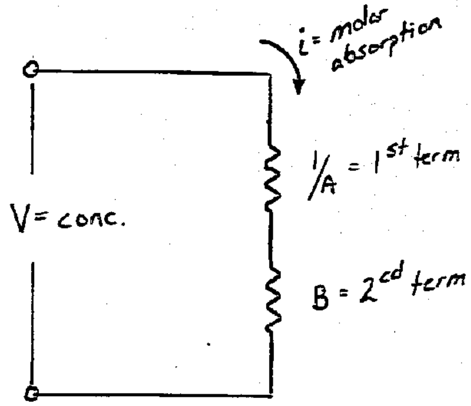

Figure F1-3. Circuit diagram

This term, the rate of molar absorption, can be thought of as the current (i) in the circuit. With this circuit, the concentration is analogous to the voltage. Now, the equation describing the rate of absorption (i) would be written as i= Conc x(AxB/A+B). We have approximated this equation by i= Conc x(A - 1/B), and assume that B is never equal to zero.

The simulation begins with B at positive infinity and proceeds toward the lower limit of zero. Based upon the molar volumes of both the product and the reactant and the stoichiometric limitations of the chemicals, the reactant (LiOH) will be exhausted long before the pore closes. Pore closure is equivalent to the 'B-equals-zero' condition. If one considers the two equations near the initial limit of B equal to infinity, the rate of absorption is nearly identical for both equations.

To be perfectly correct, the concentration of the gas should be allowed to vary over both the axial and longitudinal dimensions of the pore. This condition would require a partial differential equation in three variables. Other authors (Baasel & Stevens1961; Chrowstowski & Georgakis, 1978; Ramachandran & Smith, 1977; Szekely & Evans, 1970) have assumed the longitudinal concentration to be a constant, and written differential equations in two variables. We assume that both the axial and longitudinal concentrations within the pore are constant. This assumption is most prevalent in the second term of the overall absorption equation. This assumption allows us to combine the concentration and the diffusion constant of the second term (2cd) into one new constant K4 :(cm**2 x Vol %)/min.

The second equation describing the basic model calculates the change in volume of the pore.

Vol = Mol abs * (Vol pro - 2*Vol reac) / Num pores

where: Vol = change in volume of the pore
Mol abs = number of moles CO2 absorbed
Vol pro = molecular volume of the product
Vol reac = molecular volume of the reactant

Num pores = number of pores in each region

This change in volume of the pore is used to find the new (smaller) pore radius. The pore closes down as the reaction progresses due to the change in molar volume of the reactant as it proceeds to the product stage. It is assumed that this change (2.2 ml/mole CO_2 absorbed Markowitz, 1965) in volume of the pore is spread out evenly over the entire pore. It is known how many moles of CO_2 enter the region and the number exiting and therefore the number of moles of CO_2 absorbed. The number of moles of Li_2CO_3 formed can be calculated based on the overall chemical reaction:

$$2\ LiOH + CO_2 \ == \ Li_2CO_3 + H_2O$$

The number of moles of CO_2 absorbed for each mole of LiOH present is set at the theoretical value of 1:2 from the above equation. A weakness in our model is that the quantity of the intermediate product, $LiOH\text{-}H_2O$, is not predicted. The equation above is the overall sum of two equations:

$$LiOH + H_2O == LiOH\text{-}H_2O$$

$$2\ LiOH\text{-}H_2O + CO_2 == Li_2CO_3 + 3\ H_2O$$

Boryta and Maas (1982) performed a chemical analysis of the LiOH bed at the end of each test and found that the intermediate product $LiOH\text{-}H_2O$ could account for over ten percent of the volume of the chemical. In their experiment, Boryta and Maas changed the reactant-product ratio from 1:1 to the theoretical value of 1:2 by controlling the production of the intermediate product. They accomplished this by varying the humidity and temperature of the inlet gas. Since our model is not able to predict this intermediate product, an arbitrarily chosen intermediate value is used exclusively.

Results of the Validation of the Pore Model:

To validate this model, we used data from two independent papers by Boryta and Maas (1982) and Bernard, Kyriazi, and Stein (1979) which describe a set of continuous flow experiments. Boryta used a balanced, two-level factorial design with fractional replication composed of 39 tests including center points. The independent variables in this experiment were (a) bed length, (b) lineal gas velocity, (c) input CO_2 concentration, (d) $gCO_2/gLiOH$ -absorption capacity, (e) temperature, and (f) relative humidity. Since our model does not take all of these variables into account, we could only use a portion of his data in our validation.

Table F1-1 shows the results comparing our model, in a continuous flow mode, to Boryta's data. The tests shown below all had similar (a) bed length, (b) temperature, and (c) relative humidity characteristics. Test number 4 had an inlet gas concentration of 1.1 percent CO2, while all the other tests had 4.4 percent as the inlet CO2 concentration.

Table F1-1

Test	VEL	bT1	mT1	bT2	mT2	bT3	mT3	bCAP	mCAP
3	457	13.1	25.6	61.7	65.8	73.0	71.7	0.63	0.71
4	2901	3.3	0.0	3.9	0.0	46.8	49.6	0.27	0.26
16	2905	4.3	0.0	5.1	0.0	87.0	97.0	0.42	0.39
27	463	13.5	24.5	59.0	60.8	72.0	73.1	0.62	0.65
2	2886	4.5	0.0	5.0	0.0	47.0	49.6	0.27	0.26
39	951	2.5	0.0	21.5	33.8	34.6	40.8	0.52	0.66

Where:
TEST: Individual tests (Boryta & Maas, 1982)
VEL: Inlet lineal gas velocity (cm/min)
prefix b: Boryta's test results
prefix m: Models predicted value
suffix T1: Time for outlet fraction 0.5 % (minutes)
suffix T2: Outlet fraction 1/2 the inlet concentration
suffix T3: Final time of the test (minutes)
suffix CAP: Grams of CO2 absorbed/grams LiOH present.

Figures F1-4, F1-5, and F1-6 show the effects of varing inlet gas velocity upon CO2 fraction at the outlet of the scrubber versus time. Inlet gas velocities are: Figure F1-4) 457 cm/min. Figure F1-5) 951 cm/min. Figure F1-6) 2901 cm/min. The circles on Figures F1-4, F1-5, and F1-6 represent the value of the outlet gas concentration at the three discrete times reported by Boryta and Maas (1982). The continuous line shows the value the model predicts over time, given the same inlet gas velocity as in Boryta's experiment.

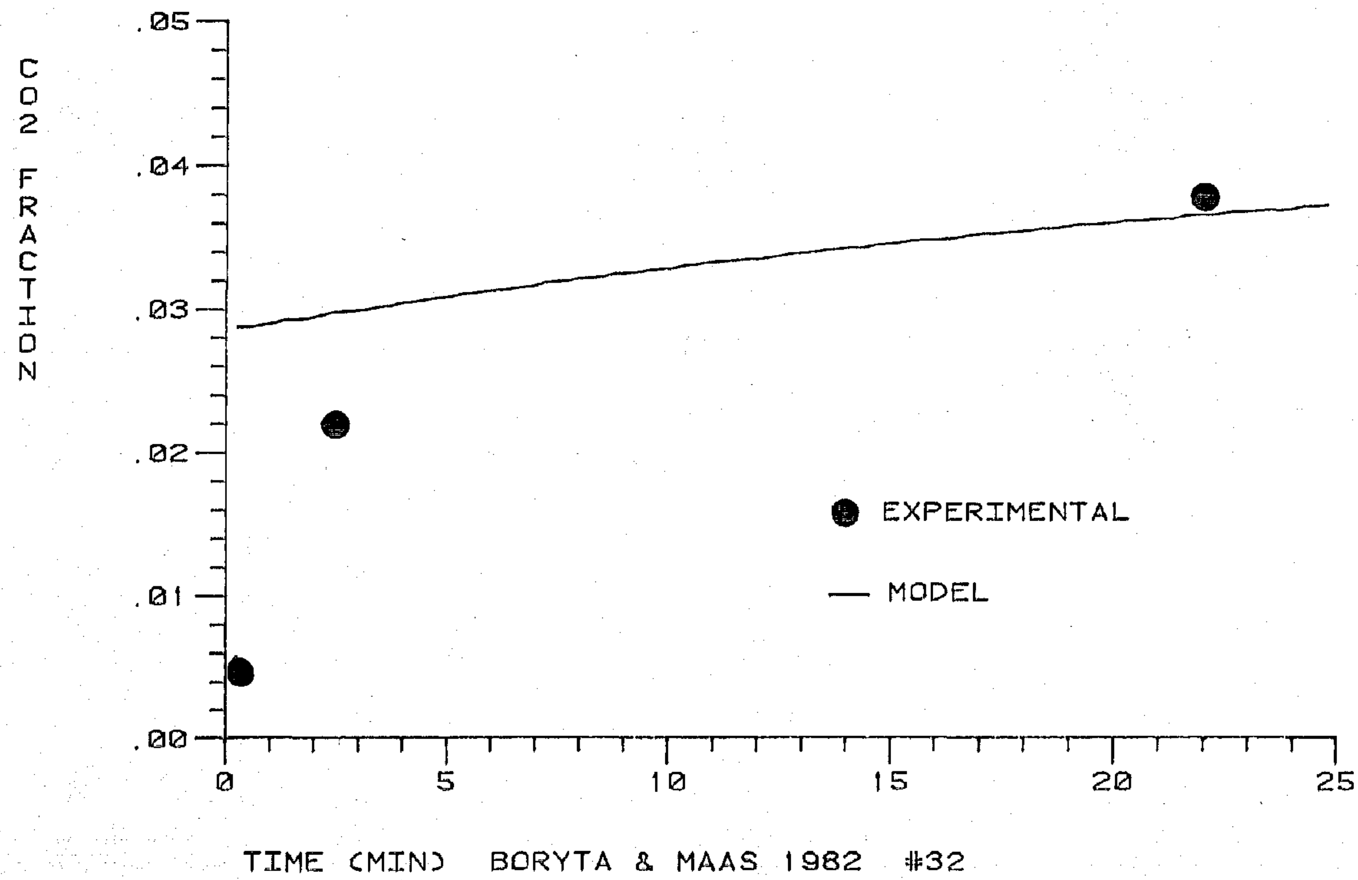

Figure F1.4. CO_2 fraction as a function of time for an inlet lineal gas velocity of 2995 cm/min (Boryta and Maas, 1982)

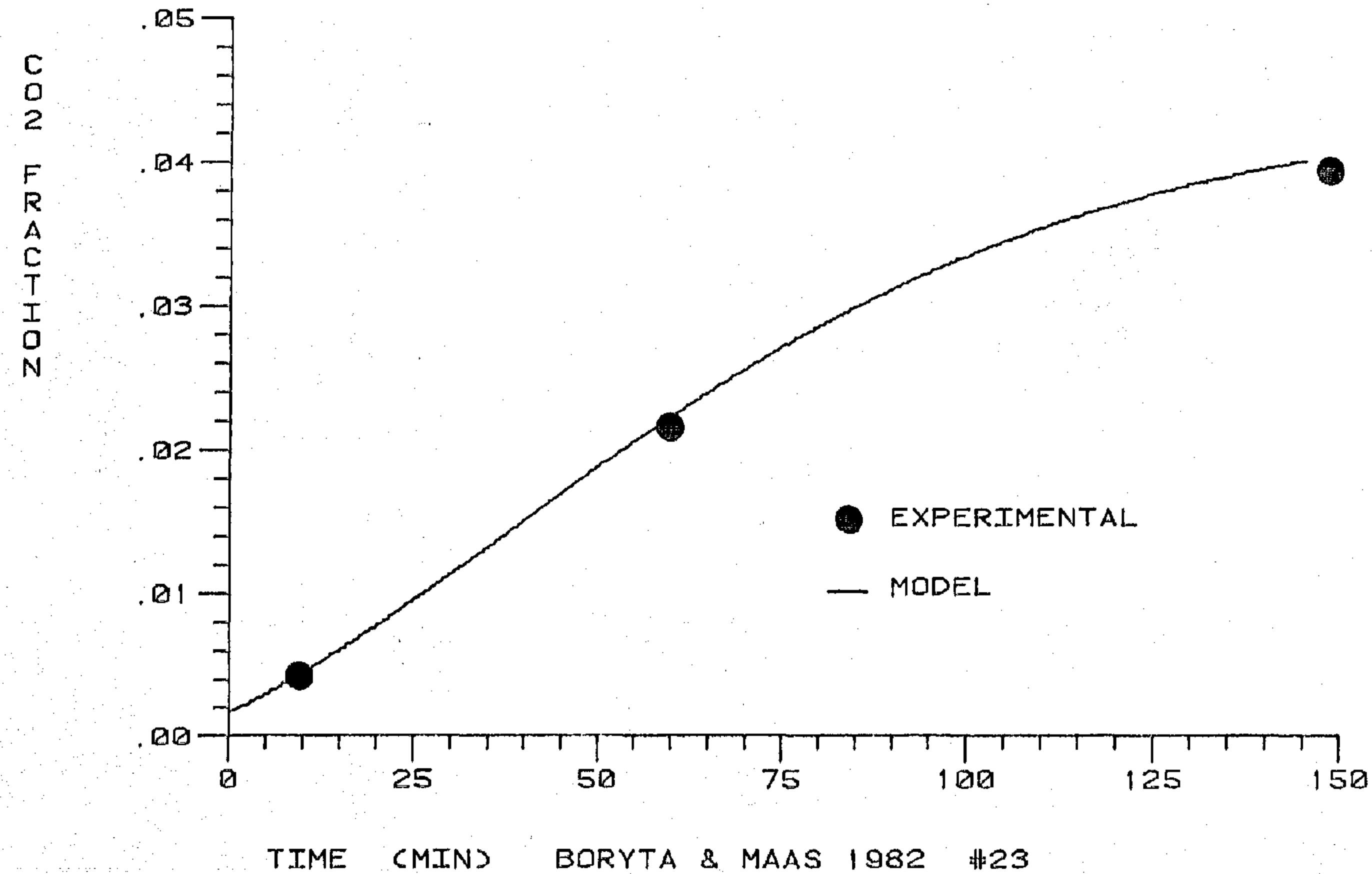

Figure F1.5. CO_2 fraction as a function of time for an inlet lineal gas velocity of 453 cm/min (Boryta and Maas, 1982)

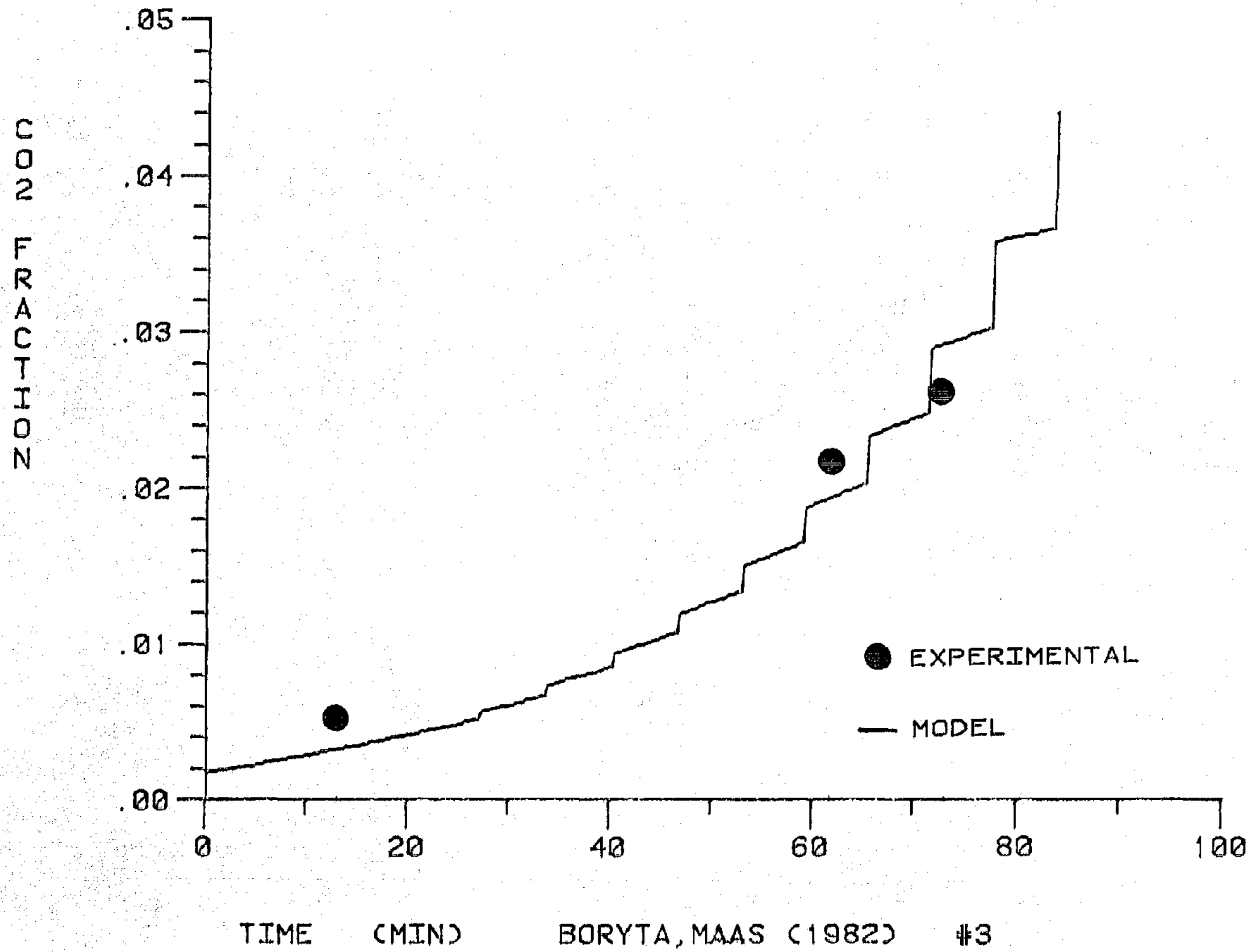

Figure F1.6. O_2 fraction as a function of time for an inlet gas lineal velocity of 457 cm/min (Boryta and Maas, 1982)

Figure F1-7 shows the results of an entirely separate set of experiments performed by Bernard, Kyriazi, and Stein (1979). They used an actual, LiOH, CO2 scrubbing unit from a production model respirator in the experiments. They connected this canister "to a breathing machine designed to simulate the human breathing pattern at a moderate work rate". This machine pumped compressed gas of 3.5 percent CO2 in air through the canister. The exit air was sampled and the CO2 concentration recorded. Three different work rates were chosen which produced three different gas flow rates. Three tests were run at each flow rate and the results averaged to obtain a mean response. "Maximum deviations about the mean were plus or minus twenty percent". Table F1-2 shows a comparison of break through times (0.5 percent CO2) between the model and Bernard's data.

Table F1-2

Flow rate (l/min)	Bernard's time (minutes)	Model's prediction (minutes)
48	216	219.7
37	318	326.4
26	495	541.4

Total Absorption Capacity 0.5 percent:gCO2/gLiOH

Bernard: 0.49   Model: 0.51

The next section is devoted to showing the internal workings of the pore model. Various investigators (Chrowstowski & Georgakis, 1978; Ramachandran & Smith, 1977) have shown similar graphs as a validation for their models. These figures show the changes in pore radius and CO2 concentration at different levels within the model. The values are shown at several different times to characterize the dynamic action of the pore model.

Each line in Figures F1-8, F1-9, and F1-10 shows the inlet CO2 fraction at each region of the bed. The total time of the test was evenly divided into six segments in order to show the variation in CO2 profiles with time. At the lower inlet gas velocities (Figure F1-4) the CO2 is absorbed near the beginning of the scrubbing canister. As the gas velocity is increased (Figures F1-9, F1-10), the concentration profile becomes more linear owing to the decreased residence time of the gas at each stage (layer) of the model (Wang, 1981).

Each line in Figures F1-11, F1-12, and F1-13 shows the pore radius at each layer within the model. The total test time was again evenly divided into six segments in order to show the change in pore radius with respect to time throughout the test. The uppermost line in each of the graphs represents the initial pore radius at time zero. These graphs depict the closing down action within the pore due to the increased molar volume of the product.

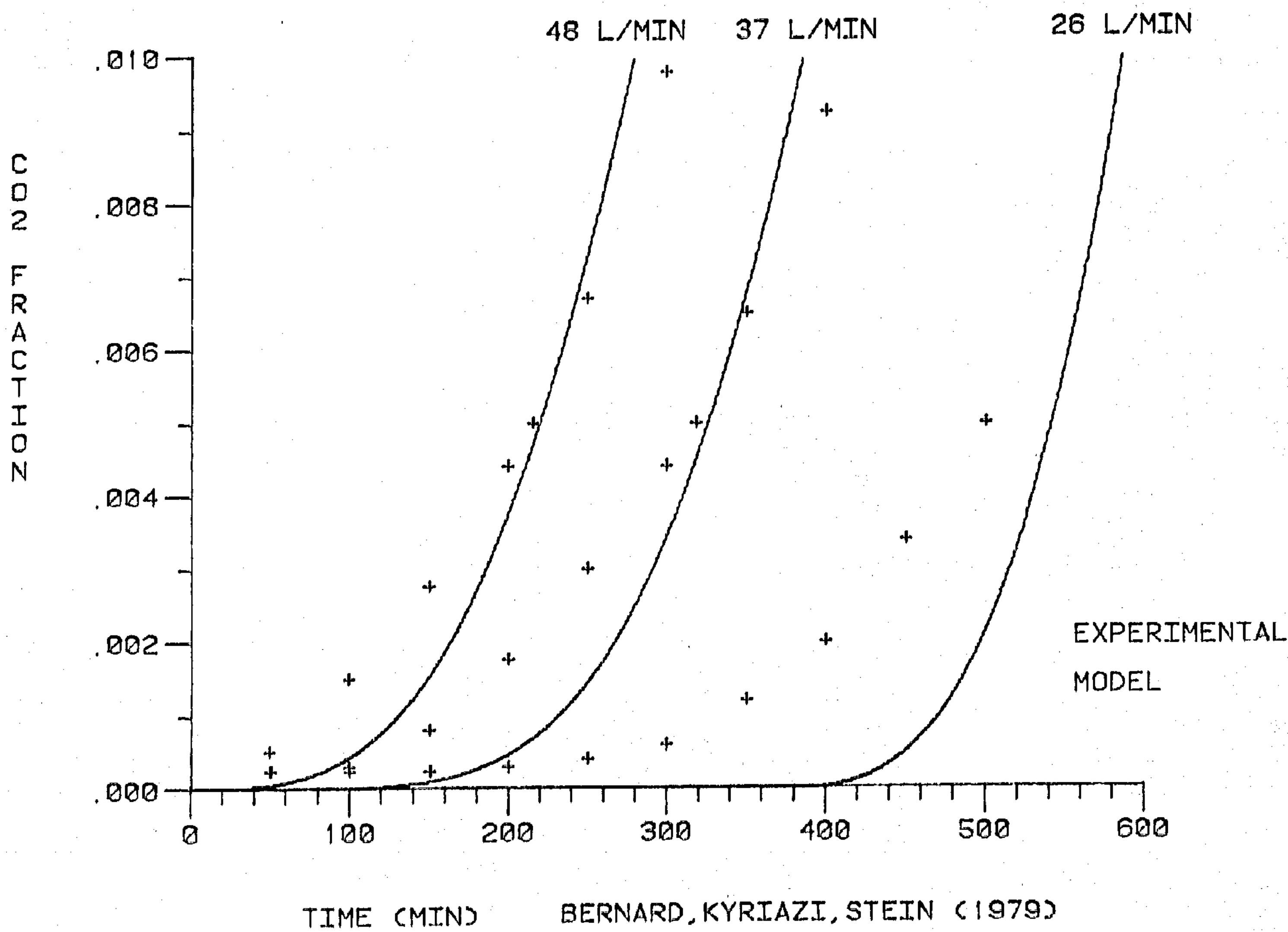

Figure F1.7. CO_2 fraction as a function of time for different inlet gas velocities

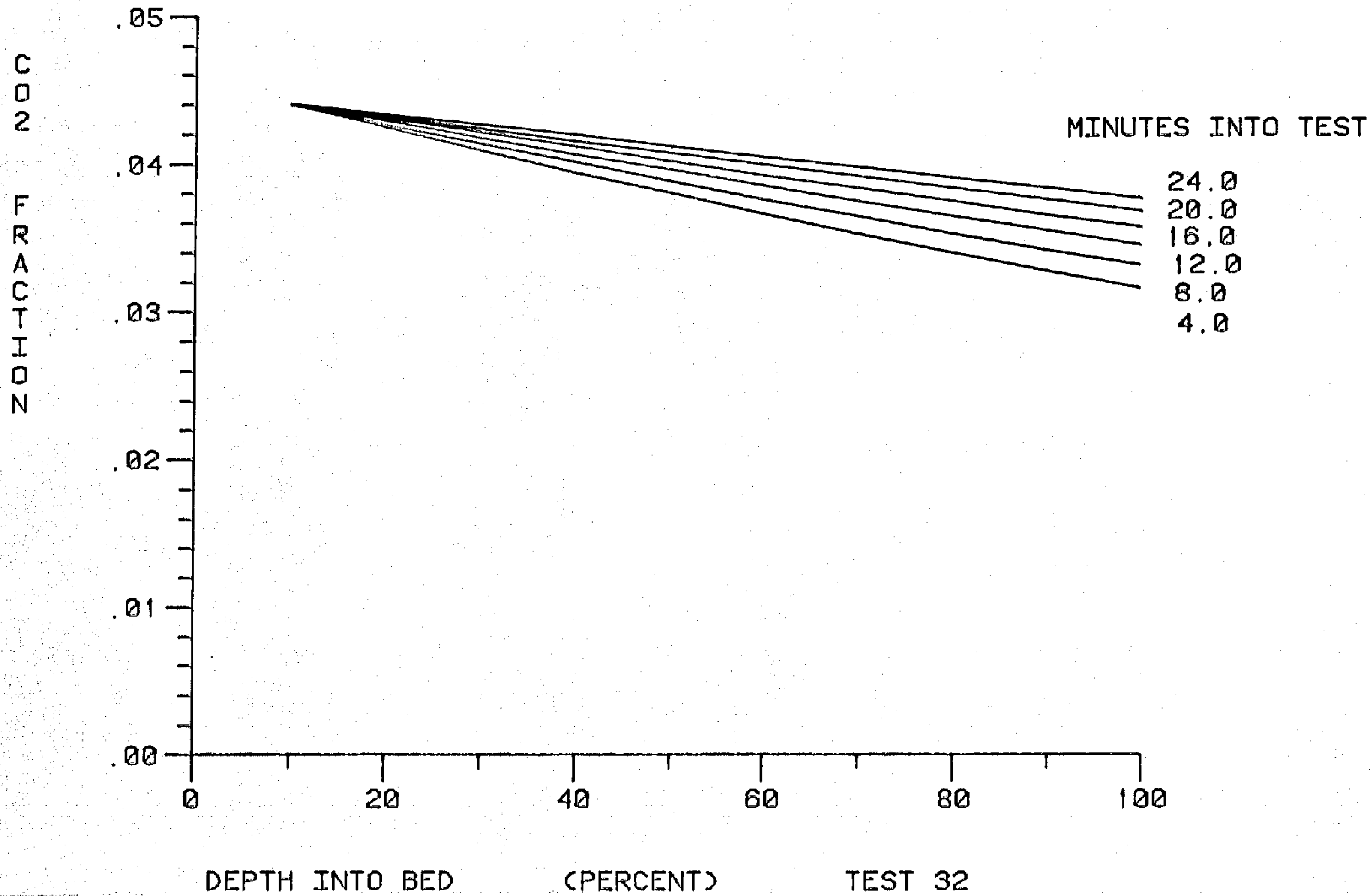

Figure F1.8. O_2 fraction as a function of distance into the CO_2 scrubber at several test times (Inlet lineal gas velocity = 2995 cm/minute)

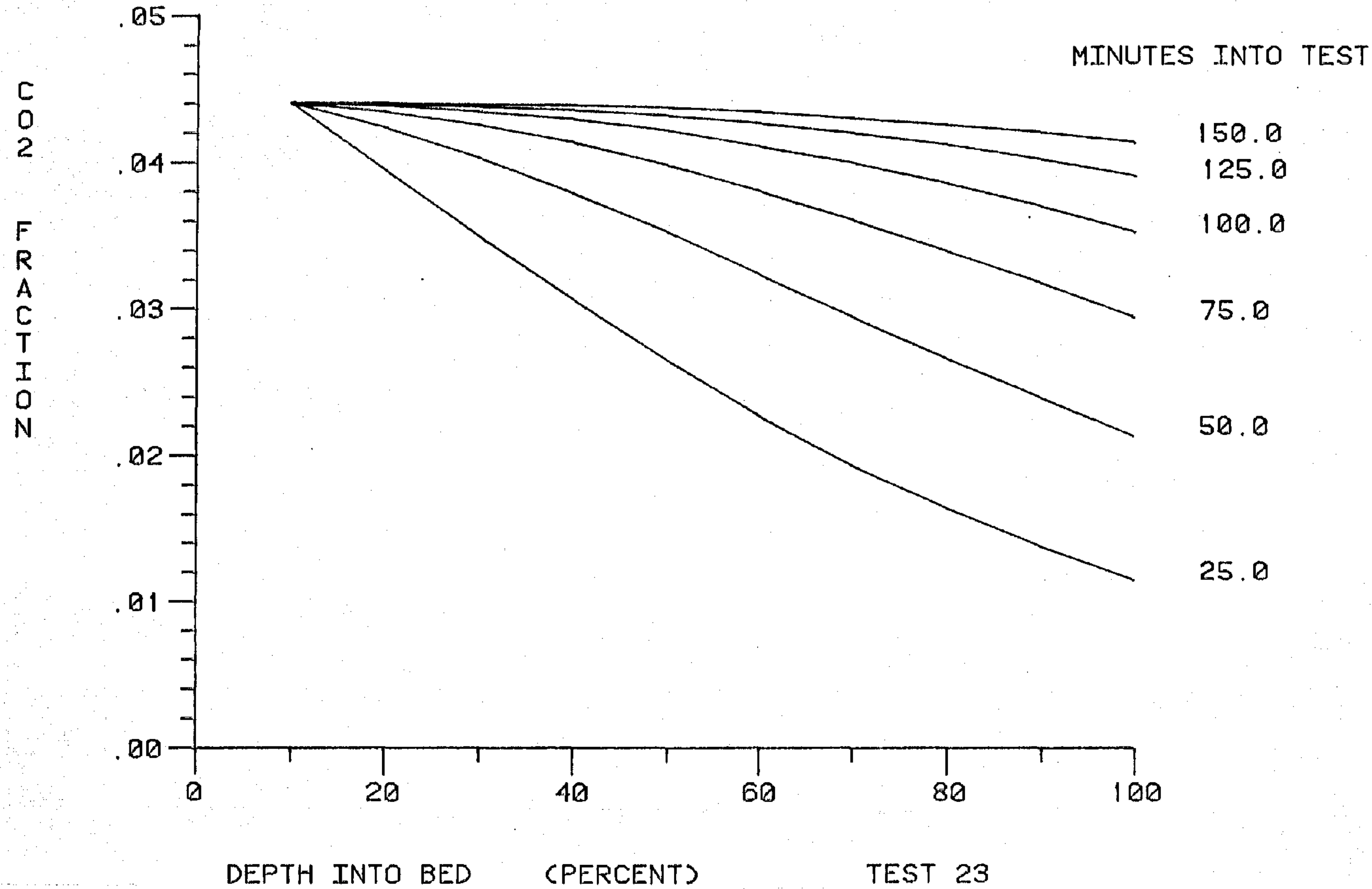

Figure F1-9. CO_2 fraction as a function of distance into the CO_2 scrubber at several test times (Inlet lineal gas velocity = 453 cm/minute)

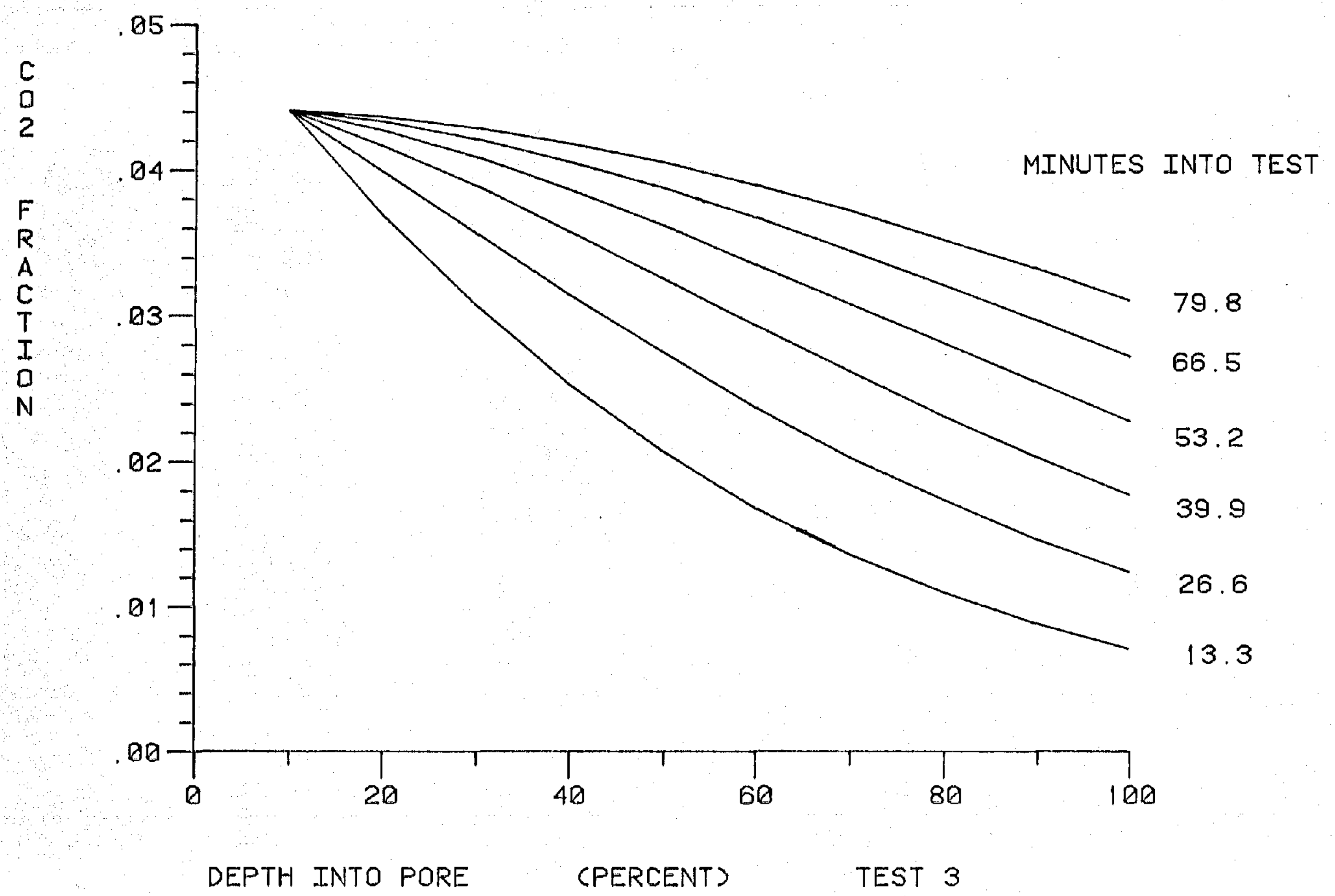

Figure F1-10. O_2 fraction as a function of distance into the CO_2 scrubber at several test times (Inlet lineal gas velocity = 457 cm/minute)

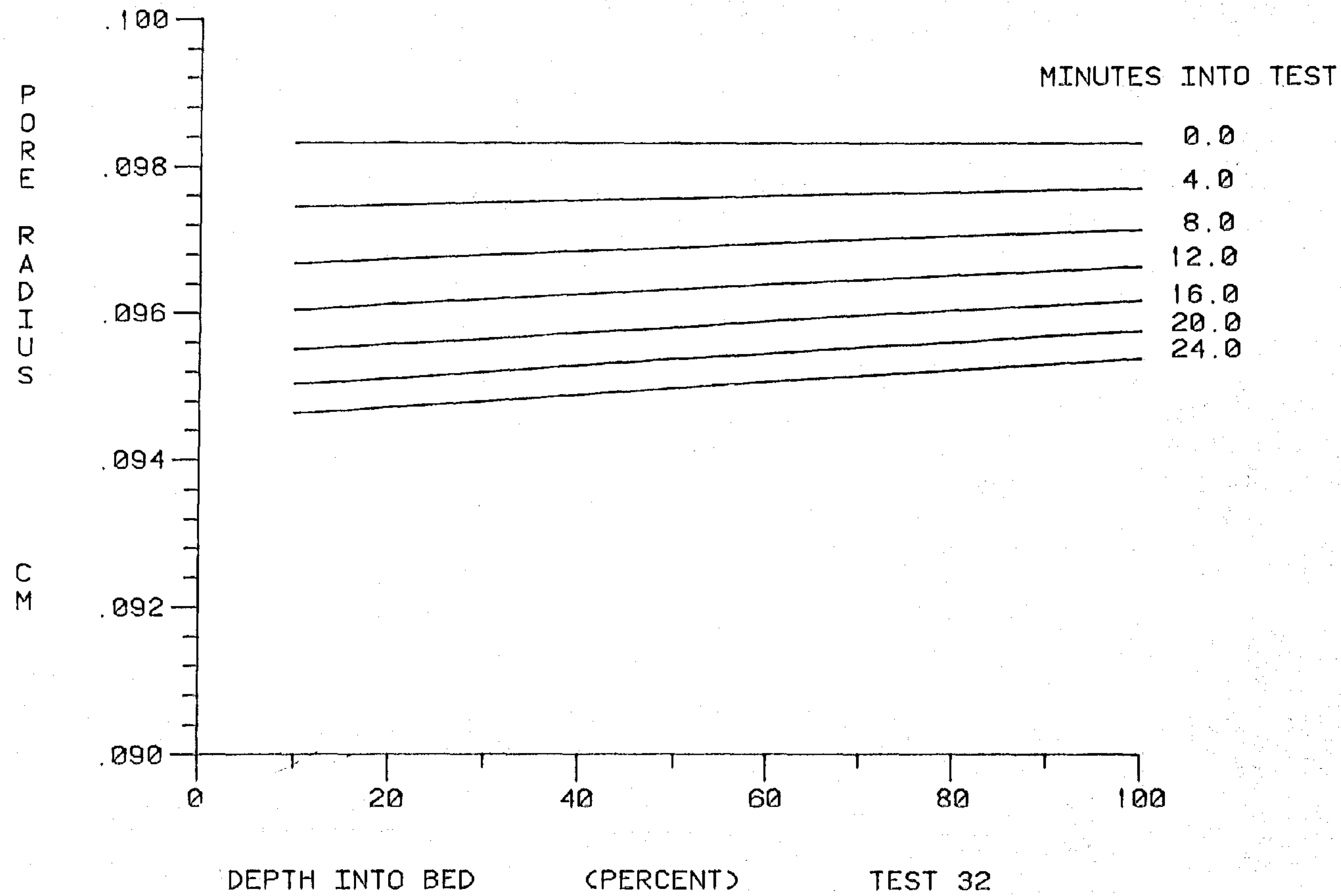

Figure F1-11. Pore radius as a function of distance into the CO_2 scrubber at several test times (Inlet lineal gas velocity = 2995 cm/minute)

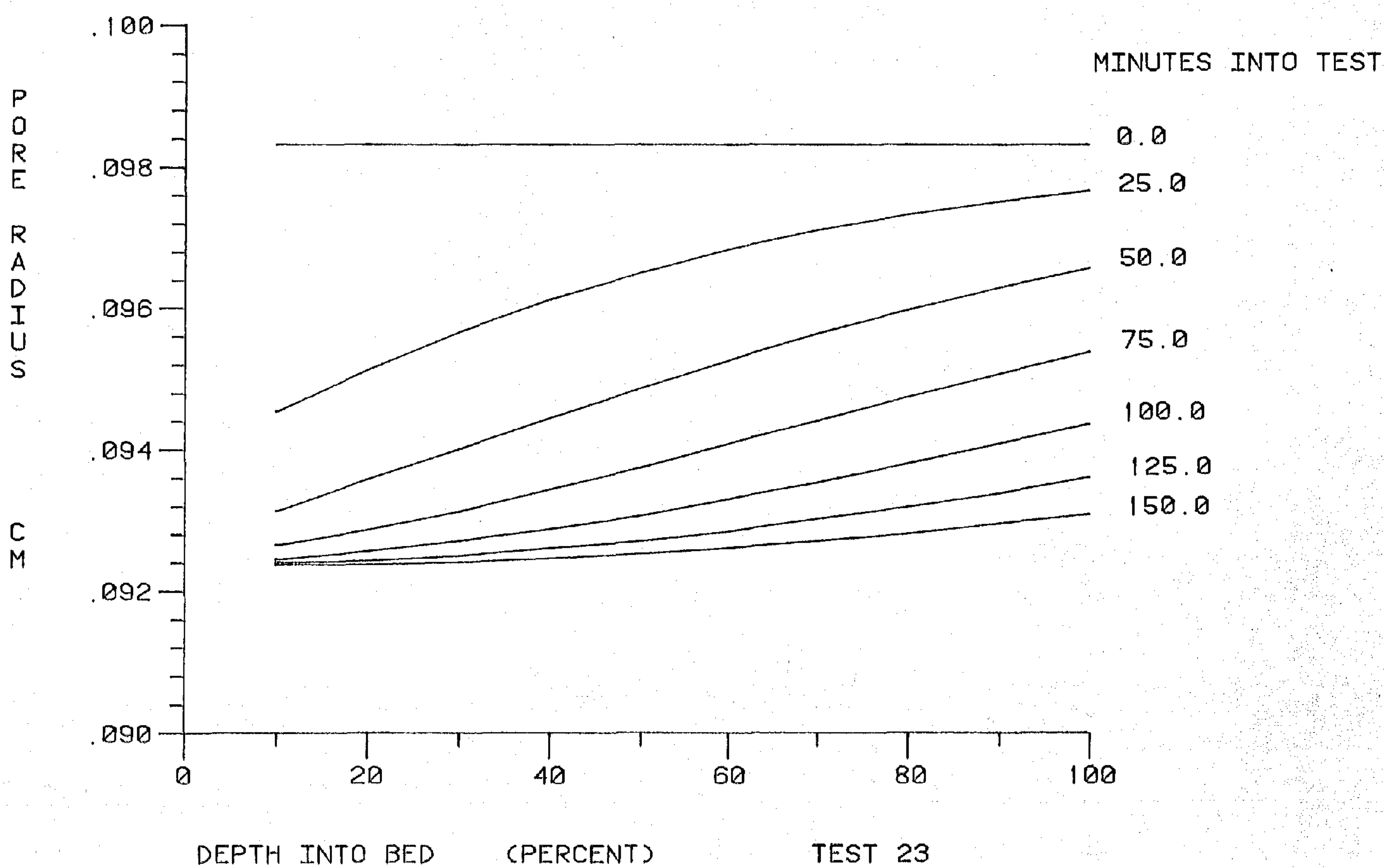

Figure F1-12. Pore radius as a function of distance into the CO_2 scrubber at several test times (Inlet lineal gas velocity = 453 cm/minute)

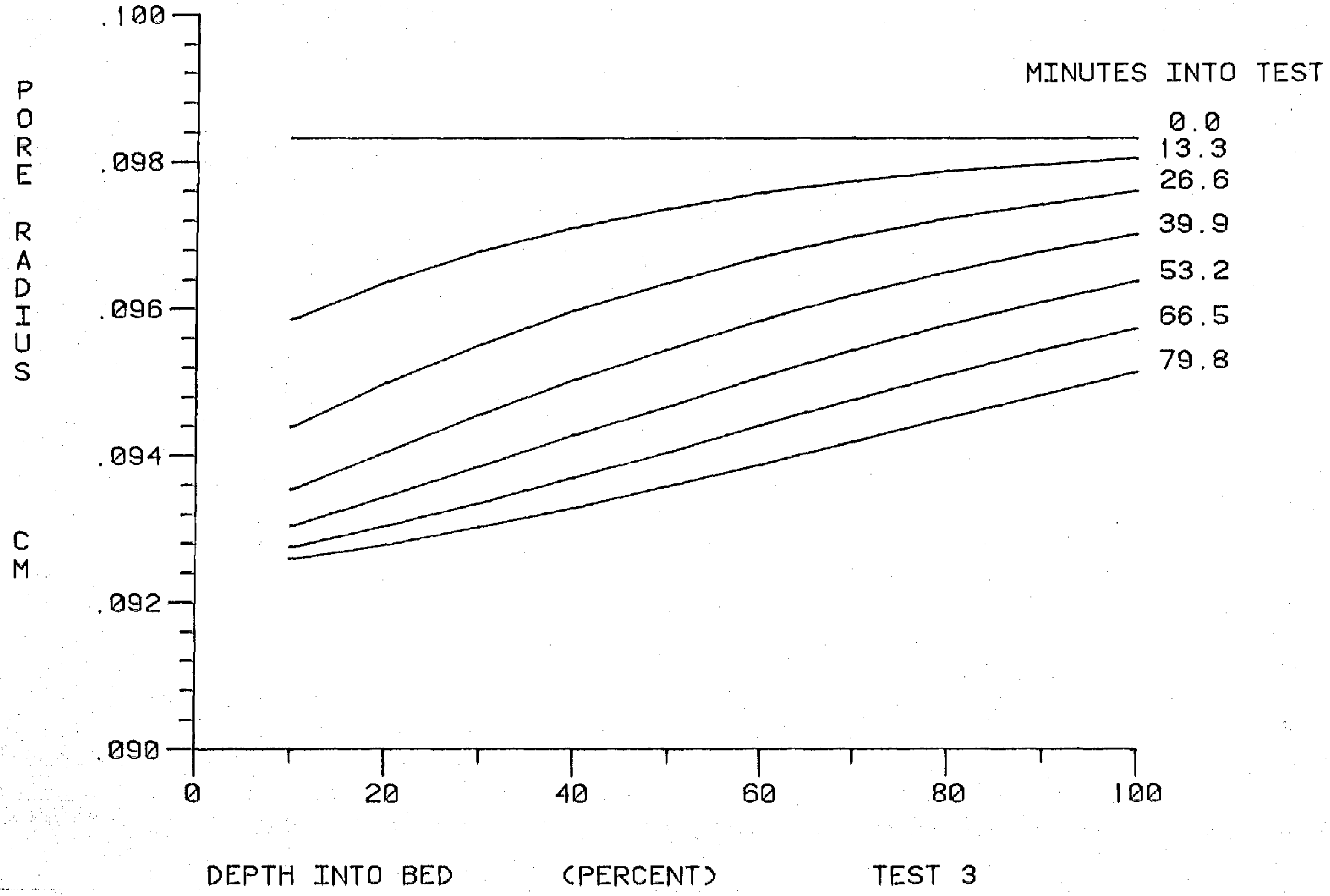

Figure F1-13. Pore radius as a function of distance into the CO_2 scrubber at several test times (Inlet lineal gas velocity = 457 cm/minute)

Discussion of these Results:

Tests 4, 16, 28, and 39 from Boryta and Maas (1982), shown in Figures F1-4 and F1-5, could not be adequately predicted at the first two times. This could be due to their set-up. The first time may have been affected by the lag time of their experimental set-up rather than by the absorption of the CO_2. The error in the second time could also be explained time of the system. This explanation seems likely after comparing the third times and the total absorption capacities. When plotting the concentration at the outlet of the canister versus time, the area under this curve would be proportional to the amount of CO_2 absorbed during the test (constant flow). Considering the possible lag in Boryta's data, our model is producing a good replication of Boryta's experimental data.

Figures F1-8, F1-9, and F1-10, giving the CO_2 fraction as a function of depth in the bed measured in terms of percent of the total bed length, show the same characteristic in a different manner. Figures F1-8 and F1-9 show an initial steep drop in the CO_2 fraction as the gas proceeds into the bed. As the total test time increases, the slope of this line decreases drastically until, near the end of the test, the concentration profile thoughout the bed is nearly constant. This constant signifies that the bed is no longer absorbing CO_2. A paper published by E.E. Peterson (1957) on "Reactions of Porous Solids" has graphs showing the same type of concentration profiles within the absorbent bed. The graph of test 32 (Figure F1-10) shows the concentration profile throughout the bed during a test with a high inlet gas velocity. This graph shows that the CO_2 is literally being blown through the canister, significantly decreasing the diffusion time and therefore severely limiting the absorption rate of the CO_2 (Adriani & Rovenstine, 1941; Wang, 1981).

Figures F1-11, F1-12, and F1-13 showing pore radius as a function of depth into the absorbent bed explicitly reveal the pores' closing down as a function of time. Near the beginning of the test, when the majority of the CO_2 is being absorbed at the beginning of the canister (Figure F1-8) the graph shows that the pores in the first three regions are closing down much more rapidly than those in the later regions. Figure F1-13 shows all the pores closing down at virtually the same rate. This is due to the elevated levels of CO_2 thoughout the bed (Figure F1-6) during the test, since diffusion and reaction rate are both proportional to CO_2 concentration.

An important characteristic of the pore radius versus depth into the bed is best exemplified in Figure F1-13. The last 2 sample times in this graph show the change in pore radius was much smaller than the previous changes. This suggests that the pore will reach some limit after which it will cease to close down. Ramachandran and Smith (1977) give an equation for predicting the maximum conversion of the reactant. When the values for LiOH granules are substituted into this equation it predicts that the pores will not close entirely. The apparent limit on the pore radius in Figure F1-13 shows this characteristic of the LiOH granules.

Figure F1-7 comparing Bernard's data to the predicted values of the model shows a slightly different slope between the two data sets. One possible explanation of this discrepency lies within the assumption of our model that channeling within the scrubber bed does not occur. This channeling within the scrubber would account for the elevated CO_2 levels during the early portion of the test. At the longer test times, the model's predictions of outlet CO_2 concentration are on the high side. This can also be accounted for by channeling. The model has used up a greater majority of its chemical during the early portion of the test, hence the ability of the bed to absorb CO_2 is greatly reduced.

The shrinking pore model that has been developed adequately predicts the output concentration and total absorption capacity of the LiOH scrubbing cannister. The most important model output in terms of actual respirator design is the length of time the LiOH in the canister keeps the output CO_2 concentration below the 0.5 percent limit established by MSHA/NIOSH. Based on Boryta's and Bernard's data, our model predicts this time well. This simplified model also shows important characteristics of the pore models described by Ramachandran and Smith (1977) , and Chrostowski and Georgakis (1978).

INSTRUCTIONS FOR RUNNING THE MODEL

1) Put protocol wanted into PROTO.DFS

   a) The form of the file is:

```
 SIMULATION OF MAN TEST  4
VCO2       RR       VO2       VE       TIME
0.336    19.700   -0.350    7.2930    2.0
```

   NOTE:

   a) VCO2, VO2, and VE are in liters/min

   b) RR is in breaths per minute

   c) TIME is the ending time for each particular work load

2) Put respirator characteristics into RESPIR.DFS

   a) The form of the file is:

```
     100.0          RESPIRATOR DEAD SPACE  ml
    5000.0          MAXIMUM BAG VOLUME ml
    1500.0          CONSTANT O2 FLOW RATE INTO BAG ml/min
  130000.0          MAXIMUM AM'T O2 PRODUCED ml
     300.0          GRAMS LIOH IN SCRUBBER
      10.2          LENGTH OF SCRUBBER cm
       4.4          RADIUS OF SCRUBBER cm
       0.5          RADIUS OF PELLETS  cm
    3500.0          INITIAL RESPIRATOR BAG VOLUME ml
     731.0          AVERAGE ATMOSPHERIC PRESSURE mm Hg
       1            1 FOR BI- 0 FOR UNI-DIRECTIONAL FLOW
       1            1 FOR INSPIRATION 0 FOR EXPIRATION
```

   NOTE: If the scrubber is not round

   a) find the cross-sectional AREA of the canister

   b) take the square root of: (AREA/3.14159)

   c) this is the radius of scrubber

3) Set up a command file with the following lines:

```
COMPILE REMOD.DDD,CO2ABS.DDD,AVERG.DDD

COMPILE HUMCSE.DDD,EXPIRE.DDD,INSPIR.DDD

LINK REMOD,CO2ABS,AVERG,EXPIRE,INSPIR,HUMCSE

RUN REMOD
```

APPENDIX G1:

EFFECT OF EXERCISE AND EXTERNAL BREATHING RESISTANCE ON FLOW RATE AND PRESSURE WAVEFORM

The effects of treadmill exercise and added respiratory resistance on breathing air flow waveforms were studied in five healthy male volunteers. For each testing session, data was collected while subjects stood at rest (EX0) or exercised at intensities of 20% (EX20), 40% (EX40), 60% (EX60), 80% (EX80), 90% (EX90) of their individual maximal VO2's. For each of the four testing sessions, one of four respiratory resistances was added to both the inspiratory and expiratory sides of the breathing apparatus. The resistances used were 1.2 (control), 11, 16, and 25 cmH2O at a flow rate of 120 l/min. Minute volumes and peak flows were obtained from the computer-generated mean waveforms for each subject at each exercise intensity and resistances.

The results seemed to indicate that with the addition of respiratory resistance and with the onset of exercise, the breathing waveforms showed a significant change in shape as they progressed from a more triangular or peaked waveform to a more rectangular waveform.

The effects of added respiratory resistance are of interest in medicine as they concern sufferers of obstructive lung disease and in industry as they concern individuals breathing gases of increased density (as occurs in scuba diving) and users of protective breathing devices (Flook and Kelman, 1973). Physiological variables that have typically been measured during resistance breathing include minute volume, peak flows, and oxygen consumption (VO2). For a given exercise intensity as respiratory resistance increased, minute volume decreases (Cerretelli et al., 1969; Flook and Kelman, 1973; Hermansen et al., 1972; Silverman et al., 1943; Silverman et al., 1945a; Silverman et al., 1945b), and peak respiratory flows decreased (Silverman et al., 1943; Silverman et al., 1945a; Silverman et al., 1945b) as VO2 showed no change (Cerretelli et al., 1969; Dressendorfer et al., 1977; Flook and Kelman, 1973; Hermansen et al.,1972). These response were shown to be completed within two minutes (Flook and Kelman, 1973).

A less commonly observed response was the change in shape factor (the ratio of peak flow to minute volume) as resistance was added. Extensive work in determination of breathing waveform shape factors was begun in 1943 by Silverman et al. A major intent of his research was to determine the rate of airflow and the minute volume in human subjects during various types of work and at several exercise intensities and resistances. From the collected data, breathing waveform shape factors could then be calculated and used to describe man's response to respiratory resistance and to aid in the design of human lung simulators.

In Silverman's first study (1943), inspiratory shape factors (ISF) were determined for bicycle and arm exercise. Results indicated that the shape of the inspiratory breathing waveform was converting from the normal resting sinusoidal pattern to a more rectangular pattern as a result of increased exercise intensity and/or inspiratory resistance. Silverman et al. (1943) noted that for a given exercise intensity, with the addition of inspiratory resistance, the waveforms became smoother and lower in amplitude (i.e., inspiratory peak flows decreased). Silverman et al. concluded that the type of work performed did affect breathing waveform. They further explained that the accessory muscles of respiration were brought into a different action when the arm were used, and that possibly the diaphragm had more freedom of movement in the standing position of arm exercise versus the sitting position of cycling (Silverman et al., 1951). Silverman et al. (1944) (reported in Silverman et al., 1951) also concluded that in contrast to cycling, treadmill work tended to produce inspiratory curves with higher peak flows, and therefore, larger shape factors.

Method

Subjects

Five young men participated in this study. The subject's ages, physical and pulmonary function test results are presented in Tables G1-1 and G1-2. All subjects were determined to be free from respiratory and cardiovascular illness.

Exercise

For each test, the subjects exercised through a progression of exercise intensities on a treadmill. During exercise intensity EX0, the subject stood at rest on the treadmill. Exercise intensities EX20, EX40, EX60, EX80, and EX90 were performed at a corresponding 20, 40, 60, 80, and 90 percent of his treadmill-determined VO2max. Prior to testing, the treadmill grades and speeds necessary to elicit the appropriate VO2's were calculated for each subject and were used throughout the testing. Speeds ranged from 2 to 7 mph and grades ranged from 0 to 20 percent.

Table G1.1. Physical Characteristics of the Subjects

Subject	Age (yrs)	Height (cm)	Weight (kg)	$\dot{V}_{O_2}max$ ($ml \cdot kg \cdot min^{-1}$)
A	23	176.0	70.1	46.9
B	17	181.5	70.5	57.5
C	23	182.5	85.0	45.8
D	20	182.5	74.1	55.5
E	23	179.6	80.5	60.0
$\bar{X}$	21.2	180.4	76.0	53.1
S.D.	± 2.6	± 2.7	± 6.5	± 6.4

$\bar{X}$ = mean.

S.D. = Standard Deviation.

Table G1.2. Individual Pulmonary Function Test Results (BTPS)

Subject	VC (l)	FVC (l)	FEV_1 (%)	FEV_2 (%)	FEV_3 (%)	MEFR ($l \cdot min^{-1}$)	MMFR ($l \cdot min^{-1}$)	MVV ($l \cdot min^{-1}$)
A	7.1	6.8	79	92	97	651	298	169
B	6.6	6.3	81	98	100	492	319	215
C	6.1	5.9	85	92	100	656	355	197
D	6.1	6.0	70	90	96	460	189	169
E	6.3	6.3	86	97	100	573	325	235
$\overline{X}$	6.4	6.3	80	93	98	566	297	197
S.D.	± 0.4	± 0.3	± 6.4	± 3.5	± 1.9	± 89.6	± 63.8	± 28.9

$\overline{X}$ = Mean.

S.D. = Standard Deviation.

VC = Vital Capacity.

FVC = Forced Vital Capacity.

$FEV_{1,2,3}$ = Forced expiratory volume at 1, 2, and 3 seconds.

MEFR = Maximum expiratory flow rate.

MMFR = Maximum mid-expiratory flow rate.

MVV = Maximum voluntary ventilation.

Resistance

Pulmonary resistance was provided by restricting inspiration and expiration with a 5-cm-long aluminum tube. This tube was placed 140 cm down-line from the breathing valve. Four pulmonary resistances were used in the testing. R1.2 cm H2O, the control condition, included the resistance offered by the breathing valve, Collin's tubing and no. 2 Fleisch pneumotachograph. R11, R16, and R25 cm H2O were provided by addition of the aluminum tube to the system. Conditions R1.2, R11, R16, and R25 provided the respective pulmonary resistances of 1.2, 11.0, 16.0, and 25.0 cmH2O at a flow rate of 120 l/min. Equal resistances were added to both inspiration and expiration at the same time.

Procedure

Subjects initially underwent a complete physical evaluation at the Noll Laboratory for Human Performance Research which included a medical history a physician-administered physical examination, a 12-lead resting ECG, a graded exercise test and a pulmonary function test.

Subjects performed four exercise intensities per day. Subjects remained at each exercise intensity for three minutes to ensure steady-state conditions. During the fourth minute, collection of expired air and breathing waveform data was begun. Collection of waveform data continued for 30 seconds, while expired air collection continues for seven minutes at exercise intensity 0 (EX0), four minutes at EX20, three minutes at EX40, two minutes at EX60, and one minute at EX80 and EX90. With the combination of exercise and high resistance, not all of the subjects were able to complete the three minutes to steady-state prior to data collection. The pulmonary resistances for the remaining tests were randomly assigned and unknown to the subjects.

Measurements

A schematic diagram of the data collection system is shown in Figure G1-1. The inspiratory and expiratory flow rates were measured by two Fleisch pneumotachographs (no. 2) which were connected to a Statham pressure transducer (Model PM15). After the flow signals were directed through single pole low pass filters with 50 Hertz cutoff frequency and buffer amplifiers, they were electrically summed to yield one output signal. This composite signal was then collected and stored on a PDP-11 computer and on a Gould 2-channel chart recorder. The computer program was designed to collect 1800 data points for each 30-second sample. The computer data were used for the final derivation of the shape factors. The chart recorder was primarily used to provide a visual check on the integrity of the data collection system during the 30-second sample period. Both the chart recorder and the computer were calibrated for flow prior to each test.

VO2, VCO2, and VE were measured using a total bag collection. Heart rates were monitored while airflow data was being collected. The computer-collected data were processed by a computer program designed to generate the inspiratory and expiratory tidal volumes, the inspiratory and expiratory peak flows and the respiration rate for each respiratory cycle. Mean and standard deviation data for each 30-second sample were then stored for later analysis. The shape factors were derived from the mean waveform data. Inspiratory and expiratory minute volumes were calculated by multiplying the corresponding inspiratory and expiratory tidal volumes by the respiration rates. The ratio of peak flow to minute volume then provided a value for the shape factor.

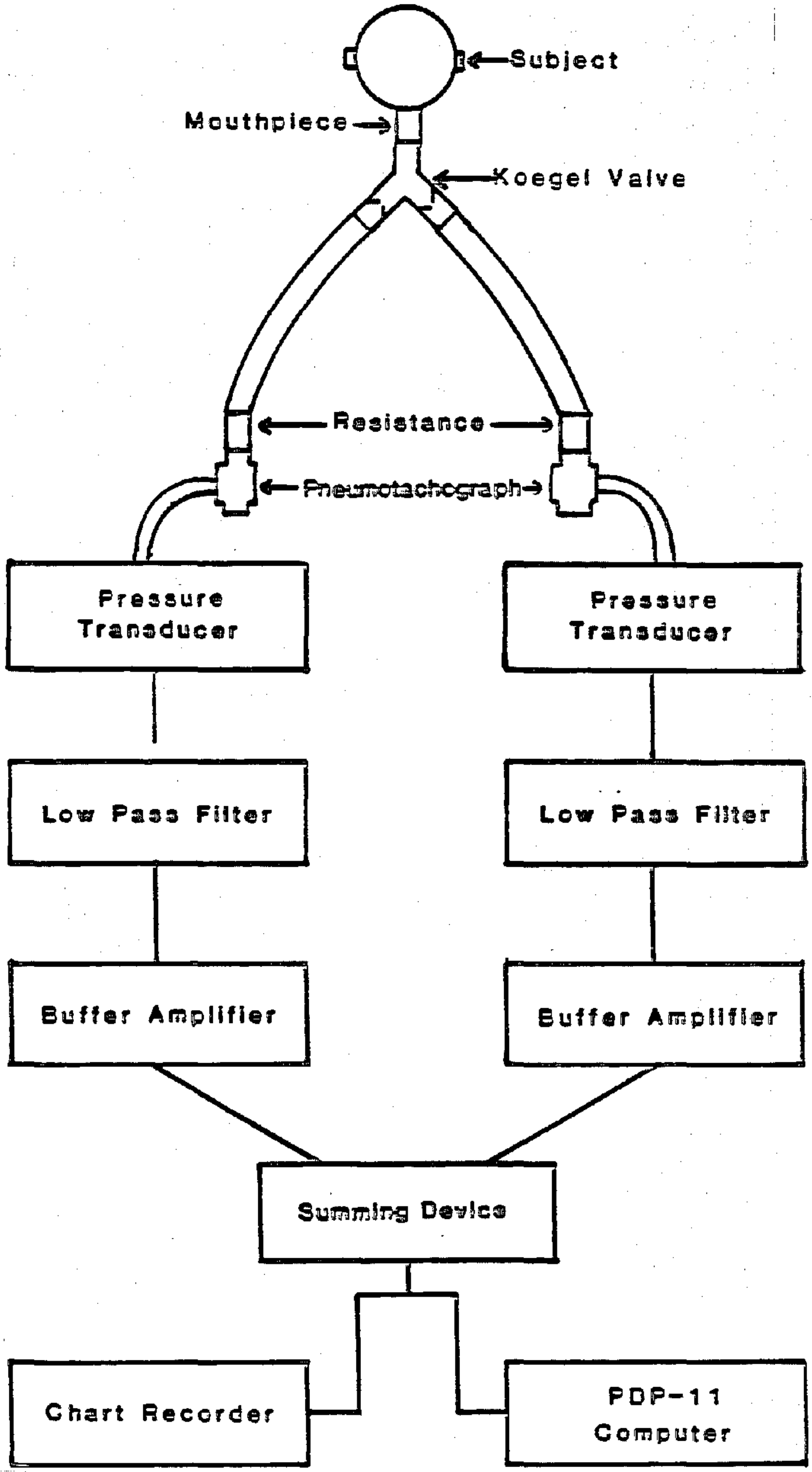

Figure G1.1. Diagram of the Breathing Apparatus and the Data Acquisition System where Inspiratory and Expiratory Pressure Signals were Transmitted to the Pressure Transducers, Low Pass Filters and Buffer Amplifiers after which they were Electrically Summed and Stored on a Chart Recorder and PDP-11 Computer

Treatment of Data

The inspiratory and expiratory shape factors (dependent variables) were analyzed separately using a two-way analysis of variance for repeated measures with exercise intensity and resistance (independent variables) as fixed factors. A dependent t-test was performed on the paired variates, inspiratory and expiratory shape factor. Minute volume, oxygen consumption and peak inspiratory and expiratory flows (dependent variables) were analyzed individually by exercise intensity across all resistances (independent variable) using a one-way analysis of variance. An alpha level of less tham 0.5 was chosen to provide a 95 percent confidence limit.

Results

Oxygen Consumption

The results of the analysis of variance at each exercise intensity across all resistances showed no significant differences between VO2's ($p < .05$) as shown in Table 3. None of the subjects, however were able to complete exercise at intensity EX90 while breathing against pulmonary resistance RZ5.

Table G1.3. Group Means and Standard Deviations for Oxygen Consumption ($\dot{V}_{O_2}$) at each Exercise Intensity (EXx) and Resistance (Rx, cmH_2O)

% $\dot{V}_{O_2}max$	R1.2	R11	R16	R25
EX0	0.34 ±0.02	0.37 ±0.03	0.34 ±0.02	0.34 ±0.02
EX20	0.83 ±0.09	0.84 ±0.09	0.79 ±0.08	0.82 ±0.09
EX40	1.52 ±0.15	1.55 ±0.21	1.51 ±0.20	1.50 ±0.22
EX60	2.33 ±0.20	2.26 ±0.28	2.30 ±0.29	2.39 ±0.39
EX80	3.12 ±0.26	2.97 ±0.28	2.95 ±0.38	2.85 ±0.23
EX90	3.62 ±0.30	3.38 ±0.34	3.31 ±0.33	----* ----

*The three minutes to reach steady-state conditions was not achieved.

Minute Volume

Table G1-4 shows the group mean and standard deviation data for minute columns at all exercise intensities and pulmonary resistances. The results show that at the individual exercise intensities EX0, EX20, EX40, and EX60 there were no significant differences in minutes volumes between all resistance conditions. At exercise intensity EX80, resistances R11, R16, and R25 showed significantly lower minute volumes than resistance R1.2. At exercise intensity EX90, minute volumes for resistances R11 and R16 were significantly lower than the minute volume for the control resistance condition R1.2 ($p < .05$).

Table G1.4. Group Means and Standard Deviations for Pulmonary Minute Volume at each Exercise Intensity (EXx) and Resistance (Rx, cmH_2O)

% $\dot{V}O_2max$	R1.2	R11	R16	R25
EX0	8.7 ±2.6	9.6 ±1.7	9.1 ±1.3	8.9 ±1.3
EX20	19.7 ±2.0	18.9 ±2.5	16.0 ±3.0	16.6 ±2.4
EX40	32.9 ±7.4	29.8 ±2.8	27.0 ±6.5	27.9 ±5.8
EX60	49.7 ±8.3	42.3 ±9.0	38.8 ±8.6	37.9 ±9.3
EX80	68.7 ±9.5	55.0 ±5.9	50.2 ±8.6	45.2 ±5.4
EX90	93.1 ±13.8	62.6 ±9.5	56.1 ±8.6	----* ----

*Steady-state conditions not achieved.

-----A bar includes values that were not significantly different ($p < .05$).

Peak Flow

The group mean and standard deviation data for peak inspired and expired flows for each exercise intensity and pulmonary resistance are presented in Tables G1-5 and G1-6. The data show that for exercise intensity EX0 there were no statistically significant changes in inspiratory and expiratory peak flows as resistance increased. ($p < .05$). For the remaining exercise intensities, peak expiratory flows showed the following results: 1) at both exercise intensities EX20 and EX40, resistances R16 and R25 were significantly less than R1.2, and R11 was not significantly different from R1.2, R16, or R25; 2) at exercise intensities EX60 and EX80, resistances R11, R16, and R25 were not significantly different but were significantly less than R1.2; and 3) at exercise intensity level EX90, resistances R11 and R16 were significantly different but were significantly less than R1.2. For the remaining exercise intensities, peak inspiratory flows showed the following results: 1) at exercise intensity EX20, resistances R16 and R25 were significantly less that R1.2; at exercise intensities EX40, EX60, and EX80, resistance R11, R16, and R25 were not significantly different but were significantly less than R1.2; and at exercise intensity EX90, resistances R11 and R16 were not significantly different but were significantly less than R1.2. Comparisons between Tables G1-5 and G1-6 show that for each exercise intensity and resistance condition, peak inspiratory flows were greater than peak expiratory flows.

Table G1.5. Group Means and Standard Deviations for Peak Expired Flow for each Exercise Intensity (EXx) and Resistance (Rx, cmH_2O)

% $\dot{V}O_2max$	R1.2	R11	R16	R25
EX0	34.1 $\pm$8.6	31.1 $\pm$8.1	26.9 $\pm$5.8	22.6 $\pm$3.6
	----	----	----	----
EX20	58.8 $\pm$10.9	48.1 $\pm$7.8	43.1 $\pm$6.6	39.6 $\pm$6.1
	----	----		
		----	----	----
EX40	96.2 $\pm$23.3	72.2 $\pm$12.2	65.6 $\pm$14.0	64.7 $\pm$15.3
	----	----		
		----	----	----
EX60	146.7 $\pm$22.3	102.4 $\pm$18.9	95.9 $\pm$18.4	90.7 $\pm$23.2
		----	----	----
EX80	215.3 $\pm$49.0	132.2 $\pm$16.7	121.4 $\pm$21.0	108.6 $\pm$18.2
		----	----	----
EX90	275.1 $\pm$56.9	153.8 $\pm$32.0	135.4 $\pm$27.1	----* ----

*The three minutes to reach steady-state conditions was not achieved.

----A bar includes values that were not significantly different ($p < .05$).

Table G1.6. Group Means and Standard Deviations for Peak Inspired Flow for each Exercise Intensity (EXx) and Resistance (Rx, cmH_2O)

% $\dot{V}O_2max$	R1.2	R11	R16	R25
EX0	39.8 ±8.1	39.1 ±12.5	38.7 ±11.0	31.9 ±5.1
EX20	74.0 ±8.3	63.5 ±5.2	52.1 ±9.5	49.8 ±4.6
EX40	114.0 ±21.7	89.6 ±6.9	81.0 ±16.2	79.0 ±10.7
EX60	159.1 ±27.5	123.3 ±15.2	109.8 ±23.5	109.8 ±22.1
EX80	236.9 ±33.2	150.6 ±12.6	135.6 ±22.6	124.3 ±11.2
EX90	284.6 ±45.8	176.1 ±13.5	150.0 ±22.4	----* ----

*The three minutes to reach steady state conditions was not achieved.

----A bar includes values that were not significantly different ($p < .05$).

Shape Factors

The post hoc analysis indicated that the mean ISF's (Inspiratory Shape Forms) for resistances R11, R16, and R25 were not significantly different, but were significantly less than the mean ISF for resistance condition R1.2. The mean ISF for exercise intensity EX0 differed significantly from the mean ISF's for exercise intensities EX20 through EX90. The mean ISF for EX20 was significantly different from the mean ISF's for exercise intensities EX0, EX80, and EX90; and the differences in the mean intensities EX40, EX60, EX80, and EX90 were not significant.

The post hoc analysis showed that the mean ESF's (Expiratory Shape Factor) for resistances R11, R16, and R25 were not significantly different, but were significantly less than the mean ESF for the control resistance condition R1.2. The mean ESF for exercise intensity EX0 was significantly greater than the mean ESF's for exercise EX20 through EX90, while the mean ESF's for exercise intensities EX20, EX40, EX60, EX80, and EX90 were not significantly different.

A dependent t-test was performed on the paired variables, inspiratory and expiratory shape factors, to determine if there was a significant difference between the two. Inspiratory shape factors were found to be significantly greater than the expiratory factors.

Discussion

The primary objective of this study was to observe the effects of treadmill exercise and added respiratory resistance on inspiratory and expiratory airflow patterns.

Oxygen Consumption

Results of this study showed that there were no significant differences between VO2's across all resistances at any exercise intensity. None of the subjects were able to complete the three minute minimum to reach steady-state at exercise intensity EX90 with resistance R25. At the highest exercise intensity, the inability of the subjects to complete the exercise at resistance R25 indicated a decrease in the maximal work capacity (VO2max) as resistance increased.

Results of this study confirm past research. Cerretelli et al. (1969), using equal inspiratory and expiratory resisitances of 6.25, 19 and 38 cmH2O at a flow rate of 120 l/min, found that the relationship between VO2 and exercise intensity remained unchanged. The maximal exercise intensity attainable, however, did decrease as resistance increased. The inability to perform maximal exercise under increased respiratory resistance was thought to be related to a voluntary point of fatigue and the subject's inability to generate an inspiratory and expiratory pressure difference of greater than 100 cmH2O (Cerretelli et al., 1969; Dressendorfer et al., 1977).

Minute Volume

The effects of increased respiratory resistance on respiratory minute volume have been demonstrated by several researchers. The typical response reported from past studies showed a decrease in minute volume with increased exercise at all resistances used.

The results of this research showed similar trends as other research (Hermansen et al., 1972; Flook and Kelman, 1973; Cerretelli, 1969; Silverman, 1945). At the lower exercise intensities, EX20 through EX60, there was a decrease in minute volumes as resistance was added; however, the decreases when present were not significant. Only at the highest exercise intensity was the decrease significant ($p < .05$). At exercise intensity EX80, the minute volumes for resistances R11, R16 and R25 were not significantly less than the minute volume at the control resistance condition R1.2. Similarly, at exercise intensity EX90, the minute volumes for resistances R11 and R16 were not significantly different, but were significantly less than the minute volume for the control resistance condition 1.2.

Peak Flow

The results of this study agreed with past studies. The general trends showed a decrease in peak flow with added resistance. The decrease in peak flow was inversely proportional to the amount of resistance so that as resistance increased, the peak flow showed a greater percentage decrease. Similar percentage decreases were seen during both the inspiratory and expiratory phases; however, comparison of peak flows consistently showed that inspiratory peak flows were consistently greater than expiratory peak flows for a given workload and resistance.

Shape Factor

The primary objective of this research was to observe the effects of exercise and pulmonary resistance on breathing waveform shape. The shape factor is a quantitative measure of shape, where shape factor is the ratio of peak flow divided by minute ventilation. Examples of the progressive changes in inspiratory and expiratory breathing waveforms from exercise intensities EX0 through EX90 for two subjects breathing against pulmonary resistance R1.2 and R25 are presented in Figures G1-2, G1-3, G1-4, and G1-5. These plots represent typical data from which the shape factors were determined. The plots also help to demonstrate the variation in breathing patterns that occurs between subjects.

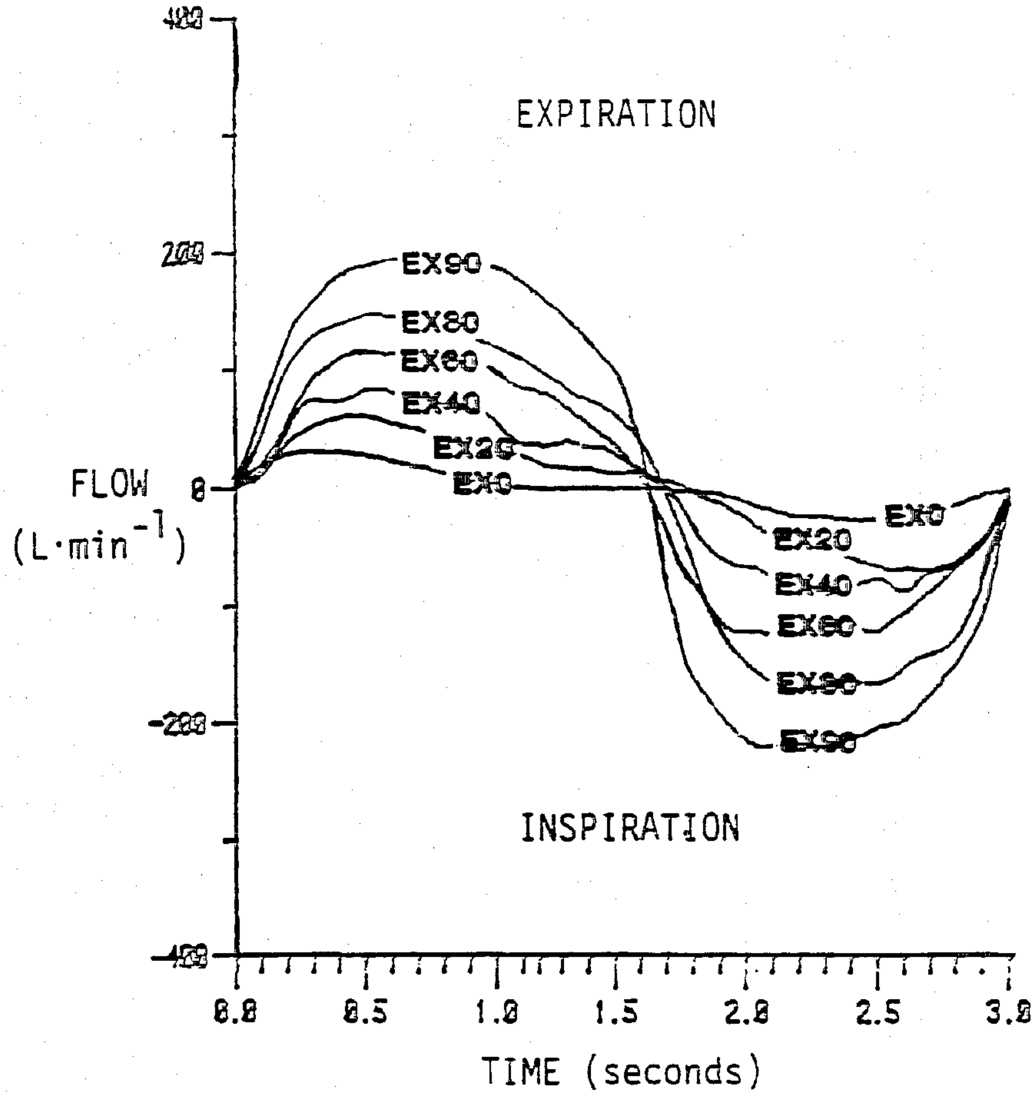

Figure G1.2. Waveforms Calculated for Several Respiratory Cycles Obtained during Exercise of Subject A at Various Relative Exercise Intensities (EXx as a Percentage of $\dot{V}_{O_2}max$). Subject was Breathing Against Resistan R1.2 cmH_2O

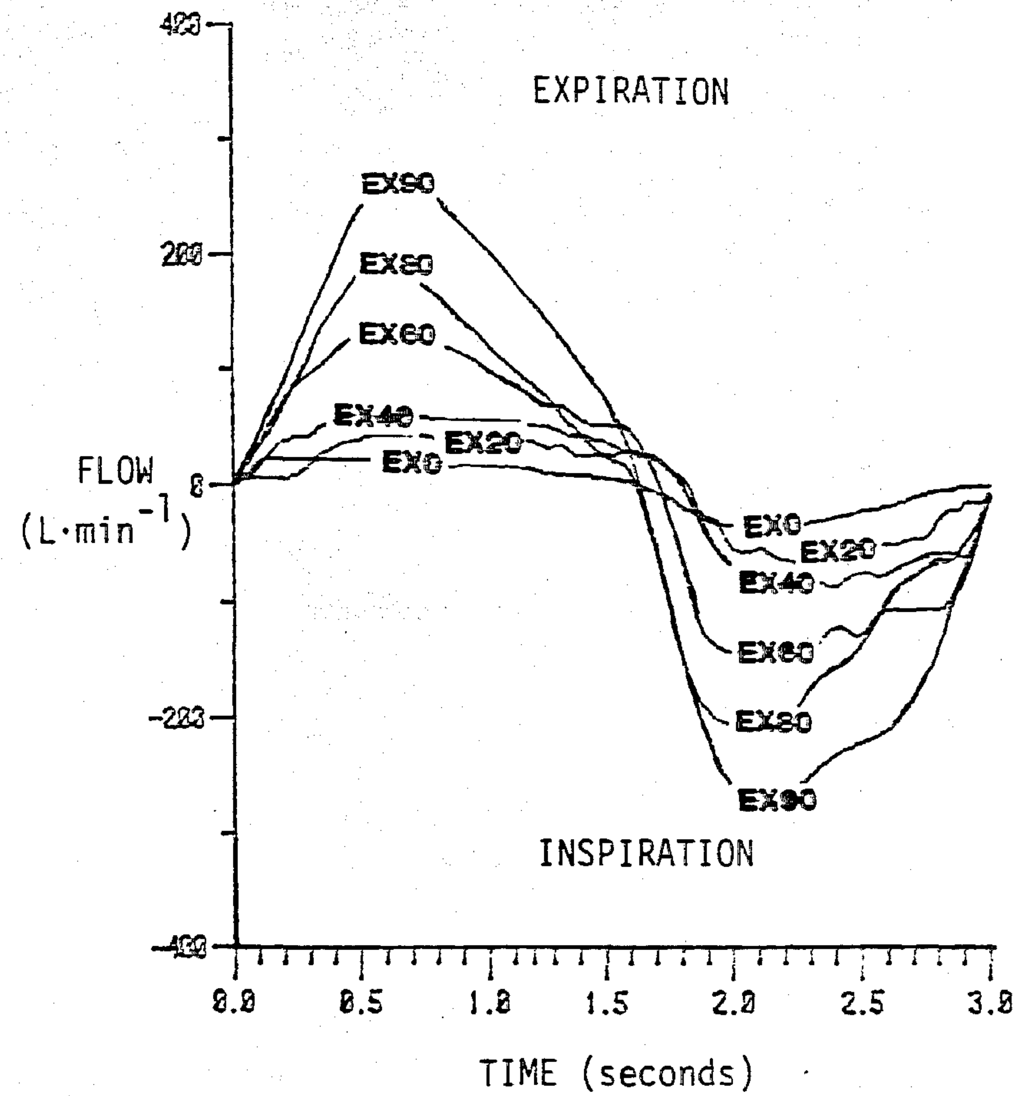

Figure G1.3. Waveforms Calculated for Several Respiratory Cycles Obtained during Exercise of Subject D at Various Relative Exercise Intensities (EXx as a Percentage of $\dot{V}_{O_2}max$). Subject was Breathing Against Resistance R1.2 cmH_2O

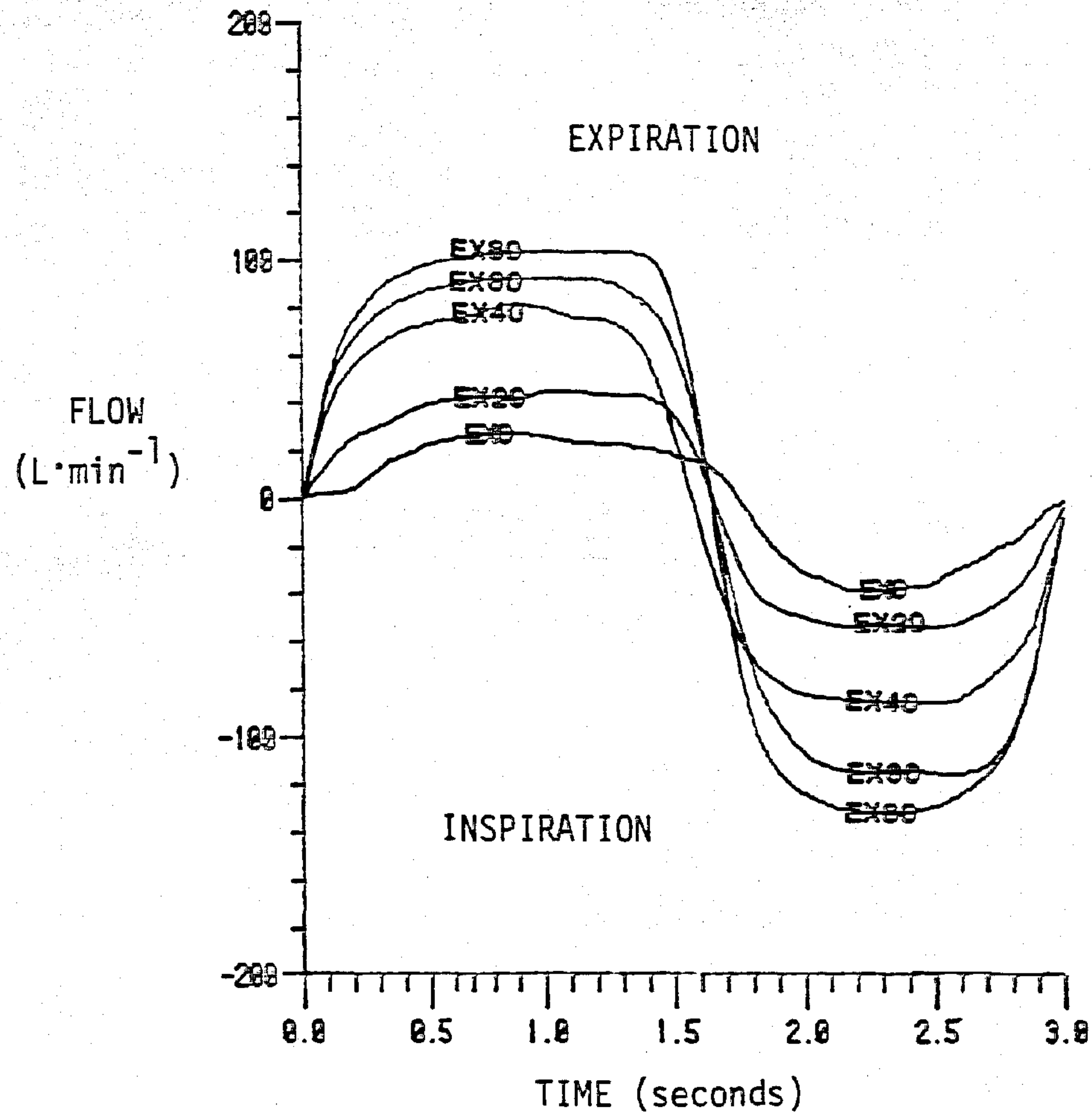

Figure G1.4. Waveforms Calculated for Several Respiratory Cycles Obtained during Exercise of Subject D at Various Relative Exercise Intensities (EXx as a Percentage of $\dot{V}_{O_2}$max). Subject was Breathing Against Resistance R25 cmH_2O

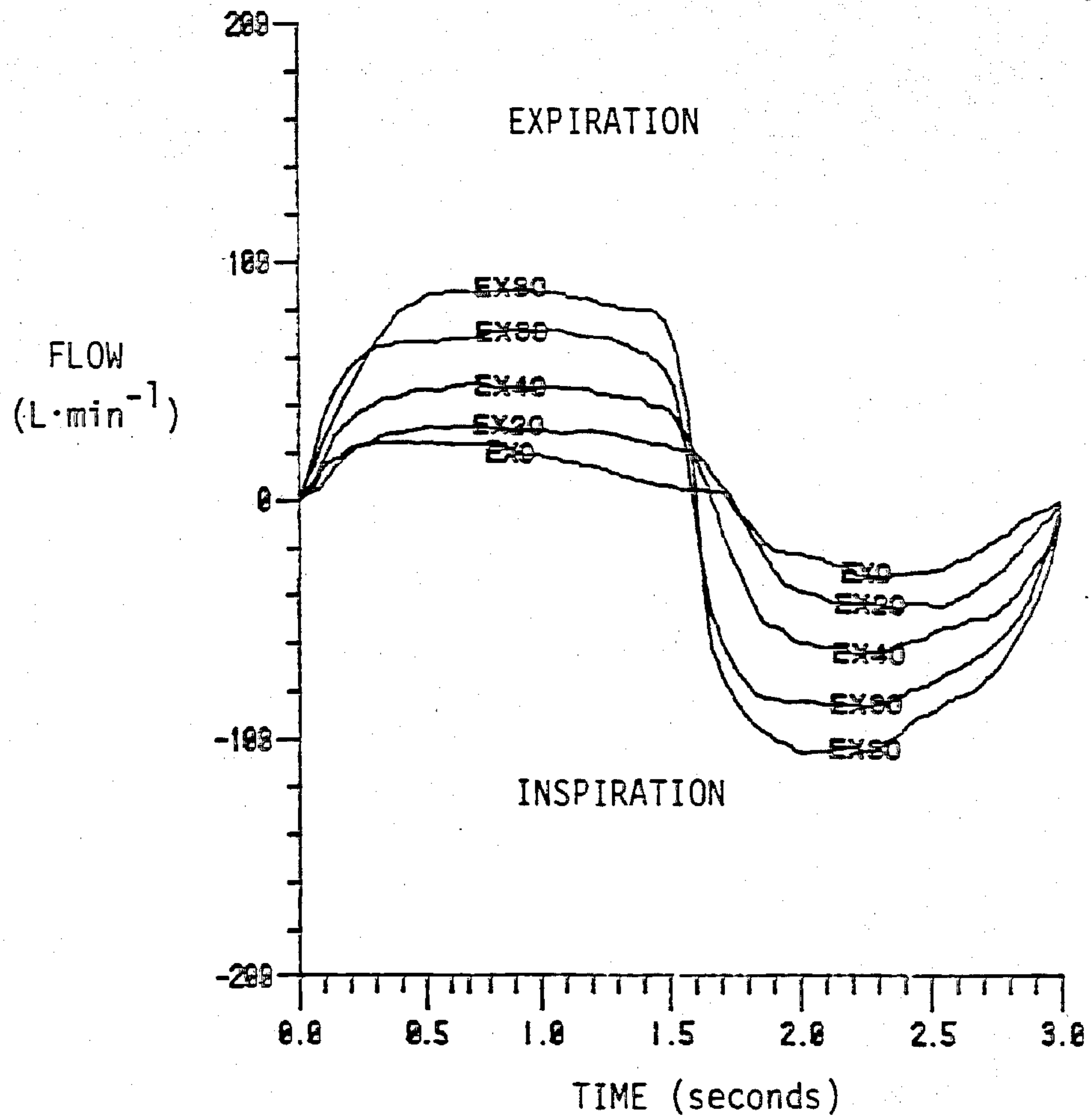

Figure G1.5. Waveforms Calculated for Several Respiratory Cycles Obtained during Exercise of Subject A at Various Relative Exercise Intenities (EXx as a Percentage of $\dot{V}_{O_2}$max). Subject was Breathing Against Resistance R25 cmH_2O

Upon examination of Figures G1-6 and G1-7, the shape factors of the resistance condition R1.2 are quite different from the shape factors of the resistance conditions R11, R16, and R25.

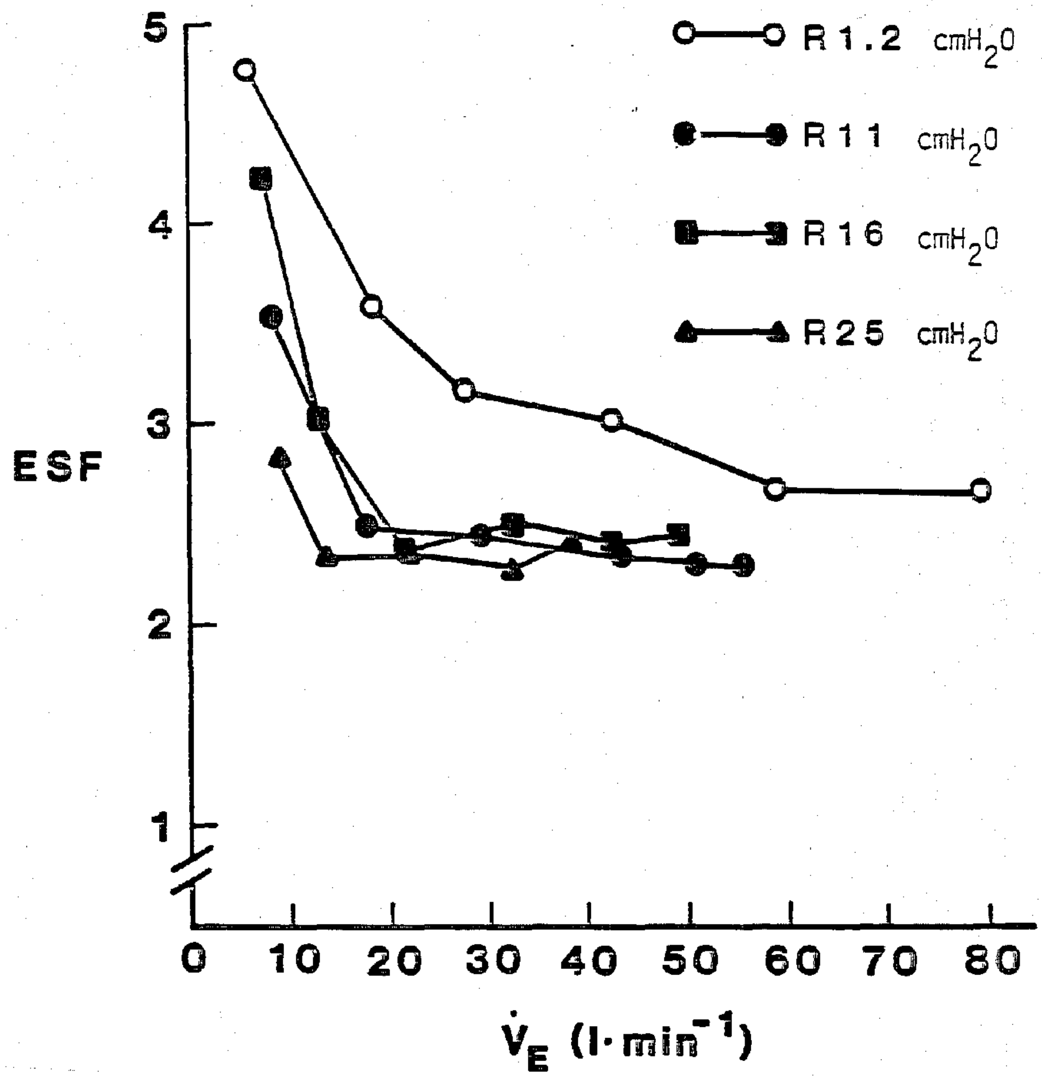

Figure G1.6. The Relationship Between the Expiratory Shape Factor (ESF) and the Expiratory Minute Volume ($\dot{V}_E$) while Exhaling through each of the Four Pulmonary Resistances, R1.2, R11, R16 and R25 (Subject A)

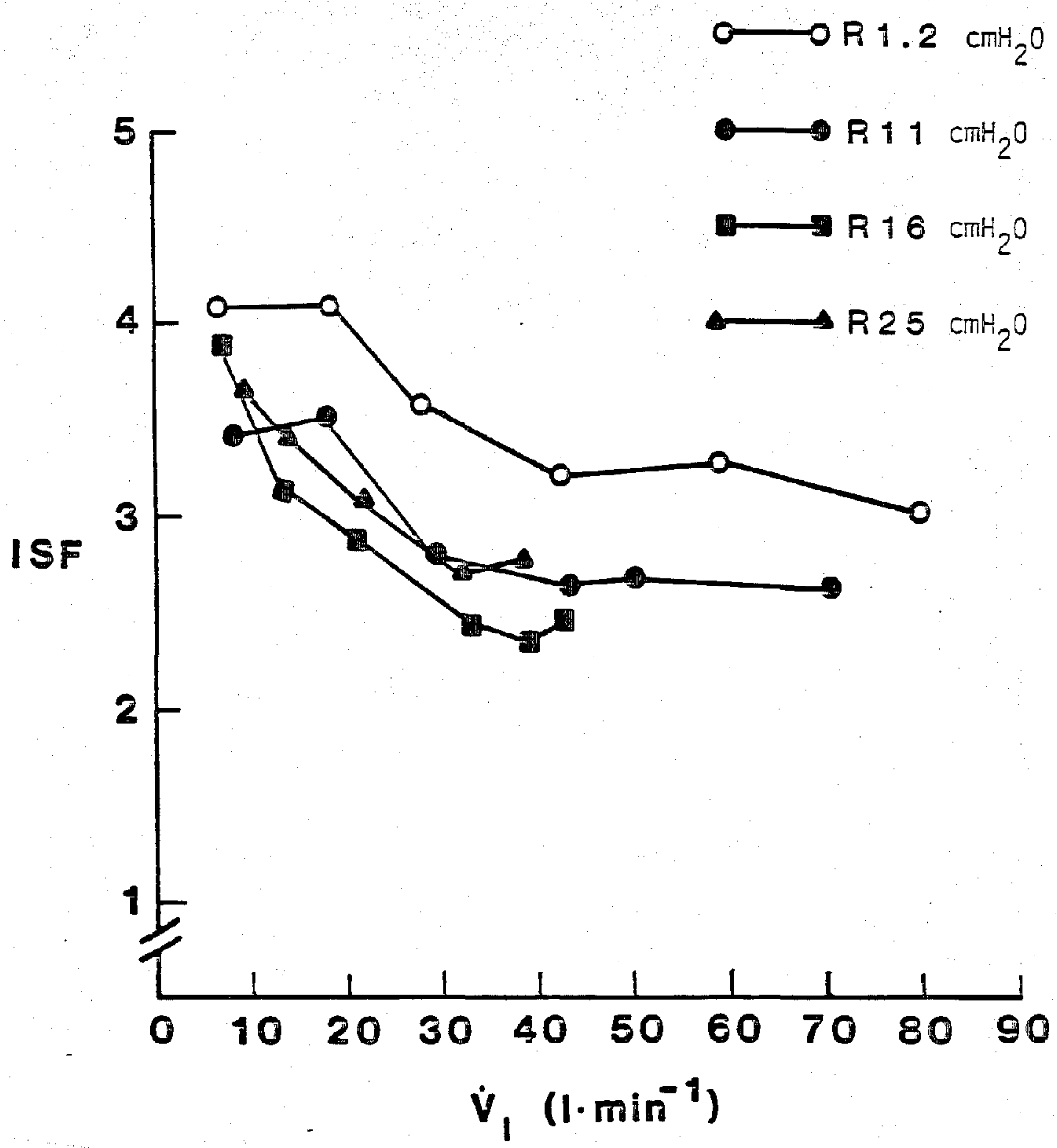

Figure G1.7. The Relationship Between the Inspiratory Shape Factor (ISF) and the Inspiratory Minute Volume ($\dot{V}_I$) While Inhaling through each of the Four Pulmonary Resistances, R1.2, R11, R16 and R25 (Subject A)

Similarly, the greatest difference in shape factor due to exercise occurred between the rest EX0 (represented by a VE of approximately 10 l/min) and the remaining exercise intensities EX20 through EX90 (represented by VE's greater than 15 l/min).

An explanation for the results of this study must begin with an understanding of the term work of breathing. Work of breathing is defined as the area under a pressure volume curve (Otis, 1964), or the integrated product of the pressure generated and the volume of air moved throughout a breathing cycle (Comroe, 1974). Changes in the shape factors of breathing waveforms reflect man's attempt at minimizing the rate of work of breathing. The work of breathing at rest represents a negligible amount of the total energy expenditure, approximately 0.5 to 1 ml of O2 per liter of air moved (Astrand & Rodahl, 1977).

At high intensity exercise, the oxygen cost of breathing may be as high as 10 percent of the total oxygen consumption (Astrand & Rodahl, 1977). As the oxygen cost of breathing becomes a larger percentage of the total oxygen consumption, the breathing waveform pattern becomes regulated, and therefore more rectangular resulting in a decrease in the work of breathing (Yamashiro & Grodins, 1971). This more rectangular breathing waveform approaches a shape factor of two. The results of this study show that once an individual had begun exercising or, as respiratory resistance was added, optimal breathing patterns were developed.

The importance of these findings lies in a better understanding of how man's respiratory system mechanically adapts to increased airway resistance. As the computer age progresses, computer driven lung simulators are being developed with the intention that simulator testing will replace some of the human subject testing currently in progress. Of significant importance is the need to ensure that the mechanical lung does indeed simulate the patterns of human respiration. Information gathered in this research concerning changes in breathing waveforms due to exercise and/or airway resistance will aid in the design of computer programs that are being developed to operate lung simulators.

*************** END OF REPORT ****************