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PHYSIOLOGICAL LIMITS OF FIREFIGHTERS

LEVEL ^{II}

L. G. MYHRE R. D. HOLDEN
F. W. BAUMGARDNER D. TUCKER
AIR FORCE SCHOOL OF AEROSPACE MEDICINE
BROOKS AFB, TX 78236

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) 4 The U. S. Air Force School of Aerospace Medicine conducted a study of respiratory stresses imposed on firefighters wearing a self contained breathing apparatus. The purpose of this study was to investigate the respiratory stresses and subsequent changes in work capacity accompanying the wearing of a self contained breathing apparatus (SCBA). Twenty volunteer subjects, ranging in age from 25 to 49 years participated in the study which included both smokers and nonsmokers of varying levels		

of physical fitness. A 30 minute SCBA, equipped with a full face mask and either a (1) demand, or (2) pressure demand regulator, was worn by the subjects while walking on a motor driven treadmill at a constant speed (3.3 mph) and up grades determined to require 50, 65 and 80 percent of each individual's aerobic capacity (VO_2 max). Following a 10 minute rest, venous blood was drawn for Hb, Hct & COHb, and lactate determinations; the subject then began a 10 minute bout of work at one of the three workloads given above. Measurement monitored continuously during work included: forehead skin, core and mask temperatures; maximum and minimum O_2 and CO_2 tensions inside the mask; breathing resistance (pressure); and heart rate (EKG). Minute ventilation and O_2 consumption were determined during minutes 6, 8, and 10 of each run. A final blood sample drawn at 5 minute post-work concluded the experiment. A 20 to 30% increase in the energy cost for any given work load was attributed to the burden (15kg) of the SCBA above, but all subjects performed all grades of work with little discomfort when connected to a free breathing system. On the contrary, the resistance to breathing imposed by the SCBA became intolerable for work requiring 80% of VO_2 max. The severe restrictions to breathing during hard work were attributable to both inspiratory and expiratory resistances which often exceeds 5 inches of H_2O when peak inspiratory flow exceeded 300 l/minute. Even greater breathing resistances were added when the tank air supply had been reduced to 30% capacity. In addition, the NIOSH rated 30 minute air supply system was exhausted within 10 minutes of work at this level. In fact, only with relatively easy work, i.e., 50% VO_2 max., was this air supply sufficient for more than 18 minutes of work.

PREFACE

This program was conducted by the USAF School of Aerospace Medicine (AFSC) Brooks Air Force Base, Texas, 78235, under contract AFCEC 77-100, Job Order Number 414N3005 for Detachment 1 AFESC (CEEDO) CNS, Tyndall Air Force Base, Florida.

Effective 1 March 1979 CEEDO was inactivated and became the Engineering and Services Laboratory (ESL), a directorate of the Air Force Engineering and Services Center located on Tyndall Air Force Base, Florida 32403.

This report summarizes work done between October 1977 and January 1979. Doctor L. G. Myhre was the principal investigator at USAFSAM. Air Force project managers (during successive periods) were Major B. Pease, Mr N. Knowles, Mr. L. Redman and Mr J. Walker.

The accomplishment of this task required the cooperation of many people which is gratefully acknowledged. Appreciation is also expressed to the activities that these individuals represent. Their willingness to allow their facilities to be used for the purposes of this work was of paramount importance to the conduct of this study.

This report has been reviewed by the Information Officer (IO) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Joseph L. Walker
JOSEPH L. WALKER
Project Officer

Robert E. Boyer
ROBERT E. BOYER, Lt Col, USAF
Chief, Engineering Division

Joseph S. Pizzuto
JOSEPH S. PIZZUTO, Col, USAF, BSC
Director, Engineering and Services
Laboratory

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SECTION I

INTRODUCTION

The open circuit self-contained breathing apparatus (SCBA) is an indispensable part of the firefighter's protective equipment ensemble. Available with a full face mask for use with either demand or pressure-demand breathing modes, this instrument is designed to provide respiratory protection for persons at rest or working during brief exposure times to toxic gaseous environments. Mining Enforcement Safety Administration-National Institute for Occupational Safety and Health (MESA-NIOSH) approval of this equipment is subject to compliance with Title 30 of the Code of Federal Regulations, presented in part in Appendix A of this report. In brief, requirements for MESA-NIOSH certification of approval of an SCBA include the following: (a) weight not more than 16 kilograms (kg) (35 pounds); (b) inspiratory resistance not to exceed 32 millimeters (mm) (1.25 inches) water-column height at a flow rate of 125 liters per minute (l/min); (c) exhalation resistance at a flow rate of 85 l/min is not to exceed 25 mm (1 inch) and 51 mm (2 inches) water-column height for demand and pressure-demand modes, respectively; and (d) service time determined by breathing machine requiring 40 l/min and by the respiratory requirements of the wearer walking on a level treadmill at 4.8 kilometers (km) (3 miles) per hour (Reference 1).

Although a given SCBA may meet these MESA-NIOSH certification requirements, there is legitimate concern as to whether it actually meets the respiratory requirements of the intended user, e.g., a firefighter who may be called upon to do more than just walk slowly on a level surface. Can the user really depend upon a 30-minute air supply from a certified 30-minute cylinder? Do breathing resistances observed during machine breathing at 85 and 125 l/min reflect those to be expected during real-life emergency conditions? From observations of the energy cost of firefighting (References 2, 3, and 4), it must be concluded that the MESA-NIOSH certification requirements for SCBA's are unrealistically tolerant for all but rather mild work requirements.

The respiratory protection provided by a SCBA is only as good as the capability of the facepiece to prevent inward leaking of toxic gases. Indeed, this is the rationale for the preferred use of the pressure-demand SCBA which allegedly maintains a positive pressure within the facepiece at all times. Manufacturers are quick to point out the importance of this quality as evidenced by the following:

"...low exhalation resistance while maintaining a positive pressure within the facepiece to prevent inward leaking of toxic gases in atmospheres where even minute levels of such inward leaking could be dangerous."^a

"In some highly toxic atmospheres, a small amount of mask leakage can be dangerous..." "A vacuum can never occur inside the mask, even under extremely high demand conditions. Leakage into the mask is impossible, because through any leak path, air is blowing outward."^b

Again, such optimism must be studied with a critical eye for the conditions under which such units were evaluated. Were they determined by observing the SCBA performance during "machine breathing," or were they determined by more valid man testing under conditions simulating the actual working environment?

The purpose of this study was to investigate the respiratory stresses and subsequent changes in work capacity accompanying the wearing of a Scott® Air-Pak II SCBA. The workloads imposed on men while wearing the SCBA were designed to simulate actual energy requirements known to occur in typical firefighting activity (Reference 2, 3, and 4).

^aMSA Data Sheet 01-02-10 (MSA Pressure-Demand SCBA)

^bSurvivair®, Models 98038 - 9838 (Data sheet accompanying Survivair® Pressure-Demand SCBA)

SECTION II

METHODS AND PROCEDURES

The two SCBA devices most widely used by civilian and U.S. Air Force firefighters are the Scott[®] Air-Pak and the Mine Safety Appliances[®] (MSA) Model 401, which are MESA-NIOSH rated as 30-minute units. Due to its prevalent use, only the Scott[®] Air-Pak was selected for complete man testing in this effort. Physical and clinical characteristics of the 21 males who volunteered as subjects for this study are presented in Table 1.

Following a class II flight physical, each subject completed eight to 12 training sessions to assure familiarity with both treadmill exercise and the use of the SCBA device. A treadmill electrocardiogram (EKG) stress test (Reference 5) for medical clearances and aerobic capacity was followed on separate days by treadmill experiments to establish the relationship between metabolic rate and workload for each subject. With treadmill speed constant at 3.3 (mph), individual workloads for the experimental protocol were selected from appropriate grades of incline to require approximately 50, 65, and 80 percent of each subject's aerobic capacity ($\dot{V}_{O_2 \text{ max}}$). Each of these three workloads was combined with the

following treatment conditions: (a) control (tennis shoes and shorts only); (b) pak (wearing the SCBA, but not using the facepiece); (c) demand (wearing and using the SCBA equipped with a demand regulator); and (d) pressure-demand (wearing and using the SCBA equipped with a pressure-demand regulator). The experimental order was assigned by random numbers, and each subject completed each of the 12 treatment conditions, at the same hour on separate days, according to the following matrix:

Percent Aerobic Capacity^a

	50	65	80
Control	x	x	x
Pak	x	x	x
Demand	x	x	x
Pressure Demand	x	x	x

Arriving post-absorptive in the morning, the subject dressed in tennis shorts, shoes, and T-shirt; he was then fitted with EKG electrodes and thermistors for monitoring forehead skin and rectal temperatures. Following 10 minutes of rest in the seated position, a control blood sample (7 ml) was drawn without stasis from an arm vein. The subject was then fitted with the appropriate SCBA combination for the given treatment condition (Figures 1 and 2).

^aActual oxygen consumption values for control experiments, i.e., without wearing the 15-kg protective equipment, average 41, 53, and 69 percent of $\dot{V}_{O_2}$ max.



Figure 1. Subject Walking on Treadmill and Wearing Demand Facepiece with Adaptor

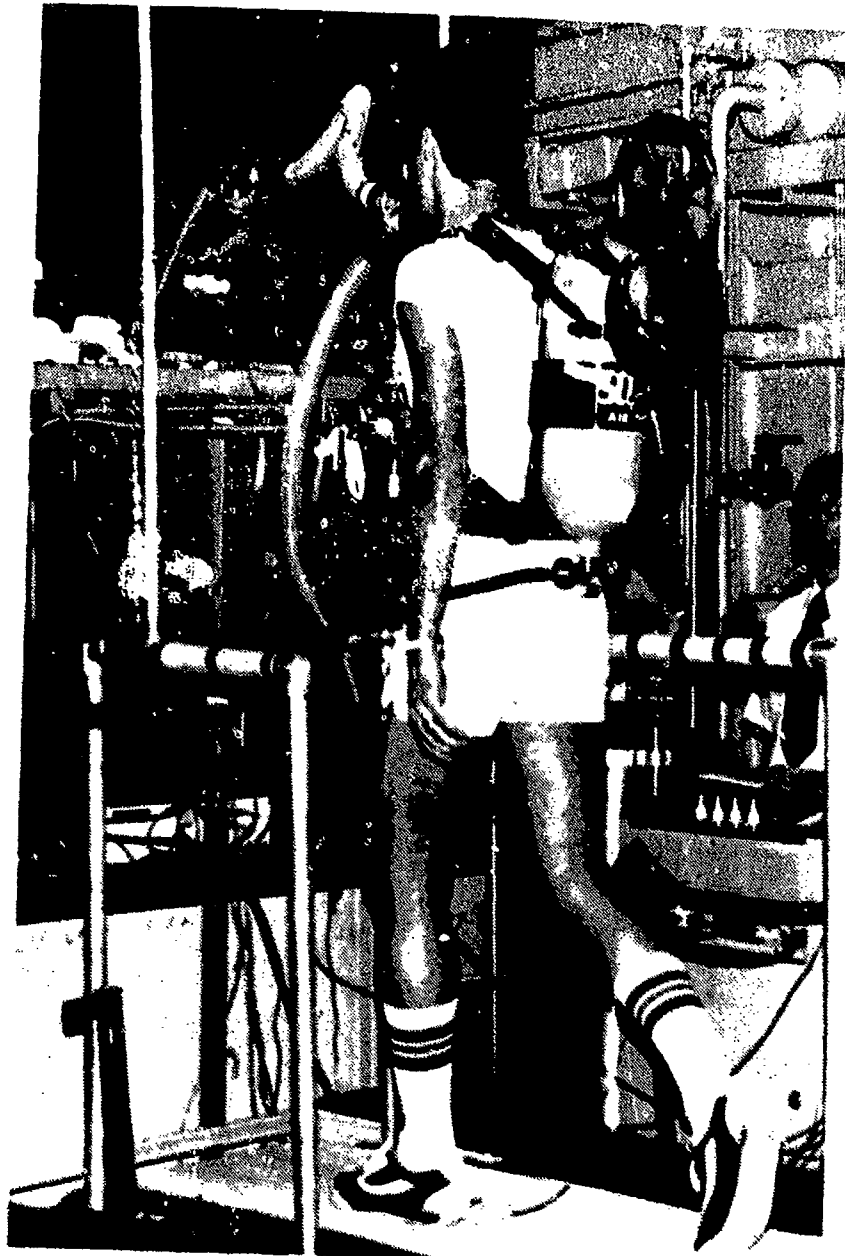


Figure 2. Subject is Talking on Treadmill Wearing Air Pak
But Breathing Through a Low Resistance Koegel Valve

TABLE 1. BIOCLINICAL CHARACTERISTICS OF SUBJECTS (n = 21)

	Mean	S.E.	Min-Max
Age	32.9	1.5	22 - 51
Height, cm	179.15	1.53	167.2 - 189.2
Weight, kg	77.700	1.826	65.73 - 98.94
Lean Body Mass, kg	61.446	1.460	52.73 - 77.05
Percent Fat	20.91	1.14	12.7 - 30.0
Fat, kg	16.396	1.124	10.01 - 27.54
$\dot{V}_E^o$ max, l/min (BTPS)	107.01	4.74	77.70 - 148.40
$\dot{V}_{O_2}$ max, l/min (STPD)	3.467	0.101	2.821 - 4.310
$\dot{V}_{O_2}^o$ max, ml/kg. min	44.54	1.30	32.3 - 53.9
Heart Rate, rest	68.1	3.0	46 - 93
Heart Rate, max	188.0	2.0	163 - 200
Systolic Pressure, rest	126.0	3.2	100 - 164
Systolic Pressure, max	184.7	3.2	160 - 220
Diastolic Pressure, rest	78.6	2.3	50 - 108
Residual Volume, ml, (BTPS)	1420.4	64.2	1012 - 2311

In experiments studying either the demand or pressure-demand regulators, the facepiece was carefully fitted on the clean-shaven subject and tested for outward leaks at 4-inches H_2O -column positive pressure. Sealed mask penetrations permitted continuous monitoring of (a) positive and negative pressures within the facepiece, (b) CO_2 and O_2 concentrations, and (c) air temperature inside the facepiece; peak inspiratory flow rates were monitored only when the subject was connected to the Koegel respiratory valve, i.e., during control and pak experiments.

All parameters were recorded continuously for 2 minutes with the subject standing quietly prior to starting the treadmill, and continued throughout the subsequent 10-minute exercise bout and the first 2 minutes of the 5-minute seated recovery. The subject completed a brief questionnaire (Appendix B), and the final blood sample was drawn at 5 minutes post-exercise; body weight was determined with and without the SCBA, and the experiment was terminated.

Oxygen consumption was determined during minutes 6, 8, and 10; expired air was collected in a Tissot spirometer and analyzed for O_2 and CO_2 by a mass spectrometer while being emptied between each collection. Inspiratory flow rates were measured by a Fleisch[®] Pneumotocograph, inspiratory and expiratory pressures by a Validyne[®] model CD 12 pressure transducer, and mask CO_2 and O_2 concentrations by a Perkin-Elmer[®] 1100 Medical Gas Analyzer. All instruments were calibrated immediately before and after each experiment; continuous data recording was obtained on both an 8-channel Brush 200[®] and a Sangamo Sabre III[®] tape recorder.

Blood was analyzed for carboxyhemoglobin (COHb) according to Myhre (Reference 6); hemoglobin concentration (H^+) was determined by the cyanmethemoglobin method analyzed on a spectrometer calibrated against Hycel's[®] standard solutions. Hematocrit (Hct) was determined by a micro-centrifuge with no corrections for trapped plasma.

Subjects were weighted to ± 20 grams on a Detecto[®] platform balance. Body volume was determined by water displacement, and body fat was estimated from body density according to Allen (personal communication).

All subjects were familiarized with the experimental protocol and briefed concerning their rights before the investigation began. They then authorized their use as subjects in accordance with the human use requirements as established by the Advisory Committee on Human Experimentation of the School of Aerospace Medicine, Brooks AFB (Appendix C). Data were analyzed using analysis of variance techniques; split-plot analysis of variance with two factors below the line was used in evaluating smokers vs non-smokers; statistical significance was set at $P < 0.05$.

SECTION III

RESULTS

The results of all exercise experiments will be presented in a way that will allow a direct comparison of the physiological responses observed for each of the four experimental conditions, hereafter referred to as (a) control, (b) pak, (c) demand, and (d) pressure-demand. The three workloads imposed on the subjects during each of these conditions were predetermined to require 50, 65 and 80 percent of each individual's $\dot{V}_{O_2}$ max while wearing the SCBA equipment (~ 15 kg). Thus, the work performed in the control experiments does not actually represent these percentages of aerobic capacity, but rather the lesser work stress of walking at the same speed and grade without carrying the burden of the SCBA. All data representing physiological responses during work were taken during the eighth minute of the submaximal exercise bouts mentioned above. In summarizing the results of this study, the total group of 21 subjects will be treated first as a single group, and later, treated as subgroups in an attempt to differentiate between smokers and non-smokers.

TOTAL GROUP ANALYSIS

Metabolic Responses - The energy cost for performing a given treadmill test, measured in terms of oxygen consumption ($\dot{V}_{O_2}$), is summarized in Figure 3. (Appendix D contains tabular data pertinent to this section.) It should be noted that the $\dot{V}_{O_2}$ values for work at 50, 65 and 80 percent averaged approximately 240, 370, and 475 mL/min greater, respectively, for the Pak experiments than those observed for walking at the same speed and grade without the SCBA, i.e., control. This represents an added energy cost ranging from 17 to 20 percent which is attributed to carrying the weight of the SCBA. The slight differences in $\dot{V}_{O_2}$

observed for all pak, demand, and pressure-demand conditions were insignificant and indicate that the added stress imposed by resistance breathing was not great enough to significantly affect the overall energy requirements for work under these conditions.

The fuel utilized for energy transformation may be estimated by calculating the non-protein respiratory exchange ratio (R) where R's of 1.0 and 0.70 indicate carbohydrate and fat as sole fuel sources, respectively. Thus, an R of 0.85 indicates that 50 percent of the energy is derived from fat and 50 percent from carbohydrate fuel sources. From Table 2 it may be noted that the fuel mixture varied from about 50:50 fat/carbohydrate mixture for the 50 percent workload to a nearly 100 percent carbohydrate fuel source for the 80 percent work experiments. (An R of 1.02 observed for the pak condition at 80 percent $\dot{V}_{O_2}$ max indicates that CO_2 is being eliminated at rates greater than it is being produced metabolically.)

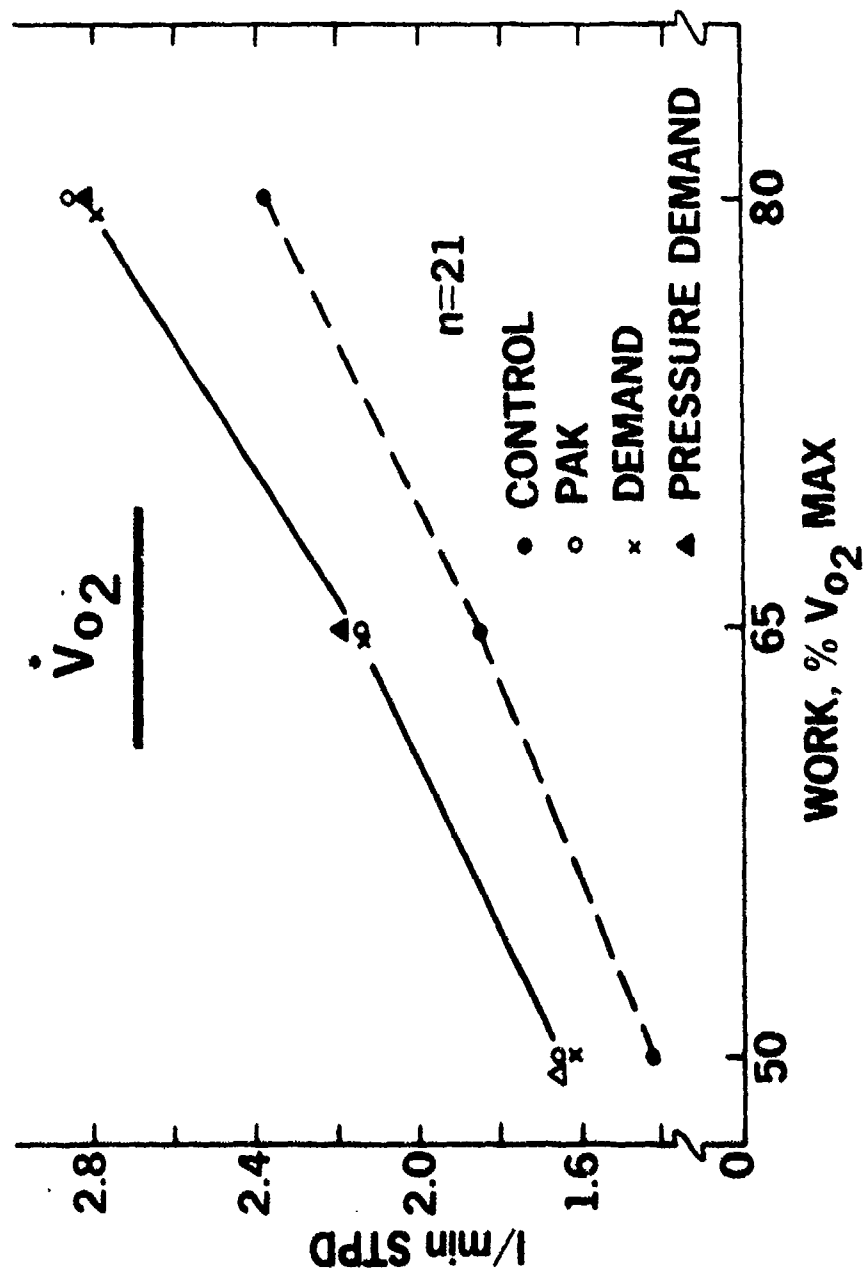


Figure 3. Mean values of Oxygen Consumption

TABLE 2. RESPIRATORY EXCHANGE RATIOS OBSERVED FOR MAN PERFORMING TREADMILL EXERCISE WHILE WEARING THE SCOTT® AIR-PAK II SCBA (MEAN $\pm$ S.E.)

Work $\% \dot{V}_{O_2} \text{ max}^a$	Respiratory Exchange Ratio			
	Control	Pak	Demand	Pressure-Demand
	(n = 21)	(n = 21)	(n = 21)	(n = 21)
50	0.87 ± 0.05	0.88 ± 0.05	0.85 ± 0.03	0.85 ± 0.06
65	0.91 ± 0.03	0.94 ± 0.04	0.89 ± 0.04	0.90 ± 0.04
80	0.94 ± 0.05	1.02 ± 0.06	0.99 ± 0.06	0.98 ± 0.06

^aActual oxygen consumption values for control experiments, i.e., without wearing the 15-kg protective equipment, averaged 41, 53, and 69 percent of $\dot{V}_{O_2} \text{ max}$.

The extent to which anaerobic metabolism contributes to the total energy transformation process may be estimated by observing increases in blood lactate resulting from the work regimen. These values, presented in Table 3, indicate that the increases in blood lactate were significantly related to work intensity with the trend for greater relative increases as workload increased. Relatively small increases, averaging less than 5 (percent) were observed for work at 50 percent with larger increases averaging 48 (mg percent) for work at 80 percent $\dot{V}_{O_2}$

max. Lactate accumulation during demand and pressure-demand breathing was always less than that during pak experiments, and these differences were statistically significant.

Ventilatory Responses - The ventilatory minute volumes ($\dot{V}_E$) observed during work are presented in Figure 4 (see Appendix D). Ventilatory requirements increased in proportion to the increases in energy cost as work loads increased from 50 to 65 percent, but a sharper rise was observed when the workload increased to 80 percent of $\dot{V}_{O_2}$ max indicating

the added respiratory stimulus accompanying the accumulation of lactic acid. As was the case with $\dot{V}_{O_2}$, the added work imposed by wearing the

SCBA produced a significantly greater ventilatory requirement which ranged from about +18 percent for the lowest work level to +43 percent for the 80 percent workload. The overall ventilatory values were always greater when breathing through either the demand or the pressure-demand regulators than those observed when breathing through the Koegel valve. These differences of about 6 liters/min for any given workload were statistically significant; there was no difference between demand and pressure-demand ventilation values.

Respiratory rate (RR) and tidal volume (TV) data are presented in Table 4. The RR for pak conditions (Koegel valve) was greater than that for SCBA breathing during 65 and 80 percent work conditions. In addition, a significant interaction was observed and indicates that the trend of increasing RR with increased work was not similar for all

breathing valves. A relatively linear increase in RR was observed with the Koegel valve which is contrasted by SCBA breathing which showed little change between 50 and 65 percent workload and then a large increase for the 80 percent workload.

Average TV ranged from 1.72 to 2.21 liters for work with the pak at 50 and 80 percent $\dot{V}_{O_2}$ max, respectively; corresponding values for SCBA

breathing were significantly greater by about 400 to 500 ml, averaging 2.06 to 2.72 liters, respectively. Tidal volumes observed for demand and pressure-demand breathing were not significantly different.

TABLE 3. INCREASE IN BLOOD LACTATE OBSERVED FOR MEN PERFORMING
10 MINUTES OF TREADMILL EXERCISE WHILE WEARING THE SCOTT®
AIR-PAK II SCBA

Work $\%V_{O_2}$ max ^a	Increase in Blood Lactate, mg%			
	Control	Pak	Demand	Pressure-Demand
	(n = 21)	(n = 21)	(n = 21)	(n = 21)
50	2.7 ±3.3	7.6 ±5.6	2.3 ±2.9	2.2 ±3.1
65	7.3 ±5.3	18.0 ±8.7	11.6 ±10.1	12.9 ±9.1
80	21.7 ±11.2	52.5 ±26.7	46.3 ±17.4	47.3 ±23.0

^aActual oxygen consumption values for control experiments, i.e., without wearing the 15-kg protective equipment, averaged 41, 53, and 69 percent of V_{O_2} max.

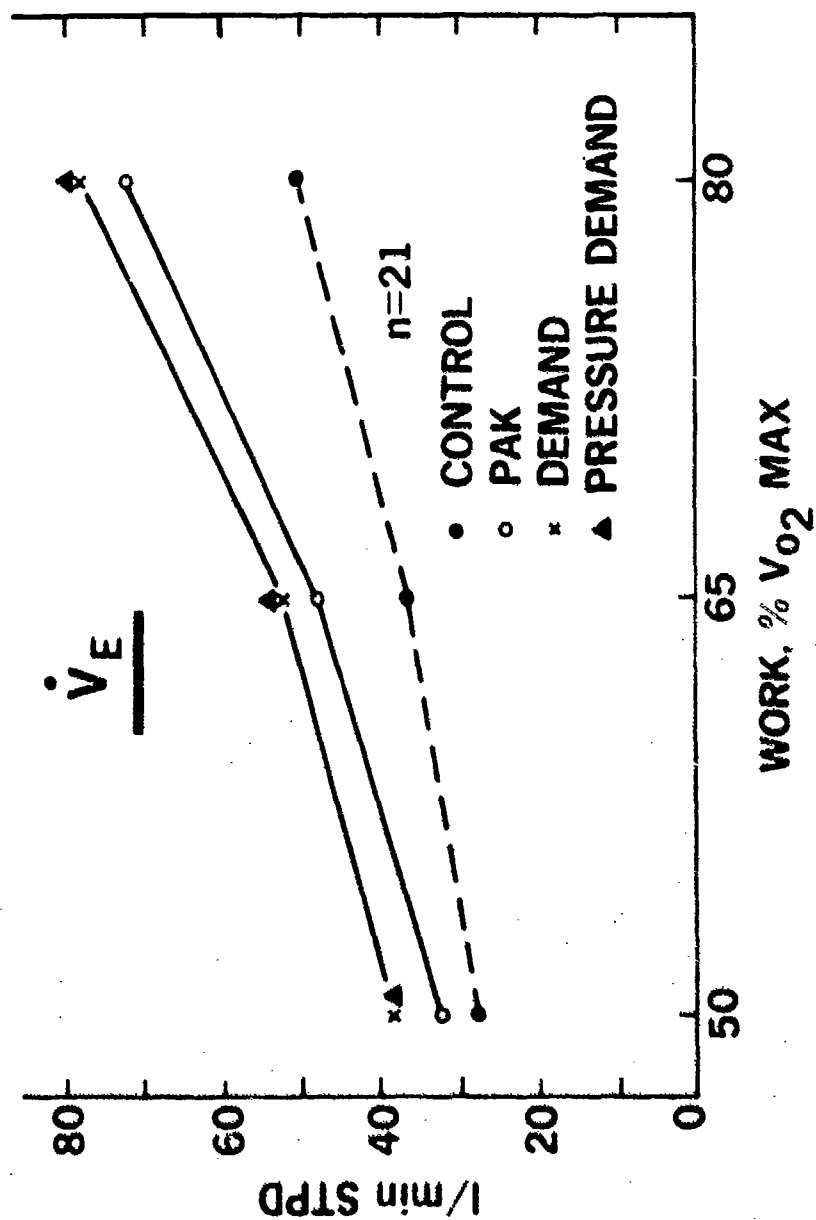


Figure 4. Ventilatory Responses

TABLE 4. VENTILATORY RESPONSES OBSERVED FOR MEN PERFORMING
TREADMILL EXERCISE WHILE WEARING THE SCOTT® AIR-PAK
II SCBA (MEAN $\pm$ S.E.)

$\%V_{O_2}$ ^a	Work max ^a	Control (n = 21)	Pack (n = 21)	Demand (n = 21)	Pressure-Demand (n = 21)
Respiration Rate					
	50	20.4 ± 5.3	23.8 ± 5.1	23.9 ± 5.8	23.0 ± 4.4
	65	22.5 ± 5.0	30.0 ± 6.1	27.5 ± 6.9	26.0 ± 5.5
	80	28.9 ± 5.5	39.2 ± 8.6	35.4 ± 7.3	35.4 ± 7.2
Tidal Volume, l/min BTPS					
	50	1.78 ± 0.52	1.72 ± 0.49	2.06 ± 0.34	2.11 ± 0.44
	65	2.09 ± 0.48	1.99 ± 0.45	2.36 ± 0.50	2.58 ± 0.43
	80	2.22 ± 0.40	2.21 ± 0.58	2.72 ± 0.37	2.72 ± 0.32

^aActual oxygen consumption values for control experiments, i.e., without wearing the 15-kg protective equipment, averaged 41, 53, and 69 percent of V_{O_2} max.

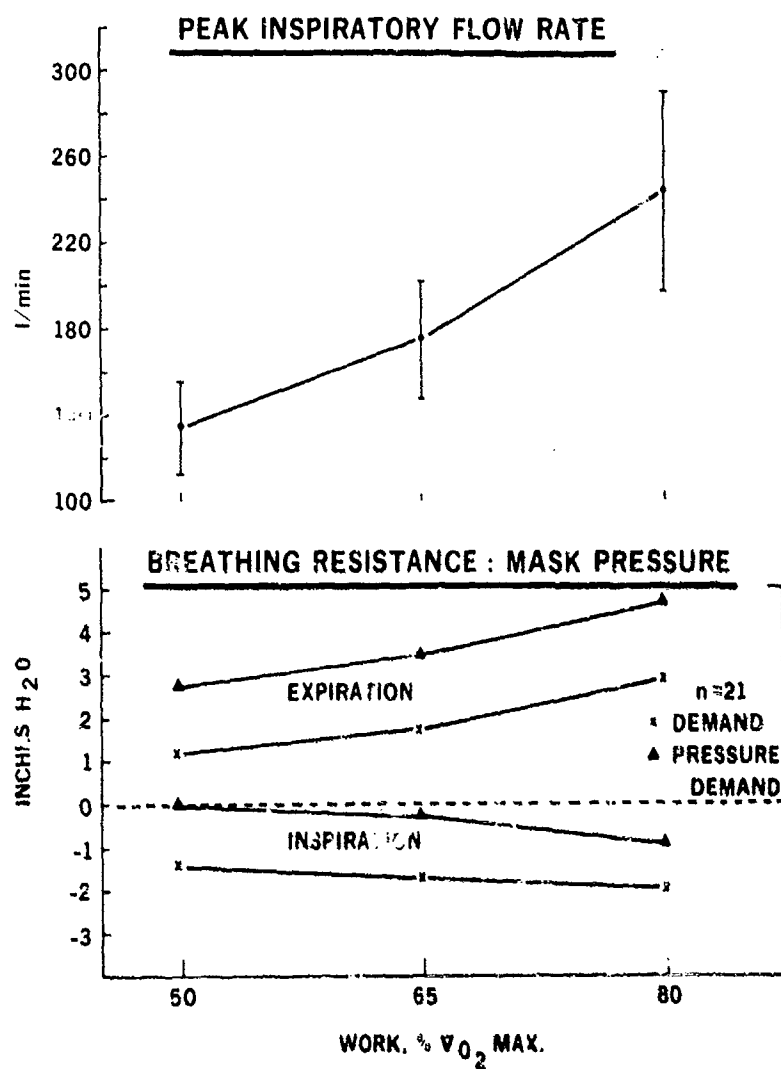


Figure 5. Peak Inspiratory Flow Rate with Corresponding Breathing Resistances

Table 5 illustrates the effect of the increased dead space characteristic of facepiece breathing on inspired O_2 and CO_2 tensions. Following an expiration, the sharp return of inspiratory O_2 and CO_2 tensions to near normal for outside air illustrates the effective low dead space characteristics of the Koegel valve used in the control and pak experiments. This is contrasted by the lower O_2 and higher CO_2 tensions during any given segment of the inspired air observed for demand and pressure-demand breathing. In general, the concentration of O_2 inside the mask at the inspiratory end point significantly increased with increasing work intensity; overall mean differences in O_2 tension related to breathing valves were also significant with observed values being 20.58, 20.71, and 20.81 percent for pressure-demand, demand, and pak, respectively.

Concomitant fluctuations were observed for mask CO_2 in the Koegel valve at end inspiration. A significant interaction and an inspection of the data suggest that only the pak condition resulted in a linear decrease in end inspiratory CO_2 concentration with increasing work intensity.

Breathing Resistance - Table 6 compares breathing resistance determined from bench test experiments with those observed during human exercise experiments. Inhalation resistance for demand mode breathing was not affected by modification of the exhalation valve to allow for collection of expired gases. However, dynamic respiratory patterns during man-work experiments exhibited 10 to 20 percent greater inspiratory resistance than that observed for a given air flow with bench testing. Similar differences between bench and man testing were observed for exhalation resistance with the demand facepiece. Thus, it appears that resistance standards determined from static breathing machine testing underestimate the resistances actually imposed on man performing work with similar flow rate requirements.

The transitory nature of both inspiratory and expiratory resistances makes a similar comparison for pressure-demand breathing difficult

to interpret (see Figures 6 through 13). Nevertheless, even during the easiest work load (50 percent V_{O_2} max), the facepiece pressure for pressure-

demand breathing drops below 0, and this is contrary to all written claims by the manufacturers which extol the continuous positive pressure characteristics of these units. Thus, the wearer of the SCBA can be expected to experience greater resistances to both inhalation and exhalation than those predicted from machine breathing bench tests.

Inspiratory and expiratory resistances imposed on working men by the demand and pressure-demand regulators, with air pressure in the SCBA cylinders exceeding 600 psi, are summarized along with peak flow rates in Figure 5 (see Appendix D).

TABLE 5. END INSPIRATORY OXYGEN AND CARBON DIOXIDE CONCENTRATIONS (PERCENT) OBSERVED IN THE RESPIRATORY VALVE (CONTROL AND PAK) AND IN THE FACE MASK (DEMAND AND PRESSURE-DEMAND) FOR MEN PERFORMING TREADMILL EXERCISE WHILE WEARING THE SCOTT®AIR-PAK SCBA (MEAN $\pm$ S.E.)

$\% \dot{V}_{O_2}$	Work ^a max	Control (n = 21)	Pak (n = 21)	Demand (n = 21)	Pressure-Demand (n = 21)
Percent O ₂					
50		20.83 ± 0.07	20.78 ± 0.23	20.59 ± 0.20	20.43 ± 0.40
65		20.78 ± 0.14	20.81 ± 0.16	20.74 ± 0.15	20.63 ± 0.18
80		20.83 ± 0.14	20.83 ± 0.13	20.80 ± 0.15	20.67 ± 0.22
Percent CO ₂					
50		0.10 ± 0.06	0.11 ± 0.04	0.33 ± 0.14	0.48 ± 0.33
65		0.10 ± 0.06	0.14 ± 0.14	0.22 ± 0.11	0.30 ± 0.14
80		0.10 ± 0.05	0.08 ± 0.05	0.19 ± 0.16	0.25 ± 0.13

^aActual oxygen consumption values for control experiments, i.e., without wearing the 15-kg protective equipment, averaged 41, 53, and 69 percent of $\dot{V}_{O_2}$ max.

TABLE 6. COMPARISON OF RESPIRATORY FLOW RATES AT
SELECTED FACEPIECE PRESSURES FOR DEMAND AND
PRESSURE-DEMAND UNITS DURING LASL BENCH TESTS
WITH THOSE OBSERVED DURING USAFSAM MAN-EXERCISE
TESTS

		Facepiece Pressure, cm H ₂ O		
		<u>2</u>	<u>4</u>	<u>6</u>
<u>Demand Mode</u>				
LASL Bench Tests				
Mask AA		105	213	298
Mask BB		111	267	344
USAFSAM, mean		102	158	214
USAFSAM-LASL Δ		-3 to -8%	-26 to -41%	-28 to -38%
<u>Pressure Demand Mode</u>				
LASL Bench Tests				68-88
USAFSAM, mean				96
USAFSAM-LASL Δ				+9 to +41%

		Facepiece Pressure, cm H ₂ O	
		<u>0 (Pressure-Demand)</u>	<u>-5 (Demand)</u>
LASL Bench Tests		278-358	278-312
USAFSAM, mean		128	250
USAFSAM-LASL Δ		-54 to -65%	-10 to -20%

As shown earlier, $\dot{V}_E$ values averaging about 39, 53, and 79 l/min were observed during workloads representing 50, 65, and 80 percent of $\dot{V}_{O_2}$ max. These, in turn, were associated with peak inspiratory flow rates averaging 134, 175, and 244 l/min, respectively. Individual peak flows exceeding 350 l/min were observed during the highest work level. Thus, as shown in Figure 5, these ventilatory requirements and peak flow levels were achieved at varying levels of inspiratory and expiratory resistances, both of which increased significantly with increasing work intensity for demand and pressure-demand breathing. Mean mask pressures during inspiration ranging from -1.38 to -1.99 inches H_2O for the demand regulator were significantly greater than those for pressure-demand breathing which ranged from -0.02 to -0.94 inches H_2O for corresponding increases in workload.

Records for comparison of demand and pressure-demand breathing resistances from representative experiments on one subject are presented in Figures 6 - 9. Characteristically, for a given workload (i.e., 50 percent and 65 percent of $\dot{V}_{O_2}$ max) requiring similar ventilatory and

peak inspiratory flow rates, inspiratory resistances were greater with the demand mode while expiratory resistances were greater for pressure-demand breathing. It should be noted that even during these relatively easy and moderate workloads, the pressure-demand regulator was not completely effective in preventing the occurrence of negative pressure within the facepiece. These momentary excursions of negative pressure appeared regularly during the initiation of the inspiratory cycle.

Only during work at 80 percent of $\dot{V}_{O_2}$ max was the ventilatory requirement great enough to nearly empty the air cylinder during the 10-minute work period. In these instances, when cylinder pressure dropped low enough to trigger the alarm bell (i.e., < 500 psi), inspiratory resistance increased markedly in both demand and pressure-demand units as shown in Figures 10 through 13.

Maximum negative pressures observed in some experiments exceed -6.5^a inches H_2O during work at 80 percent of $\dot{V}_{O_2}$ max for both pressure-

demand and the demand regulators. The observed duration of negative pressure within the pressure-demand face mask throughout the entire inspiratory phase at this work level (Figures 10, 11), even while cylinder pressure was supposedly adequate for efficient regulator performance, is of notable concern.

The time duration of negative pressure within the facepiece equaled the sum of the time spent in inspiration for the demand regulator, but varied considerably for the pressure-demand regulator. However, some insight as to the number of seconds/min that the facepiece was exposed to negative pressure during the pressure-demand mode, determined for six representative experiments on one subject, is presented in Table 7. It is apparent that one may experience negative pressures inside the pressure-demand facepiece for as much as 22 seconds out of every minute when performing work at 80 percent of $\dot{V}_{O_2}$ max.

^aOff-scale recordings

CYLINDER PRESSURE = 1000 psi

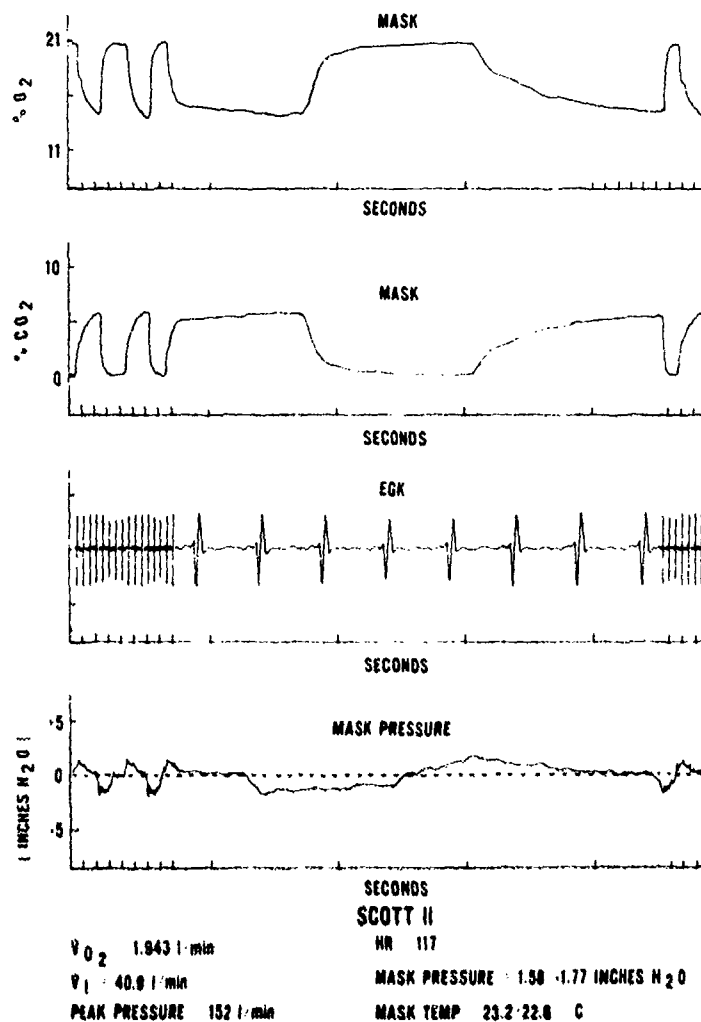
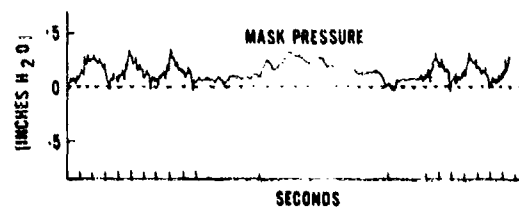
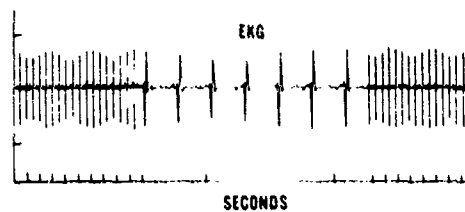
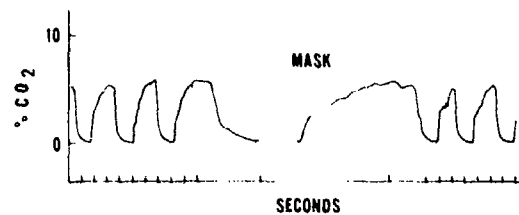
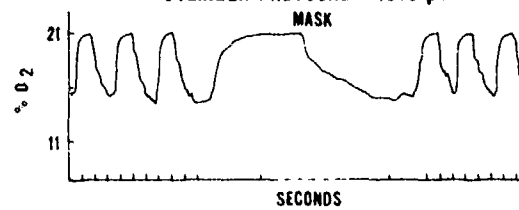


Figure 6. Treadmill Exercise Requiring 50 Percent $\dot{V}O_2$ in Demand Mode

50% PRESSURE DEMAND 5-6 MIN

CYLINDER PRESSURE = 1300 psi



SCOTT-II

V_{O_2} 1.995 l/min	HR 115
V_I 43.4 l/min	MASK PRESSURE 3.39 -0.22 INCHES H_2O
PEAK FLOW 151 l/min	MASK TEMP 24.0-23.5 C

Figure 7. Treadmill Exercise Requiring 50 Percent VO_2 in Pressure Demand Mode

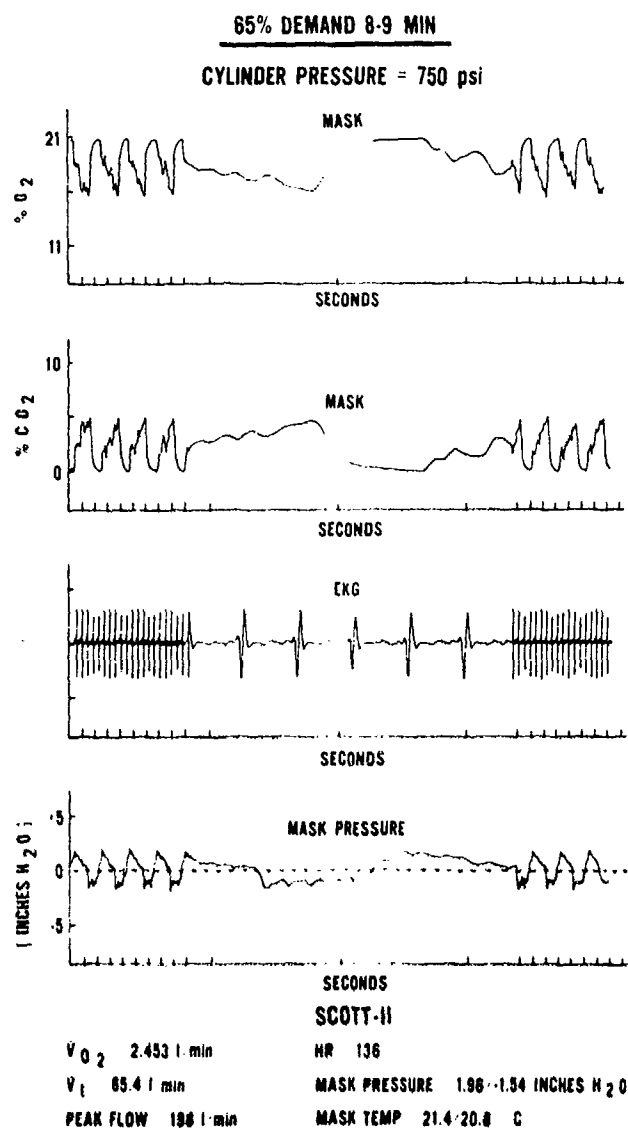


Figure 8. Treadmill Exercise Requiring 65 Percent $\dot{V}O_2$
in Demand Mode

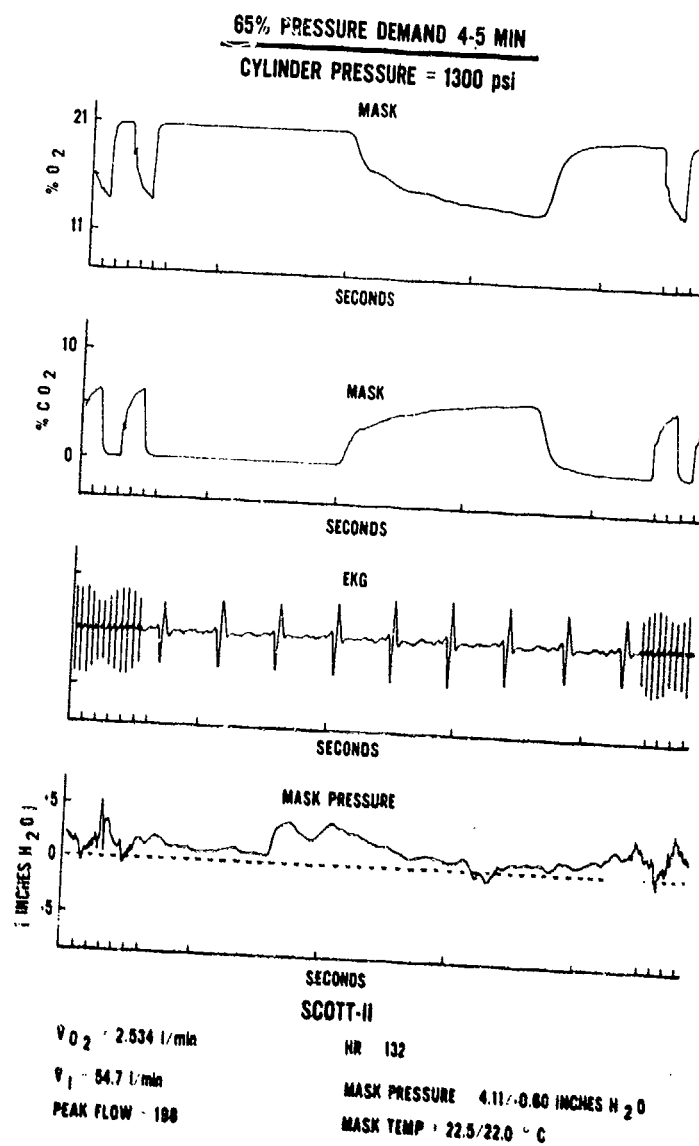
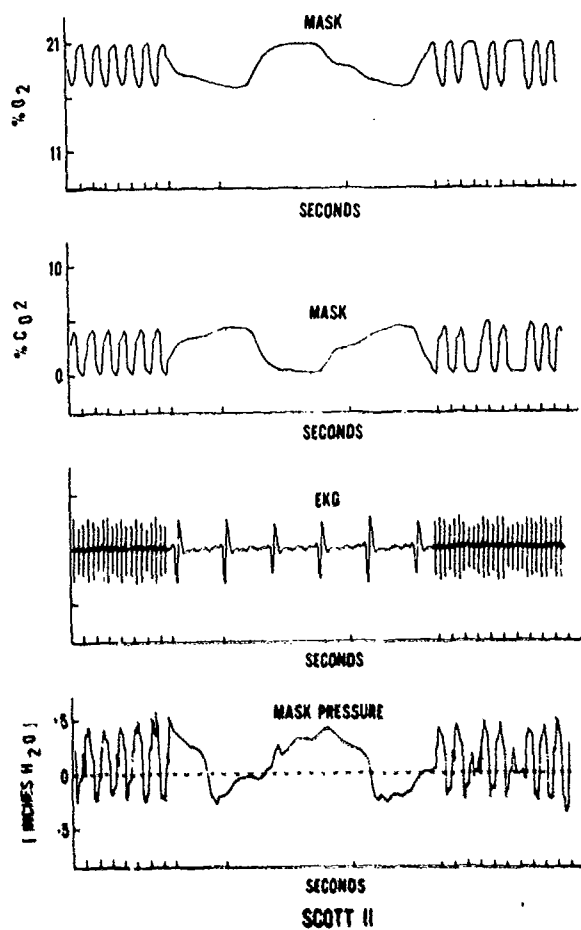


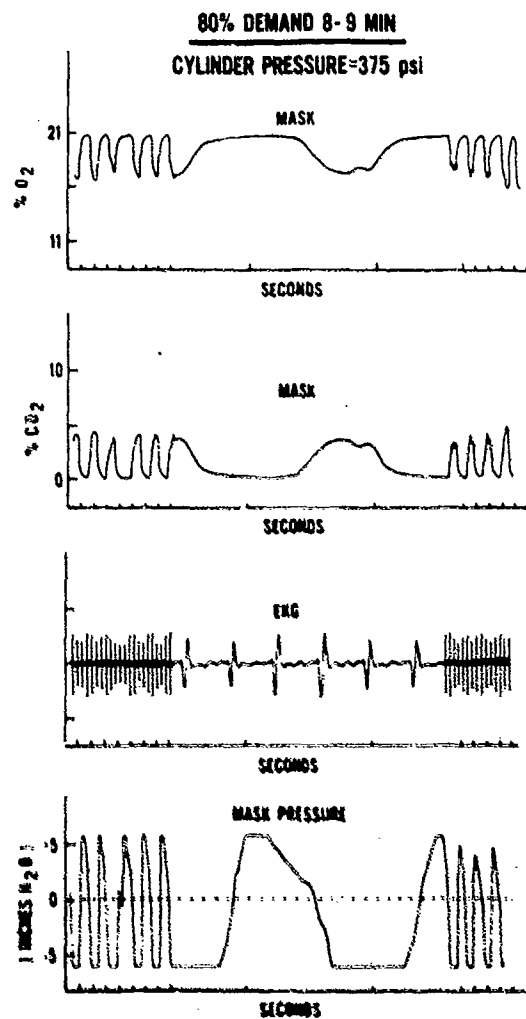
Figure 9. Treadmill Exercise Requiring 65 Percent $\dot{V}O_2$ in Pressure Demand Mode

80% DEMAND 5-6 MIN
CYLINDER PRESSURE = 1100 psi



SCOTT II
 $\dot{V}O_2 = 3.350 \text{ l/min}$ $\dot{V}E = 180$
 $\dot{V}_I = 110.7 \text{ l/min}$ MASK PRESSURE = 4.85/-2.44 INCHES H₂O
 PEAK FLOW = 360 l/min MASK TEMP. = 20.0/18.3 °C

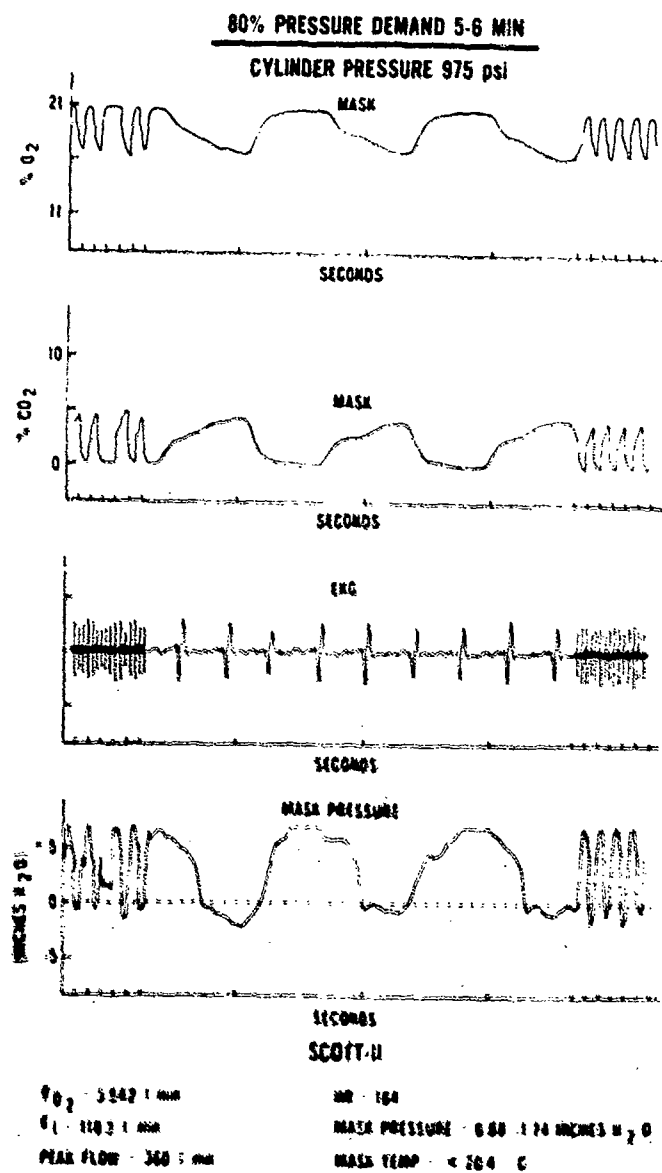
Figure 10. Treadmill Exercise Requiring 80 Percent $\dot{V}O_2$ 5-6 Minutes, in Demand Mode



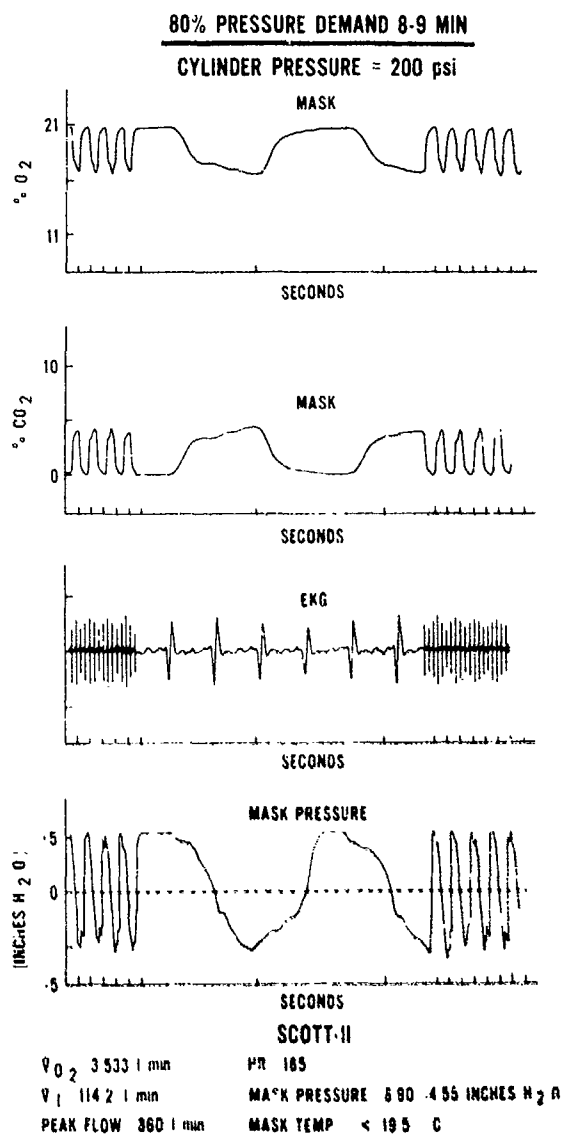
SCOTT-H

$\dot{V}O_2$ - 3.483 l/min	HR - 165
$\dot{V}I$ - 123.3 l/min	MASK PRESSURE - 6.10 - 6.41 INCHES H_2O
PEAK FLOW - 360 l/min	MASK TEMP - $< 19.3^\circ C$

Figure 11. Treadmill Exercise Requiring 80 Percent $\dot{V}O_2$
8-9 Minutes, in Demand Mode



**Figure 12. Treadmill Exercise Requiring 80 Percent $\dot{V}O_2$
5-6 Minutes, in Pressure Demand Mode**



**Figure 13. Treadmill Exercise Requiring 80 Percent $\dot{V}O_2$
 8-9 Minutes, in Pressure Demand Mode**

TABLE 7. NUMBER OF SECONDS PER MINUTE THAT THE SCBA DEMAND AND PRESSURE-DEMAND FACE MASK IS EXPOSED TO NEGATIVE PRESSURE DETERMINED FOR SIX REPRESENTATIVE EXPERIMENTS REQUIRING A VARIETY OF VENTILATION AND PEAK INSPIRATORY FLOW RATE VALUES

Work	$\overset{a}{V}_I$	PFR ^b	RR	<u>Negative Pressure in Face Mask</u>	
%V _{O₂} max	l/min	l/min		seconds/respiration	seconds/min
Demand					
50	40.3	151	18	1.50	27.0
65	61.5	196	19	1.20	22.8
80	119.5	226	39	0.72	28.1
Pressure-Demand					
50	43.4	151	19	0.10	0.2
65	54.7	196	18	0.27	4.9
80	110.3	226	48	0.45	21.6

$\overset{a}{V}_I$ = Inspiratory Ventilation, STPD

^bPFR = Peak Inspiratory Flow Rate observed for pak condition and used here to estimate the flow occurring during SCBA breathing for the same workload with similar ventilation rates.

Cardiovascular Responses - Cardiovascular responses to work are represented by observations of heart rate (HR) as given in Figure 14. Again, as expected, HR increased linearly with increases in energy expenditure. Performance of a given task while carrying the weight of the SCBA was accompanied by HR's averaging 14 percent greater than those observed for performing the same walk on the treadmill without the SCBA burden. There was no difference in HR at any work level that could be attributed to the breathing device being used. Analysis of the EKG recording revealed no rhythm irregularities that could be attributed to any of the 12 treatment conditions.

Hematological Responses - Initial hematocrit (Hct) averaged 45.0 for all work loads, but final Hct was significantly greater averaging 46.1, 47.1, and 49.5 for work at 50, 65, and 80 percent of V_{O_2} max, respectively. This trend for increasing Hct with increasing workload was significant and occurred for every breathing mode condition. There were no differences in degree of hemoconcentration with work that could be attributed to the breathing device used. These findings were also true for Hb concentration, another index of hemoconcentration.

Percent carboxyhemoglobin (%COHb) averaged 1.87 before and 1.67 following exercise, and this difference was significant at $P < 0.001$. There was no difference in the rate of %COHb decrease that could be related to the breathing devices used.

Blood lactate increased significantly for workloads with the trend for greater increases as the workload increased. The overall increases observed for pak conditions were only slightly greater than those observed for demand and pressure-demand breathing, but these differences were significant.

Thermoregulatory Responses - Air temperature measured inside the facepiece (Figure 15) increased during expiration and decreased with inspiration. Both of these temperatures decreased significantly with

increasing work intensity, and the temperature with demand breathing was always slightly, but significantly, lower than that with pressure-demand breathing. For workloads greater than 50 percent of $\dot{V}_{O_2}$ max, this

difference averaged $< 0.5^{\circ}\text{C}$. Overall mask air temperatures averaged 22.4° to 23.0°C , and 23.0° to 23.5°C for demand and pressure-demand breathing, respectively.

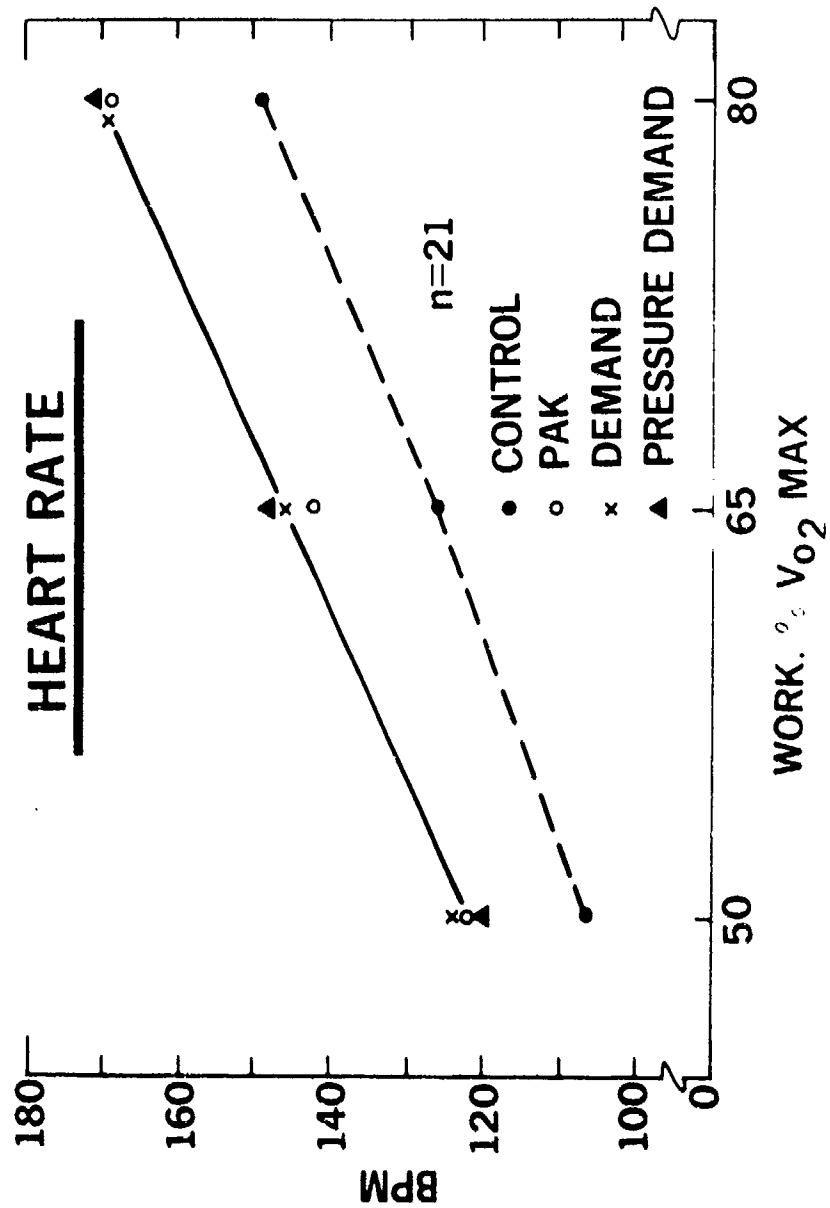


Figure 14. Mean Heart Rate Performing Treadmill Exercise While Wearing Air-Pak

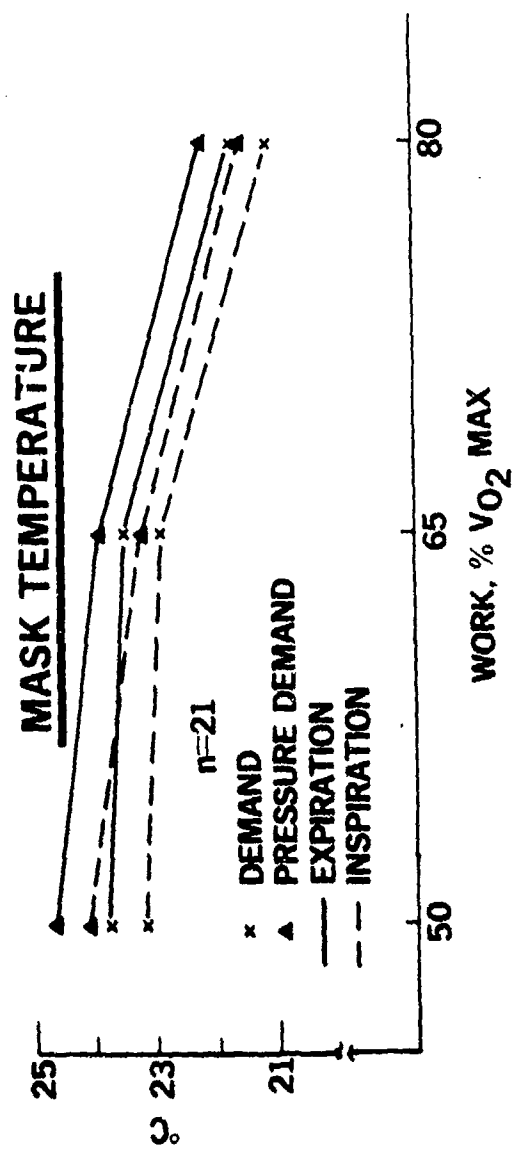


Figure 15. Mean Mask Air Temperatures Performing Treadmill Exercise While Wearing Air-pak

Forehead skin (T_f) temperature responses to 10 minutes of work in an environment ranging from 20° to 22°C were closely related to the breathing device used, generally increasing during pak experiments and decreasing when breathing through the facepiece. T_f increased about 0.8°C and 1.0°C, respectively, for workloads requiring 65, and 80 percent of $\dot{V}_{O_2}$ max. On the other hand, T_f under the face mask in the

demand mode decreased 0.9°, 1.5°, and 1.7°C for work at 50 65 and 80 percent $\dot{V}_{O_2}$ max, respectively. Corresponding decreases in T_f with

pressure-demand breathing averaged 1.2°, 1.7°, and 2.5°C.

Rectal temperature (T_r) was little affected by 10 minutes of work in this cool environment. Initial T_r averaged 37.1°C for all workloads and for all breathing conditions. Final T_r showed average increases of about 0.2°C for work at 50 and 65 percent $\dot{V}_{O_2}$ max, and a 0.3°C increase

for work at 80 percent $\dot{V}_{O_2}$ max. These increases, although hardly representa-

tive of heat stress, were statistically significant. Neither the weight of the SCBA nor the demand or pressure-demand breathing had any significant effect on these slight increases in T_r with 10-minute exercise.

SMOKERS VS NON-SMOKERS

By design, this study incorporated the selection of both smokers (S) and non-smokers (NS) as volunteer subjects. Bioclinical characteristics of these subgroups are presented in Table 8. A comparison of the S and NS physiological responses to the conditions in this study is presented in Tables D-5 and D-6. In general, the only significant differences observed that could be attributed to smoking were those related to aerobic capacity, i.e., physical fitness, and blood chemistry.

As a group, the NS were more fit as evidenced by their significantly greater values for $\dot{V}_{O_2}$ max. Consequently, although both S and NS were

assigned treatment workloads that approximated 50, 65 and 80 percent of $\dot{V}_{O_2}$ max, the absolute workloads in calories per hour were significantly

greater for the NS. On the other hand, except for the 80 percent work level, the ventilatory requirements of NS were not significantly greater than those for S. The mechanical efficiency of the NS in performing work was slightly, but significantly greater than for S.

TABLE 8. BIOCLINICAL CHARACTERISTICS OF SMOKERS (n - 9) AND NON-SMOKERS (n = 12) (MEAN $\pm$ S.D.)

	Non-Smokers	Smokers
Smoking, pack years	0	21.4 $\pm$ 25.8
Age	6.7	34 $\pm$ 7.2
Ht, cm	180.3 $\pm$ 7.4	176.1 $\pm$ 7.1
Wt, kg	77.84 $\pm$ 6.55	77.52 $\pm$ 10.77
% Fat	18.5 $\pm$ 4.6	24.2 $\pm$ 4.3
$\dot{V}_{O_2}$ max, l/min	3.706 $\pm$ 0.448	3.149 $\pm$ 0.251
$\dot{V}_{O_2}$ max, ml/kg min	47.5 $\pm$ 4.9	40.7 $\pm$ 5.2
$\dot{V}_E$ max, l/min STPD	116.8 $\pm$ 21.4	94.0 $\pm$ 14.7
HR, rest	64.3 $\pm$ 13.5	73.2 $\pm$ 12.9
HR, max	189.3 $\pm$ 6.7	186.3 $\pm$ 11.2
Systolic BP, rest	123.3 $\pm$ 11.6	129.6 $\pm$ 17.7
Diastolic BP, rest	78.5 $\pm$ 5.8	78.7 $\pm$ 15.3
Systolic BP, max	186.8 $\pm$ 16.4	181.8 $\pm$ 12.1

Smokers exhibited significantly greater venous Hct and COHb than did their NS counterparts. Although the increases in hemoconcentration with work were similar for both groups, the decrease in COHb was greater during the 10 minutes of work for S than for NS. This is obviously due to the fact that the NS level of COHb was initially at nearly the minimal physiological value. Initial venous Hb concentrations were slightly greater for S than NS, averaging 16.8 and 16.1 g, respectively, but these differences were not statistically significant.

SUBJECTIVE RESPONSES OF SUBJECTS

The results of the subjects' responses to the questionnaire completed immediately after completing a given experimental condition are presented in Table 9.

Perceived Stress Index - On a scale from 6 to 22, mean responses to the question for rating the total stress perceived during each of the 3 work levels differed significantly at $P < 0.001$, showing an increase in work stress rating with an increase in workload in terms of percent $\dot{V}_{O_2}$ max.

These ratings were the same for all breathing regulator conditions, i.e., no differences in this response that could be related to the breathing valve being used. Also, a lack of a significant interaction indicates that the trends did not differ for the three breathing valve conditions.

Work Intensity - This question is closely related to the perceived stress question above, and the results were the same except for a significant interaction which may indicate a slight preference for the Koegel valve at the 50 percent workload, the pressure-demand regulator for 65 percent workload, and the demand regulator for the 80 percent workload. Although statistically significant at $P < 0.05$, these differences were slight in magnitude, never exceeding 0.3 points on a 7-point scale.

Inspiratory Resistance - Overall subjective response to inspiratory resistance increased significantly ($P < 0.001$) as work increased from 50 through 80 percent of $\dot{V}_{O_2}$ max. The resistance ratings of breathing

valves also differed significantly at $P < 0.025$, with the Koegel valve being least resistant for all workloads. The pressure-demand regulator was rated less resistant than the demand regulator only for the 50 and 65 percent workloads; the two being rated equally for the 80 percent workload. A lack of a significant interaction indicates no difference among the breathing devices in the trends to rate the resistance increase with increasing workload.

Expiratory Resistance - Again, the ratings for expiratory resistance increased significantly at $P < 0.001$ as workload increased, and as was the case with inspiratory resistance, the Koegel valve provided significantly lower ($P < 0.002$) expiratory resistance for all workloads. A lack of a significant interaction indicates that the trend to increase the expiratory resistance rating with increasing workload was not affected by the breathing valve being used.

TABLE 9. SUBJECT RESPONSES TO QUESTIONNAIRE COMPLETED IMMEDIATELY
FOLLOWING WORK ON THE TREADMILL WEARING THE SCOTT®AIR-PAK
SCBA (MEAN DATA)

Work %V _O ₂ max	Pak (n = 21)	Demand (n = 21)	Pressure-Demand (n = 21)	All Conditions (n = 63)
<u>Perceived Stress Index</u>				
50	9.3	10.0	9.7	9.7
65	12.9	12.6	12.4	12.6
80	16.0	15.9	16.0	16.0
Mean	12.8	12.8	12.7	
<u>Workload; scale 1-7 (easy to hard)</u>				
50	2.0	2.4	2.2	2.2
65	4.0	4.0	3.8	4.0
80	5.6	5.2	5.5	5.4
Mean	3.9	3.9	3.9	
<u>Ease of Inspiration; scale 1-7 (easy to hard)</u>				
50	1.5	2.6	1.9	2.0
65	2.2	2.7	2.5	2.5
80	2.8	3.5	3.5	3.3
Mean	2.2	3.0	2.7	
<u>Ease of Expiration; scale 1-7 (easy to hard)</u>				
50	1.8	2.1	2.2	2.0
65	2.1	2.6	3.0	2.6
80	2.9	3.5	3.6	3.3
Mean	2.3	2.7	3.0	
<u>Temperature inside mask; scale 1- (cool to hot)</u>				
50	2.1	3.0	2.6	2.6
65	2.8	3.6	3.3	3.2
80	3.2	3.8	3.4	3.5
Mean	2.7	3.5	3.1	

TABLE 9 (Concluded)

Sweating inside mask; scale 1-7 (light to heavy)

50	1.7	2.1	2.1	2.0
65	2.8	2.8	2.8	2.8
80	3.0	3.5	3.0	3.2
Mean	2.5	2.8	2.7	

Temperature Inside Mask - Mean responses to mask temperature differed significantly at $P < 0.001$ showing an increase with an increasing workload over all experimental conditions. This is in contrast to recordings of facepiece temperature (Figure 15) which actually decreased with increasing workloads. The pak condition, which refers only to face and forehead temperature since no mask was used, was rated coolest for all workloads, and this was significant at $P < 0.01$. (It should be noted that actual forehead skin temperatures, which were always cooler during facepiece breathing, do not agree with this subjective response.) Face temperature during pressure-demand breathing was rated as being 0.3 to 0.4 points cooler than demand breathing for all work conditions, and a lack of significant interaction indicates that the trend to rate increased mask temperature with increased workload was not affected by the breathing mode.

Sweating Inside Mask - Mean responses for face and forehead sweating differed significantly showing an increase with increasing workload. However, no difference was observed in sweating response related to breathing valves, and a lack of interaction indicates that the trend to rate increased sweating with increased workload was not affected by the breathing mode.

SECTION IV

DISCUSSION

Physiological responses to work while wearing a self-contained breathing apparatus (SCBA) in either demand or pressure-demand modes are not a great deal different from those observed in men repeating the same work while wearing the SCBA back pack while breathing through a low-resistance, high-velocity Koegel valve. The energy cost for performing treadmill exercise increased from 17 to 20 percent as a result of wearing the 15-kg SCBA, but it was not measurably affected by the respiratory stresses attributed to either demand or pressure-demand facepiece breathing. This is in agreement with Davis (Reference 7) who reported a 17 to 21 percent decrement in maximal work time while wearing the SCBA, and that these decrements were due to the added weight alone and not significantly related to facepiece breathing. Indeed, Craig (Reference 8) concluded that fitness for work was the most important criterion for predicting work performance while wearing a SCBA. Put very simply, these authors concluded that "the longer one can work unmasked; the longer one can work masked." Provided that the bulk and weight of the pak are borne efficiently and comfortably on the back and that the facepiece is properly and comfortably fitted, the only other significant physiological consequences inherent in Scott^(R) Air-Pak II breathing are those related to what may be termed "air insufficiency" during the relatively high breathing resistance associated with the harder workloads.

Other than exhibiting a generally lower level of physical fitness, smokers responded no differently than non-smokers to work while wearing the SCBA. It should be noted, however, that any low-fitness subject, smoker or non-smoker, will probably experience less distress with facepiece breathing due to his inability to work hard enough to push the SCBA to its ventilatory and flow rate limits.

Facepiece breathing was associated with a lower respiratory frequency and a greater tidal volume, the net result being a small but significantly greater minute ventilation than when performing the same work without

the facepiece. The greater awareness of respiratory actions with resistance breathing undoubtedly contributed to this altered ventilatory pattern. However, this is in contrast with the findings of Gee (Reference 9) and Cerretelli (Reference 10) who reported a decrease in $\dot{V}_E$ as airway resistance increased at any level.

The continued high quality of the inspired air with facepiece breathing, i.e., $> 20\% O_2$ and $< 0.5\% CO_2$ at end inspiration, is attributed to the rapid and efficient flushing of the mask dead space.

Although neither the inspiratory nor expiratory resistances of the demand and pressure-demand modes present any great problems to men working at 50 percent of their aerobic capacity ($\dot{V}_{O_2 \text{ max}}$), these devices

may create serious distress in men working at 80 percent $\dot{V}_{O_2 \text{ max}}$. Low

resistance breathing when ventilatory requirements exceed 80 l/min with concomitant peak inspiratory flow rates exceeding 200 to 250 l/min appears to be beyond the present capabilities of both of these breathing regulators. This is contrary to the findings reported from bench testing methods, and it is probably attributable to the dynamic nature of human respiratory movements during work as opposed to the static nature of breathing machines.

The trade-off of high expiratory resistance in exchange for a lesser inspiratory resistance, characteristic of the pressure-demand regulator, is not always appreciated by the working man. In many instances, men found this resistance to expiration to be more irritating than was the greater inspiratory resistance of the demand mode. This response is in agreement with Silverman (Reference 5) who reported that expiratory resistance is much less tolerated than is inspiratory resistance.

Aside from subject acceptance of demand or pressure-demand modes, the obvious asset of the latter is in the degree of protection it provides in a toxic environment where any inward leaking could be extremely

dangerous. As pointed out earlier, this capability as extolled by the manufacturers is not at all supported by our data as illustrated in Figures 6-13. The impossibility of an inward leak due to continuous positive pressure inside the facepiece is a strong statement; indeed it is an incorrect one which may lead to serious consequences. Negative pressures inside the mask occur frequently, and of both increasing magnitude and duration with increasing workload as evidenced in Figure 5 and Table D-4. Data presented here represent breathing resistances to be expected when the SCBA cylinder is pressurized above the alarm level of 500 psi. The situation rapidly deteriorates when cylinder pressure drops below this level, and this occurs when the subject expects that he still has a 5-minute air supply, possibly the time required to egress from a hazardous environment. The alarming effect of decreasing cylinder pressure on inspiratory resistance is evident from data presented in Figure 16.

Resistance breathing had no effect on the exercise heart rate and this is in agreement with others (References 3, 7, 8). Although having no apparent effect on EKG, inspiratory resistances exceeding 4 inches H_2O markedly altered respiratory mechanics. During work at 80 percent of $\dot{V}_{O_2}$ max while wearing the demand regulator, a particular subject

successfully altered his normal breathing pattern to maintain inspiratory negative pressures of less than -2 inches H_2O only so long as the cylinder pressure exceeded 500 psi. The occasional sharp decreases in negative pressure indicate a breakthrough of the subject's normal or preferred inspiratory pattern in spite of attempts to control the rate and depth of inspiration to avoid the stress of breathing against excessive negative pressure. Negative inspiratory pressures greater than -5.5 inches H_2O were unavoidable when cylinder pressure had dropped below 500 psi. In the pressure-demand mode, no adjustment in inspiratory pattern was required to keep negative pressures at a modest -1.0 inch H_2O while cylinder pressure exceeded 500 psi; thereafter, however, negative pressures varied from about -3 inches to more than -5 inches H_2O in this particular experiment. Note that the lower respiratory frequency observed for the demand mode breathing was not the result of a lesser exercise or respiratory stress. On the contrary, it represents a rate forced on the subject by the highly resistant demand regulator.

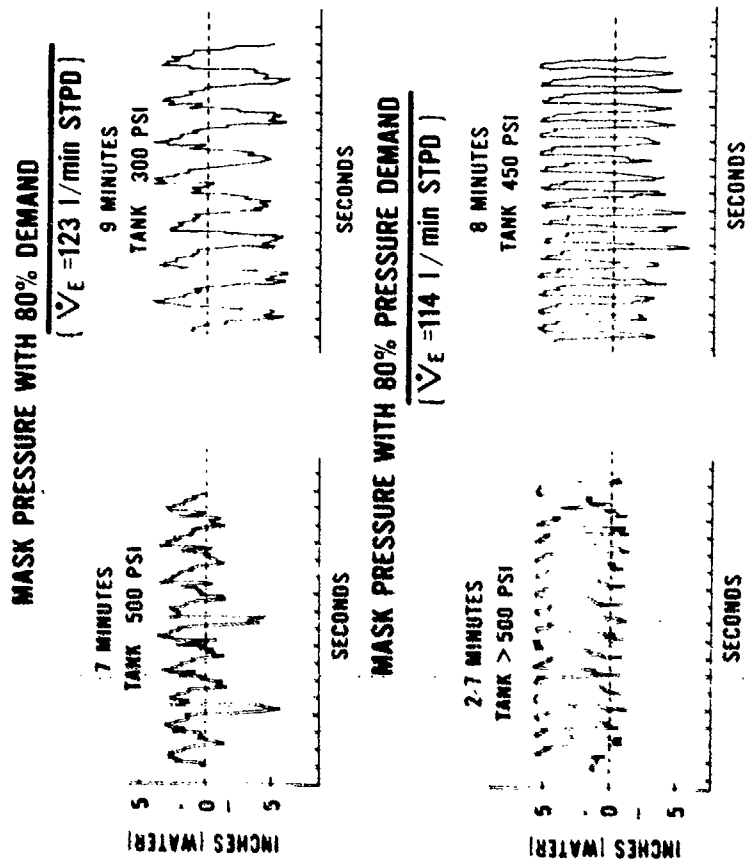


Figure 16. Effect of Cylinder Pressure on Breathing Resistance While Performing Treadmill Exercises at 80 Percent $\dot{V}_{O_2}$

The selection of a ventilatory requirement of 40 l/min in determining the duration of air supply available in a SCBA (Reference 1 and 5) is indeed open to severe criticism. This ventilatory requirement is more typical of a postman walking on a sidewalk while carrying a mail bag than it is for a firefighter who is called upon to climb stairs and ladders and then to perform strenuous physical work while faced with the added stress of a life-threatening environment (References 2, 3, and 4). The same argument could be made for the certification requirements which specify limits for SCBA breathing resistances when tested at flow rates of only 85 and 125 l/min (Reference 5). In our experiments, ventilatory volumes of 40 l/min were observed with a heart rate of 122 during work at 50 percent $\dot{V}_{O_2}$ max with peak flows of about 135 l/min. A flow rate

of 85 l/min is attained during very easy work with minute volumes of only 30 l/min and/or heart rate of only 116. How can the certification agencies justify a breathing resistance standard which is based on a ventilatory requirement which is typical of such easy work? A much more realistic approach would be to determine the requirements of a given occupation and then to rate the air supply and flow-rate requirements accordingly.

Del Veccio and Himel (Reference 3) monitored 6 New York City firefighters during normal active duty and observed average peak pulse rates to be 140-160 while at the nozzle, and 170 during climbing and forcible entry. Individual peak heart rates of 180 were recorded. Lemon and Hermiston (Reference 10) studied the energy cost of performing 4 selected firefighting tasks and reported that, even in the absence of the external stresses present at an actual fire, this occupation may be classified as heavy physical work requiring 60 to 80 percent of $\dot{V}_{O_2}$ max.

Bernard and Duncan (Reference 2) reported that the heart rate of a Los Angeles firefighter was maintained above 160 for over 90 minutes in two consecutive fires. These authors also noted a 15-minute period of extremely high heart rate averaging 188 beats per minute.

To re-evaluate current standards for SCBAs, ventilatory requirements for a man performing a given workload may be predicted from the exercise heart rate and/or $\dot{V}_{O_2} \text{ max}$ (see Figures 4 and 14). Figure 17

shows the high correlation obtained for the linear relationship between inspired ventilation ($\dot{V}_I$) and flow rate for the conditions imposed in this study. Thus, from the regression formula given, one may estimate peak flow rates for a given $\dot{V}_I$; peak flow rates may then be used in Figure 18 to estimate corresponding inhalation and exhalation resistances to be expected from the Scott® Air-Pak II. These resistances will represent actual man-exercise experimental data, and consequently, they will not always agree with values reported for the less demanding machine breathing bench testing methods. In addition, it must be remembered that inhalation resistance increases greatly when cylinder pressure drops below 500 psi (see Figure 16).

Figure 18 summarizes the inspiratory and expiratory resistances observed during work as a function of peak flow rate. For any peak flow rate between 80 and 280 l/min the regression equations permit the estimate of breathing resistance to be expected during Scott® Air-Pak II demand and pressure-demand mode breathing.

The two points representing peak flow rates exceeding 300 l/min (see Figure 17) were omitted from these figures because the corresponding expiratory and inspiratory resistances during pressure-demand breathing were excessive; to include them in determining the regression equations for estimating breathing resistances would have imparted considerable error in the use of these equations for the more typical flow rates between 90 and 280 l/min. However, these two extreme values, representing flow rates of 352 and 360 l/min exhibited by the more fit subjects performing work at 80 percent $\dot{V}_{O_2} \text{ max}$, may provide valuable insight into

the operating characteristics of the pressure-demand unit. Using a freshly cleaned facepiece-valve assembly, with a cylinder pressure < 975 psi, a flow rate of 360 l/min was achieved with expiratory pressures

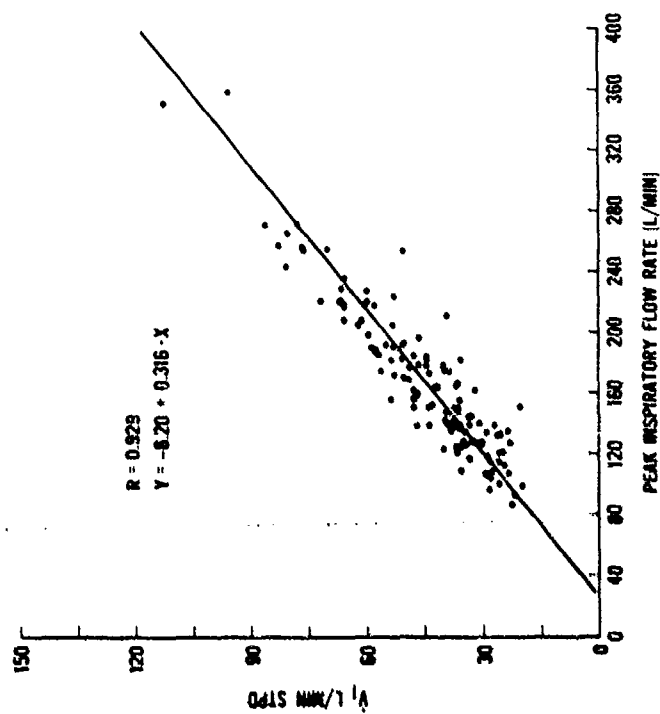


Figure 17. Relationship of Peak Inspiratory Flow Rate to Ventilation Performing Treadmill Exercise Requiring 50, 65, and 80 Percent $\dot{V}O_2$ max

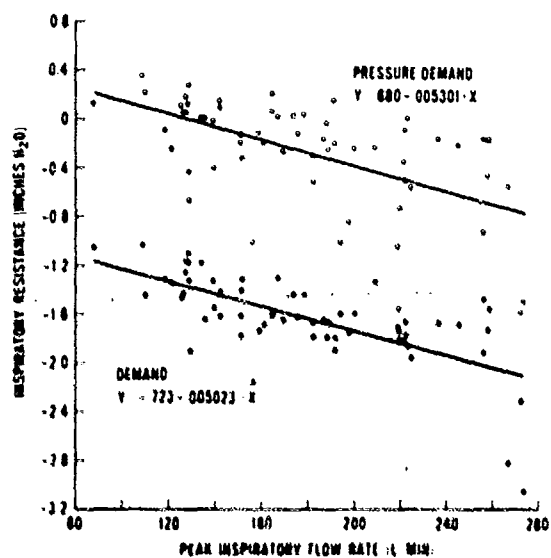
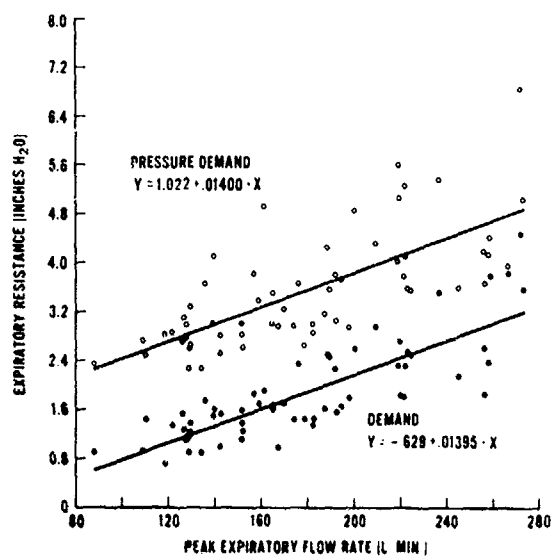


Figure 18. Regression Equations Derived for Predicting Breathing Resistances from Peak Inspiratory Flow Rates When Using the Scott[®] Air-Pak II SCBA in Demand and Pressure Demand Modes

exceeding 7 inches, and inspiratory pressures averaging -1.7 inches H_2O . The regression equation would have predicted +6.1 and -1.2 inches H_2O , respectively. During the same experiment, when cylinder pressure had dropped to < 500 psi, expiratory resistance remained relatively constant while inspiratory resistance increased rapidly to exceed -6 inches H_2O . In the other experiment with peak flow rates of 352 l/min, the cylinder pressure never dropped below 600 psi, and yet both inspiratory and expiratory resistances exceeded 6 inches H_2O . Thus, it appears that the Scott® Air-Pak II pressure-demand mode exhibits a disproportionately large drop in performance when flow rates exceed 300 l/min, and this decrement in performance may occur even when cylinder pressure exceeds 500 psi.

Air insufficiency may become absolute as indicated in Table 10. The 30-minutes SCBA cylinder (MESA/NIOSH-rated) is truly overrated for all but the lightest forms of physical exercise. In addition, although the cylinders used in this study have a filling capacity of 2216 psi, our observations both here and in other fire departments indicate that they are seldom filled to over 1900 psi, thus further reducing the already overrated air supply.

These time estimates represent the "average" air supply calculated for the 21 subjects participating in this study. It is particularly distressing to note that the air supply may be even less than 9 minutes for the more fit subjects who are capable of a greater work performance with corresponding greater ventilatory requirements.

Skin temperature of the face as well as air temperature within the mask were comfortably cool during all workloads. Although some sweating did occur, the short duration of these tests (10 minute) precluded any problems related to thermal comfort that may have occurred during prolonged exercise. However, the air supply in a "30-minute" cylinder does not permit the wearer to work long enough to experience irritations related to body or skin temperature. Of course, this is not to say that the mask air and face skin temperatures would remain comfortable under

actual firefighting conditions where the environmental heat stress could become severe where nozzlelemen may face temperatures exceeding 400°F (Reference 3).

The lesser increases in blood lactate with facepiece breathing were unexpected. Since the physical workloads were the same as those for pak experiments, and the O_2 tension in cylinder air was analyzed to be that of outside air, the only conceivable reason for a lower rate of anaerobic metabolism for a given bout of work during facepiece breathing seems to be that of overventilation. With facepiece breathing, ventilatory volumes were 9 to 18 percent greater than for performing the same work without the facepiece. The relationship between hyperventilation and lactate accumulation remains to be tested, but it is doubtful that the small differences observed here, although statistically significant, represent any real physiological advantage for facepiece breathing.

TABLE 10. MEAN AIR SUPPLY IN MINUTES PROVIDED BY A 30-MINUTE
SCBA CYLINDER FOR MEN PERFORMING THREE LEVELS OF
TREADMILL EXERCISE

Work, % $\dot{V}_{O_2}$ max	Initial Cylinder Pressure, psi		
	1900	2000	2216
50	28.1	29.6	32.8
65	20.5	21.6	23.9
80	13.8	14.5	16.1

Although beyond the scope of this paper, something should be said regarding the job performance of the firefighter while wearing the Scott® Air-Pak II. Granted, he may well survive instances where inspiratory and expiratory resistances exceed 5 inches H₂O, but will this stress, which may seem life-threatening at the time, have an effect on his ability to pursue his duties as a firefighter?

The SCBA characteristics presented in this paper are those for a properly maintained unit, not subjected to many of the problems one may expect in firefighting with various amounts of airborne debris. Proper cleaning and maintenance of the respiratory valves must be stressed; one series of experiments was lost due to the observed unusually high breathing resistance with the pressure-demand system. Upon returning the unit to LASL it was learned that a relatively minor accumulation of a substance, probably salivary in origin, was sufficient to markedly increase the expiratory resistance. It is conceivable that such valve malfunction is an everyday occurrence in firefighting.

SECTION V

CONCLUSION

Heart rate and oxygen consumption depend only upon the physical workload and are not affected by the breathing resistances imposed by the SCBA under the conditions of these experiments.

Ventilation is slightly higher for a given sub-maximal workload with SCBA breathing.

There was no evidence of EKG arrhythmia during resistance breathing under the conditions imposed on the subjects of this study.

Forehead skin temperature and air temperature inside the mask during exercise at normal room temperature were comfortable and presented no cause for complaint.

Breathing resistance imposed by the open-circuit Scott[®] Air-Pak II SCBA, for both demand and pressure-demand modes, just meet MESA-NIOSH certification requirements when tested under the specified conditions of 85 and 125 l/min peak flow rates. The fact that these flow rates do not represent actual use conditions is apparently not of major concern to these regulatory agencies.

Contrary to manufacturers' claims, negative pressures do in fact occur with great regularity inside the facepiece with pressure-demand breathing.

Extremely high inspiratory resistances occur when cylinder pressure drops below 500 psi, and this corresponds with triggering the alarm that warns the firefighter of low cylinder pressure. This is a very dangerous situation because the rapid onset of high breathing resistance might occur at the most inopportune time, i.e., when the firefighter is attempting to flee from a life-threatening environment. It should also be noted

that, contrary to instructions for the use of SCBA, the air supply remaining in the cylinder when the alarm is set off is considerably less than 5 minutes for a man performing work typical of a firefighter.

Cylinder air supply does just meet MESA-NIOSH certification requirements of 30 minutes when used at a rate of 40 l/min. Since it is indeed unusual to find firefighting activities that require such low ventilatory rates, the "30 minute" supply specification is unnecessarily, possibly dangerously, misleading.

It is possible to predict peak flow values from ventilation and/or heart rate, parameters which are readily obtained during actual firefighting conditions. It is recommended that the needs of the user be considered when federal agencies establish certification requirements for SCBA equipment.

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APPENDIX A
EXCERPT FROM
TITLE 30 - CODE OF FEDERAL REGULATIONS - PART 11

11.85-3 Breathing bag test.

(a) The bag will be operated during this test by a breathing machine with 24 respirations per minute and a minute-volume of 40 liters.

11.85-4 Weight requirement.

(a) The completely assembled fully charged apparatus shall not weigh more than 16 kg (35 pounds).

11.85-5 Breathing resistance test; inhalation.

(a) Resistance to inhalation airflow will be measured in the facepiece or mouthpiece while the apparatus is operated by a breathing machine as described in 11.85-3.

(b) The inhalation resistance of open-circuit apparatus shall not exceed 32 mm (1.25 inch) water-column height (at a flow rate of 125 liters per minute).

11.85-6 Breathing resistance test; exhalation.

(a) Resistance to exhalation airflow will be measured in the facepiece or mouthpiece of open-circuit apparatus with air flowing at a continuous rate of 85 liters per minute.

(b) The exhalation resistance of demand apparatus shall not exceed 25 mm (1 inch) water-column height.

(c) The exhalation resistance of pressure-demand apparatus shall not exceed the static pressure in the facepiece by more than 51 mm (2 inches) water-column height.

11.85-8 Gas Flow test; open-circuit apparatus.

(a) The flow from the apparatus shall be greater than 200 liters per minute when the pressure in the facepiece of demand apparatus is lowered by 51 mm (2 inches) water-column height when full container pressure is applied.

(c) Where pressure-demand apparatus are tested, the flow will be measured at zero gage pressure in the facepiece.

11.85-10 Service time test; open-circuit apparatus.

(a) Service time will be measured with a breathing machine as described in 11.85-3.

(b) The open-circuit apparatus will be classified according to the length of time it supplies air or oxygen to the breathing machine.

11.85-18 Man tests; performance requirements.

(a) The apparatus shall satisfy the respiratory requirements of the wearer for the classified service time. (Note: this will be determined by a man test in which the SCBA wearer walks on a level treadmill at 4.8 km (3 miles per hour).

APPENDIX B

SAMPLE QUESTIONNAIRE

Name: _____ Date _____ Experimental Order Number _____
 Condition _____ %VO2 max _____ Valve _____

You are preparing for a 10-minute bout of work on the treadmill. In some experiments you will be wearing a self-contained breathing device; in others you will simply breathe through a rubber mouthpiece. At the end of the work you will be asked to answer the following questions related to comfort and/or stresses experienced during the experiment.

ANSWER ALL QUESTIONS BY CIRCLING THE APPROPRIATE NUMBER. Do not spend too much time on a single question.

	Very easy	Moderate					Very hard
1. Work	1	2	3	4	5	6	7
2. Ease of Breathing							
a. Inspiration	1	2	3	4	5	6	7
B. Expiration	1	2	3	4	5	6	7
	Very Cool	Moderate					Very Hot
3. Temperature inside mask	1	2	3	4	5	6	7
	Very Light	Moderate					Very Heavy
4. Sweating inside mask	1	2	3	4	5	6	7

APPENDIX C
SAMPLE OF VOLUNTEER CONSENT FORM

1. I hereby volunteer to participate as a subject in a test program designed to learn the physiologic effects and workload limitations imposed upon firefighters by protective clothing, breathing equipment, and life support equipment during different work levels.
2. I understand that hazards associated with this test program include overwork or exhaustion during exercise on a treadmill, a fast or irregular heart beat, and tripping or falling from the treadmill. I realize that preliminary testing shall be performed to establish my maximum (100%) work capacity. Subsequent testing will then include exercise on the treadmill at 30, 50, or 70 percent of my work capacity. To help insure my personal safety, electrocardiography (EKG) will be monitored. To help prevent injury associated with falling or tripping on the treadmill, an observer will be in attendance. I understand that I may immediately stop the treadmill by pushing a button that is located at hand level, and I may immediately cease exercise by stepping from the treadmill. Although a hazard associated with drawing a sample of blood analysis is very light, I realize an 8 ml volume of venous blood must be drawn before and after each exercise period.
3. I understand that my participation is solely concerned with the testing of firefighters protective clothing and breathing apparatus.
4. This consent is voluntary and has been given under circumstances in which I can exercise free power of choice. I am aware that I MAY AT ANY TIME REVOKE MY CONSENT and withdraw from participation in a test in progress WITHOUT PREJUDICE on the part of designated supervisory personnel, who may in some instances be charged with its execution. It is further understood that the investigator or physician may terminate my participation in this test at any time regardless of my wishes.

5. I certify that I have read and understand the hazards, constraints, and responsibilities expressed above, and agree to participate as a test subject in programs pursuant to this protocol. I understand that before my use as a test subject, I must inform the principal investigator and project physician of any change to my medical or dental care/treatment received since my last use as a test subject or since my medical examination.

(Signature of Volunteer) (Date)

(Signature of Officer who Advised of Possible Consequences) (Date)

(Signature of Witness)

APPENDIX D

RESPIRATORY DATA

TABLE D-1. OXYGEN CONSUMPTION VALUES DETERMINED FOR MEN
PERFORMING TREADMILL EXERCISE WHILE WEARING THE
SCOTT® AIR-PAK II SCBA (MEAN + S.E.)

Work	$\dot{V}_{O_2}$, liters/min			
$\% \dot{V}_{O_2} \text{ max}^a$	Control	Pak	Demand	Pressure-Demand
	(n = 21)	(n = 21)	(n = 21)	(n = 21)
50	1.419 ±0.220	1.658 ±0.275	1.662 ±0.233	1.615 ±0.291
65	1.846 ±0.325	2.215 ±0.340	2.179 ±0.340	2.172 ±0.358
80	2.377 ±0.405	2.853 ±0.508	2.820 ±0.486	2.849 ±0.507

^aActual oxygen consumption values for control experiments, i.e., without wearing the 15-kg protective equipment, averaged 41, 53, and 69 percent of $\dot{V}_{O_2} \text{ max}$.

TABLE D-2. VENTILATION VALUES OBSERVED FOR MEN PERFORMING
TREADMILL EXERCISE WHILE WEARING THE SCOTT® AIR-PAK
SCBA (MEAN ± S.E.)

Work $\% \dot{V}_{O_2 \max}^a$	Ventilation, liters/min STPD			
	Control (n = 21)	Pak (n = 21)	Demand (n = 21)	Pressure-Demand (n = 21)
50	27.6 ±4.7	32.7 ±5.6	38.5 ±5.2	38.5 ±6.9
65	36.5 ±7.0	48.1 ±7.7	52.7 ±10.7	53.3 ±7.7
80	50.8 ±8.4	72.8 ±14.3	78.6 ±20.0	79.2 ±17.4

^aActual oxygen consumption values for control experiments, i.e., without wearing the 15-kg protective equipment, averaged 41, 53 and 69 percent of $\dot{V}_{O_2 \max}$.

TABLE D-3. PEAK INSPIRATORY FLOW RATES OBSERVED FOR MEN
PERFORMING TREADMILL EXERCISE WHILE WEARING THE
SCOTT® AIR-PAK II SCBA

Work $\% \dot{V}_{O_2 \text{ max}}^a$	Peak Inspiratory Flow Rate, l/min		
	Mean + S. E.		Maximum Values Observed
	Control (n = 21)	Pak (n = 21)	Pak (n = 21)
50	121.6 ±17.8	134.3 ±21.4	187.7
65	150.5 ±27.7	174.5 ±26.6	224.6
80	185.8 ±32.9	244.0 ±46.5	360.3

^aActual oxygen consumption values for control experiments, i.e., without wearing the 15-kg protective equipment, averaged 41, 53 and 69 percent of $\dot{V}_{O_2 \text{ max}}$.

TABLE D-4. MASK PRESSURES OBSERVED DURING EXPIRATORY (MAXIMUM VALUES) AND INSPIRATORY (MINIMUM VALUES) PHASES OF THE RESPIRATORY CYCLE FOR MEN PERFORMING TREADMILL EXERCISE WHILE WEARING THE SCOTT AIR-PAK II SCBA IN THE DEMAND AND THE PRESSURE-DEMAND BREATHING MODES (MEAN $\pm$ S.E.)

Work % $\dot{V}_{O_2}$ max ^a	Respiratory Phase	Breathing Resistance, Inches H ₂ O			
		Demand	Pressure- Demand	Extreme Observations Demand	Pres.-Demand
50	Exp	1.21 ± 0.27	2.75 ± 0.27	1.60	3.27
	Insp	-1.38 ± 0.24	-0.02 ± 0.26	-1.90	-0.66
65	Exp	1.74 ± 0.41	3.45 ± 0.62	2.59	4.91
	Insp	-1.65 ± 0.21	-0.25 ± 0.35	-2.15	-1.01
80	Exp	2.93 ± 1.00	4.68 ± 1.09	5.09	6.98
	Insp	-1.99 ± 0.60	-0.94 ± 1.39	>-6.50 ^b	>-6.50 ^b

^aActual oxygen consumption values for control experiments, i.e., without wearing the 15-kg protective equipment, averaged 41, 53, and 69 percent of $\dot{V}_{O_2}$ max.

^bOff-scale reading.

TABLE D-5. COMPARISON OF NON-SMOKERS (NS) AND SMOKERS (S)
PHYSIOLOGICAL RESPONSES TO WORK ON THE TREADMILL
WHILE WEARING THE SCOTT[®] AIR-PAK II SCBA (MEAN DATA)

Work $\% \dot{V}_{O_2}$ max (estimate)	NS (n = 12)	S (n = 9)	NS (n = 12)	S (n = 9)
	$\% \dot{V}_{O_2}$ max		Work, Cal/hr	
50	47	48	59.0	34.9
65	63	63	102.0	72.0
80	83	79	150.5	104.9
	$\dot{V}_{O_2}$ l/min STPD		$\dot{V}_{O_2} / \dot{V}_E$ l/min STPD	
50	1.734	1.526	0.047	0.043
65	2.343	1.984	0.044	0.041
80	3.095	2.501	0.038	0.036
	$\dot{V}_E$ l/min STPD		TV ^a l/min STPD	
50	37.2	35.7	1.96	1.98
65	53.4	46.6	2.45	2.13
80	81.2	69.8	2.69	2.43
	Heart Rate		O_2 pulse, ml/beat	
50	124	120	0.014	0.013
65	148	142	0.016	0.014
80	172	165	0.018	0.015
	Heart Rate, % Max		Heart Rate, 80-100 sec recovery	
50	65	64	83	87
65	77	76	99	106
80	90	89	124	126
	R^b			
50	0.86	0.86		
65	0.91	0.92		
80	0.99	1.00		

^aTV = tidal volume

^bR = respiratory exchange ratio

TABLE D-6. COMPARISON OF NON-SMOKERS (NS) AND SMOKERS (S)
HEMATOLOGICAL RESPONSES TO WORK ON THE TREADMILL
WHILE WEARING THE SCOTT® AIR-PAK II SCBA (MEAN DATA)

Work $\dot{V}_{O_2}$ max Estimate	NS (n = 12)			S (n = 9)		
	Pre	Post	Δ	Pre	Post	Δ
	<u>Hematocrit</u>					
50	44.1	45.1	1.0	46.4	47.5	1.1
65	44.1	46.2	2.1	46.3	48.4	2.1
80	44.0	47.5	3.5	46.3	49.7	3.4
	<u>Hemoglobin Concentration, g%</u>					
50	16.2	16.6	0.4	16.7	17.2	0.5
65	16.0	16.9	0.9	16.7	17.5	0.8
80	16.2	17.4	1.2	16.9	18.0	1.1
	<u>Carboxyhemoglobin, %</u>					
50	0.557	0.478	-0.079	3.651	3.311	-0.340
65	0.504	0.487	-0.017	3.603	3.080	-0.523
80	0.529	0.500	-0.029	3.732	3.338	-0.394
	<u>Blood Lactate, mg%</u>					
50	8.6	12.5	3.9	9.0	13.7	4.7
65	9.1	21.9	12.8	9.5	24.6	15.1
80	9.2	58.7	49.5	8.3	56.3	48.0

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