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Positive Pressure Closed Circuit Breathing Apparatus and the Energy Cost of Fire Fighting

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ABSTRACT

This report provides insight to the relationship between the physiologic work tolerance level of male fire fighters, as measured by oxygen uptake, and the energy demands of their job plus those external factors which are suspected to influence this relationship. The external factors selected for investigation were heat, anxiety and three attributes of positive pressure closed circuit breathing apparatus--increased oxygen content, breathing resistance and equipment weight. The study provides evidence regarding the physiologic advantages of positive pressure closed circuit breathing apparatus.

CONTENTS

FIGURES

TABLES

INTRODUCTION

All respirators, from simple valveless disposables to long duration closed circuit self-contained units, should provide health protection with as little interference as possible upon the performance of an individual's work. Members of the Testing and Certification Branch of NIOSH have the opportunity to influence whether respirators do in fact perform in this manner by recommending criteria for respiratory protective equipment which insure, to as great a degree as possible, that respirators not only will protect against the inhalation of airborne contaminants, but also will provide this protection with a minimum of burden to their users. It is the purpose of this report to provide insight to the relationship between the physiological work tolerance level of male fire fighters, as measured by oxygen uptake, and the energy demands of their job plus those external factors which are suspected to influence this relationship. The external factors selected for investigation are heat, anxiety and three attributes of positive pressure closed circuit breathing apparatus--increased oxygen content, breathing resistance and equipment weight. The report is intended to assure self-contained breathing apparatus users that their device will provide health protection during the most demanding conditions with a minimum contribution by the device to the physical energy expenditure necessary to meet the needs of an imposed task.

An important consideration during the preparation of this report was the desire to make appropriate allowance for those components that influence the effectiveness and acceptability of respirators, but for which the Institute has no direct control. For example, it is obvious that the characteristics of an individual respirator user cannot be regulated. However, it must be remembered that variability does exist between individuals within a population of respirator users with regard to personal attributes, such as age, gender, weight and smoking habits. These attributes are particularly important when an extremely strenuous task is to be performed, since the combined physiologic demands placed upon an individual by both an imposed task and the wearing of a respirator cannot be tolerated for more than a few minutes at an individual's maximum aerobic capacity. Another uncontrollable factor involves the environment in which a task is to be performed while wearing a respirator. Beyond the emotional stress of working in a toxic atmosphere concurrent exposure to extremes of temperature and humidity can also influence a respirator user's performance.

Emphasizing a close relationship between the attributes of a respirator and the physiologic capacities of the respirator user is a slight deviation from the previous approach of individuals with responsibility for setting respirator criteria, who have tended to overemphasize the abilities of manufacturers to meet standards with currently available equipment. The basic concept used to prepare this report, i.e., standards should dictate equipment design, rather than the performance characteristics of available equipment dictating the standards, was recently suggested by Dr. R.G. Love during the 1980 International Respirator Research workshop (Love, 1980). The idea is not new, however, but was similarily proposed in 1961 at a British respirator design and use symposium (Cotes, 1962), in a 1958 American Industrial Hygiene Association Journal article (Jordan, 1958) and in a 1943 report to the Office of Scientific Research and Development (Silverman, 1943).

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WORK TOLERANCE OF FIRE FIGHTERS

To establish an understanding of the physiologic limits of typical self contained breathing apparatus users, a semi-log graph (figure 1) was prepared relating the physical working capacity of fire fighters to working time. The characteristics of fire fighters were selected as a basis for the graph because of the availability of information on this group of respirator users, but more importantly because of the belief that respirators which meet criteria established to protect individuals engaged in the demanding activities of fire fighting would provide more than adequate protection during any other application. A similar graph published by Bink (1962) was used as a pattern for the one in this report.

The graph point identifying the physical working capacity for 5 minutes (13 kcal./min.) represents the caloric equivalent of a maximum aerobic capacity of 2.7 liters of oxygen per minute, assuming the quantity of energy liberated per liter of oxygen utilized in the body averages approximately 4.825 kilocalories (Guyton, 1976). Even though well-trained, highly motivated individuals may maintain oxygen uptake at a maximal level for at least 15 minutes, 5 minutes was used as the time period for this level of constant physical activity, since most individuals feel forced to stop after 4 to 5 minutes at a work load which taxes the oxygen-transporting systems to a maximum (Astrand, 1977). The 13 kcal./min. value for maximum aerobic capacity was in part derived from data recently published by Kilbom (1980) and shown in Table 1. The author warned in the text of his article, however, that physiologic values for Swedish firemen are not directly comparable to firemen in the United States, because of the more prevalent occurrence of self-contained compressed air line breathing apparatus in Swedish fire fighting companies.

The results of three other studies served to provide more insight into the general physiologic capacity of U. S. fire fighters. Pipes (1977), using a step increment type of work capacity test, reported a mean maximum aerobic capacity of 3.344 liters per minute with a standard deviation of 0.271 liters per minute for a group of 20 male recruits of the Los Angeles City Fire Department. The recruits ranged in age between 21 and 29 years. This value of mean maximum aerobic capacity is not significantly different from those values reported by Kilbom (1980) for the same age group. The mean represents an approximate per weight value of 41 ml./min./kg. Dotson (1977) reported a mean maximal oxygen consumption of 3.28 liters per minute with a standard deviation of 0.55 liters per minute for a sample of 100 professional fire fighters from the Metropolitan Council of Governments, Washington, D. C. Although test subjects ranged in age between 21 and 57 years (mean of 33 years $\pm$ 7.63 (S.D.)), no age grouped data was presented. The mean maximal oxygen consumption represents a per weight value of 39.6 ml./min./kg.

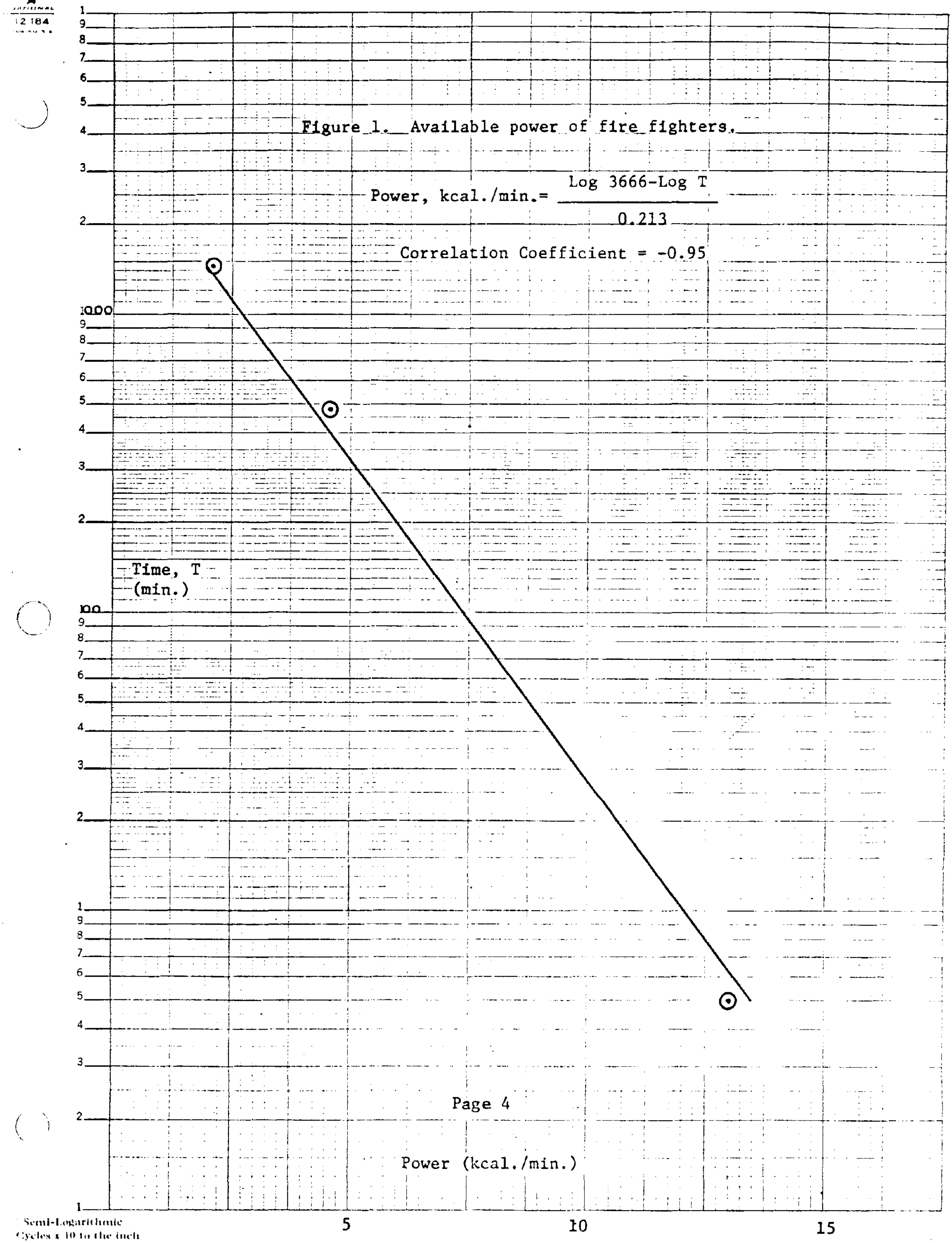

Figure 1. Available power of fire fighters.

Table 1. Maximal aerobic power of full-time and part-time firemen as published by Kilbom (1980). Values were calculated on the basis of submaximal exercise tests, except for the groups from the United States and Canada, for whom maximum values were measured. The mean values ± 1 SD for maximal oxygen uptake are given along with the number of subjects.

Firemen	Age Group, Years			
	20--29	30--39	40--49	50--59
Stockholm (full time)				
Number	128	145	52	74
VO_2 max l/min	3.67±0.74	3.39±0.69	2.91±0.55	2.54±0.51
ml/min x kg body wt.	48.0±8.9	43.5±8.0	37.8±7.4	31.5±7.2
Marsta, Jarfalla & Sollentuna (full-time)				
Number	26	40	12	
VO_2 max				
l/min	3.69±0.68	3.39±0.67	3.16±0.63	
ml/min x kg body wt.	49.2±8.5	42.9±8.1	40.0±9.8	
Helsingborg (full time)				
Number	14	29	15	6
VO_2max				
l/min	3.6	3.2	2.9	3.4
ml/min x kg body wt.	51	46	41	34
California, USA (full-time)				
Number	11	21	12	
VO_2 max				
l/min	3.52	3.19	2.84	
Canada (full-time)				
Number	15	15	15	
VO_2 max				
l/min	3.5	3.4	2.7	
ml/min x kg body wt.	43±4	40±6	32±7	
Helsingborg (part time)				
Number	5	14	14	9
VO_2 max				
l/min	3.5	2.9	2.4	2.2
ml/min x kg body wt.	50	39	32	30

The results of a study by Byrd (1980), based upon submaximal multistage cycle ergometer testing of 52 fire fighters from the Homewood, Alabama Fire Department, appear in Table 2. Maximum Oxygen consumption data for this table was estimated by extrapolating actual heart rate-work load relationships to maximum heart rate, and subsequent calculation of estimated oxygen consumption requirements for that particular load. Although the estimation of oxygen uptake from recorded heart rate may be subject to considerable inaccuracy, it has been shown that the method may be used with confidence as a basis for the estimation of work load when the work operation involves the use of the same large muscle groups as are used on the bicycle ergometer (Astrand, 1977). The mean maximal oxygen consumption determined during this study for all subjects of 2.85 liters per minute (34 ml./min./kg.) is particularly interesting because it is significantly lower than the other previously reported means. Although greater accuracy is expected in the prediction of energy output by using a bicycle ergometer rather than less readily quantified treadmill ergometry methods (Astrand, 1977 and Wasserman, 1975), the influence of the test method selected to predict mean maximum work capacity for this particular sample population is believed to be minimal. The indicated difference for mean maximal oxygen uptake between this group and other sample populations of fire fighters is therefore an accurate indication that the study participants from the Homewood Department do have dimished mean work capacity.

Based upon the evidence in the preceding reports, the approximate maximum physiologic demand that can safely be performed by the majority of fire fighters has been placed at 13 kcal./min. or an equivalent of 2.7 liters of oxygen uptake per minute. The decision to use this value was influenced mainly by the data reported by Kilbom (1980) and Byrd (1980), which offered insight regarding the physiologic capabilities of individuals according to age-group categories. The importance of information presented in this fashion is not due to the demonstration of an age-induced decline in physical work capacity, since it is well known that both maximum oxygen uptake and maximum heart rate decline with increasing age (Astrand, 1977) regardless of the population sampled. Rather, the information is important because it suggests quantitatively the extent of physical work capacity decrement to be expected along a fire fighter's career. The mean physical work capacity, described as mean maximal oxygen uptake, for the older age groups of these studies perferentially affected the establishment of the value for the maximum work capacity of fire fighters. This was done because of recent evidence that fire service personnel in older age categories are at greater risk of death not only from heart attack, but for all diseases of the cardiovascular system (Ferguson, 1981). The preferential use of data from the older age groups was necessary to achieve a proper perspective regarding the margin of safety to be expected when comparing the energy expenditure demands of fire fighting tasks to the energy expenditure abilities of those expected to routinely perform these tasks. This will provide better guidance to the extent of influence permitted by the attributes of self-contained breathing apparatus to energy expenditure.

Table 2. Means and Standard Deviations of Variables Associated with 52 Fire Fighters (Byrd, 1980)

Variable	Total Group (N = 52	Ages 20-29 (N = 16)	Ages 30-39 (N = 14)	Ages 40-49 (N = 12)	Ages 50-59 (N = 8)
(1) Age (years)	34.6 ± 9.0	26.4 ± 1.7	33.8 ± 2.5	43.3 ± 2.9	53.0 ± 2.8
(2) Weight (kg)	83.8 ± 12.0	83.1 ± 14.6	84.8 ± 9.7	85.7 ± 9.6	80.3 ± 13.8
(3) Maximum Oxygen Uptake(ml/min(kg)	34 ± 8	40.8	34.7	26.± 3	28.7
Maximum Oxygen Uptake(l./min.) ((2) x (3)) divided by 1000	2.85	3.32	2.88	2.23	2.25

Possible exposure to emotional or psychological pressures and/or exposure to a hot environment while working and wearing a self-contained breathing apparatus also affected the selection of the 13 kcal./min. data point, for although these factors do not show up as conspicuous increments of the energy cost of physical activity, they do have a significant effect upon an individual's heart rate (American Industrial Hygiene Association, 1971), and therefore increase the risk for the occurrence of adverse health effects when the cardiovascular system is overstressed. The influences of anxiety and heat upon performance are discussed in greater detail later in this report.

The second point used to design the graph of Figure 1 is the maximum energy expenditure rate which should be consumed for an 8 hour work day; beyond this rate muscular fatigue can be expected to occur, along with an increased risk for injury (Barnard, 1980). The energy value for this point of 4.6 kcal./min. is the product of 35 percent and the previously determined maximum energy expenditure allowable for 5 minutes of 13 kgm./min. The decision to use 35 percent of the short-term maximum energy expenditure rate was based upon the results of the following studies.

Christensen (1955) proposed that work could be performed safely for an 8 hour work day at a rate below 50 percent of an individuals maximum aerobic power. Astrand (1960 and 1967) conducted research which indicated that this is too high an expectation, and research by Brouha (1960) supports the theory that a work capacity limit based on 50 percent of the maximum aerobic power of an individual was a fatigue-generating energy expenditure rate (Garg, 1978). Additional research conducted by Astrand (1977) led to the suggestion that a value between 30 and 40 percent was a more reasonable average upper limit for physical work performed regularly over an 8-hour working day. A graph prepared by Bink (1962) indicates 35 percent of maximum working capacity as the preferred 8-hour expenditure (Blair, 1981). The reliability of Bink's curve has been supported by data reported by Bonjer (1962). Observations reported by Rodgers (1978) on the level of effort selected by workers to perform their assigned tasks at Eastman Kodak Company also support the 35 percent guideline. Similarly, a percentage of maximum energy expenditure of 33 percent was recommended as the most appropriate maximum metabolic demand for an 8-hour work duration in the NIOSH technical report, Work Practices Guide for Manual Lifting (U. S. Department of Health and Human Services, 1981).

The last point used to create the graph of Figure 1 is the estimated per minute mean food intake required by a fire fighter during 24 hours to maintain balance between daily energy expenditure and nutritional intake. The 2.1 kcal./min. value selected for this quantity represents a daily mean food intake of 3000 kcal./day. Selection of this value was based upon the recommended nutritional requirements suggested by the World Health Organization (Passmore, 1974) and the National Research Council (Committee on Dietary Allowances, 1980).

Bink (1962) used a value of 2.85 kcal./min. as the mean food intake necessary during a 24 hour period based upon Netherland food table values for a 35 year old man, whose occupation involves heavy muscular work. This represents a 24 hour equivalent intake of 4100 kcal. Guyton (1976) reported that over a 24 hour period a laborer can achieve a maximum rate of energy utilization as great as 6000-7000 kcal. In relation to these values, the current international standard for energy intake for moderately active individuals is 3000 kcal./day for males and 2,200 kcal./day for females. These values are referenced to a man or woman 25 years of age and weighing 65 kg. (143 lb.) and 55 kg. (121 lb.), respectively. Examples of males involved in this degree of activity are most men in light industry, students, construction workers (excluding heavy laborers), many farm workers, soldiers not on active service, and fishermen. Examples of females are workers in light industry, housewives without mechanical household appliances, students, and department-store workers. The international standard for very active individuals is 3,500 kcal./day for males and 2,600 kcal./day for females. Examples of males involved in this degree of activity are some agricultural workers, unskilled laborers, forestry workers, army recruits, soldiers on active service, mine workers, steel workers, and athletes. Examples of females are some farm workers (especially in peasant agriculture), dancers and athletes.

The United States standard for mean food intake is 2700 kcal./day for males and 2000 kcal./day for females. These values are referenced to a man weighing 70 kg. (154 lb.) and a woman weighing 55 kg. (121 lb.) throughout a period of adult life ranging between 23 and 50 years of age. U. S. standard energy allowances are the same as international standards for individuals engaged in occupations requiring light activity, whereas the degree of activity of most adults worldwide is classed as moderate. The difference is primarily due to the more frequent use of automobiles in this country than is encountered throughout the rest of the world (Briggs, 1979). Based upon the previous information, the daily nutritional requirement for U. S. fire fighters has been set at 3000 kcal. or 2.1 kcal. per minute.

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ENERGY DEMANDS OF FIRE FIGHTING

Over the years, the energy costs of many occupational tasks have been reported, with the most often cited report (Passmore, 1955) published almost 30 years ago. It has only been within the last five years, however, that information has been reported in the United States which quantitatively describes the human energy cost of fire fighting activities. Although a Swedish report (Zylberstein, 1973) existed prior to this period, its results have only recently been made available to English speaking readers through an article by Kilbom (1980). Kilbom stated: "According to Zylberstein (1973) the average physical load on a fireman during simulataed fire fighting under highly realistic conditions is equivalent to an oxygen uptake of 1.9 liters per minute. His results were based on measurements of pulmonary ventilation in fire fighters wearing a smoke mask and performing given tasks in a building on fire. Individual heart rate measurements disclosed that some phases of the work were exceptionally demanding and induced maximal or near-maximal heart rates. The average heart rate and body temperature disclosed that the subjects wearing smoke masks were exposed to considerable additional loading because of the heat. Thus, average heart rates were around 30 beats per minute higher during fire fighting than under the corresponding work load at room temperature. The conclusion was that fire fignting in a smoke mask could not be recommended for more than 20-25 minutes."

It should be emphasized that the suggested value for equivalent oxygen uptake of 1.9 liters per minute was based upon pulmonary ventilation measurements and not upon extrapolation from heart rate data. For, as will be shown later in this report, increasing ambient temperature results in a higher heart rate, but the effect on metabolic rate is minimal.

Comparing the equivalent power of an oxygen uptake of 1.9 liters per minute, which equals 9.2 kcal./min., to the available power of fire fighters, which is shown by figure 1 of the previous section, suggests that 87 to 90 percent of available aerobic power is required to meet the demands of fire fighting for 20 to 25 minutes. This is in agreement with the results of a study by Dotson (1977) who investigated the ability of 74 fire fighters to perform five field tasks representative of fire fighting activities. All tasks were performed wearing full turnout gear, i. e., helmet, coat, boots, and demand breathing apparatus. Heart rate responses indicated that approximately 90 percent of the fire fighters physical work capacity was needed to complete the five field tests. The average completion time for the five tasks was 7.03 minutes. It was concluded that the successful completion of fire fighting tasks requires a physical performance profile reflecting youth, high aerobic capacity, high muscular strength and endurance, above average lean body weight and minimal body fat.

Although the average physical load values of Zylberstein (1973) and Dotson (1977) are useful, in terms of the strain imposed upon an individual, the peak load of a task is more important than the mean energy expenditure (Astrand, 1977). Lemon (1977) reported individual approximate energy costs for the four most strenuous fire fighting tasks as judged by the men and administrators of the City of Windsor, Ontario Fire Department. The tasks selected were (1) aerial ladder climb, (2) "victim" rescue, (3) hose dragging, and (4) ladder raise. Ten male fire fighters participated in each of the four work tasks wearing partial turnout gear, i.e., helmet, coat, and boots, but minus breathing apparatus. The results of this study appear in Table 3. The energy expenditure required of the four tasks represent a range of physiologic demand from 81 to 95 percent of the maximum aerobic capacity of fire fighters, as established in the previous section.

It appears justifiable to conclude from the previous reports that fire fighting can be termed "heavy" physical work. The next section will serve to indicate how heat, anxiety, and three attributes of positive pressure closed circuit breathing apparatus--increased oxygen content, breathing resistance and equipment weight modify this high rate of physical activity.

Table 3. Adjusted mean values describing the energy costs of four strenuous fire fighting tasks as evaluated by Lemon (1977).

Task	Oxygen Uptake l./min.	Caloric Energy Demand kcal./min.	Performance Time, sec.
Aerial ladder climb	2.19	10.57	100
"Victim" rescue	2.53	12.20	32
Hose dragging	2.55	12.30	30
Ladder raise	2.30	11.10	31

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VARIABLES WHICH AFFECT A FIRE FIGHTER'S ENERGY EXPENDITURE

Heat

Fire fighters typically work in temperatures ranging from 38°C (100°F) to 66°C (150°F), while in some instances air temperatures have been recorded as high as 232°C (450°F) (Duncan, 1979 and Coombs, 1981). Astrand (1977) stated that available evidence shows that the effect of environmental temperature, as such, on the metabolic work is very small (Consolazio, 1963). Nelson (1948) found that metabolic heat production for a given amount of work remained unchanged in three men walking in seven hot environments between 32°C (90°F) and 49°C (120°F)(Astrand 1977). Brouha (1967) concluded, after conducting a series of experiments requiring the performance of continuous work under environmental temperatures ranging between 22°C (72°F) and 37°C (99°F), that pulmonary ventilation, oxygen consumption rate and blood pressure were influenced very little by the environment.

Heart rate, however, is markedly affected by increasing temperature. Kamon (1971) conducted tests requiring subjects to carry cartons weighing 10, 15, and 20 kg. by the hands in front of their bodies at speeds of 4 and 5 km/hr. on level and at 4 percent grade at ambient temperatures of 20°C (68°F), 35°C (95°F) and 45°C (113°F). As expected, no significant differences in metabolic cost were observed under the three thermal conditions, but heart rate was found to increase between 7 and 10 beats/min. for each 10°C rise in air temperature. Duncan (1979) subjected 11 healthy Los Angeles City fire fighters wearing turnout uniforms plus breathing apparatus to work loads on a treadmill set up in a sauna; the breathing apparatus was only carried during each trial. Temperatures in the sauna, measured with a Botsball wet globe thermometer, averaged 41.8 $\pm$ 0.2°C (107°F). The results of this experiment support the findings of the studies described earlier, which reported no change in oxygen uptake values for the same workload at different ambient temperatures, but significant increases in heart rate values. The investigators of this study offered evidence to the extent of the heat build-up problem with currently available turnout uniforms and urged that further research be initiated concerning uniform design and the types of material best suited to fire fighting activities.

The temperatures used in all of the previous reports are relatively low in relation to those routinely experienced firefighters. It can be quite easily reasoned from the foregoing information, however, that the large demand placed on a fire fighter's heart to produce bloodflow to the periphery for thermo-regulatory purposes will reduce significantly cardiac output available to working muscles (U. S. Department of Health and Human Services). It therefore is obvious that reductions in demand from other metabolic energy users, e.g., the self-contained breathing apparatus, will have an important effect upon the performance and health of fire fighters.

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Anxiety

The extra energy cost of performing mental work or withstanding emotional or psychological pressure also does not show up as an identifiable increment to the energy cost of physical activity (American Industrial Hygiene Association, 1971), but it is generally agreed, and has been well demonstrated, that in healthy people marked mental or emotional stress can evoke cardiovascular responses very similar to those of exercise. There is an increase of heart rate and stroke volume and the cardiac output is raised. There is also evidence of an increase of sympathetic activity and it is probable that the circulating catecholamines are increased (MacLennan, 1969). It is well established that the heart rate increases linearly with increasing physical work load, provided there is no major change in an individual's emotional state (Astrand, 1977).

Bernard (1975) has reported the results of a study designed to observe electrocardiographic and heart rate response during a fire fighter's work day. This was done as a result of observations that fire fighters experience a high incidence of ischemic responses to a standard near maximal exercise test (Barnard and Gardner, 1975) and are required to perform sudden exercise without benefit of warm-up, which has been shown to produce an ischemic condition in the heart (Barnard and Gardner, 1973, and Barnard and MacAlpin, 1973). Heart rate responses of 35 fire fighters responding to a total of 189 alarms indicated a state of high anxiety immediately after the alarm sounded as well as on the truck approaching a fire. it was not possible to determine, however, why the heart rate of some individuals increased by only 15 to 20 beats/min. in response to one alarm and then increased 70 to 80 beats/min. in response to another. Although movement artifact prevented the monitoring of heart rate during actual fire fighting, almost all cases observed during the first 3 to 5 minutes at a fire scene were very high, ranging between 175 and 195 beats/min.

It has been suggested that an increase in heart rate due to anxiety prior to physical exercise may have a positive effect upon performance (MacLennan, 1969). However, heart rate values between 175 and 195 beats/min. are distressingly high when one considers that the burdens of high temperature exposure, breathing apparatus weight, and the task to be performed had not yet been imposed. This lends strong support to the belief that the energy cost of wearing a self-contained breathing apparatus should be minimized to its least extent.

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Increased Oxygen Content

Closed circuit breathing apparatus can be divided into two basic types depending upon whether they contain a cylinder of compressed or liquid oxygen, or a canister of an oxygen-generating chemical. Regardless of the type used, the atmosphere breathed by the device user contains a higher oxygen fraction than is encountered in "normal" air. Breathing an oxygen enriched atmosphere has been demonstrated by several clinical and experimental investigations to have both advantages and disadvantages. The following description of the advantages of increased oxygen concentration has been adopted from a report by van den Berg (1977).

It is known that an increased oxygen content of inspired air may have a positive effect on the ability to accomplish a heavy work task. Wilson (1975) found that the maximal performance time increases significantly as the oxygen fraction of inspired air increases. This is in agreement with the work of other investigators (Asmussen 1946 and 1958, and Bannister, 1954), who also showed a longer endurance time for individuals breathing extra oxygen. Ekblom (1975) showed an average maximum oxygen uptake increase of 12.6 percent for nine clinically healthy male physical education students exposed to a 50 percent oxygen in nitrogen mixture. An increase in maximal oxygen consumption is known to lead to an increased maximal performance capacity which will result in a longer endurance time at submaximal work load (Asmussen 1946 and 1958, Bannister 1954, and Wilson, 1975), in blood lactic acid concentration, in submaximal cardiac output and in heart rate, whereas maximal cardiac output and heart rate are unchanged (Ekblom, 1975).

Within just a short time after the discovery of oxygen 200 years ago, Joseph Priestley, one of its codiscoverers, was already cautioning that oxygen "might burn the candle of life too quickly, and too soon exhaust the animal powers within" (Priestley, 1775). Priestley's prescient speculations about the toxic nature of excess oxygen have been confirmed by a host of succeeding investigators. By 1945 enough work had been performed for Bean (1945) to have collected 350 references on the subject (Pierce, 1975). The prevention of pulmonary oxygen toxicity is of concern primarily to physicians involved in intensive care who are confronted by situations in which prolonged hyperoxic therapy is a necessary part of the management of neonatal and adult patients with severe respiratory distress. The clinical sequelae of pulmonary oxygen toxicity are designated as broncopulmonary dysplasia in the infant lung, and simply as oxygen-induced lung injury in the adult patient. The exact contribution of ventilator therapy to the eventual spectrum of lung injury is still being debated. Many of the clinical reports of oxygen associated lung damage show a substantial degree of correlation between the incidence and extent of pulmonary pathologic features and the duration of exposure to a fractional concentration of oxygen in inspired air geater than 40 to 50 percent (Frank, 1979).

Normal man experiences respiratory symptoms from 6 to 30 hours after breathing 100 percent oxygen at atmospheric pressure (Pierce, 1975). The commonest complaint of normal humans breathing oxygen for prolonged periods is substernal distress. Generally, it is the earliest symptom encountered and occurs as early as 4 hours after the start of oxygen breathing, but usually develops between the twelth and sixteenth hour (Sackner, 1975). Other symptoms are paresthesias, nausea and vomiting, general malaise, and fatigue. Normal voluntary tolerance for exposure to one atmosphere of oxygen is on the order of 53 to 75 hours; the maximum reported tolerance time has been 110 hours (Pierce, 1975).

An important feature lacking in the experimental studies of oxygen toxicity, or at least little stressed in most reports, is an explanation of the great individual variation in susceptibility/resistance to oxygen toxicity observed in many of the studies. Clinicians who use hyperoxic therapy daily and monitor its effects on individual patients are well aware of this factor of individual responsiveness to potential oxygen toxicity. Also, in most animal studies, while a majority of the test population die of oxygen lung injury within a rather narrow and replicable time span, a smaller proportion of animals is often observed to die much earlier than the others, and another small group often survives the acute lethality and appears to go on to tolerate even more prolonged durations of hyperoxic exposure. The basis for this range of individual variation is not known, nor has it been extensively investigated. There are known distinct species differences in ability to survive a hyperoxic stress as well as pronounced age differences (Frank, 1979).

The health risks associated with intermittent exposure to high concentrations of oxygen are of greater concern to the majority of self contained breathing apparatus users than the risks of prolonged exposure. Unfortunately, essentially no information exists concerning the quantitative influence of intermittent exposure upon oxygen tolerance in man (Clark, 1971). Carefully controlled studies of the rate of development of pulmonary toxicity in individuals exposed intermittently to hyperoxia are needed to establish optimum schedules for increasing pulmonary oxygen tolerance by the use of intermittent exposures (Clark, 1971).

Cotes (1962) offered his opinion that a disadvantage of oxygen based breathing apparatus might be the possibility for impairment of mental performance as a result of carbon dioxide accumulation during maximal exercise while breathing 100 percent oxygen. Poulton (1974) confirmed this suspicion in a report of a 1952 experiment performed in the context of escape from a submarine stranded at the bottom of the sea. Twelve men performed a step tracking task involving short-term memory while breathing pure oxygen from a demand type oxygen mask, while breathing air from the mask, and in a control condition without the mask. A reliable ($p < 0.01$) progressive deterioration over 8 minutes was found while breathing oxygen, but not in the other two conditions. The progressive deterioration was particularly marked in the most difficult short-term memory condition (Poulton, 1974). The effects on short-term memory of breathing concentrations of oxygen less than 100 percent are unknown.

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Breathing Resistance

Energy is expended by the respiratory muscles to not only expand the lungs, but also overcome the viscosity of the pulmonary tissues and the resistance of the respiratory passage ways. During normal quiet respiration, the total energy expenditure necessary to energize the pulmonary ventilatory process is only 2 to 3 percent of the total energy expended by the body (Guyton, 1976). During very heavy exercise, the absolute amount of energy required for pulmonary ventilation can increase as much as twenty-five-fold. However, this still does not represent a significant increase in percentage of total energy expenditure because the total energy release in the body increases at the same time as much as fifteen-to-twenty-fold. Thus, even in heavy exercise only three to four percent of total energy expenditure is used for ventilation (Comroe, 1962 and 1974, and Guyton, 1976). Pulmonary diseases that decrease pulmonary compliance, increase airway resistance, or increase viscosity of the lung or chest wall can also increase the work of breathing (Guyton, 1976).

Just as it is generally accepted that aerobic work tolerance, measured by maximal oxygen uptake and endurance, is not normally limited by pulmonary ventilation, it is also generally accepted from previous findings on maximal work with breathing resistance that volitional fatigue occurs before oxygen transport to the active limbs and anaerobic metabolism become limiting (Dressendorfer, 1977). As can be seen by the length of the non-cited references at the end of this section, much has been written regarding the effects of increased breathing resistance. Unfortunately, the information contained in these reports, despite encompassing a variety of experimental approaches, is insufficient to define an accurate relationship between acceptable breathing resistance, work rate, and duration (Love, 1980). In fact, only Deno (1981) has reported the results of a study which systematically investigated the effect of breathing resistance and exercise intensity for both short and prolonged exercise periods. Data for this study was collected from treadmill exercise tests performed by seven male college students with a mean age of 26 $\pm$ 4(S.D.) years. Results of the tests indicated that symmetrical breathing resistances of 11 cm. (4.33 inches) and 16 cm. (6.3 inches) of water pressure at a flow rate of 120 liters per minute have no effect on performance at 60 percent of an individuals maximum aerobic capacity over one hour; 60 percent of maximum aerobic capacity is considered the average exercise intensity limit for one hour of exercise. This suggests that non-respiratory factors predominate and determine the maximum tolerable exercise limits for resistance conditions up to a combined resistance level of 32 cm. (12.6 inches) of water pressure measured at a flow rate of 120 liters per minute.

The regulations of 30 CFR Part 11 presently limit the breathing resistance allowable for closed-circuit breathing apparatus to a combined value of 10 cm. (4 inches) of water pressure at a flow rate of 120 liters per minute. The results of Deno's study indicate that this combined resistance would have a negligible influence on the energy demands of a fire fighter wearing a positive pressure self contained breathing apparatus. However, because of the acknowledged absence of systematic research involving the psychological problems associated with respirator wear (Morgan, 1980), increasing the present breathing resistance allowable limit for closed circuit breathing apparatus is not recommended, even though an increase would scarcely be noticed from the standpoint of physiological demand.

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Equipment Weight

The weight of protective equipment worn by fire fighters has been demonstrated to have a very signficant influence on the energy expenditure level necessary during fire fighting activities. Data published by Raven (1977) showed a maximal work performance time decrease of 17.5 percent attributable to the wearing of a non-operating Scott$^{(R)}$ Air-Pack. The total weight of the fully charged test unit was 15.82 kg. (34.9 lbs.). The data was collected from progressive exercise tests performed by 15 male volunteers of the Energy Research and Development Agency's (ERDA) fire fighting force at the Los Alamos Scientific Laboratory (LASL). The mean age of the test subjects was 31.0 $\pm$ 2.0 (S.E.) years.

A Scott$^{(R)}$ Air-Pack was also worn, but not operated, during treadmill experiments (Myhre, 1979) performed by 21 male volunteers, ranging in age from 22 to 51 years, with a mean age of 32.9 $\pm$ 1.5 (S.E.) years. The results of these experiments showed that on the average the weight of the self-contained breathing apparatus increased the energy needed to perform at 50, 65, and 80 percent of each individual's maximum aerobic capacity by 16.8, 20 and 20 percent, respectively.

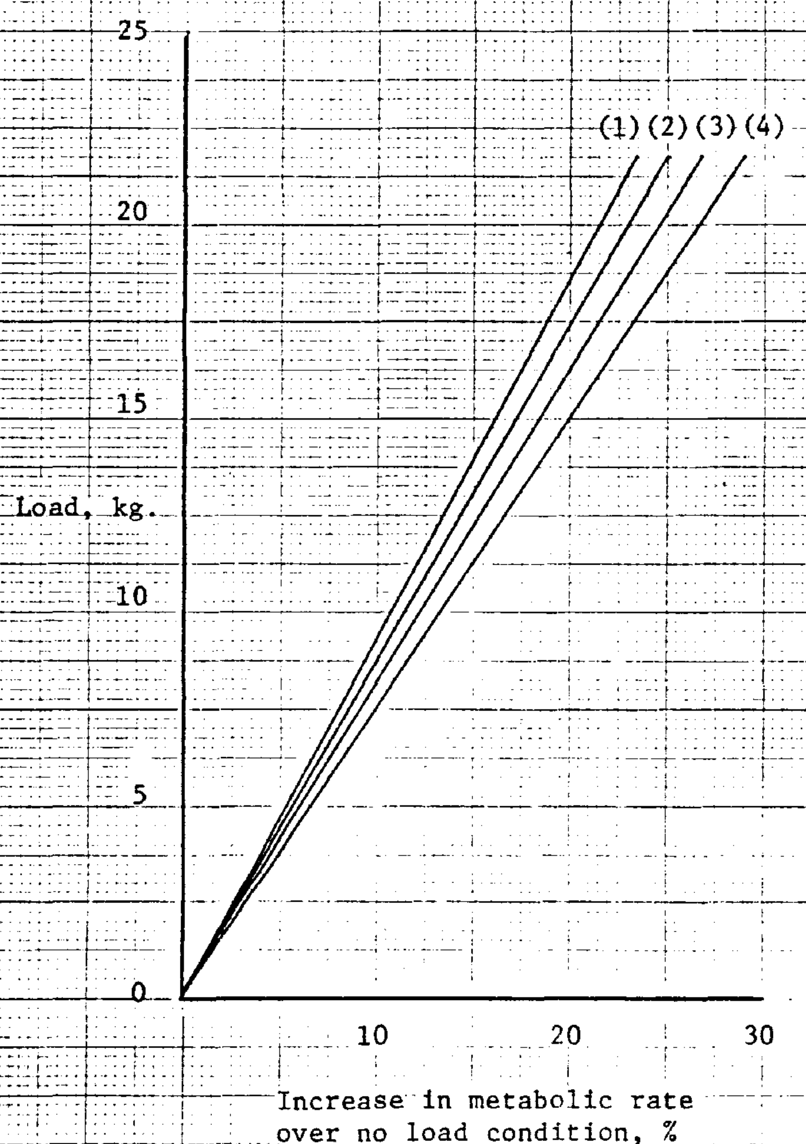
Duncan (1979) subjected 11 healthy Los Angeles City fire fighters to treadmill tests in order to compare the energy expenditure of exercise with the men wearing a normal "blue" uniform and while wearing "Turnouts" (heavy, rubber-lined, fire and water resistant trousers and coat), boots and a non-operating self contained breathing apparatus. In contrast to the progressive test method used by Raven (1977), Duncan conducted his trails at a uniform treadmill setting of 4.0 km./hr. (1.11 m./sec.) and 10 percent grade for 15 minutes. These experiments showed that wearing the "turnouts" and breathing apparatus increased the energy requirements of the imposed work rate by 47 percent. As reported to him by personal communication, the author conveyed that this value was similar to the increase in energy of 33 percent observed at the University of Maryland during studies of men working in fire fighting equipment.

Pandolf (1977) published the following equation for predicting the metabolic rate of carrying backpack loads while walking:

$$M = 1.5W + 2.0(W+L)(L/W)^2 + n(W+L)[1.5V^2 + 0.35VG]$$

where M = the metabolic rate, watts; W = subject weight, kg; L = load carried kg; V = speed of walking, m/sec.; G = grade, percent; and n = terrain factor (n=1.0 for treadmill, 2.1 for sand and 4.1 for 3.5cm. soft snow). Using this equation and the parameters reported by Duncan (mean subject weight = 81.25 kg., V = 1.11 m/sec., G = 10 and n = 1.0), gives the following results. Wearing a 15.82 kg. breathing apparatus is shown to require an increase in metabolic rate of 16.7 percent when compared to a no load condition. This value compares very well with the difference in activity shown by both Raven (1977) and Myhre (1979), although the mean weight of Raven's subjects, (74 kg.), and Myhre's, (78 kg.), were both less than those of Duncan's (81 kg). Adding the weight of the "turnouts", (6 kg.) to the weight of the breathing

Figure 2. Metabolic rate increase imposed by backpacked loads as predicted by the equation reported by Pandolf (1977). (see text for equation)



line	subject weight, kg.	walking speed, m./sec.	grade, %	terrain factor
1	81.25	1.11	10	1.0
2	81.25	2.0	12	1.0
3	70.0	1.11	10	1.0
4	70.0	2.0	12	1.0

apparatus shows that their combined weight, (21.82 kg.), requires a predicted metabolic increase of 23.8 percent over the no load condition. Comparing this value to the experimental increase of 47 percent derived by Duncan indicates that although the "turnouts" are much lighter, they have an influence on metabolic activity equal to the 15.82 kg., (35 lb.), breathing apparatus. These results are in agreement with the findings of Teitlebaum (1972), who concluded from his study on the metabolic cost of added clothing that there is a significant increase in metabolic cost of working with multi-layered clothing over the corresponding cost of just carrying the weight of the clothing. This increase is attributed to a "friction drag" between clothing layers (i.e., the frictional resistance as one layer of material slides over another during movement) and/or a "hobbling" effect of the clothing (i.e., interference with movement at the body's joints, produced by the bulk of the clothing). The existence of a "hobbling" effect has been suggested previously by Belding (1945), Johnson (1947), and Gray (1951).

Figure 2 shows the metabolic increase expected for backpacked weights carried on a treadmill under four different conditions, as predicted by the equation of Pandolf (1977). The curves indicate that metabolic rate increases by about 1.2 percent for every kg. of added weight (0.5 percent per lb.), but since fire fighting does not take place on a treadmill surface, this value can be expected to increase as the terrain factor increases.

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CONCLUSION

Although the information contained in the preceding sections of this report is intended primarily to serve as a basis for the establishment of criteria for positive pressure closed circuit breathing apparatus, existing criteria of other types of breathing equipment are also potentially impacted. For example, a major criticism of present open circuit compressed air breathing apparatus operated in either the demand or pressure-demand mode is that the equipment does not provide the rated 30 minute duration in fire service (Burgess, 1975). Clearly, the fault is not with the equipment, but with the fact that the minute volume of 40 liters per minute selected to rate service time is too low to adequately represent the level of physical activity actually experienced by fire fighters.

With respect to positive pressure breathing apparatus, to effectively exclude inboard facepiece leakage the device should remain positive in comparison to ambient pressure during peak levels of physical activity. To lessen false expectations regarding device duration, breathing apparatus service time should also be based upon the level of peak physical activity. It was previously reported that certain strenuous fire fighting tasks are capable of demanding oxygen uptake values as high as 2.55 liters per minute for short time periods (Lemon, 1977). Increasing this value by 18 percent, to allow for the average physiologic demand exerted by the maximum weight presently permissible for a self-contained breathing apparatus of 16 kg. (35 lb.), gives a value of 3.00 liters per minute. It is possible to convert this value to an equivalent volume of air by using information provided by Consolazio (1963), who advised that normal values for the ventilatory equivalent of oxygen are approximately 20 to 25 liters of air per liter of oxygen. This implies that to provide adequate protection during periods of peak energy demand positive pressure should be present within a facepiece at minute volumes of 60 to 75 liters per minute and peak flows of 240 to 300 liters per minute. Breathing apparatus service time also should be based upon these maximum minute volumes. Minute volumes between 60 and 75 liters per minute are in agreement with the results of field testing on fire fighters under work conditions at a training facility conducted by Burgess (1975). The median value for minute volume was found to be 58 liters per minute and in 20 percent of the cases, the minute volume exceeded 70 liters per minute.

Information in a report by Dotson (1977) suggests that even minute volumes of 75 liters per minute may be too low. A mean ventilatory equivalent of 39.6 liters of air per liter of oxygen uptake was determined during the performance of simulated fire fighting tasks by 74 active fire fighters. This data suggests that positive pressure should be present at, and device duration based upon a minute volume of approximately 120 liters per minute.

When compared to open circuit self-contained breathing apparatus, the lighter weight, increased duration, and increased oxygen content of closed circuit breathing apparatus are important attributes when the physiologic demands of fire fighting are considered. With regard to device weight, Figure 2 of this report indicates that a reduction of 6 kg. (13.2 lb.) in the weight of a breathing apparatus from 16 kg. (35.3 lb.) to 10 kg. (22.0 lb.) would reduce the increased cost of wearing the device on a treadmill from the range of 15 to 20 percent down to the range of 10 to 13 percent.

Hom (1980) found while investigating the role of breathing apparatus in fire fighter deaths that the most prominent incident resulting in death involved a disoriented fire fighter trapped by fire or smoke, subsequent exhaustion of air supply and death from smoke inhalation. The longer duration possible with closed circuit breathing apparatus may help to reduce the risk of death from this kind of occurrence.

With the information on the physical demands of fire fighting presented in this report, it is difficult to dispute the advantages of closed circuit breathing apparatus. However, the addition of positive pressure to this type of device has been the object of much concern. The issue is not based upon energy demand, for as was noted previously much higher breathing resistances than those that are presently permissible are required to have any noticeable effect on energy demand. Also, studies by Raven (1977) and Myhre (1979) have demonstrated that for open circuit equipment, there is no significant difference in oxygen uptake between the positive pressure mode and demand mode. Rather, the issue of debate has been whether a positive pressure closed circuit oxygen-based breathing apparatus presents a significant flammability risk to its user. Although reports of investigations have been published (Griffin, 1969 and Held, 1980), a solution to the problem has yet to be found, because the risks have not been clearly defined so that a judgment can be made. A piece of information that seems to have escaped comment during the confusion of this issue, is the fact that most of the early closed circuit devices, e.g., the Gibbs, the McCaa, and the Chemox had positive pressure in all parts of their circulatory system (Morrow, 1961). No reports of death or injury have been attributed to ignition of oxygen leakage for any of these devices.

The advantages of positive pressure are well known (Davis, 1979). This report has provided insight to the advantages of closed circuit devices. It is the conclusion of this author that NIOSH should proceed with the creation of criteria for positive pressure closed circuit breathing apparatus.

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