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Determination of average inspiratory pressures and flow rates in industrial respirators at various work rates

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The University of Arizona, 1989
DETERMINATION OF AVERAGE INSPIRATORY PRESSURES
AND FLOW RATES IN INDUSTRIAL RESPIRATORS
AT VARIOUS WORK RATES

by

Le Trinh Kim Pham

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STATEMENT BY AUTHOR

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ABSTRACT

This study determined the parameters which affect the internal mask inspiratory pressure and flow rate during respirator wear. The average inspiratory pressure and inspiratory flow rate were measured on 30 subjects who performed various submaximal work rates on a cycle ergometer while wearing air purifying respirators. The half-mask and full-face respirators were equipped with three levels of cartridge resistance.

The results indicated that work rate, cartridge resistance, and mask type affected the inspiratory pressure and flow rate significantly. The findings of this study would allow the quantitative negative pressure respirator fit test to evaluate respirator fit over a wide range and representative of actual work condition.
INTRODUCTION

Respirators have been used widely as control strategies to protect workers against airborne contaminants in many types of industry. In 1982, there were approximately two million American workers routinely dependent on respirators to prevent the inhalation of toxic air contaminants (Rosenthal and Paull, 1982).

However, the protection afforded to workers depends as much on the quality of the respirator program as on the device itself. The American National Standards Institute provides guidelines for personal respirator protection (ANSI Z88.2, 1980). According to this standard, respirator fit testing is an essential part of an industrial respiratory protection program. Respirator fit testing is also mandated by Federal Law (OSHA, 1980). OSHA section 1910.134(e)(5), a general industry standard on respiratory protection, specifies that an employer must provide adequate fit testing to guarantee that a respirator issued to an employee fits properly. Generally, respirator fit tests could be categorized as either qualitative or quantitative tests.

Respirator Fit Testing

Qualitative Fitting Tests (QLFT). A qualitative test relies on the wearer's subjective response to evaluate leakage. One type of qualitative tests involves the response of a respirator wearer to a challenge agent which is
generated outside the mask. Respirator fit is determined by whether or not the wearer can sense the challenge agent inside the mask. Common challenge agents include isoamyl acetate, saccharin, and irritant smoke (Prichard, 1976).

Other qualitative fitting tests, based on negative and positive pressure induced by the lungs, and thus avoid exposing the wearer to chemicals. They are usually used to give gross estimates of fit and usually are performed immediately after donning the respirator (Teresinski and Cheremisinoff, 1983).

**Quantitative Fitting Tests (QFT).** Quantitative tests are designed to quantify the degree of fit for a given respirator. All quantitative fitting tests involve placing the wearer in a confined exposure chamber containing a challenge gas, vapor, or aerosol. A sampling probe is inserted through the respirator mask into the wearer's breathing zone to measure the challenge agent concentration inside the respirator. The concentration of the challenge agent in the exposure chamber atmosphere and inside a respirator being worn in the chamber are monitored simultaneously. The comparison of these concentrations can be used to quantify the degree of fit by the calculation of a fit factor (Willeke, 1981). The fit factor is calculated by dividing the concentration of the challenge agent in the chamber atmosphere by its concentration in the respirator.
The respirator fit factor indicates how much protection a respirator provides. Generally, a half mask air purifying respirator should provide a fit factor of ten or greater, and a full face air purifying respirator provides a fit factor of fifty or greater (Hyatt, 1976). A fit factor assumes only face seal leakage, and not leakage through air-purifying elements, valves, or other pathways.

The quantitative fit tests differ with respect to the challenge agent being generated. Different challenge agents require different methods of collection and detection. The common challenge agents used in quantitative tests are Freon-12 gas, and aerosols of uranine, sodium chloride, di-octyl phthalate (DOP), limestone, corn oil, or smoke-corn oil.

Problems Associated with Present Respirator Fitting Tests

Qualitative Fit Tests Qualitative fit tests have the advantage of being fast and easy to administer, requiring no complicated, expensive equipment. However, qualitative tests rely on the wearer's subjective response, and are not entirely reliable. A major drawback is that the odor threshold varies widely among individuals. Different persons have been shown to have different sensory thresholds (Hardis et al, 1983). Furthermore, olfactory fatigue occurs during the test so that the respirator wearer may not be able to detect actual leakage, and may respond to only high vapor concentrations.
Qualitative fit tests also have the disadvantage of providing only limited information about respirator fit with their lack of numerical documentation. They test and judge only on a pass-or-fail basis. This results in the inability of the qualitative fit test to select the better fitting of two respirators when both have an adequate fit.

Quantitative fit tests. Although quantitative fit tests permit numerical documentations of respirator fit, and do not rely on a subjective response, they also have certain drawbacks. Quantitative respirator fit tests have several disadvantages which limit their widespread application in industry. The major disadvantages are associated with the complexity and cost of the tests. The instrumentation used to measure the challenge agent is often complicated, bulky, and difficult to calibrate. The complexity of the tests leads to high costs. An estimate of the current cost of quantitative respirator fit test systems ranges from $8,000 to $40,000 (Pritchard, 1976). In addition, the sample face piece cannot be worn in actual service because each test respirator must be equipped with a sampling probe to allow removal of a continuous air sample from the face piece.

A study by Myers et al (1986) has indicated another problem associated with quantitative fit testing. Sampling bias associated with sample probe location affects measurement of face piece contaminant. The variables studied
included probe placement, probe depth, leakage site, and breathing distribution. Myers hypothesized that streamlining of the contaminant from the leakage sites into the respirator system caused the bias. This finding contradicts the assumption that good, instantaneous mixing occurs in the face piece during respirator sampling.

**Toxicity of Challenge Agents** The toxicity of challenge agents is a common disadvantage associated with all the quantitative and qualitative fit tests. There is a concern for Diocyl Phthalate (DOP) as a possible human carcinogen. Isoamyl acetate is known to cause irritation of eyes, nose, and throat. The irritant smoke test involves possible exposure of the test subject to highly irritating hydrochloric acid (Cheresmisinoff and Teresinski, 1983).

**Quantitative Negative Pressure Fit Test**

In search of a better technique, a new method of quantitatively determining respirator fit for chemical cartridge respirators termed the "quantitative negative pressure fit test" has been developed at the University of Arizona. This method as described by Eroh (1986) and Murphy (1989) has the ability to quantitatively determine fit based on the flow rate of air required to be removed from a sealed respirator in order to induce and sustain a pre-selected negative pressure within the respirator while the respirator wearer holds his breath.
The pre-selected negative pressure replicates the inspiratory driving force for air flow through both the air purifying path and any air leakage paths into the respirator. The exhaust flow rate required to sustain a given level of negative pressure in the sealed respirator is a direct measure of leakage rate into the mask. This leakage flow rate is then divided into a theoretical average inspiratory flow rate to determine the ratio of air which enters the respirator via a leakage path during each breath. This resultant ratio is equivalent to the fit factor.

\[
\text{Fit factor} = \frac{\text{Average inspiratory flow rate}}{\text{Leakage flow rate}}
\]

Eroh conducted a study to evaluate the feasibility of the quantitative negative pressure fit test in 1986. He compared the new method to an accepted Freon-12 fluorocarbon quantitative fit test method using a variety of respirator brands and found a high degree of correlation between the two testing methods. The measures of respirator fit obtained from the two tests indicated correlation coefficients ranging from 0.978 to 1.000.

In 1989, Murphy compared an automated system for quantitative respirator fit testing by negative pressure against a computerized aerosol fit test system. The results indicated that negative pressure fit factors were consistently more conservative than aerosol fit factors and
showed less variability.

The above pioneer works on quantitative negative pressure fit test were done using air purifying respirators. This is due to the problem of face seal leakage which causes contaminants to penetrate into a respirator associated only with negative pressure respirators such as non-powered air purifying respirators, demand supplied-air respirators, and demand self-contained breathing apparatus. These respirators are those in which air pressure inside the face piece is negative during inhalation with respect to ambient air pressure. Face piece pressure becomes positive during exhalation. Contaminant leakage into negative pressure respirators occurs predominantly during the inspiratory segment of the respiratory cycle when the direction of air flow through leaks is inward.

Leak sites do not present the same problem with positive pressure respirators. The positive pressure respirator mask is designed to prevent inward leakage by virtue of slight positive pressure inside the face piece throughout the breathing cycle.

Two critical elements of a quantitative negative respirator fit test are: firstly, the negative pressure produced within the respirator by inspiration; which represents the driving force for both the air purifying path and any air leakage path during inspiration; and secondly,
the average inspiratory flow rate. Eroh and Murphy used the average inspiratory flow rate of 25.862 ml/min and 34.483 cm³/min in their studies. This average flow rate was based upon work reported by Harris and Fraser (1976). For the inspiratory negative pressure, Eroh used an assumed value of minus 1 inch (2.54 cm) and Murphy used 0.5 inch (1.27 cm) of water pressure, respectively.

The Respiration Processes and Breathing

Respiration Processes Respiration includes the two processes of external respiration and internal respiration. External respiration is the absorption of oxygen and removal of CO₂ from the body as a whole. Internal respiration is the exchange of gases between body cells and the fluids surrounding them.

External respiration could be subdivided into the two processes of ventilation and gas transfer. Ventilation is the movement of air into and out of the lungs during breathing. Breathing is the mechanical process which leads to air being taken into the lungs (inspiration) in order to supply oxygen to the alveoli, and expelled from the lungs (expiration) in order to remove accumulated carbon dioxide. Gas transfer is the exchange of oxygen and carbon dioxide between the air in the alveoli and blood in the capillaries around these structures.
Mechanisms of Breathing  The movement of air into and out of the lungs is effected by sinusoidal alterations in the volume of the thoracic cavity, with the lungs following these volume changes (Ballantyne and Schwabe, 1981). The lungs contain elastic tissues. This is one reason why they are normally under a tendency to recoil, which is increased during inspiration because of the volume expansion. Because of the recoil phenomenon, the pressure within the pleural space (the intrapleural pressure) is subatmospheric.

Figure 1: Comparison of changes in interpleural and intrapulmonary pressures and in volume of air breathed during a single breathing cycle (Ballantynene and Schwabe, 1981)
Due to elastic recoil properties of the lungs and thoracic wall, work is necessary to increase the volume of the lungs during inspiration. This is provided by the muscles of respiration which are the intercostal muscles and the diaphragm. As a consequence of the contraction of the external intercostal muscles and the diaphragm, the volume of the cavity is increased. The lung volume will be correspondingly increased because of its adherence, through the pleural fluid layer, to the thoracic cavity wall (Comroe, 1975). A pressure differential is thus created between air in the lung and that in the atmosphere, causing air to be drawn through the respiratory passages into the lung. Inspiration pressure is applied by the inspiratory muscles to overcome two main types of force, elastic and resistive. Elastic forces are related to change in volume, and resistive forces are related to air flow.

At the end of inspiration the external intercostal muscles and diaphragm relax, and the volume of the thoracic cavity and lungs is reduced by the elastic recoil of the lung and thoracic wall. Air pressure in the lungs is thus temporarily in excess of atmospheric pressure, causing air to pass out of the lungs. Expiration is thus, essentially, a passive process.

**Physiological Responses to exercise**

An increase in metabolic rate of the exercising muscles
is a basic factor common to all forms of exercise. Muscle metabolism at moderate levels of exercise follows aerobic pathways almost entirely; at high levels of exercise the delivery of oxygen to muscles become critical and anaerobic metabolism is then increasingly important (Gibson, 1984).

**Ventilatory Responses** The stimuli to increase breathing on exercise are several and include both chemical (CO₂, acidity) and neurogenic factors. The relationship between ventilation and work performed is linear up to about 50-60% of maximum VO₂ (see Figure 2). Above this level (the anaerobic threshold) ventilation increases disproportionately and is more closely related to CO₂ output, which also increases by a relatively greater rate at high work loads because of the contribution of anaerobic metabolism. Even in relation to VCO₂ there is a disproportionate rise in ventilation at high work loads (Wasserman, 1973).

The increase in ventilation at low and moderate work loads is achieved mainly by an increase in the depth of breathing (tidal volume) with a relatively smaller contribution from breathing frequency. A maximum tidal volume is usually reached at a value of 50-60% of the vital capacity; above this, further increases in ventilation are the result of an increase in breathing frequency (respiratory rate) alone (Spiro, 1974). Figure (3) shows the relationship
Figure 2: Ventilation during progressive exercise in normal subject related to oxygen consumption and power output (Gibson, 1984)

Figure 3: Tidal volume (solid line) and breathing frequency (broken line) during progressive exercise (Gibson, 1984)
of tidal volume, breathing frequency and work load.

Ruttiman and Yamamoto (1972), Yamashiro and Grodins (1973), and Johnson and Masaitis (1976) have all shown the airflow pattern resulting from minimization of work rate during exercise to be rectangular. Minimization of work rate implies that the mechanical respiratory system is regulated in a way which minimizes work required to produce a given level of ventilation. Silverman et al (1951) experimentally showed a tendency toward rectangular airflow pattern during exercise.

Tidal volume, minute volume, and respiratory rate are the criteria used to assess respiratory characteristics. Tidal volume is the volume of air inhaled or exhaled during a single breath. An average tidal volume for a normal person is 500ml for both man and woman. Respiratory rate is the number of breaths per unit of time. Respiratory minute volume is the volume of air breathed per minute. This value is the product of tidal volume and breathing rate.

**Circulatory Responses** Cardiac output on exercise increases progressively in relation to VO₂ but the relationship is slightly curvilinear with a lower rate of increase at higher work loads. During mild exercise both increasing stroke volume and heart rate contribute. The stroke volume, however, approaches a maximum at relatively low levels of exercise and subsequent increases in cardiac
output depend on increasing heart rate. The systemic blood pressure increases on exercise but to a lesser extent than the cardiac output, implying a reduction in peripheral vascular resistance (Kamon, 1972).

According to Gibson (1984), with training, normal subjects achieve more exercise as a result of greater stroke volume and ejection fraction. As a consequence, the cardiac frequency is then reduced. There is a linear relationship between the cardiac frequency and the expenditure of energy. Therefore at a given rate of work, while the cardiac output of two subjects are similar, the stroke output is smaller in the non-athlete. As a result, the cardiac frequency is higher and reaches a limited value at a lower activity.

**Physiological Effects of Respiratory Protective Devices**

All respirators have technical features which usually impair work performance. The most important factors affecting physiological work are additional inspiratory and expiratory breathing resistance, and equipment dead space. These factors impose specific loads on pulmonary and cardiac function (Haber et al, 1984). The resistance to airflow, the "flow resistive load", may be present in both inspiration and expiration; however it is predominantly an inspiratory load in non powered air-purifying respirators. The other major load is "dead space" representing the volume of exhaled air that is rebreathed from the mask with each inspiration.
Shephard (1962) stated that the respiratory load is increased both by the ventilation of the external dead-space of the respirator and by the flow resistance of the absorbent canister and valves. The total volume of air breathed in is increased as a requirement to overcome the rebreathing (dead space) effect of the respirator. An increased plural pressure must be generated by the respiratory muscles to overcome the airflow resistance of the respirator. The net effect of the increased resistance and increased ventilation volume is a significant increase in the work of breathing. These effects are accentuated during heavy physical work and lead to a reduction of maximal physical work capacity.

Raven et al (1979) noted other physiological responses imposed by the respirator. The weight of the respirator device may increase both the energy demands of the task and the cardiorespiratory demands of any particular job. Field of vision and the clarity of vision may be decreased and there is interference with the physiology of normal speech. In addition, psychological response to a feeling of claustrophobia and anxiety can also produce physiological stress. Heat stress has also been a primary factor in the use of respirators in many working situations.

Maximal and Submaximal Work Performance. In industry, filtering devices and air-line apparatus are usually worn in light or moderately heavy tasks of a long duration. The use
of a self-contained breathing apparatus is limited to short
duration for rescue and repair tasks which often require
maximal or near maximal physical effort.

Several studies have demonstrated that respirators
increase respiratory work load, decrease endurance time, and
decrease maximal work capacity in subjects performing
moderate to heavy work while wearing a respirator
(Hermansen et al, 1972; Thompson and Sharkey, 1966;
Cerretelli, 1969). Raven (1989) conducted a test to study
physiological effects of pressure demand respirators on
progressive exercise to maximal levels. The results indicate
a greater physiological effort required to generate flow.
Performance time was reduced significantly and peak inspired
flow was also decreased with respirator wearing.

Similar decrements in work performance have been
observed in fire fighters wearing a SCBA respirator (Raven et
al, 1977). A 17 to 21 percent decrement in maximal work
performance was noted with this specific study. Raven also
investigated the use of clinical pulmonary function testing
to predict performance time on maximal and endurance type
exercise tests. He found that respirator mask wear reduced
clinical pulmonary function measures from 7 to 15 percent
from mouth-piece controls (Raven et al, 1989). Craig et al
(1970) reported that the face piece without filters had a
degrading effect upon endurance. Reduction of work capacity
utilizing the air-purifying respirators approximated 21-27 percent of performance time.

Loujhevaara and associates (1984) studied the effects of air-purifying, air-line, and self contained breathing apparatus (SCBA) on pulmonary ventilation, oxygen consumption, and heart rate with progressive submaximal work levels. The results show that all three types of respirators hampered respiration, which led to hypventilation and a fall in the respiratory exchange ratio. This study also suggests that the combined inspiratory and expiratory breathing resistance of the filtering device was more strenuous than the expiratory resistance of the air line apparatus.

From the preceding information it can be stated that inspiratory breathing resistance added during submaximal and, particularly maximal exercise by a respirator hinders ventilation and results in hypoventilation and retention of carbon dioxide. The different breathing patterns of subjects, coupled with considerable interindividual differences, produces unpredictable changes in gas exchange at light and moderate exercise levels.

**Resistance to Air Flow.** Extra mechanical work must be done to overcome the resistance which respiratory protective devices offer. The increased respiratory work is performed by increasing the inspiratory pressures generated by the respiratory muscles. A classical work by Silverman (1951)
investigated the effects of breathing against resistance while working at various rates on a bicycle ergometer. The work rates selected ranged from 0 to 1660 Kg.m/min and were used in conjunction with inspiratory resistances ranging from 0.6 cm (0.39 inches) to 10.6 cm (4.14 inches) water measured at flow rate of 85 L/min. He concluded that increases in respiratory resistance resulted in a decreased submaximal oxygen uptake, and 20 percent declined minute volume with increased respiratory exchange ratio. The inspiratory flow rate in his study for work rates of ranging from rest up to 500 Kg.m/min varied between 40 and 90 L/min.

Cooper's work on the resistance of respirators suggested that the use of a simple air filter of very low resistance could increase the work of respiration by 20 to 30 percent, and a closed circuit breathing apparatus, by 100 percent. He has also suggested that the estimation of the work done in ventilating respirators was the most useful, single measurement in providing the knowledge of resistance to respiration. He likened the human respiratory system to a reciprocating pump with sine-wave flow (Cooper, 1960).

Some later work confirmed the findings of Silverman and Cooper. Flook and Kelman (1973) studied the effect of increased inspiratory resistance to breathing during submaximal exercise and found that there was a progressive decrease of volume with increasing resistance. Other
important points which this study showed include hypoventilation accompanied by a lengthening of inspiration. Tidal volume increased with increasing resistance during light exercise, remained unchanged during moderate exercise, and fell slightly during heavy exercise.

Bentley (1973) investigated the subjects' ability to tolerate the added respiratory work load. He concluded that excessive pressure exerted during inspiration is a major factor in determining subjective tolerance. He suggested that 90% of a population breathing through apparatus with low-resistance expiratory valves should experience no discomfort, if the pressure across the apparatus does not exceed 17 cm water. The results of this work also indicate that the degree of dyspnea was a function of the negative intrathoracic pressure.

Bentley's work appeared to confirm the general principles on which the standards suggested by Silverman et al (1951), and Cooper (1960) were based. Cooper's acceptable limit on total breathing resistance (up to 50 percent being expiratory) was equivalent to a pressure drop of 25 cm H$_2$O (10.2 inches), which compared with the figure of about 13 cm H$_2$O (5.12 inches) derived from Silverman's work. Cooper suggested that an ideal value should be half of his own standard, close to that of Silverman. Bentley's work indicated that acceptable values of resistance probably lie
somewhere within this range depending on other conditions.

It should be possible to conclude from the results of the studies mentioned above that breathing resistance lies between 2-25 cm H\textsubscript{2}O (0.79-9.84 inches). For inspiratory or expiratory resistance alone values not more than half of this could be considered as acceptable, although an inspiratory pressure swing of 14 cm H\textsubscript{2}O is believed to be acceptable (Bentley et al, 1973). For respirators which are likely to be worn for prolonged periods during light to moderate work, a much lower value of inspiratory resistance is desired, as low as possible but probably giving rise to a pressure drop not greater than 2-5 cm H\textsubscript{2}O.

Craig et al (1970) studied men who worked to exhaustion on a treadmill. Their results show that increased resistance to breathing significantly reduced times to exhaustion with the greatest percent change occurring at the lighter workloads. When the frequency of respiration increased during work, the time for inspiration was conserved at the expense of the time for expiration. Johnson and Berlin (1974) confirmed that exhalation time does decrease with time during moderate to maximal exercise, and the minimum exhalation time can describe the point of respiratory exhaustion of a person wearing a respirator.

Using the concept of minimizing average respiratory power, Johnson and Masaitis (1976) have developed equations
of respiratory regulation to predict inhalation / exhalation time ratios for the respiratory system. The equations demonstrated that if the respiratory period was known, exhalation time could be calculated.

**Individual Variations in Lung Function**

Variation in lung function between individuals results from several factors. The most common factors include sex, age, body size which is usually represented by height, and ethnic differences.

**Size, Sex and Ethnic Differences.** Large individuals generally have large lungs, and variation in size in the normal adult population may produce extremes of total lung capacity from less than 4 L in a small woman to 10 L in a very tall man [The effect of variations in lung size causes the differences in lung volume, measurements of ventilation, oxygen consumption, pulmonary compliance and ventilatory responses to carbon dioxide and hypoxia (Gibson, 1984).]

Cotes (1979) mentioned that a person who, on account of his size, has a relatively small vital capacity also has a small exercise tidal volume. This results in an increase in breathing frequency. Recent evidence indicates that lung volumes may differ significantly in regard to race or ethnic origin (Ruppel, 1986). Subjects of European origin generally having values of vital capacity 10-15% larger than non-Europeans of the same height.
Many of the normal sex differences in respiratory function result from differences in size, but even after taking account of size, important differences in certain tests remain. After adolescence the vital capacity and total lung capacity of boys exceed those of girls of a similar height and the residual volume is similar (Cotes, 1979). Gibson et al (1976) stated that maximum respiratory pressures are greater in men than women, and this explains the greater maximum lung recoil pressure in men. Pulmonary compliances parallel the differences in volume, and the CO2 diffusing capacity.

**Age Difference.** Peak performance of the lungs is achieved between the ages of 15 to 25 years and thereafter follows a gradual decline. The lungs share the general aging changes of connective tissue elsewhere in the body—just as the turgor of the skin is lost in the elderly, so elastic recoil of the lung diminishes. In consequence the pressure-volume curve is shifted to lower values of recoil pressure at all lung volumes (Gibson et al, 1976).

**Environmental and Smoking effects.** One important environmental factor which affects measurements of respiratory function is altitude. Altitude determines the inspired PO2, and even at modest altitudes, results in a lower PaO2 and a need to adjust accepted normal ranges. This also applies to PaCO2 as ventilation is stimulated by hypoxemia.
Cigarette smoking has been shown to produce a measurable increase in the airway resistance of normal subjects. The effect of a cigarette may persist for up to an hour. The effect may be partly related to the increased carboxyhemoglobin content of blood, and a reduction of blood in the pulmonary capillaries (Burrows et al, 1977).

Research Objective:

Most of the previous work aimed at evaluating the effect of respirators on inspiratory pressures and flow rates had been done at maximal work rates. Information about submaximal work rates would be useful in the assessment of normal work conditions. Furthermore, a precise determination of inspiratory driving force and inspiratory flow rate at various levels of work load, cartridge resistance, and mask type is essential for a validated quantitative negative pressure respirator fit testing. For this reason, an inquiry after the parameters which affect the internal mask inspiratory pressure and flow rate during respirator wear was the basis of this study.

The research objective was to determine the average internal mask inspiratory pressures and flow rates at various work rates and for various air purifying media. The average inspiratory pressure and inspiratory flow rate was measured on subjects who performed various submaximal work rates on a cycle ergometer while wearing air purifying respirators
equipped with different levels of respirator cartridge resistance. The effect of the difference in respirator mask types on inspiratory pressure and inspiratory flow rate was also evaluated. At the same time correlation between subjects' size, sex, and age difference and the various level of inspiratory pressures and flow rates was examined. Predicted values for inspiratory pressures and inspiratory flow rates were derived from statistical analysis of normal subjects wearing standard air purifying respirator.
MATERIALS AND METHODS

Subjects

The experiment was conducted on 30 fit young adult subjects who were volunteer students from the University of Arizona. To ensure that these subjects did not have any underlying respiratory disease problem, they were asked to fill out a screening health history form prior to the test session (Appendix A). In addition, each subject's pulmonary functions was also evaluated by a Vanguard digital spirometer. The forced vital capacity (FVC) and the forced expiratory volume over one second (FEV$_1.0$) were recorded by a computerized data acquisition system connected to the digital spirometer. The characteristics of the subjects are presented in Table 1.

The subjects were divided into three groups. Nine of the subjects were females who wore half-mask respirators during the test. Almost half of the male subjects (nine) wore full-face respirators, while the remaining males (twelve) males had half-mask respirators on while they performed work various rates during the inspiratory pressure and flow test. These subject grouping allowed evaluation of the effects of sex, and mask related variables on inspiratory pressure and flow rates.

Respirator Equipment

The respirators used were air purifying devices
### Table I: Demographic characteristics of study subjects

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<th>Sub #</th>
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<th>Weight (lbs)</th>
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<th>Sex</th>
<th>Norm FEV1.0 (L)</th>
<th>Obs FEV1.0 (L)</th>
<th>Norm FVC (L)</th>
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**Note:** Norm = Normal. Obs = Observe. FEV$_{1.0}$ = Forced expiratory volume over one second. FVC = Forced vital capacity.
including full face (MSA-Ultra vue), and the half mask (MSA-Comfo II) models. These test respirators had integrated sampling probes which enabled the measurement of the intermask inspiratory pressure. The respirators were equipped with three different types of air purifying media which are representative of low, medium, and high cartridge resistances. MSA GMA-S, MSA GMA-H, and MSA GMB-B cartridge was used to represent low, medium, and high levels of resistance.

Respirator fit testing was also performed on each subject to ensure that the respirator was fitted properly. The quantitative negative pressure fit test method described by Murphy (1989) was used for respirator fit testing in this study. The system measured mask leakage flow rate while maintaining a pre-selected negative pressure within the sealed facepiece. The facepiece was sealed by two air-tight manifolds which were inserted in place of the air-purifying elements. The negative pressure test protocol is outlined in Appendix B. This test protocol was approved by the Human Subjects Committee of the Arizona Health Sciences Center on November 9, 1987.

Exercise Test

The intensity of exercise can be quantitated in one of two ways: in terms of either metabolic load where the variables measured are related to oxygen consumption, or by
external work rate or power output. For this research, the external work rate obtained from a Monark cycle ergometer was used to quantify the degree of exercise. The cycle ergometer was calibrated daily using calibration weights over the range of 0.5-2.0 Kg.

The essential feature of a cycle ergometer is a flywheel which is restrained by a friction belt. The cycle ergometer allows the work load to be varied by adjustment of the resistance to pedaling. The flywheel of the ergometer turns against a belt that has both ends connected to a weighted physical balance. The rate of energy expenditure is related to work done, which is the product of the load on the flywheel and the distance through which it is moved per minute; this is the circumference of the flywheel multiplied by the number of its revolutions per minute. Work load may be expressed as the rate of work in power (Kg·m/min) which is work per unit of time.

The work rates in this study were calculated as followed:

Circumference of the flywheel = 6m
Distance/min = Revolution * Track distance
Work rate = Force * Distance/min

Resistance of 0.50, 1.00, and 1.5 Kg were used to obtain the desired submaximal work rates in this study. The work rates in this experiment were classified into four
separate periods as follows:

1. Resting rate is equivalent to 90 kg.m/min of energy expenditure.
2. Light work = 0.50 Kg * 360 m/min = 180 Kg.m/min
3. Moderate work = 1.00 Kg * 360 m/min = 360 Kg.m/min
4. Heavy work = 1.50 Kg * 360 m/min = 540 Kg.m/min

During the period of a 5-minute exercise starting from rest, the changes in the ventilation minute volume may be subdivided into an initial phase when the ventilation is rising steeply, an exercise phase when the ventilation may be regarded as representative of the exercise, and a recovery phase after exercise when the ventilation is returning to its previous levels (Figure 4). The initial phase usually occupies 2 or 3 minutes. The exercise phase is usually reached by the 4th minute of exercise. During moderate exercise, it may be represented by a single value which is the steady-state ventilation of the subject.

Figure 4: Ventilation minute volume during a 5-min period of test exercise in a normal subject (Cotes, 1979).
The steady-state exercise test protocol was used to determine work load in this study. Steady tests were designed to assess parameters of cardiopulmonary function specifically under conditions of constant metabolic demand. This type of test is useful for assessing responses to a known workload. Work was performed for approximately 5 minutes at the predetermined level to allow a steady state to develop. Steady state usually achieved after 3 to 4 minutes of exercise. Inspiratory pressure and inspiratory flow measurements were performed during the last 1 minute of the period. Successive steady-state determinations at higher power outputs were made continuously.

Each subject underwent testing while he/she was performing four work rates of 90, 180, 360, and 540 Kg.m/min for each type of air purifying cartridge (low, medium, and high). The study protocol called for each work rate to be sustained for approximately five minutes. Between each set of cartridges, a short resting period was provided to allow the subject to get back to his/her pre-exercise state. Subject pulse rates was taken prior to and after the rest period to determine if a subject had recovered to his/her normal resting state. A subject would have been considered to recover to a resting state if the pulse rate obtained after the post-exercise break period is higher within 5 beats in comparision to the pre-exercise heart rate.
**Inspiratory Pressure Measurement System**

The inspiratory pressure was measured by a pressure transducer in the negative pressure system connected by tubing to the probe in the test respirators. The inspiratory period data was also measured by the negative pressure system. The negative pressure system used in this research was the same type described by Murphy (1989). A computerized data acquisition system connected to the negative pressure system recorded the negative inspiratory pressure measurements. The pressure transducer in the negative pressure system was calibrated against a Dwyer water manometer over the range of 0.00-2.00 inches H₂O. The digital voltmeter of the negative pressure system and the computerized data acquisition system were calibrated against a Fluke Voltmeter over the range of 1 to 3 Volts.

**Inspiratory Flow Rate Measurement System**

Average inspiratory flow rates were obtained through the measurement of tidal volume (Vₜ). The Vₜ may be the volume of gas inspired or expired during each respiratory cycle. Conventionally, the expired volume was measured as tidal volume in this study. Inspired tidal volume was assumed to be approximately equal to expired tidal volume in this project based on the fact that human air-flow shows a tendency toward a sine-wave pattern (Cooper, 1960). The difference between inspired tidal volume, and expired tidal
volume is very small (approximately 1%). Expired tidal volume was converted to BTPS using a conversion factor of 1.08.

Expired tidal volume was measured by connecting a standard spirometer hose to the test respirators's exhalation valve. The spirometer hose was in turn connected to a Bionix 400 Pneumotach spirometer. The pneumotach spirometer was calibrated against a Collin calibration syringe over a range of 0.5 to 3.0 L. Inspiratory period data was measured by the negative pressure system connected by tubing to the probed test respirators. Mean inspiratory flow rates for each test work rate was computed by dividing the tidal volume by the inspiratory period:

\[
\text{Flow rate} = \frac{\text{Tidal volume}}{\text{Inspiratory period}}
\]

The Vt and inspiratory period data was recorded by a computerized data acquisition system connected to the negative pressure system. Figure 5 illustrate the set up of the measurement system for inspiratory pressure and inspiratory flow rate.

**Test Protocol**

The inspiratory pressure and flow rate test protocol was approved by the Human Subjects Committee of the Arizona Health Sciences Center on May 23, 1989. To prepare for the
test, a complete explanation of the protocol was given, and informed consent was provided by each participant. A screening health history and screening spirometry were then performed to assure normality of the subjects. After respiratory screening, the subjects were fitted with either a half-mask or full face air purifying respirator using the quantitative negative pressure fit testing method. The subjects then performed three sets of test exercise.

Figure 5: The set up of the measurement system for inspiratory pressure and flow rate.
Each exercise set consisted of submaximal work rates of 90, 180, 360, and 540 Kg.m/min on a cycle ergometer while wearing an air purifying respirator. Each work rate was sustained for five minutes. Inspiratory pressures and flow rates were measured during the last minute of exercise for each work rate. Three repetitions of the set of exercises allowed measurements for low, medium, and high cartridge resistances. The subjects were given a short resting period to allow them to recover to their pre-exercise level while the cartridges were changed between each exercise set.
RESULTS

Measurement Precision

Table II lists the data regarding the precision of the inspiratory pressure and flow rate measurements for three randomly selected subjects at low cartridge resistance. The coefficient of variation for inspiratory pressure measurements was in the range of 5-12 %, and for inspiratory flow rate, between 4-10 %.

Table II: Precision of inspiratory pressure and flow rate measurements for three randomly selected subjects (low resistance cartridge).

<table>
<thead>
<tr>
<th>WR (Kg.m/min)</th>
<th>PRESSURE (inches H2O)</th>
<th>FLOW RATE (LPM)</th>
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<td>Mean</td>
<td>SD</td>
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<tr>
<td>540</td>
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Note: WR = Work rate. n = Ventilatory cycle.
Average Inspiratory Pressures and Flow Rates

Inspiratory pressure and flow rate data for each of the three subject groups (male equipped with half mask respirators, male equipped with full mask respirators, and female equipped with half mask respirator) are presented in Tables III, and IV. Group means and standard deviations are illustrated for the four submaximal work rates and three different levels of cartridge resistance. Inspiratory pressures and flow rates showed significant increase due to increased work loading.

Difference Within Each Cartridge Resistance Levels

Three-way ANOVA was used to compare the effects and interactions of the independent variables [involves 3 factors: 1) work rate, 2) Sex, and 3) Mask] on the dependent variable (inspiratory pressure or inspiratory flow rate) for each cartridge. There were four levels of the work rate factor, two levels of the sex factor, and two levels of the mask factor. Differences among the levels of the mask factor were also evaluated. Table V displays the results of the analysis of variance for inspiratory pressure as a function of work rate, sex, and mask for the low, medium and high cartridge resistances. Table VI shows the results of the analysis of variance for inspiratory flow rate as a function of the previously listed independent variables for the three different cartridges.
Table III: Average inspiratory pressures as a function of work rates and cartridge resistance levels.

<table>
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<tr>
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<th>M-FF (n=9)</th>
<th>F-HM (n=9)</th>
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<tr>
<td>360</td>
<td>0.377</td>
<td>0.074</td>
<td>0.497</td>
</tr>
<tr>
<td>540</td>
<td>0.515</td>
<td>0.111</td>
<td>0.693</td>
</tr>
<tr>
<td>CART 90</td>
<td>0.345</td>
<td>0.067</td>
<td>0.395</td>
</tr>
<tr>
<td>MED 180</td>
<td>0.545</td>
<td>0.120</td>
<td>0.621</td>
</tr>
<tr>
<td>360</td>
<td>0.667</td>
<td>0.135</td>
<td>0.886</td>
</tr>
<tr>
<td>540</td>
<td>0.913</td>
<td>0.199</td>
<td>1.130</td>
</tr>
<tr>
<td>CART 90</td>
<td>0.548</td>
<td>0.126</td>
<td>0.642</td>
</tr>
<tr>
<td>HIGH 180</td>
<td>0.928</td>
<td>0.209</td>
<td>1.118</td>
</tr>
<tr>
<td>360</td>
<td>1.228</td>
<td>0.207</td>
<td>1.563</td>
</tr>
<tr>
<td>540</td>
<td>1.681</td>
<td>0.300</td>
<td>2.037</td>
</tr>
</tbody>
</table>

Note: WR = Work rate. M-HM = Male wearing half mask respirator. M-FF = Male wearing full face respirator. F-HM = Female wearing half mask respirator.
Table IV: Average inspiratory flow rates as a function of work rates and cartridge resistance levels.

<table>
<thead>
<tr>
<th>WR (Kg.m/min)</th>
<th>M-HM (n=12)</th>
<th>M-FF (n=9)</th>
<th>F-HM (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (Lpm)</td>
<td>SD (Lpm)</td>
<td>Mean (Lpm)</td>
</tr>
<tr>
<td>360</td>
<td>74.428</td>
<td>19.735</td>
<td>96.348</td>
</tr>
<tr>
<td>540</td>
<td>93.469</td>
<td>17.270</td>
<td>111.332</td>
</tr>
<tr>
<td>MED 180</td>
<td>54.224</td>
<td>11.919</td>
<td>63.885</td>
</tr>
<tr>
<td>360</td>
<td>64.450</td>
<td>13.375</td>
<td>85.181</td>
</tr>
<tr>
<td>CART 90</td>
<td>30.430</td>
<td>9.142</td>
<td>35.362</td>
</tr>
<tr>
<td>HIGH 180</td>
<td>47.374</td>
<td>8.321</td>
<td>58.274</td>
</tr>
</tbody>
</table>

Note:

WR = Work rates.
M-HM = Males wearing half mask respirators.
M-FF = Males wearing full face respirators.
F-HM = Females wearing half mask respirators.
Table V: Results of analysis of variance of inspiratory pressure for 3 levels of cartridge resistance as a function of work rate, sex, and mask type.

<table>
<thead>
<tr>
<th>Source</th>
<th>LOW-PRESSURE</th>
<th>MED-PRESSURE</th>
<th>HIGH-PRESSURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-Ratio</td>
<td>P</td>
<td>F-Ratio</td>
</tr>
<tr>
<td>A (WR)</td>
<td>111.52</td>
<td>0.00</td>
<td>78.22</td>
</tr>
<tr>
<td>B (Sex)</td>
<td>4.30</td>
<td>0.04</td>
<td>7.55</td>
</tr>
<tr>
<td>AB</td>
<td>0.38</td>
<td>0.76</td>
<td>0.18</td>
</tr>
<tr>
<td>C (Mask)</td>
<td>33.98</td>
<td>0.00</td>
<td>21.13</td>
</tr>
<tr>
<td>AC</td>
<td>5.26</td>
<td>0.00</td>
<td>2.17</td>
</tr>
<tr>
<td>BC</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>ABC</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Note:
Low-pressure = inspiratory pressure for low cartridge resistance.
Med-pressure = inspiratory pressure for medium cartridge resistance.
High-pressure = High cartridge resistance.
WR = Work rates.
Table VI: Results of analysis of variance of inspiratory flow rate for 3 levels of cartridge resistance as a function of work rate, sex, and mask type.

<table>
<thead>
<tr>
<th>Source</th>
<th>LOW-FLOW</th>
<th></th>
<th>MED-FLOW</th>
<th></th>
<th>HIGH-FLOW</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-Ratio</td>
<td>P</td>
<td>F-Ratio</td>
<td>P</td>
<td>F-Ratio</td>
<td>P</td>
</tr>
<tr>
<td>A(WR)</td>
<td>55.41</td>
<td>0.00</td>
<td>77.79</td>
<td>0.00</td>
<td>116.03</td>
<td>0.00</td>
</tr>
<tr>
<td>B(Sex)</td>
<td>0.00</td>
<td>0.99</td>
<td>3.23</td>
<td>0.07</td>
<td>0.29</td>
<td>0.59</td>
</tr>
<tr>
<td>AB</td>
<td>0.10</td>
<td>0.96</td>
<td>0.95</td>
<td>0.42</td>
<td>0.99</td>
<td>0.40</td>
</tr>
<tr>
<td>C(MASK)</td>
<td>17.20</td>
<td>0.00</td>
<td>23.00</td>
<td>0.00</td>
<td>30.93</td>
<td>0.00</td>
</tr>
<tr>
<td>AC</td>
<td>0.36</td>
<td>0.78</td>
<td>1.35</td>
<td>0.26</td>
<td>1.99</td>
<td>0.12</td>
</tr>
<tr>
<td>BC</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>ABC</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Note: LOW-FLOW = inspiratory flow rate for low cartridge resistance. MED-FLOW = Medium cartridge resistance. HIGH-FLOW = High cartridge resistance. WR = Work rates.
**Inspiratory Pressure.** Three way ANOVA tested at 0.05 significance level indicated that inspiratory pressures were significantly different among the various work rates \( (p < 0.001) \). Figure 6 illustrates the different work rate effects on inspiratory pressure for males wearing half mask respirators (mask type held constant) equipped with three different cartridges. Sex differences in inspiratory pressures were statistically significant at \( p < 0.001 \). Figure 7, 8, and 9 shows the effect of sex on inspiratory pressure at low, medium, and high cartridge resistance (keeping mask type constant).

![Graph](image)

**Figure 6:** Inspiratory pressure for male wearing half mask respirator \( (n = 12) \)
Figure 7: Difference in inspiratory pressure for males and females wearing half mask respirator with low resistance cartridge.

Figure 8: Difference in inspiratory pressure for males and females wearing half mask respirator with medium resistance cartridge.
Figure 9: Difference in inspiratory pressure for males and females wearing half mask respirator with high resistance cartridge

The type of mask had significant effect on inspiratory pressure, \( p < 0.001 \). Figure 10 shows the effect of full face and half mask respirators on inspiratory pressure for males at low cartridge resistance. The ANOVA results did not indicate any interaction among the three factors (work rate, sex, and mask) at a 0.05 level of significance.
INSpiratory FLOW RATE. Analysis by three way ANOVA showed significantly difference in inspiratory flow rate as a function of work rate (P < 0.001). Figure 11 indicates the effect of work rate on inspiratory flow rate for males wearing half mask respirators. Sex did not have any effect on inspiratory flow rate, nor was there any significant
interaction among the factors of work rate, sex, and mask. Figure 12 reveals the effect of sex on inspiratory flow rate. Mask type also had significant effect on inspiratory flow rate, with $p < 0.001$. Figure 13 illustrates the effect of mask type on inspiratory flow rates (Sex and cartridge were held constant).

Figure 11: Inspiratory flow rates for males wearing half mask respirators ($n = 12$)
Figure 12: Difference in inspiratory flow rates for males and females wearing half mask respirators with low resistance cartridge.

Figure 13: The effect of mask type on inspiratory flow rates for male breathing through low resistance cartridge.
Inspiratory pressure and inspiratory flow rates were interrelated. Figure 14 illustrates the effect of pressure on flow rate.

Figure 14: Relationship between pressure and flow rate
Differences among cartridge resistance levels

A two-way ANOVA was performed at a 0.05 significance level to examine the effect of different cartridge resistance levels on inspiratory pressure and flow rate at various work rates. The results show that inspiratory pressures were significantly different at different cartridge resistance levels (p < 0.001). Work rate and cartridge resistance interacted and had highly significant effects on inspiratory pressure, with p < 0.001. However, cartridge resistance did not have any effect on inspiratory flow rate, (p = 0.12). Tables VII and VIII present two-way ANOVA results for the tests of inspiratory pressure and flow rate as a function of different cartridges.

Table VII: Results of analysis of variance of inspiratory pressure as a function of different cartridge resistances.

<table>
<thead>
<tr>
<th>Source</th>
<th>F-Ratio</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(WR)</td>
<td>108.00</td>
<td>0.00</td>
</tr>
<tr>
<td>B(CART)</td>
<td>260.24</td>
<td>0.00</td>
</tr>
<tr>
<td>AB</td>
<td>14.33</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Note: WR = Work Rate. CART = Cartridges
Significance level = 0.05
Table VIII: Result of analysis of variance of inspiratory flow rate as a function of different cartridge resistances.

<table>
<thead>
<tr>
<th>Source</th>
<th>F-Ratio</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(WR)</td>
<td>122.95</td>
<td>0.00</td>
</tr>
<tr>
<td>B(CART)</td>
<td>2.13</td>
<td>0.12</td>
</tr>
<tr>
<td>AB</td>
<td>1.48</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Note: WR = Work rate. CART = Cartridges
Significance level = 0.05

Demographic effect

Observed spirometry data (FEV$_{1.0}$ and FVC) were compared with those values obtained from a normal value nomogram (Appendix C and D) by using a paired t-test at the 0.05 significance level. Results show that there was no significant difference between the observed spirometry data and nomogram data ($R = 0.79$ for FEV$_{1.0}$, $R = 0.86$ for FVC). Table IX shows t-test results for observed spirometric data and nomogram spirometric value.

Multiple regression analysis used to determine the effects of height, weight, and sex on inspiratory pressures or flow rates shows very low correlation. The results of this analysis are presented in Table X. Figure 15 illustrates the effect of weight on inspiratory pressure at a work rate of 180 Kg.m/min with a half mask respirator.
Table IX: Correlation between observed spirometric data and nomogram spirometric values.

<table>
<thead>
<tr>
<th>Variables</th>
<th>M</th>
<th>SD</th>
<th>T</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEV_N</td>
<td>4.14</td>
<td>0.59</td>
<td>0.62*</td>
<td>0.79</td>
</tr>
<tr>
<td>FEV_O</td>
<td>4.09</td>
<td>0.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FVC_N</td>
<td>5.18</td>
<td>0.84</td>
<td>-0.53*</td>
<td>0.86</td>
</tr>
<tr>
<td>FVC_O</td>
<td>5.23</td>
<td>1.10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: FEV_N = Nomogram Force Expiratory Volume. FEV_O = Observed FEV. FVC_N = Nomogram Force Vital Capacity. FVC_O = Observed FVC.

Table X: Correlation between Height, Weight, and Sex effect and inspiratory pressures or flow rates.

<table>
<thead>
<tr>
<th></th>
<th>Height</th>
<th>Weight</th>
<th>Sex</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>.3791</td>
<td>.5406</td>
<td>-.4673</td>
</tr>
<tr>
<td>MP</td>
<td>.3091</td>
<td>.5190</td>
<td>-.4822</td>
</tr>
<tr>
<td>HP</td>
<td>.2013</td>
<td>.4228</td>
<td>-.3923</td>
</tr>
<tr>
<td>LF</td>
<td>.1789</td>
<td>.4151</td>
<td>-.0577</td>
</tr>
<tr>
<td>MF</td>
<td>.1906</td>
<td>.3243</td>
<td>-.4509</td>
</tr>
<tr>
<td>HF</td>
<td>-.0538</td>
<td>.1389</td>
<td>-.1595</td>
</tr>
</tbody>
</table>

Figure 15: Effect of weight on inspiratory pressure at work rate of 180 kg.m/min and with half mask respirators
DISCUSSION

The results of this study indicate that inspiratory pressure inside the mask and inspiratory flow rate are significantly related to work rate, cartridge resistance, and mask type. The findings also show that demographic effects of sex, height, and weight do not influence inspiratory pressure and flow rate. These observations are result from several loads on breathing which are imposed by working with an air-purifying respirator. These loads include the inspiratory flow resistance, respiratory mask dead space, and increased pulmonary ventilation during exercise.

Work rate effect

The observed linear increase in inspiratory pressure and flow rate with increased work rate is in agreement with findings previously reported by Silverman (1951), and Haber (1982). This is expected because ventilation should increase during increased work loads due to an increase in metabolic rate of the exercising muscles. At high flow rates, as during exercise, the air flow is turbulent in the trachea and the main bronchi, giving a high flow resistance. Therefore, the respiratory muscles must generate higher force to overcome the increase in flow resistance, thus inspiratory pressure would be increase. The increase in ventilation at low and moderate work loads is achieved mainly by an increase in the depth of breathing (tidal volume) with a relatively
smaller contribution from breathing frequency. Since the change in tidal volume require a higher pressure to overcome the elastic force, inspiratory pressure would also be increase.

**Air Flow Resistance Effect**

The increase in inspiratory pressure as a function of increasing cartridge resistance is consistent with the results of studies conducted by Cooper (1960), Bentley (1973), Craig (1980), and Flook and Kelman (1973). Because flow resistive load is predominantly an inspiratory load in air purifying respirators, the pleural pressure must be increased to overcome the air flow resistance of the respirator. These studies also showed that inspiratory volume was decreased by resistance. Therefore, inspiratory flow rate, which is a function of volume/time, would be decreased. However, Haber's study (1982) which evaluated the combined effect of resistance, dead space, and exercises indicates that peak inspiratory flow rate was decreased by resistance and increased by dead space. Because of opposing effects, combined dead space and resistance did not have a significant effect during exercise. The finding about the effect of resistance on flow rate in the present study is consistent with the results of Haber's research.

**Mask Dead Space Effect**

The results of this study show significant effect of
mask type on inspiratory pressure and flow rate. Because a full face mask is larger than a half mask, it contains a higher volume of residued exhaled air that is rebreathed from the mask with each inspiration. The rebreathing (dead space) effect requires an increase in total volume of air breathed in order to overcome the dead-space effect, and thus further increase ventilation. The outcomes of the mask type effect in this present research project support previous studies conducted by Haber (1982), and Shepard (1962).

Demographic effect

It was hypothesized that parameters such as sex, height, and weight could be used to predict inspiratory pressures and inspiratory flow rates. The results of this study did not support the above hypothesis. The parameters of sex, height, and weight did not significantly affect internal mask pressure or inspiratory flow rate as shown by very low correlations.

Body weight is not related to the oxygen uptake in exercises such as cycling where the body is not lifted. Further, individual dimensions such as height and weight are not decisive for the size of the lung volumes. The lung volumes are about 10 percent smaller in women than in men of the same age (Astrand and Rodahl, 1986). This difference in volume also associates with the difference in maximum respirator pressure in men and women (greater in men than in
women). This phenomenon takes account for the sex difference in inspiratory pressure observed in this study.

Sex difference, however, does not affect inspiratory flow rate because flow rate is a function of volume and inspiratory time. Since the energy demand for each work rate is constant, women whose lung volumes are smaller than men's, would have to accommodate by breathing longer to meet the energy requirement for the work load. Therefore, the end result flow rates would be the same for both men and women at a specific work rate.
SUMMARY

This study was conducted to determine and define the parameters that significantly affect internal mask pressure and inspiratory flow rate during respirator use. The effects of working while wearing a respirator (resistance, dead space, and exercises) were evaluated independently and in combination. The knowledge of the parameters that affect inspiratory pressure and flow rate would enhance the capability of the quantitative negative pressure respirator fit testing over a wide range of work conditions.

The results indicate that work rate, cartridge resistance, and mask type are important parameters which significantly affect inspiratory pressure inside the mask and the inspiratory flow rate. The linear increase in inspiratory pressure was observed with increase work loads, cartridge resistance, and dead space of the mask type. Inspiratory flow rate was observed to increase linearly with elevated work rates and respirator mask dead space, but remained unchanged with increases in cartridge resistance.

The parameters of sex, height, and weight could not be used to predict inspiratory pressure or flow rate. These parameters did not correlate well with the observed internal mask inspiratory pressure or inspiratory flow rate.

Based on the findings of this study, a model could be developed to allow precise selection of the test challenge
pressure for the quantitative negative pressure respirator fit test. The technique is based on a controlled negative pressure and directly measures the leakage flow rate of air into a temporarily sealed respirator. During the fit test, the respirator's internal pressure is held at a constant negative pressure representative of inspiratory pressure inside the mask under normal use. The negative pressure acts as a driving force for airflow through leakage paths into the respirator. An appropriate challenge pressure must be selected prior to fit test execution. Thus, the precise selection of the test challenge pressure at various levels of work load, cartridge resistance, and different mask types would allow determination of respirator fit over a wide range of work conditions.

The exhaust flow rate required to sustain a given level of negative pressure in the sealed respirator is a direct measure of the leakage rate into the mask. This leakage flow rate is then divided into a theoretical average inspiratory flow rate to determine the ratio of air which enters the respirator via leakage path during each breath. This resultant ratio is the fit factor. Therefore, the mean inspiratory flow rates determined in this study can be used to translate measured leakage flow rates into respirator fit factors.
APPENDIX A

Screening Health History

Name______________________________ Age______ Sex _____
Height ________ Weight ____________

1) SMOKER: YES____ NO____
   (If yes, packs per day ____)
   (If quit, years ago_______)

2) HISTORY OF LUNG PROBLEMS: YES____ NO____
   (asthma, emphysema, COPD)

3) HISTORY OF HEART DISEASE: YES____ NO____
   (If yes, specify: ________________________________
   ________________________________)

4) HISTORY OF HYPERTENSION: YES____ NO____

5) PLEASE LIST ANY MEDICATIONS YOU ARE CURRENTLY TAKING: 


6) DO YOU DRINK TEA, COFFEE, OR ALCOHOL? YES____ NO____
   If yes, Do you now...
   ( ) Drink coffee
       _______ cups/day
   ( ) Drink tea
       _______ Cups/day
   ( ) Drink Beer
       _______ Cans/week (12oz)
   ( ) Drink wine
       _______ oz/week
   ( ) Drink alcohol
       _______ oz/week (1 shot=1 oz)

7) IF FEMALE, ARE YOU PREGNANT? YES____ NO____

8) ARE YOU DOING EXERCISES ON A REGULAR BASIS? YES____
   (If yes, specify: ________________________________)
   NO____
APPENDIX B

Test Protocol for Negative Pressure System
(Murphy, 1989)

Test Administrator:

- Replaces respirator's cartridges with manifolds
- Connects sampling lines from manifolds to system
- Selects desired test pressure (-0.5" or -1.1" w.g.)

Subject:

- Dons respirator
- Holds his breath
- Plugs breathing port

System:

- Generates and sustains test pressure within facepiece
- Records leakage flow rates at test pressure
- Ends test when subject unplugs breathing port
APPENDIX C
Normal Value Nomogram for Males
(Ruppel, 1986)

Spirometric standards for normal males (BTPS)

To use nomogram:
Lay a straightedge between the subject's height as read on the height scale, and
his age as it appears on the age scale.

\[
\text{FVC, L} = 0.148 H_m - 0.025 A - 4.241 [0.65 0.74]
\]
\[
\text{FEF}_{25-75\%}, L/sec = 0.047 H_m - 0.045 A + 2.513 [0.53 1.12]
\]
\[
\text{FEF}_{200-1200}, L/sec = 0.109 H_m - 0.047 A + 2.010 [0.44 1.66]
\]
APPENDIX D

Normal Value Nomogram for Females (Ruppel, 1986)

Spirometric standards for normal females (BTPS)

To use nomogram:
Lay a straightedge between the subject's height as read on the height scale, and
her age as it appears on the age scale.

Females

\[ \text{FEF}_{200-1200} = 0.145 \text{ H}_{\text{in}} - 0.036 \text{ A} - 2.532 \quad [0.53 \ 1.19] \]

\[ \text{FEF}_{25\% - 75\%} = 0.060 \text{ H}_{\text{in}} - 0.030 \text{ A} + 0.551 \quad [0.56 \ 0.80] \]

\[ \text{FEV}_{1.0 \text{ sec}} = 0.089 \text{ H}_{\text{in}} - 0.025 \text{ A} - 1.932 \quad [0.73 \ 0.47] \]

\[ \text{FVC} = 0.115 \text{ H}_{\text{in}} - 0.024 \text{ A} - 2.852 \quad [0.71 \ 0.52] \]
SELECTED BIBLIOGRAPHY


Code of Fedederal Regulations, Title 29, part 1910. 134, Section (e) (5).


