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INTRODUCTION

Many studies have been done on the effects of respirator masks on exercise time (Caretti and Whitley, 1998; Coyne and Johnson, 2000; Harber, et al., 1982; Johnson and Berlin, 1973; Johnson, et al., 1995; Johnson, et al, 1999; Sulotto, et al., 1993). Some of these have included varied resistances to inhalation or exhalation (Caretti and Whitley, 1998; Harber, et al., 1982; Johnson and Berlin, 1973; Johnson, et al., 1995; Johnson, et al, 1999). It has been shown that the length of work time is shorter and the accomplished work rate is lower while wearing a respirator mask. Increasing the resistance to inhalation or exhalation further decreases the work time and work rate (Coyne and Johnson, 2000). These effects, however, vary with different individuals.

It is possible that the difference in results among individual subjects is a function of fitness, athletic ability, or general health. An additional factor, however, could be facial configuration. If different facial configurations cause a variance in the resistance inside a respirator mask, this could have an effect on the amount of time and the rate at which one could perform work while wearing such a mask.

The proposed study would take a group of subjects with a large spectrum of measurements in certain facial characteristics and ask them to breathe deeply while wearing a respirator mask. The characteristics to be noted are head length, head depth, bizygomatic breadth, lip length, and menton-sellion length. Resistance to inhalation or exhalation will be varied in each of the trials. The data collected will be analyzed for possible correlations between facial characteristics and resistance.

As it has been found that long, thin facial structures tend to cause more turbulent airflow, and thus more resistance inside a respirator mask (Johnson, et al., 1973), it is surmised that the proposed study will find longer menton-sellion lengths, coupled with shorter bizygomatic breadths to have significant correlations to breathing resistance in the mask. Shorter lip lengths are also expected to have a significant effect, as they might allow more air to bypass the mouth and flow into crevices in the mask, which will also create turbulence (Johnson and Cummings, 1975).

LITERATURE REVIEW

Background

In order to complete this project design, it was necessary to have an understanding of all factors involved. It was important to be familiar with the Occupational Safety and Health Administration's (OSHA) standards for respirator use and the conditions under which respirator use is accepted by the workers in any applicable industry. Two factors that affect such acceptance are comfort of the mask and ease of breathing while working in a mask. A thorough understanding of the configuration of the M40 full-facepiece, air-purifying, respirator mask and the way it functions was therefore also necessary.

A related topic, of equal importance, was the resistance inside the respirator masks and the effect that differing resistances may have on work quality and the endurance of workers wearing the respirator masks. Many studies have been done on various levels of work and different environmental factors under which workers may have to perform while wearing a respirator (Johnson, et al., 1995; Johnson and Berlin, 1973; Johnson, et al., 1973; Sulotto, et al., 1993; Stark, et al., 1988; Johnson and Cummings, 1975). The effects of the respirator on the flow of air have been briefly addressed (Johnson and Cummings, 1975; Johnson, et al., 1973), along with the dead space inside a respirator mask (Hinds and Bellin, 1993; Harber, et al., 1982; Johnson, et al., 1992). Anxiety levels of subjects, with and without respirator masks, have also been discussed (Caretti and Whitley, 1998; Johnson, et al., 1995; Johnson, et al., 1992).

The facial configurations to be examined were not chosen arbitrarily, but were carefully selected based on a review of prior studies concerning fit factors of respirator masks (Liau, et al., 1982; Leigh, 1975; Oestenstad and Perkins, 1992) and on military studies that deemed certain measurements more useful than others for determining mask facepiece sizing (McConville and Churchill, 1976). In addition, conversations were held with David Carretti, who has performed many studies on respirator masks for the United States Army Engineering and Research Edgewood Chemical Biological Center. It was under the guidance of Mr. Carretti that the five facial characteristics (these are head length, lip length, bizygomatic breadth, menton-sellion length, and depth of face) were chosen.

Subjects with facial hair were not included in this experiment design. Several studies (Hyatt, et al., 1973; Skretvedt and Loschiavo, 1984) have shown that facial hair has an inhibiting effect on the seal of the respirator mask around the outside of the face. This allows for air to flow around the face seal of the mask; therefore, results of the study would be skewed if individuals with facial hair were permitted to participate.

It was also very important to understand the respiratory system and methods of measuring respiratory factors such as airways resistance and forced expiratory volume. Literature was reviewed on the respiratory system itself, spirometers, plethysmographs, and the Airflow Perturbation Device, which was developed recently for measuring respiratory resistance (Lausted and Johnson, 1999).

The Respiratory System

In concept, the respiratory system seems simple enough -- oxygen is inspired and carbon dioxide is expired. This is the way in which life is sustained.

In reality, respiration is carried out by a complex system containing many components that perform many intricate activities. A full, detailed, description of the respiratory system is not within the scope of this thesis; however, a basic explanation will add to the understanding of the need for respirator masks in some situations.

The organs that compose this system include the nose, pharynx, larynx, trachea, bronchi, smaller bronchial branches, and the lungs. Terminal air sacs, called alveoli, reside in the lungs (Marieb, 1997). Air is brought into the body through the nose or mouth. As the air turbulently passes through the nasal cavity, inhaled dust, dirt, and other particles are trapped on the mucus-coated surfaces and prevented from reaching the lungs (Marieb, 1997).

The pharynx is the organ commonly referred to as the throat. It is a muscular passageway, about 13 cm in length, that extends from the back of the nasal cavity to the top of the larynx. Both food and air travel through the pharynx. Food is directed into the esophagus, while the air is directed into the larynx. Once past the larynx, the air enters the trachea, considered the main conducting tube (Mines, 1981). After about 10-12 centimeters, the trachea splits into the right and left primary bronchi. As the air travels through the pharynx, trachea, and primary bronchi, it is in the process of being warmed, humidified, and purified (Marieb, 1997).

The primary bronchi further divide into two more tubes, which in turn divide. This pattern continues for about 20-23 divisions, which results in 1-8 million terminal tubes called bronchioles (Mines, 1981). At the ends of the bronchioles are the alveoli, where gas exchange occurs between the air and blood. The average human lung system contains about 300 million alveoli, and each alveolus has a diameter of 75-300 micrometers. This means the total surface area available for gas exchange is about 70 square meters (Mines, 1981). In the average healthy human, the thickness of the alveolar wall is a small fraction of a micron. This makes it easy for gas diffusion to occur (Mines, 1981).

Since carbon dioxide is continually diffusing into the alveoli from the blood while oxygen is continually leaving the lungs enroute to other areas of the body, the alveoli contain a higher percentage of carbon dioxide - approximately 5.5% - and a lower percentage of oxygen - approximately 14.5% - than the air entering the trachea. The average pressure of oxygen in the alveoli is 103 mm Hg, and that of carbon dioxide is 39 mm Hg (McArdle, et al., 1996). This pressure for oxygen is much greater than the pressure of oxygen in the venous blood that enters the pulmonary capillaries (this is the blood that has come from the tissue cells). Oxygen thus diffuses into the venous blood from the alveoli, since gases have a tendency to move from areas of higher pressure to those of lower pressure. The opposite effect happens for carbon dioxide. The higher pressure of CO_2 in the venous blood causes this gas to be transported into the alveoli. In both cases, diffusion occurs until equilibrium is reached between the partial pressure in the alveoli and the partial pressure in the venous blood (McArdle, et al., 1996). Of course, the blood is continually flowing, so this process is virtually continuous. Much of the carbon dioxide that enters the alveoli subsequently leaves the lungs during expiration (Marieb, 1997).

The chest cavity is lined with a membrane called the parietal pleura, while the lungs are encased in a similar membrane called the visceral pleura (Mines, 1981). The *pleural fluid* is a thin, slippery secretion that allows the lungs to glide easily over the wall of the thorax, while also causing the parietal and visceral pleuras to cling together. During breathing movements, the lungs are held tightly to the thorax wall (Marieb, 1997). Therefore, the lungs and chest wall expand to the same volume during inhalation and decrease by the same volume during exhalation (Mines, 1981).

The basic muscles used in inspiration are the diaphragm and the external intercostal muscles. As the diaphragm contracts, it flattens out, which causes the thoracic cavity to increase in volume. Simultaneously, the external intercostals cause the rib cage to pull outward, which further increases this space. Due to the increased volume, the air pressure inside the thoracic cavity is reduced below that of the outside air. This pressure differential causes air to be drawn into the lungs (air tends to flow from from areas of higher pressure to those of lower pressure) (Marieb, 1997).

During rest, expiration is a passive process. The diaphagm and intercostals relax, thus reducing the volume of the thoracic cavity and causing higher air pressure in the lungs. In this way, air is forced out of that space, into the atmosphere, where the pressure is now less than that in the lungs (Marieb, 1997). During exercise, expiration can become active. The abdominal muscles contract, forcing the diaphragm upward, which further reduces the volume of the thoracic cavity and increases the pressure within (Mines, 1981).

There are various different values for lung volume that are of interest. Tidal Volume, TV, is the amount of air inspired or expired during a normal breath. Normal values of TV, while the subject is at rest, are 600 ml for men and 500 ml for women (McArdle, et al., 1996). Total Lung Capacity, TLC, is the maximum volume of air that the lungs can contain when a subject inspires as much as possible. TLC is generally about 6000 ml in men and 4200 ml in women (McArdle, et al., 1996). When a subject exhales as much air as possible (the starting point is TLC), the amount of air expelled is the Vital Capacity, VC (this is also referred to as Forced Vital Capacity, FVC). Forced expiratory volume (FEV_1) is the percentage of FVC that can be expired in one second. The Residual Volume, RV, is the amount of air that cannot be exhaled. The RV helps to keep the alveoli inflated, and allows for continuous gas exchange between the alveoli and the blood, even between breaths. RV is typically around 1200 ml in men and 1000 ml in women, and FVC is about 4800 ml in men and 3200 ml in women (McArdle, et al., 1996). Functional Residual Capacity, FRC, is the amount of air remaining in the lungs after a subject expires his Tidal Volume while at rest. This is about 2400 ml in men and 1800 ml in women, or about 40% of an individual's TLC (McArdle, et al., 1996). If a subject exhales normally, then inhales as much air as possible, he inhales his Inspiratory Capacity, IC. If he inhales his Tidal Volume, then inhales as much more air as possible, the excess air inhaled is his Inspiratory Reserve Volume, IRV. Typical values for IC are 3600 ml for men and 2400 ml for women, while IRV values are 3000 ml and 1900 ml, respectively. The final volume of note is the Expiratory Reserve Volume, ERV, which is the maximum amount of air that can be expired after the subject has already exhaled his Tidal Volume. Typical values are 1200 ml for men and 800 ml for women (McArdle, et al., 1996).

Measuring Respiratory Factors

Forced vital capacity (FVC) and the forced expiratory volume in one second (FEV_1) are two common measurements made with a device called a spirometer. The spirometer used in the proposed study is the WinPFT-2001^{TM} Spirometer by Diagnostic Monitoring (Santa Ana, CA). This spirometer can also calculate many other respiratory factors, including maximum voluntary ventilation (MVV), slow vital capacity (SVC), peak expiratory flow rate (PEFR), and respiratory rate (RR), among others. The WinPFT-2001^{TM} uses a pneumotachometer to measure flow, and the volume is found by flow integration. The pneumotachometer is a device that provides a small amount of resistance to the airflow, using fine mesh screens. This converts the airflow into a differential pressure, which can be converted into a voltage by a pressure transducer (Covox, 2001). The electrical signal produced in this way is proportional to the airflow, and is translated by the Spirometer computer program. During a spirometry test, the subject must blow as fast and as hard as possible into the tube connected to the spirometer. The researcher requires the subject to wear a nose clip during this procedure. Often, the spirometric test is completed three or more times. The computer presents values and graphs for FVC and the other factors mentioned. The two best values for FVC are generally within 5% of each other (Teresinski and Cheremisinoff, 1983).

Before the computerized spirometer was developed, this device consisted of an upside-down water-sealed can called a bell. When the subject breathed into and out of the tube connected to this bell, a pen would trace his breathing movements on paper. The gas in the spirometer would be at Ambient Temperature and Pressure, Saturated (ATPS) and the gas in the lungs of the subject would be at Body Temperature and Pressure, Saturated (BTPS), so the equation required to find the lung volume would be

$$V_2 = (P_1V_1T_2) / (T_1P_2) \tag{1}$$

where V_2 is the lung volume, V_1 is the gas volume recorded by the spirometer, T_1 is the spirometer temperature, T_2 is the body temperature, P_1 is pressure in the spirometer (this is barometric pressure minus the vapor pressure of water at T_1), and P_2 is pressure in the lungs (this is barometric pressure minus the vapor pressure of water at T_2) (Mines, 1981).

A plethysmograph can be used to determine the total Thoracic Gas Volume (TGV). This device uses Boyle's Law (Mines, 1981):

$$P_1V_1 = P_2V_2 \tag{2}$$

As the subject sits in an airtight box and breathes the outside air through a tube, a pressure gauge records the pressure in the tube. If there is no flow of gas through the tube, this pressure will be equal to the alveolar pressure. A spirometer records the lung volume, as the lungs expand and displace air into the spirometer. Once the initial values of pressure and volume are recorded, the airway is closed, so that the subject is trying to breathe against an occluded airway. Changes in pressure (ΔP) and volume (ΔV) are then recorded, and TGV is calculated with the equation

$$V = (\Delta V)P / \Delta P \qquad (3)$$

Once again, the pressure used is barometric pressure minus the vapor pressure of water (Mines, 1981).

Respiratory airways resistance can now be measured by a relatively new innovation called the Airflow Perturbation Device (APD) (Johnson, et al., 1984). Although airways resistance can also be measured by the plethysmograph, the APD is quicker, easier, and much more portable. This device has been found to measure not only airways resistance, but lung tissue and chest wall resistance, as well. These three values together are considered "respiratory resistance" (Lausted and Johnson, 1999). The Airflow Perturbation Device consists of a pneumotachograph with differential pressure transducer, to measure airflow as the subject breathes normally into a small tube. As described by Lausted and Johnson (1999), "A small hole in the proximal flange of the pneumotachograph serves as a mouth pressure tap." As the subject breathes into the device, the air flows through a rotating wire screen on a motor-driven wheel that causes perturbations, or resistance to the airflow and pressure (the airflow decreases and the mouth pressure increases). The wheel is divided into four segments, only two of which are screened. Thus, the perturbations occur twice for each rotation of the wheel (Lausted and Johnson, 1999). The perturbation frequency is about 6 Hz. The pressure and flow perturbations form a set of rotating vectors with both in-phase and out-of-phase components. Respiratory resistance is found using only the in-phase component. It is the ratio of the magnitude of pressure perturbation to the magnitude of flow perturbation (Johnson, et al., 1984). A data acquisition computer records the measurements, using software in Visual Basic for Applications (Lausted and Johnson, 1999).

Transducers

There are many different types of transducers. All of the transducers used by the equipment in this proposed study are variable reluctance pressure transducers. The term "reluctance" refers to the reluctance of a magnetic path, in the form of an air gap between two coils. There is a core, or diaphragm, between the coils. When this diaphragm is in a neutral position, the air gap is the same on both sides. This causes the magnetic flux to be the same on both sides. Differential pressure, e.g. from a pneumotach, will cause the diaphragm to move toward the side with lower pressure. The reluctance on that side decreases, while the reluctance on the other side increases. As the coils are connected into an alternating current (AC) bridge circuit, a net output voltage is created by the motion of the diaphragm (Doebelin, 1990).

Health Hazards Caused by Inhalants

The smooth, biological process of respiration can be upset in many different ways. This paper is mainly concerned with the effects of inhalants, or airborne pathogens. Inhalation is the most frequent way in which the human body takes in foreign matter. It is also the most significant way, as the lungs have a very large surface area with which to contact the toxic material, and a very large volume of air passes through the lungs during the work day (Ruch and Held, 1975).

Airborne pathogens can be formed by liquids or solids. Liquid particles, often produced by atomization or condensation, can be in mists (these are larger particles) or fogs (these are the smaller particles). Solids are categorized as dust, fumes, or smokes. Mechanical processes such as crushing, grinding, or drilling produce dusts from solid materials. Dust particles can range in size from visible to submicroscopic. Fumes are usually formed from metal oxides in processes such as combustion, sublimation, and condensation. Smokes are formed from combustion of organic materials (Ruch and Held, 1975). Aerosols consist of a suspension of very fine solid or liquid particles that remain suspended in the atmosphere for a very long time. These can also be composed of very fine fibers (Wang, 1993). Although fibrous materials such as asbestos sometimes enter the alveoli, most dust particles must be smaller than five microns, in order to enter these small lung components (Ruch and Held, 1975).

The inhalation of foreign matter may cause some substances to get trapped within the respiratory system, while others can find their way into the blood, gastrointestinal tract, or lymphatic system (Teresinski and Cheremisinoff, 1983). Breathing patterns can determine the amount of particle deposition within the body. During quiet breathing, when the body is at rest, a large proportion of the inhaled particles may leave the body during exhalation. When the body is working harder, and larger volumes of air are being inhaled at relatively high velocities, the rate of deposition of foreign matter may increase (Rajhans and Blackwell, 1985).

There are eight basic types of responses to the inhalation of foreign matter: behavioral (e.g. oxygen deficiencies can cause loss of perception or mercury can cause emotional problems), biochemical (e.g. organophosphorous insecticides can cause nerve tremors), carcinogenic (e.g. vinyl chloride can cause cancer of the liver), mutagenic (e.g. DNA and gene changes in infants can occur), pathological (e.g. silica can cause deformities in lung tissue), physiological (e.g. ammonia gas can cause decreased pulmonary function), reproductive (e.g. cadmium affects the reproductive organs and their ability to function properly), and teratogenic (e.g. thalidomide can cause damage to a developing offspring in a pregnant female) (Teresinski and Cheremisinoff, 1983).

Of the possible effects of foreign substances in the body, death is the most serious. Asphyxia, or lack of oxygen, is a common cause of immediate death. A related phenomenon, chemical asphyxia, is caused by carbon monoxide atoms attaching themselves to hemoglobin, which normally carries oxygen through the blood. With the hemoglobin otherwise occupied, the oxygen has no way of being transported to the tissues and organs of the body. Air contaminants that cause asphyxia are grouped under the classification "oxygen deficiency" (Ruch and Held, 1975).

Other responses to inhaled particulate matter involve dysfunction of an organ or system of the body. Contaminants causing these ailments are mostly of the type "toxic and nuisance atmospheres" (Ruch and Held, 1975). The liver and kidneys can be affected by substances in the blood. They tend to extract foreign materials, and the liver may metabolize them. Chemicals such as DDT can be found in human fatty tissues, and most of the lead taken into the body may be found in the skeleton (Teresinski and Cheremisinoff, 1983).

Substances that are either acidic or alkaline can irritate the lining of the respiratory tract. If materials are soluble in the blood, they are easily removed from the body. Those that do not dissolve become trapped in the respiratory system and cause problems (Teresinski and Cheremisinoff, 1983). One such problem, produced by the welding of aluminum, is that the dust from the aluminum causes decreased elasticity in the walls of the alveoli. Breathing then requires more effort. Another problem occurs when inhaled dust or fibers become lodged in the lungs - a condition referred to as pneumoconiosis. Black lung, which is caused by coal dust, is a form of pneumoconiosis. Silicosis is another type. Silica particles get lodged in the lung, and the phagocytes (these are cells of the natural protective system of the lungs) try to engulf them. These phagocytes are destroyed by the silica, but other phagocytes form layer-nodules within the lung. Asbestosis is another lung disease caused by inhaled fibers (Teresinski and Cheremisinoff, 1983). These are just a few of the ailments that can be caused by airborne contaminants in the workplace.

OSHA / Regulations for Safety in the Workplace

Federal regulations do exist, to protect employees from health hazards in the workplace. In January of 1969, Congressman James O'Hara introduced an "Occupational Safety and Health" bill into the House of Representatives. The following year, the Senate and the Executive Branch of Congress each introduced their own versions of such a bill. On December 29, 1970, The Occupational Safety and Health (OSH) Act was signed into law by President Richard Nixon. About four months after the signing, the OSH Act of 1970, also referred to as the Williams-Steiger Act, took effect (Wang, 1993).

The OSH Act was written in broad terms, to cover any business that employs one or more persons and any business activity that mush be accomplished through an employee. The entity that was created to enforce the OSH Act is called the Occupational Safety and Health Administration (OSHA). OSHA functions as an administrative agency within the Executive Branch of the federal government (it is specifically within the Department of Labor). It also has status as an "expert agency", meaning it was acknowledged that Congress alone did not have the means and the expertise to deal with hazards in the workplace, and therefore needed a group of specialists to develop and enforce standards and regulations. Compliance and Health Officers (CSHO's) from OSHA regularly travel to different businesses to inspect for safety and health violations. If any are found, the CSHO's have the authority to initiate penalty proceedings against the offending employers (Wang, 1993).

There are a few types of workplaces that are not regulated by OSHA. These include self-employed individuals with no employees, farms with no employees except immediate family members, workplaces already protected under other federal agencies, airlines, atomic and nuclear operations, and operations controlled by the United States Coast Guard. The Environmental Protection Agency (EPA) regulates some non-employee situations, which are also exempt from OSHA's jurisdiction (Wang, 1993). The Mine Safety and Health Administration (MSHA) inspects all mining activities in the United States, so these also do not fall under OSHA regulations. In addition, government employees are exempt from OSHA coverage; however similar standards have been adopted for occupational health and safety in some states, and all government employers are required to protect the health of their employees in some way (Wang, 1993).

The National Institute for Occupational Safety and Health (NIOSH) is another agency that was created by the OSH Act of 1970. It has several functions in common with OSHA, including research and innovation in controlling safety and health hazards and the creation of training programs to educate employers and employees on occupational safety and health. Research and training are the main functions of NIOSH. As such, it has no enforcement powers; although it has some limited power to investigate complaints and issue subpoenas (Wang, 1993).

Many of the standards enforced by OSHA and its sister agencies are adopted from various private or non-governmental organizations. Many of the safety standards come from the American National Standards Institute (ANSI), and many of the health standards come from the American Conference of Governmental Industrial Hygienists (ACGIH). In 1968, the ACGIH published a list of Threshold Limit Values (TLV's). These values were based on the concept of a maximum safe exposure level to airborne contaminants on a daily, forty hour week basis (Wang, 1993). An example of the use of TLV's, given by Ruch and Held (1975) is as follows:

> "Assuming that an employee is exposed to a solvent with
> a TLV of 100 ppm and his exposure consists of one hour
> at a concentration of 250 ppm, four hours at 200 ppm and
> three hours at 100 ppm,
> [(1 hr)(250) + (4 hr)(200) + (3 hr)(100)] / 8 hr = 169 ppm
> This is above the TLV of 100 ppm, and therefore in violation
> of the standard for that material."

The TLV's have been tested and updated on an annual basis. OSHA has adopted these TLV's in their standards, under the title "Permissible Exposure Levels (PEL's)" (Wang, 1993). Some materials have a "ceiling" value, above which the concentration should never be allowed to go. Others may temporarily go above the threshold values, as long as the eight-hour average remains below it (Ruch and Held, 1975).

OSHA mandates that employers attempt to control workplace hazards first by engineering controls. If these are unsuccessful, other methods should be attempted in the following order: administrative controls, work practices, personal protective equipment, or remedial controls (Wang, 1993).

Engineering controls are specially designed processes, materials, or equipment that are installed at or around the production process itself. If successful, these controls will prevent the hazard from entering the workplace and coming into contact with an employee. Administrative controls are non-engineering methods to reduce worker exposure to hazards. They may include worker scheduling and rotation, workplace monitoring, biomedical screening, and safety rules. Work practices are put into place by the employer, but are solely under control of the employee. They may include turning on ventilation systems, putting chemicals under hoods, or any other practice to ensure safety. Personal protective equipment is only used if the first three methods fail to keep hazards out of the workplace (Wang, 1993). This includes any equipment worn by the worker to shield the body from harmful substances. Respirator masks - the element with which the proposed study is concerned - are included in this category. Remedial controls are used only after a hazard has already occurred in the workplace. These may include eyewashes, fire-fighting systems, decontamination, and many other practices (Wang, 1993).

Respirator Masks

Respirator masks are designed to protect individuals from breathing harmful substances. There are two basic types of respirators. An air-supplying respirator provides clean air for the wearer to breathe. The ambient air is kept away from the face by various means, depending on the type of device. Usually, the air being supplied to the respirator has a pressure greater than that of the ambient air, so air only flows out of the device (ambient air cannot flow into it). An air-purifying respirator removes particulate matter from the air before the same air reaches the face of the wearer (Revoir and Bien, 1997).

There are a few different types of oronasal coverings that serve to shield the wearer from the outside atmosphere. The two general categories of these are "loose-fitting" and "tight-fitting". Loose-fitting coverings are generally used with air-supplying respirators. They may cover anything from part of the head, to the whole body. A flexible hose is generally connected to the covering somewhere near the face, with the other end connected to the air-supplying element (Revoir and Bien, 1997).

Tight-fitting coverings are referred to as "facepieces". They are designed to make a tight seal on the wearer's face. Different varieties of these include full-facepiece, which covers the eyes, nose, and mouth, and usually extends from the hairline to below the chin; half-mask facepiece, which covers the nose and mouth, and seals beneath the chin; and quarter-mask facepiece, which covers the nose and mouth, and seals between the mouth and chin. Masks with tight-fitting oronasal coverings are usually of the air-purifying type, and are usually made of a molded flexible elastomer. There are also disposable types of half-mask respirators, which are made of fabric that is designed to protect against particulate matter. Another type of tight-fitting covering, which is only used for emergency escape situations, consists only of a nose clamp and a mouthpiece, which is held between the teeth while the lips make a tight seal around it (Revoir and Bien, 1997).

The proposed study is only concerned with air-purifying respirators. These can come in the powered or nonpowered varieties. Each of these two varieties can come in one of three types: particle-removing, gas-vapor-removing, or combination particle-gas-vapor-removing (Revoir and Bien, 1997). The facepieces on each of these contain an exhaust valve with an exhaust valve cover. Upon exhalation, the exhaust valve opens to allow exhaled air to exit the facepiece. As exhalation ends and inhalation begins, the exhaust valve closes instantly, to prevent contaminated air from entering the mask through this port. A small amount of uncontaminated air always get trapped between the exhaust valve and its cover. This air gets drawn back into the mask as inhalation begins, while the exhaust valve is properly sealing. The facepiece also has one or two air inlets with valves that prevent the exhaled air from escaping via these routes. The inlet air enters through cartridges or canisters containing particulate filters, chemical sorbents, or a combination of these (Ruch and Held, 1975).

Gas or vapor removing respirator masks contain a chemical cartridge that is specifically made to absorb particular types of vapors or gases. These must be approved by NIOSH and labelled correctly with the type of atmosphere against which it protects and the maximum concentration of gas or vapor in which it may be used. Chemical cartridges become less efficient as they become saturated, so they are made for one-time use only (Ruch and Held, 1975).

Particle removing respirator masks use a mechanical filter that traps particles before they can enter the mask. The filters are generally made of a fibrous material through which the particles cannot pass. A high-efficiency (HEPA) type filter can remove 99.97% of particles that are 0.3 microns or larger in size. As a point of comparison, the average human hair is about 50 microns in diameter (Ruch and Held, 1975).

With the powered type of air-purifying devices, a battery-powered blowing device pulls the contaminated air through the filter or chemical cartridge. The clean air then enters the facepiece. One advantage of this device is that it puts the facepiece under positive pressure with respect to the outside atmosphere. In this way, air cannot enter through leaks in the mask. With the non-powered respirator masks, the air inside the mask is under negative pressure when the wearer inhales. If any leaks are present in the mask, outside air can easily be drawn in (Ruch and Held, 1975). The mask to be used in the proposed study is an M40, negative pressure, air-purifying, non-powered, full-facepiece respirator.

Air Filters

Air-purifying respirator masks utilize filters to remove particles from the air. These filters are generally made of fibrous materials, to which particulate matter adheres because of intermolecular forces of attraction known as Van der Waals forces. The filter must allow enough airflow for the wearer to be able to breathe, and it must not get clogged as particles adhere to it. Therefore, it cannot be designed simply as a sieve, which removes particles that are larger than the spaces between the particles. Instead, the fibers in the filter create a sort of maze, and the Van der Waals forces cause particles to adhere to the maze without necessarily being lodged in the open spaces (Revoir and Bien, 1997). An extensive discussion of chemistry would be required to fully explain Van der Waals forces, but a brief explanation will be attempted. Although the average distribution of charge on a nonpolar molecule - such as the molecules in our filters or in the particulate matter - over a period of time is uniform, electrons have the ability to move. If, at a particular instant, the electrons have accumulated at one side of the molecule, a small dipole will occur. This dipole can cause opposite dipoles to occur in adjacent molecules, as the negative charge on the first molecule attracts the positive charges on the second molecule (Solomons, 1996). Thus, the two molecules adhere to one another.

There are various ways in which the particles come to collide with the fibrous material before they are held there by the Van der Waals forces. The characteristics of the particles that affect mode of deposition include size, shape, density, and electrical charge. Significant characteristics of the filter include fiber diameter, density of the medium, thickness of the medium, and electrical nature of the fibers (Revior and Bien, 1997).

Larger particles may fall out of the general stream of airflow, due to gravity or inertia, and settle on the fibrous medium. As particle size decreases to around one micrometer, the frequency of this method of deposition decreases greatly. Impaction is the process in which a particle that is moving in a curved path around a fiber is affected by a centrifugal force that causes the particle to move in a less curved path and possibly collide with another fiber. The Van der Waals forces then keep it attached to the fiber. Particles affected by impaction are also greater than one micrometer in size (Revior and Bien, 1997). Very small particles in the air may be affected by Brownian motion. This means the particles move very erratically, due to being constantly bumped by molecules of air, which are also moving randomly (Serway, 1992). The erratic motion of the particles may cause them to collide with and be attracted by the fibers in the filter. If there are very large particles in the air, they may be caught in the filter by the action of sieving, which means they are too large to fit through the holes in the fiber network. Sieving is an undesired effect, as it causes large resistances to air flowing through the filter. Filters are usually designed to avoid this effect. Some filters are designed to take advantage of electrostatic attraction. They may contain negatively charged granules, which attract positively charged particles, and positively charged fibers, which attract negatively charged particles (Revoir and Bien, 1997).

In designing a filter, it is necessary to determine the most effective ratio of small fibers and large fibers. Expected air velocity may be a factor, since small particles are trapped more readily at low air velocities (there is more time for diffusion to occur), and large particles are trapped more readily at higher air velocities, due to increased centrifugal force. Small diameter fibers are most effective for removing all particles; however, they must be very closely spaced, and the deposition of large numbers of particles may close the spaces and cause large resistances to airflow. If the smaller fibers are dispersed within an open lattice network of large fibers, this problem may be avoided. Some complex filters contain a layer of large fibers to remove the larger particles, followed by a layer of smaller, more densely packed, fibers to remove smaller particles. This prolongs the effect of increasing resistance to airflow as more particles are deposited in the filter. As large particles get trapped in the outer layer, there is still enough space between them to allow air, as well as small particles, through. In any type of filter, however, there will be increasing resistance to airflow as more particles are deposited (Revior and Bien, 1997).

Air Flow and Dead Space Inside a Respirator Mask

Air flow

Fluid flow can be laminar or turbulent. In laminar flow, all fluid particles move in a straight line, in the same direction, and the particles in each line generally do not move into other streamlines. That is, there is no mixing. The velocity profile for laminar flow is generally parabolic, with fluid particles near the sides of the chamber flowing more slowly than those in the center lines of flow (Johnson, 1999). In turbulent flow, the fluid particles move in more random directions, with much crossing of paths. This type of flow causes more energy dissipation and heating of the fluid (Johnson, 1999). Although the fluid particles are not necessarily moving at the same rate, the net effect of turbulent flow is a velocity profile that is flat, or uniform (Johnson, 1999).

The Reynolds number (Re) is a good indicator of the conditions under which fluid flow changes from laminar to turbulent. This number is a measure of the ratio of inertial force to viscous force on an element of fluid (Munson, et al., 1998). The equation for the Reynolds number is

$$Re = (\rho VD)/\mu \quad (4)$$

where ρ is the fluid density, μ is the fluid viscosity, V is velocity, and D is the chamber diameter (Johnson, 1999). At Reynolds numbers much less than one, the density of the fluid is generally not important and it may be possible to neglect the effects of inertia. For large Reynolds numbers, viscosity may not have much effect, and inertia is the more important variable (Munson, et al., 1998). At Reynolds numbers of about two thousand, fluid flow starts to change from laminar to turbulent (Johnson, 1999).

One cause of the change from laminar to turbulent flow includes temperature changes near the bottom of a vessel, where fluid density becomes smaller near the source of the heat. Eventually the less dense fluid starts to rise, while the colder fluid sinks toward the bottom. This motion causes mixing of the fluid. As the temperature gradient increases further, the fluid motion becomes more and more chaotic, and the heat transfer rate is greatly increased (Munson, et al., 1998). This process may occur inside a respirator mask, as the warmer exhaled air meets the cooler air entering the mask. Depending upon the amount of space between the wall of the mask and the face of the wearer, the air particles inside the mask have sufficient volume in which to rise or fall, and thus cause mixing. Turbulence may also be caused by higher flow rates, or by corners and irregularities in the flow path (Johnson and Cummings, 1975). Johnson, et al. (1973) found that subjects with a long, thin facial structure were more likely than others to create turbulent flow within a respirator mask. It is possible that some facial characteristics may lead to further turbulence, by allowing the air to flow more freely into crevices in the mask. More airflow into the mask, instead of directly into the mouth or the exhalation valve might also provide for more movement of air in the heating and mixing process that creates turbulence. It is hypothesized that the proposed study will find that longer menton-sellion lengths, coupled with shorter bizygomatic breadths will cause more turbulent airflow, and thus more resistance inside the respirator mask. Shorter lip lengths might also have a significant effect, as they might allow more air to bypass the mouth.

The fluid continuity equation relates volume flow rate (Q) to average flow velocity (V) and cross-sectional area for flow (A) (Johnson, et al., 1973):

$$Q = VA \tag{5}$$

For laminar flow, the pressure drop in a horizontal pipe is directly proportional to flow rate. For turbulent flow, the pressure drop is proportional to flow rate raised to the n^{th} power, where n varies from 1.7 to 2.0 (Johnson, et al., 1973). This relationship can be modeled by the Rohrer equation:

$$P = k_1 V + k_2 V^2 \tag{6}$$

where P is pressure, V is flow, k_1 is a coefficient describing laminar flow, and k_2 is a coefficient describing turbulent flow (Johnson, 1991). Resistance then becomes

$$R = P/V = k_1 + k_2 V \tag{7}$$

where R is resistance, and other symbols are the same as in equation 6 (Johnson, 1991).

Dead Space

The volume of air that is inside the respirator mask, but external to the face of the wearer, is called “respirator dead space” (Hinds and Bellin, 1993). Not all of the air inhaled goes into the lungs, and not all of the air exhaled exits the respirator mask. Some of this air stays in the respirator dead space. In this way, some of the exhaled air is mixed with incoming filtered air and any aerosol or particles that penetrate the filter. The effect of this mixing process is that the concentration of aerosol or particles inhaled is reduced from what it would be if the dead space did not exist. The two factors that determine the average inhalation concentration are F_{dep}, which is the lung retention (this is the fraction of inhaled particles that get deposited in the respiratory system and are not exhaled), and V_{ds}/V_t, which is the ratio of the volume of the respirator dead space to the tidal volume of the wearer (Hinds and Bellin, 1993). Harber, et al. (1982) found that, during conditions of rest or light work, tidal volume tends to decrease due to filter resistance and increase due to dead space loading. Tidal volume could also increase when going from submaximal to maximal exercise. This means that the value of V_{ds}/V_t will not always be a static number.

Harber, et al. (1982) found that the effects of dead space in the respirator mask were threefold: they increased minute ventilation and respiratory rate, and they shortened respiratory time periods (although Johnson, et al. (2000) found that during heavy exercise there was no change in minute ventilation). Hinds and Bellin (1993) noted that these effects are largely due to the fact that the mask wearer is rebreathing a portion of the exhaled CO_2. They also found that the increase in tidal volume ranges from 50% to 90% of the respirator dead space volume.

Hinds and Bellin (1993) developed equations to model the flow and mixing of air as it travels from the filter to the respiratory system of the mask wearer. They modeled two possible cases – that of the flow through the dead space being well-mixed air and that of the flow being "plug flow" (this is where the dead space air gets pushed into the mouth by the incoming air, with no mixing of the two). The equation for the well-mixed case would be

$$C_F(V) = C_o P_F - (C_o P_F - C_I)e^{-V/V(ds)} \qquad (8)$$

Where $C_F(V)$ is the instantaneous concentration of aerosol in the respirator dead space, after a volume V has entered the respirator during an inhalation. C_o is the outside concentration; C_I is the initial concentration in the dead space at the beginning of the inhalation; P_F is the fractional penetration of aerosol through the filter; and V_{ds} is the volume of the respirator dead space.

The equation developed by Hinds and Bellin (1993) for plug flow is

$$C_F(V) = C_I + (C_oP_F - C_I)(V/V_{ds}), \tag{9}$$

for plug flow and $V <= V_{ds}$

$$C_F(V) = C_oP_F, \text{ for plug flow and } V > V_{ds} \tag{10}$$

By experimentation, Hinds and Bellin (1993) determined that the flow through the dead space is best approximated by the well-mixed model. They further concluded that, as dead space increases, the average aerosol concentration in the mask during exhalation increases and the average inhalation concentration decreases. A full-facepiece respirator mask has about 300 mL of dead space (Johnson, et al., 1992), although the M40 mask to be used in this study has a well-fitting nose cup that serves to reduce fogging in the face shield. This nose cup effectively separates inhalation and exhalation flow (when it fits the wearer well), creating a condition equivalent to a small dead space (Hinds and Bellin, 1993). Therefore, dead volume would have a much smaller effect on concentration of aerosols; and for the proposed study, it should have a minimal effect on respiratory rate.

Facial Configurations

While very few studies have specifically looked at facial features as they relate to the resistance inside a respirator mask, facial dimensions have always been of interest in studies involving mask fit factors. These studies can provide some insight into the range of anthropometric measurements in society as a whole. They also may provide some foreshadowing as to which facial characteristics may be found to influence mask factors most directly.

Liau, et al. (1982) took a sample of two hundred and forty-three civilian industrial workers who used respirator masks. They were primarily concerned with face length (this is also called menton-sellion length) and nasal root breadth; however, they also took five measurements from photographs of the subjects. These included face width (this is also called bizygomatic breadth), mouth width (this is also called lip length), nose protrusion, nose length, and chin length. The mean value found for face length was 11.25 centimeters, with a standard deviation of 0.80 centimeters. For bizygomatic breadth, they found a mean of 13.57 centimeters, with a standard deviation of 0.80 centimeters. The mean for mouth width was 5.62 centimeters with a standard deviation of 0.58 centimeters. The investigators in this study concluded that face width had the highest correlation with protection factors obtained from fit-testing of respirator masks. Mouth width had the second highest correlation.

In another respirator fit test study, done by Leigh (1975), the characteristics deemed important were lip length, face length, and face width. One thousand, three hundred and forty males, and one hundred and twenty-seven females were tested. Lip lengths ranged from 3.45 centimeters to 7.95 centimeters. Face length ranged from 8.35 centimeters to 14.35 centimeters. Face width ranged from 10.85 centimeters to 16.25 centimeters.

In 1976, McConville published a study in which he examined anthropometric features from as many military studies as he was able to find. The surveys he found were conducted over a period of twenty-five years. He attempted to do a detailed quantification of head and facial variability, although the surveys used were conducted by different individuals for different purposes and sometimes with different measuring techniques. Two principal sources of variability were ethnic origin and gender.

African-American males were found to differ from Caucasian males by as much as ten percent in nasal root breadth, nose breadth, and lip to lip length. They differed by at least five percent in biocular breadth, interpupillary breadth, interocular breadth, nose protrusion, lip length, ear protrusion, philtrum, and menton-subnasale length. Caucasian women differed from African-American women by at least ten percent in nose breadth and lip length. Another collection of data showed only minor deviations between ethnic subgroups of males and the total group mean. Deviations of more than two percent were seen in African-American interpupillary breadth, Puerto Rican and Spanish head length, and Japanese face breadth and head breadth.

The samples found by McConville (1976) also showed that, in comparison with males, females generally have smaller overall heads and faces with less pronounced features. The female measurements averaged about 92% of comparable male measurements, although there was much overlap between the smallest male faces and the largest female faces (this overlap ranged from 20% to 50%, depending on the feature).
Among all surveys studied by McConville, the range of measurements for head length was 18.2 to 21.8 centimeters for men, and 16.8 to 20 centimeters for women. Bizygomatic breadth ranged from 13 to 15.6 centimeters for men and 11.6 to 14.4 centimeters for women. Lip lengths were between 4.43 and 5.5 centimeters for men and 3.96 and 4.8 centimeters for women. Menton-sellion length ranged from 10.6 to 13.5 centimeters for men and 9.2 to 12.4 centimeters for women. Depth of face was not measured in this study, but by subtracting the mean values of "tragion to wall" from the mean values for "pronasale to wall", the mean face depth for subjects in this study can be approximated to 11.65 centimeters for men and 11.02 centimeters for women.

McConville (1976) also determined that most morphological traits in human populations are continuous and are distributed normally. The frequency of measured values, given a large sample size, for any one trait will approximate the bell-shaped distribution curve, with sixty-eight percent of the distribution about the mean within plus or minus one standard deviation. Therefore, the increase in variance for any one facial feature is relatively constant about the mean, but increases greatly at the tail ends of the distribution. It is impossible to design one respirator mask that would accommodate all values of variation within the distribution; however, designers can try to provide a mask that properly fits ninety to ninety-five percent of the population. Different sizing categories might also be established, based on sets of key variables that might be found through analysis of the correlations among all variables.

Oestenstad and Perkins (1992) also found that facial dimensions were good predictors of respirator fit. Their study only involved half-masks. Many facial features were found to be highly correlated with each other, so that it was not useful to have all features in the analysis. They primarily concentrated on the correlations between face length, face width, and lip length with fit factors for half-mask respirators.

For face width, the mean value for all subjects in the study by Oestenstad and Perkins was 13.5 centimeters with a standard deviation of 0.8 centimeters. This was broken down into a mean of 13.9 centimeters for males (the standard deviation was also 0.8 centimeters) and 12.9 centimeters for females (the standard deviation was 0.6 centimeters). The mean lip width was 4.9 centimeters for all subjects, with a standard deviation of 0.4 centimeters; 5.1 centimeters for males, with a standard deviation of 0.4 centimeters; and 4.8 centimeters for females, with a standard deviation of 0.3 centimeters. Menton-sellion length had a mean of 12.2 centimeters for all subjects, with a standard deviation of 0.7 centimeters; 12.6 centimeters for males, with a standard deviation of 0.7 centimeters; and 11.8 centimeters for females, with a standard deviation of 0.5 centimeters.

Of the factors analyzed by Oestenstad and Perkins (1992), menton-sellion length, lip width, and lower face length were found to have significant regression coefficients, indicating that they were reasonable predictors of fit for half-mask respirators. The most efficient model for using facial features to predict fit factors used menton-sellion length and lower face length together.

The current study will use five facial characteristics. These are head length, lip length, bizygomatic breadth, menton-sellion length, and depth of face. These are the characteristics currently deemed most useful by the United States Army for determining mask facepiece sizing (D. Caretti, United States Army Engineering and Research Edgewood Chemical Biological Center, personal communication, College Park, Maryland, 29 March 2001). Table 1 shows the minimum and maximum measurements in the general population for these five characteristics, determined from the studies summarized above.

Table 1. Population minimum and maximum measurements for facial characteristics

Characteristic	**Minimum**	**Maximum**
Head Length	16.8 cm	21.8 cm
Bizygomatic Breadth	10.85 cm	16.25 cm
Lip Length	3.45 cm	7.95 cm
Menton-sellion Length	8.35 cm	14.35 cm
Depth of Face	11.02 cm (mean for women)	11.65 cm (mean for men)

Effects of Respirator Masks on Work Quality and Endurance

Many studies have been done on the decrement in performance time caused by the use of respirator masks. A large percentage of this decrement is often due to the resistance to inhalation or the effect of resistance on exhalation time. Johnson, et al. (1995) did a study on the effects of respirator masks on exercise metabolic measures. They concluded that the inhalation resistance of the mask interferes with oxygen consumption and causes exercise metabolism to proceed more anaerobically than without a mask. This causes blood lactate to build up more quickly, which may cause an individual to terminate exercise sooner than they would, under normal conditions.

Several studies have found that, although the use of respirator masks does not appear to affect heart rate, it seems to be associated with a decreased respiratory frequency, an increased tidal volume, and a decreased minute volume (Johnson and Berlin, 1973; Sulotto, et al., 1993; Stark, et al., 1988). Johnson, et al. (1995) found these effects to differ according to the work rate; however, maximum oxygen deficit always occurred sooner with a mask than without a mask. In another study, Johnson, et al. (1999) tested subjects at constant work rates, with a wide variety of resistance levels. They found performance times to be inversely linearly related to the level of resistance. Johnson and Berlin (1973) also found an inverse linear relationship between distance run and mask resistance; although they also found this relationship between distance run and rise in rectal temperature.

Johnson, et al. (1973) demonstrated that, for laminar inhalation flow, the percentage of the respiratory cycle representing expiration is greater than in turbulent flow. This may be due to greater resistance, which is defined as pressure divided by flow. It has also been found that exhalation times become shorter with increasing work rates, and work is terminated as exhalation time diminishes to the limiting value for a particular individual (Johnson and Cummings, 1975). Therefore, turbulent flow can cause shorter work times for individuals wearing respirator masks.

Of the above-mentioned studies, only Johnson and Berlin (1973) mentioned the possible contribution of facial configuration to the external resistance. However, if it can be shown that certain facial characteristics cause conditions in which this resistance is augmented, this might provide mask designers with some valuable information for respirator mask sizing. It also might provide employers with some insight into what causes certain workers to be more uncomfortable in masks than others.

Anxiety Levels

In many studies, anxiety has been found to have an effect on breathing response, comfort level of the mask, and level of work performance. Caretti and Whitley (1998) found that, with higher inspiratory resistances imposed by the respirator mask, subject anxiety levels increased significantly following exercise at 80% of their maximal oxygen consumption. Lower exercise performance times appeared to be linked to both anxiety and breathing discomfort. Johnson, et al. (1995) noted that responsiveness to CO_2 is linked to anxiety, and thus breathing difficulties can ensue, if anxiety is caused by the state of the environment, the wearer, or the mask conditions. Johnson, et al. (1992) determined that emotional responses can lead to hyperventilation, tachycardia, and acute increases in circulatory levels of epinephrine - all of which may increase the burden of a respirator mask. In their efforts to create a rating table for factors that affect respirator performance, these authors also found that psychological factors become more important at lower work rates. This is largely due to the fact that work performed at lower rates is usually done for longer periods of time; therefore, the individual has a longer amount of time in which to be aware of the respirator mask and its effects, both real and imagined, on breathing.

In the 1995 study by Johnson, et al., the effect of anxiety on work performance was the main topic. The study used subjects with a wide range of anxiety levels, based on the state-trait anxiety test (Spielberger, et al., 1970). Using treadmill exercise adjusted to maintain a constant indicator of physiological stress, Johnson, et al. (1995) tried to determine how much reduction in performance was due to the anxiety level of the subject. Subjects were asked to exercise until they felt they had to stop. The investigators reported a clear downward trend in performance times as anxiety levels increased above a score of 30 on the anxiety test. Average anxiety scores were low, for those subjects who exercised for longer amounts of time. It was also noted that those subjects with higher anxiety scores were the ones who were more likely to experience discomfort in the mask or to complain about not being able to breathe in the mask. Based on the data collected in this study, Johnson, et al. (1995) were able to derive an equation for performance rating (this is defined as 100 times the ratio of performance with a mask to performance without):

$$\text{Perf Rating} = 409.6e^{-0.0424(\text{anx})} \tag{11}$$

This equation, only useful with anxiety (anx) scores of 34 and above, predicts what percentage of work duration without a mask can be completed by the same person while wearing a mask (e.g. a person with an anxiety score of 40 would work for only 75% of their normal time).

Since highly anxious people have been found, generally, to have higher resting respiration rates than calmer people (Johnson, et al., 1995), anxiety levels may also be a factor in deep breathing while wearing a respirator mask. Therefore, results of the state-trait anxiety test (Spielberger, et al., 1970) are of interest in the proposed study.

Effects of Facial Hair

Several studies have shown that most types of facial hair interfere with the seal of the respirator mask against the face. This presents a high risk of leakage of the outside atmosphere into the mask.

Hyatt (1973) did an experiment that tested the effects of all types of facial hair on respirator mask seal. This included moustaches in small, medium, and large (the "large" category included handlebar moustaches); beards in "small van dyke" (this mainly only covers the chin), "large van dyke" (this covers the chin and some of the jaw line), "full short", and "full long"; and sideburns in short, medium, long, and "Prince Albert" (the sideburns connect with the moustache). Clean-shaven individuals were used as the control group. In addition, some subjects that were initially clean-shaven were tested with daily growth of stubble.

Two types of quantitative tests were performed. The subject group with daily stubble growth was given a dioctyl phthlate (DOP) aerosol test, done in a man-test chamber. The DOP aerosol was released into the chamber, while the amount of leakage inside the masks was determined with a forward-light-scattering photometer. During this test, the subjects performed only normal and deep breathing exercises. It was found that the leakage percentage increased gradually, over the eight days that the subjects were tested with progressive stubble growth. With one of the full-facepiece masks, there was a steep increase in the first three days, followed by a more gradual increase. In this case, the maximum allowable leakage of 0.5%, for full-facepiece respirators in atmospheres containing one hundred times the Threshold Limit Value of this aerosol, was exceeded by the end of the first day. In other cases, it was exceeded by the end of the eight-day test period.

In the second test, Hyatt used a Wright Nebulizer to supply a NaCl aerosol to a portable test hood. Sampling from the masks was done at one liter per minute and injected into a flame photometer burner. This test was done only on subjects with established facial hair. The protocol involved having the subject perform a series of exercises, including normal and deep breathing while sedentary, turning the head from side to side and up and down, smiling, reading, coughing, and a second sedentary period for comparison with the first. It was found that small moustaches, small van dyke beards, and short sideburns do not interfere with the sealing of some masks. For some subjects with fine-textured beards with sparse growth, the leakage rates were also within acceptable values. For all other subjects, however, the leakage percents almost always exceeded the 0.5% allowable for full-facepiece respirators or 5% allowable for half-mask respirators.

In 1984, Skretvedt and Loschiavo published a study on the effect of facial hair on the face seal of negative-pressure respirators. In this experiment, only subjects with fully established beards were tested; although they had a variety of beard lengths, shapes, densities, and textures. Both a qualitative fit test and a quantitative fit test were performed. In the qualitative test, the mask wearer entered a chamber in which a paper towel soaked in isoamyl acetate had been hung on a hook. The masks were equipped with a combination organic vapor/high-efficiency filter cartridge. The test subject performed a set of exercises similar to the ones in the study by Hyatt. If the subject detected the odor of the isoamyl acetate at any time during the five minute test, the test was considered a failure. None of the bearded subjects in the study passed this qualitative fit test. Only 2% of the clean-shaven subjects failed this test with a half-mask respirator, and none of the clean-shaven subjects failed it with a full-facepiece respirator.

The quantitative test was a DOP aerosol test very similar to the one performed by Hyatt. For bearded subjects with half-mask respirators, the median face seal leakage was two hundred and forty-six times greater than the median for clean-shaven subjects. Those bearded subjects wearing full-facepiece respirators experienced a mean leakage more than three hundred and thirty times greater.

These two studies (Hyatt, 1973; and Skretvedt and Loschiavo, 1984) show that, while some persons with facial hair can achieve an adequate seal with a respirator mask, these persons are more likely to risk experiencing leakage in a mask than are clean-shaven individuals. Those respirator wearers with thick beards are certain to exceed acceptable leakage percentages.