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**VALIDATION OF PROTECTION PROVIDED BY ONE
BRAND OF FILTERING FACEPIECE RESPIRATOR**

by

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A RESEARCH PROJECT REPORT

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These results would indicate that the previous laboratory study underestimated the protection provided by the respirator, and that the ANSI APF is a conservative measure of fit for this respirator. The respirator was found to provide about the same level of protection for males and females. Contrary to a previous report, this study found that the saccharin QLFT was not a good predictor of fit for this respirator.

Interpretation of these results is conditional upon the apparent contradiction of measured QNFT PFs being greater than the maximum resulting from filter penetration alone. This would indicate that the Large Particle Quantitative Fit Test (LPQNFT) method may be subject to particle deposition in leak sites and to the influence of conditions inside the facepiece that may lead to sampling bias. Further studies should be conducted to identify the cause of this contradiction.

DEDICATION

This research project is dedicated to my fiancée, Renee Turner, and to my mother, Nancy R. Peacock, for their encouragement and support.

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ABBREVIATIONS FOR THE APPENDICES

AVECO	= Average concentration outside the filter (particles per cubic centimeter)
CI	= Concentration behind the filter (particles per cubic centimeter)
GEN	= Gender, where 1 = male and 2 = female
LNPFCORR	= Natural log of the protection factor adjusted by 0.6 for particle deposition in the respiratory tract
PEN	= Filter penetration
PFCORREC	= Protection factor adjusted by 0.6 to account for particle deposition in the respiratory tract
QLFT	= Qualitative fit test, where 0 = fail and 1 = pass
SENS	= Sensitivity; number of squeezes to elicit a response
SUB	= Subject
TEST	= Test

INTRODUCTION

History of Respiratory Protection

The use of respiratory protection dates back to around 50 A.D. when Pliny noted the donning of loose fitting animal bladders in an attempt to protect against lead oxide dust in the Roman mines (1). Agricola (circa 1556) recommended the fastening of loose veils over workers' faces to prevent a mine dust with acidic properties from being inhaled (2). Ramazzini (circa 1700) approved of the practice of bakers and millers covering their faces with linen cloth, but realized the limitations stating it would not keep the atoms of flour from the deepest parts of the lungs (3). In 1854, it was discovered that activated charcoal could be used to remove gases and vapors and from this point the basic components of the present-day respirator were available. These components are a layer to protect against dusts and particulates, a layer to protect against acid gases, and an activated charcoal layer to protect against organic gases and vapors (1).

The probable impetus for introduction of respirators in the United States was for the lung protection of firefighters (1). The Nealy Smoke Mask patented in 1877 was one of the earliest respirators of U. S. origin. As late as 1910, many fire departments were ignorant of respirators or thought them unmanly. In 1916, the U.S. entered World War I and with it came poisonous gas warfare.

The task of providing adequate respirators for the U.S. Army was given to the Bureau of Mines (BOM) (5). After WWI, the BOM saw the need for and established respiratory protection standards. The Gibbs Oxygen Breathing Apparatus manufactured by the Mine Safety Appliances Company received the first BOM approval on January 15, 1920 (4). Today, the National Institute for Occupational Safety and Health (NIOSH) sets respirator approval regulations (30CFR11) and respirator use recommendations replacing the duties

of the defunct Bureau of Mines ⁽⁵⁾. Other standard producing agencies include the American National Standards Institute (ANSI), which publishes the American National Standard for Respiratory Protection,⁽⁶⁾ and the Occupational Safety and Health Administration (OSHA), which sets general (29CFR1910.134)⁽⁷⁾ and specific respirator use regulations. OSHA's 29CFR1910.134 was adopted from the ANSI Z88.2-1969.

Types of Respirators

Respirators may be classified according to: type of inlet covering, pressure in the facepiece, or mode of operation ⁽⁸⁾. Types of inlet coverings are tight-fitting, usually called facepieces, or loose-fitting. Facepieces may be quarter-mask, half-mask, or full-facepiece. Quarter-mask facepieces cover the nose and mouth with the lower sealing surface between the mouth and chin. Half-mask facepieces cover the nose to under the chin. Full-facepieces cover from the hairline to under the chin. Facepieces are constructed of materials such as flexible molded rubber and neoprene and are held on the wearer by headstraps. Examples of loose-fitting inlet coverings are hoods, helmets, suits, and blouses.

Facepiece pressure may be positive or negative. Positive pressure facepieces maintain positive pressure on the inside of the respirator relative to the exterior even during inhalation, though if the inhalation is strong enough a negative pressure can result. Negative pressure facepieces allow the pressure inside the respirator to become negative upon inhalation. This is undesirable in that contaminants will readily enter the facepiece if any faceseal leaks are present.

When using mode of operation to classify respirators, the two main types of respirators are air-purifying respirators and atmosphere-supplying respirators ⁽⁸⁾.

Air-purifying Respirators

Air-purifying respirators work by removing contaminants such as gases, vapors, fumes, and particulates from the ambient air (8). Types of air-purifying respirators include particulate filtering, vapor and gas removing, a combination of particulate filtering and vapor and gas removing, and powered air-purifying. Some of the types of air-purifying respirators are disposable, where a disposable respirator is defined as being discarded after the end of its recommended period of use, after excessive resistance or physical damage, or when odor breakthrough or other warning indicators render the respirator unsuitable for further use.

Particulate filtering respirators are used for protection against dusts, mists, and/or fumes with the filters of these respirators being constructed of fibrous material (8). A single fiber's efficiency at trapping particles is a function of the particle's size relative to the fiber size, the particle's velocity, and the composition, shape, and electrical charge of both the particle and fiber. Filtration efficiency is a function of the single fiber efficiency, fiber density, and filter thickness. Filtration efficiency must be balanced against breathing resistance for as fiber density and filter thickness increase, so does breathing resistance. Particulate respirators may have reusable or replaceable filters, be disposable, or be for single use. Particulate respirators may be classified as: high efficiency particulate aerosol (HEPA) respirators; Dust / Mist / Fume (D/M/F) respirators; Dust / Mist (D/M) respirators; or single-use dust and mist respirators.

HEPA respirators contain filters that are 99.97% efficient at preventing filter penetration of 0.3 μm dioctyl phthalate particles (DOP) and are certified for protection against dusts, fumes, and mists having an exposure limit less than 0.05 milligram per cubic meter (8). D/M/F respirators contain filters that are approximately 99% efficient at preventing filter penetration of a lead fume aerosol and are certified for protection against dusts, fumes, and mists having an exposure limit not less than 0.05 milligrams per cubic meter. D/M and single-use dust and mist respirators contain filters that are approximately 99% efficient at preventing filter penetration of a silica dust particle with a geometric mean (GM) diameter of 0.4 to 0.6 μm and a geometric standard deviation (GSD) not greater than 2.

Vapor and gas removing air-purifying respirators are designed for use against specific vapor and gas contaminants (8). Contaminant removal mechanisms include adsorption, absorption, and catalysis. Adsorption is the surface retention of contaminant molecules and is based upon physical attraction between the contaminant and the sorbent. Activated charcoal is the most common adsorbent. With absorption, the contaminant molecules penetrate deeply into the molecular spaces of the sorbent and are retained chemically. Absorbents are mostly used for protection against acid gases. Catalysts influence the rate of chemical reactions between other substances without being changed. An example is hopcalite which is used to speed the reaction between carbon monoxide and oxygen to form carbon dioxide.

Combination air-purifying respirators protect against both particulates and gases and vapors (8). The respirator is designed such that contaminated air first passes through the filter and then through the sorbent. An example of a combination respirator is the Universal canister which may contain several different sorbents, a catalyst, layers of a drying agent to protect the catalyst, and a HEPA filter.

Powered air-purifying respirators use a blower to route air to a contaminant removing element and then to the respiratory inlet covering for inhalation (8). The purifying element may be a filter for particulates, some sorbent for gases and vapors, or some combination. The covering may be a facepiece, hood, or helmet.

Atmosphere-supplying Respirators

The second main type of respirator is the atmosphere-supplying respirator (8).

Atmosphere-supplying respirators may be a self-contained breathing apparatus (SCBA), supplied-air, or some combination of these two. SCBAs contain enough air or oxygen for up to four hours and are classed as either closed- or open-circuit. Closed-circuit SCBAs take the exhaled air, remove the carbon dioxide, and replenish oxygen to a specified concentration, and return the air for inhalation. There are two basic types of closed-circuit SCBA with one using a cylinder of compressed oxygen and the other a solid oxygen generating substance.

Open-circuit SCBAs exhaust the exhaled air to the exterior instead of recirculating it (8). There are two types of open-circuit SCBAs, demand and pressure-demand. With the demand type, inhalation causes a negative pressure in the facepiece relative to ambient pressure. The pressure-demand type is designed to maintain a positive pressure in the facepiece at all times, however a momentary negative pressure can result during forceful inhalations.

A supplied-air respirator may be either an airline respirator or a hose mask respirator (8). The airline respirator uses compressed air from a stationary source delivered through a hose at a pressure not to exceed 125 psi at the point where the hose attaches to the air supply. These respirators may be of the demand, pressure-demand, or continuous-flow

type and the inlet covering may be a hood, helmet, facepiece, or complete suit. The air supply must be of Grade D or higher quality as described in ANSI / Compressed Gas Association G-7.1-1989 (9).

Hose mask respirators use a hose to supply air under low or no pressure to the respiratory inlet covering (8). Air under low pressure is supplied to the respiratory inlet covering by a hand or motor operated blower. When no blower is used, the air supply is under no pressure and the movement of air through the hose depends on lung exertion.

Atmosphere-supplying respirators are key components in two combination respirators that NIOSH has certified (8). One combination respirator is the supplied-air / air-purifying respirator. This respirator is certified under the air-purifying respirator class due to the requirement of certifying combination respirators by the component that provides the least protection to the user. The supplied-air / air-purifying respirator cannot be used in an immediately dangerous to life and health environment (IDLH). A typical use of this combination respirator might be to use the air-purifying element to enter an area, subsequently connect the airline respirator to an air supply, and then use the air-purifying element upon exit from the area.

The other combination respirator is the supplied-air / SCBA respirator (8). These units are typically used for emergency entry into and escape from an IDLH atmosphere. This combination respirator may be used for emergency entry into a hazardous atmosphere only when the SCBA is classified for 15 minutes or longer service and not more than 20% of the air supply's rated capacity is used during entry.

Respirator Fit

For a respirator to be efficacious, it is necessary for the respirator to have a good fit on the wearer. Leakage into the facepiece may prevent attainment of a good fit. This leakage can result from respirator defects, the air-purifying element, the face seal, or some combination. Several terms help to define leakage: penetration, efficiency, protection factor (PF), and fit factor (FF) (8). Penetration is the ratio of the concentration inside the facepiece to the concentration outside the facepiece. Efficiency is the outside concentration minus the inside concentration then subsequently divided by the outside concentration. The PF is the ratio of some concentration outside the facepiece (C_o) to some concentration inside the facepiece (C_i). Though used at one time interchangeably with PF, today a FF is used when discussing flows instead of concentration (10). The FF is the ratio of a flow into the respirator to a flow out of the respirator.

Several terms are used in defining respirator fit: assigned protection factor (APF), workplace protection factor (WPF), and simulated workplace protection factor (SWPF) (8). The APF is defined as a measure of the minimum anticipated workplace level of respiratory protection that would be provided by a properly functioning respirator or class of respirators to a percentage of properly fitted and trained users. APFs are issued by both NIOSH and ANSI. The NIOSH APFs were determined by Los Alamos National Laboratories (LANL) by conducting quantitative fit testing on a panel of human volunteers. Multiplication of the APF by the exposure limit for a contaminant yields the maximum specified use concentration for that respirator.

The WPF is a measure of the actual protection provided in the workplace under the conditions of that workplace by a properly functioning respirator when correctly worn and used (8). WPF is defined as the ratio of the estimated contaminant C_o the respirator facepiece to the contaminant C_i the respirator facepiece. Restrictions on C_i and C_o are

that both should be concurrent time-weighted average (TWA) samples taken while the respirator is being properly worn and used during normal work activities.

The SWPF is determined in a laboratory simulation of a workplace setting rather than in the actual workplace (8). The same restrictions that apply to WPF apply to SWPF. For laboratory protection factor testing to reliably estimate WPFs, a relationship must be demonstrated between the two tests.

Fit-testing is the process of assessing a respirator's fit on a wearer (8). Types of fit-tests include pressure checks, qualitative fit tests (QLFTs), and quantitative fit tests (QNFTs). Two assumptions underlie fit-testing. One is that the respirator has no defects; the other is that the air-purifying element is 100% efficient in preventing filter penetration into the respirator. Thus, these assumptions mean that the purpose of fit-testing is to check for faceseal leakage to ensure a proper fit on the wearer.

Pressure Checks

Pressure checks may be by a negative pressure test or a positive pressure test (8). Both the negative and positive pressure tests may be done by the respirator wearer outside the location of intended use; one of the tests should be performed prior to entry into any hazardous atmosphere. Both tests are limited to tight fitting facepieces. The negative pressure test involves closing off the respiratory inlet(s) with the palm(s) or replacing the seal(s), or of squeezing the breathing tube so that it does not pass air. Next, the wearer inhales gently so that the facepiece collapses slightly and holds his or her breath for 10 seconds. The respirator is considered adequate if after 10 seconds the facepiece remains slightly collapsed and no inward leakage is detected.

The positive pressure test is basically the converse of the negative pressure test (8). It is performed by closing off the exhalation valve(s) with the palm(s), exhaling gently to expand the facepiece, and holding his or her breath for 10 seconds. The respirator is considered adequate if slight positive pressure can be built up inside the facepiece and no outward leakage is detected. If the respirator has an exhalation valve cover that would require removal and replacement, the negative pressure test is recommended instead of the positive pressure test so as to cause less disturbance of the respirator fit.

Qualitative Fit Tests

QLFTs rely on the wearer's ability to sense the presence of an external test agent inside the respirator facepiece (8). These tests may utilize isoamyl acetate, saccharin, or irritant fume. The use of all three test agents requires the same general procedure of: threshold screening, respirator selection, and the fit test. Threshold screening involves the exposure of the test subject to a pre-specified amount of the test agent to ensure that the subject can taste or smell the test agent. If the subject is unable to taste or smell the respective test agent, one of the other two test agents should be tried or the test subject may be fit using a QNFT. If the subject passes threshold screening, he or she next selects a respirator.

The test subject is instructed on how to don a respirator, how to position the respirator on the face, how to set the strap tension, and how to assess the comfort of the respirator (8). After a respirator is chosen by the test subject, he or she conducts negative and positive pressure fit checks. If the pressure fit checks are passed, the subject is ready for the QLFT.

The fit test procedure calls for the subject to perform a series of exercises while being exposed to the test agent (8). These exercises may include normal breathing, deep breathing, the turning of the head from side-to-side, nodding the head up and down, and

talking. Frequently, the talking portion of the exercise is done by having the subject read the Rainbow Passage, which was designed to result in a wide range of facial movements when read. If the test agent is not detected by the subject at any point in the fit test, the subject passes the fit test and may use the respirator in contaminated atmospheres up to 10 times the permissible exposure limit (PEL) for a given contaminant.

Quantitative Fit Tests

QNFT is the use of an objective, quantifiable method to determine the face seal leakage of a respirator (5), (10), (11). QNFT methods may be grouped into the general categories of 1) gases and vapors, 2) negative pressure, 3) pressure decay, and 4) aerosols. Fit is determined for the methods utilizing gases and vapors and aerosols by quantitatively measuring an aerosol concentration outside and inside the respirator and comparing these concentrations. The pressure decay and negative pressure methods both use flow measurement, though in different ways, to determine fit (10), (11). For the negative pressure method, the FF is defined as the ratio of average inspiratory flow rate to leakage flow rate (11). For the pressure decay method, FF is defined as the ratio of the volumetric flow rate of clean air entering through the filter cartridge to the volumetric flow rate of contaminated air entering through the leak (10).

Gases and vapors used in QNFT to create a test atmosphere in the exposure chamber include dichlorodifluoromethane (Freon #12), sulfur hexafluoride, or argon (1), (5). Adley and Wisehart used Freon #12 to look at various performance characteristics of respirators that were used for non-emergency radiological protection (12). A MSA™ (Mine Safety Appliance Co.) High Sensitivity Benzol Indicator was used to measure Freon #12 concentrations within the test chamber between 5 000 ppm and 115 000 ppm. The Benzol Indicator detected Freon #12 via a Wheatstone bridge. As the mixture of Freon #12 and air was burned, the resistance of the Wheatstone bridge increased and

caused a flow of current. By comparison to a reference filament sealed in air, the Freon #12 concentration was determined. Concentrations of Freon #12 within the mask were measured continuously using a Davis Halide Meter, which measures Freon photometrically. This meter was calibrated to detect 10→1000 ppm Freon; the test subjects were not exposed to Freon #12 concentrations exceeding 1000 ppm. The percent leakage for one full-face mask ranged from 0.012% to 0.22% for seven subjects performing a single test. The percent leakage for another full-face mask ranged from 1.0% to 16.4% for seven subjects performing a single test. For a "respirator", the percent leakage ranged from 1.0 → 32%. Adley and Wisheart's definition of a "respirator" was not given.

The pressure decay quantitative fit test involves closing all respirator inlets except for a pressure port that will monitor respirator cavity pressures ⁽¹⁰⁾. The subject dons the respirator and then inhales deeply and holds his or her breath. A syringe is used to place a negative pressure inside the respirator. As all inlets are closed, any leakage will be from the face seal. Face seal leakage will allow the respirator cavity to return to atmospheric pressure. The time rate of pressure change can be used to determine the leakage flow which is directly related to the fit of the respirator and can be further used to calculate a FF for the respirator.

The negative pressure quantitative fit test involves exhausting air from a temporarily sealed respirator facepiece to create and maintain a constant negative pressure inside the facepiece while the wearer holds his or her breath ⁽¹¹⁾. The exhaust rate is chosen to create a negative pressure that will closely approximate the inspiratory flow inside the respirator during normal wear. With the air-purifying paths into the respirator closed, exhaust flow measurement is equivalent to measuring the leakage flow into the mask for

inhalation under normal wear. By comparing the average inspiratory flow rate, which is determined by work rate and gender, to the leakage flow rate, a FF is determined.

A special type of aerosol QNFT is the Condensation Nucleus Counter (CNC) (5). The CNC does not require a test chamber but instead uses dust particles found in the ambient environment. Air sampled by the CNC goes through a heated chamber saturated with alcohol and then enters a cooled chamber that causes the alcohol vapor to condense on the dust particles. The alcohol condensing on the particles causes an increase in the particle's size to about 10 μm . The particles then enter a forward light scattering chamber for counting. The CNC alternately samples the room and the respirator, determines the particle concentrations in each, compares these two particle concentrations, and then calculates a PF.

Substances used to create aerosols for QNFT include sodium chloride, corn oil, mineral oil, dioctylsebacate (DOS), and polyethylene glycol (PEG) (5), (10). DOP was once used, but concerns regarding its safety have terminated its use. For the sodium chloride test, a nebulizer is used to continuously generate a liquid aerosol from a salt water solution (1), (5). The liquid aerosol is dried to produce discrete submicron salt particles and is then dispersed into the test chamber. A commercially available sodium chloride generator produces a test atmosphere of 15 mg/m^3 and a test aerosol with a 0.6 μm mass median aerodynamic diameter (MMAD). No GSD was given. However, as reference was made that the commercial units were based on the NaCl aerosol test apparatus developed at LASL and the LASL unit has a GSD of approximately 2.1 μm (13), it is reasonable to assume the commercial units have a similar GSD.

Because of the safety concerns of DOP and given that DOP was widely used with a Laskin nozzle aerosol generator for respirator fit testing requiring a liquid aerosol, a

substitute for DOP was sought (14). Hinds et al. investigated using corn oil, DOS, mineral oil, and PEG as substitutes for DOP by comparing the size distributions of each produced by the Laskin nozzle aerosol generator to the size distribution of DOP for a given set of conditions. For the aerosol generator output at 140 kPa, DOP had a MMAD of $0.7\mu\text{m}$ with a GSD of $1.53\mu\text{m}$. Size distributions for all four substances were similar to DOP; the size distributions of corn oil and mineral oil gave the closest match. The corn oil MMAD was $0.77\mu\text{m}$ with a GSD of $1.53\mu\text{m}$ while the mineral oil MMAD was $0.7\mu\text{m}$ with a GSD of $1.52\mu\text{m}$. Though not explicit, Hinds et al. seem to favor the use of mineral oil over corn oil as a DOP substitute. Advantages cited of mineral oil compared to corn oil were a closer refractive index match to DOP, being odorless, nonhygroscopic, nonirritating, having good oxidation stability, and not readily supporting the growth of microorganisms.

The use of test aerosols with an approximate MMAD of $0.7\mu\text{m}$ and an approximate GSD of $1.5\mu\text{m}$ is not without problems when performing quantitative fit tests on D/M respirators. Tuomi points out that aerosols with MMAD in the size range of 0.1 to $1\mu\text{m}$ will not allow distinction between filter penetration and face seal leakage without the use of special HEPA filter adaptations (15). Accordingly, in standard aerosol QNFT, HEPA filters replace the normal filter in the D/M and D/M/F respirators so as to eliminate filter penetration by the aerosol and thus allow the only source of aerosol penetration to be via face seal leakage (8). Several studies of filter penetration of disposable D/M respirators have been published.

Cooper et al. determined the percentage of respirator penetration attributable to filter penetration for the 3M™ 8710™ D/M respirator for a $1.8\mu\text{m}$ monodisperse DOP aerosol generated by a vibrating orifice aerosol generator (VOAG) (16). In this experiment, the 3M 8710 was attached to a mannequin which was connected to a breathing simulator.

The mannequin was designed by the U.S. Army to approximate the facial features of an average male and was used in testing military respirators. The breathing machine inhaled an air volume of 37 liters in one minute with a respirator rate of 23 cycles per minute. The respirator was tested while simply strapped on the mannequin and also while fully taped to the mannequin. The purpose of taping the respirator to the mannequin was to eliminate face seal leakage thus allowing determination of filter penetration into the interior of the respirator. The filter penetration of the 3M 8710 was found to be 1.5% of the challenge aerosol with a standard error of 0.24%.

Ruuskanen et al. determined filter penetration of the 3M 8715™ D/M respirator for an undiluted corn oil challenge aerosol generated by an atomizer (17). No particle size distribution for the challenge aerosol was given, but based on work by Hinds et al. and mentioned previously, the corn oil aerosol probably had a MMAD $\sim 0.7 \mu\text{m}$ and a GSD $\sim 1.5 \mu\text{m}$ (14). In this experiment, a dummy test was used (17). The dummy test involved mounting the respirator on a filter holder; petroleum jelly was applied around the periphery of the respirator to eliminate any facesal leakage. A suction or flow was applied to the interior of the respirator to simulate the various inspiratory pressures that occur with human breathing. These flows ranged from 0 to 50 liters per minute (LPM). The number C_i the mask and the test chamber was measured by an optical particle counter (OPC) and an aerodynamic particle sizer (APS). The APS detected particles with aerodynamic diameters between $0.6 \mu\text{m}$ to $15 \mu\text{m}$; the OPC measured optical particle sizes between $0.78 \mu\text{m}$ and $6 \mu\text{m}$. For a flow of 40 LPM, the percent filter penetration of the challenge aerosol was $\sim 9\%$ for a $0.8 \mu\text{m}$ particle, $\sim 7\%$ for a $1 \mu\text{m}$ particle, $\sim 1.2\%$ for a $2 \mu\text{m}$ particle, $\sim 0.4\%$ for a $3 \mu\text{m}$ particle, and $\sim 0.1\%$ for a $4 \mu\text{m}$ particle. For a flow of 30 LPM, the percent filter penetration of the challenge aerosol was $\sim 7\%$ for a $0.8 \mu\text{m}$ particle, $\sim 5\%$ for a $1 \mu\text{m}$ particle, $\sim 0.9\%$ for a $2 \mu\text{m}$ particle, $\sim 0.25\%$ for a $3 \mu\text{m}$ particle, and $\sim 0.1\%$ for a $4 \mu\text{m}$ particle.

The problem of preventing filter penetration of a D/M or D/M/F respirator in a liquid aerosol quantitative fit test without requiring replacement of the regular filter with a HEPA filter has been addressed by a method termed the Large Particle Quantitative Fit Test (LPQNFT) (18). The QNFT of D/M and D/M/F respirators without requiring modifications of these respirators with HEPA filters is desirable in that the respirator tested can be the same as that worn in the field thus providing a better estimate of the true fit. The size of the challenge aerosol differentiates the LPQNFT from the standard aerosol QNFT. The LPQNFT consists of a VOAG, an exposure chamber, a single-particle optical counter, and a data recording device. The VOAG is used to generate a corn oil aerosol with a MMAD of $2.5\text{ }\mu\text{m}$ and a GSD of $1.1\text{ }\mu\text{m}$ which was shown to produce an average filter penetration of 0.1% ($n = \text{three}$) for the 3M 8710 D/M respirator. Thereby, this allows for the determination of facesal leakage for D/M and D/M/F respirators.

The aforementioned study by Cooper et al., in addition to discussing filter penetration, confirmed the importance of facesal leakage in affecting the fit of D/M respirators (16). This study determined the percentage of penetration attributable to facesal leakage for the 3M 8710 D/M respirator and found that the face seal leakage around the 3M 8710 is about one-sixth of the flow through the mask. In this experiment, the 3M 8710 was attached to a mannequin which was connected to a breathing simulator. The mannequin was designed by the U.S. Army to approximate the facial features of an average male and was used in testing military respirators. The breathing machine inhaled an air volume of 37 LPM with a respirator rate of 23 cycles per minute. The respirator was tested while simply strapped on the mannequin and also while fully taped to the mannequin. By taping the respirator to the mannequin, the percentage of penetration attributable only to filter penetration can be found. Subtracting the percentage of filter penetration from the

penetration found for the strapped respirator gives the penetration due to face seal leakage. The face seal leakage was found to be on average 17% of the challenge concentration with a 95% confidence interval of 9% to 25% face seal leakage.

WPF Studies of Disposable Particulate Respirators

Three studies were found that dealt with WPF studies of disposable particulate respirators (19), (20), (21). The respirators studied, all in different workplace environments, were the 3M 9910™, the 3M9906™, and the 3M 8710. The 3M 9906 and the 3M 8710 are disposable D/M respirators; the 3M 9910 is a disposable D/M/F respirator.

Reed et al. conducted a WPF study of the 3M 9910 D/M/F respirator worn by workers while mixing and packaging a concrete patching compound (19). Nineteen pairs of samples were collected over three days on seven different workers. Sampling equipment for each worker consisted of two Dupont P2500 constant flow personal sampling pumps with one used to sample the inside of the respirator and the other used to simultaneously sample the outside of the respirator at the worker's lapel area. Samples were collected on 37 mm, 0.5 μ m polyvinyl chloride filters for as much as possible of the six hour shift. The samples were analyzed by gravimetric means. The GM of the WPFs was found to be 18 with a GSD of 3.1. Reed et al. pointed out that one method for defining an APF is to do so in terms of the proportion of workers the APF is thought to protect. This proportion is usually 95%. Thus a computed 5th percentile WPF should equal or exceed the respective APF. This study found a 5th percentile WPF for the 3M 9910 of 3. The APF for this type of respirator is 10 (6), (8).

Fergin conducted a WPF study of the 3M 9906 D/M respirator worn by workers in the potroom of a prebake aluminum reduction plant (20). Fit tests were conducted on 18 workers. The job task during sampling for 11 of the 18 workers was carbon setting; the

other 7 workers were filling the ore bucket when sampling occurred. The sampling strategy was to sample one potline crew per day in each of four potlines over a four-day period. Samples were collected during a one hour carbon setting period in the morning in one room and a one hour period in the afternoon in the other room of the potline. Sampling equipment for each worker consisted of two MSA Model G portable sampling pumps with one used to sample C_i of the respirator and the other used to simultaneously sample the C_o of the respirator at the worker's lapel area. Samples were collected on glass fiber filters. The samples were analyzed gravimetrically as total particulate. A GM protection factor of 161 was reported by Fergin; using the given data, a GSD of 1.43 was calculated. Fergin concludes that the 3M 9906 provides acceptable protection to the wearer and that the protection capability of this respirator is "undoubtedly" underestimated. Calculation of the 5th percentile WPF for the 3M 9906 utilizing the given data yields 15. As the APF for this type of respirator is 10, Fergin's conclusion has merit (6), (8).

Wallis et al. conducted a WPF study of the 3M 8710 D/M respirator worn by workers involved in the processing of manganese dioxide powder in several alkaline battery plants (21). The number of workers on which fit tests were performed was not stated nor was the time period over which sampling occurred. A total of 70 pairs of measurements were collected. Pairs of samples were collected during the four main job tasks of transfer of the virgin manganese dioxide powder, processing of the powder, transfer of the processed powder, and insertion of the processed powder into cans. Sampling equipment for each worker consisted of two Dupont P2500 constant flow personal sampling pumps with one used to sample the C_i of the respirator and the other used to simultaneously sample the C_o of the respirator at the worker's lapel area. Samples were collected on 37 mm, 0.8 μ m mixed cellulose ester filters for about 30-40 minutes. The samples as well as blanks were analyzed by atomic absorption spectroscopy. Of the 70 pairs of samples collected,

12 pairs were collected when the ambient manganese dioxide dust concentration was greater than 5 mg/m^3 , which is the level above which respirator use is mandatory. The GM of the WPFs was found to be 250 for these 12 paired samples with a corresponding 5th percentile WPF of 35. For all 70 pairs of samples, the dust concentration ranged from 0.14 to 77.4 mg/m^3 and the GM of the WPFs was 50 with a 5th percentile WPF of 7.5. For dust concentrations in the range of 0.14 to 5 mg/m^3 , the 58 pairs of samples yielded a GM for the WPFs of 37 and a 5th percentile WPF of 6.8. The APF for the 3M 8710 is 10.

Laboratory PF Study of Disposable D/M Respirators

Lowery et al. conducted a laboratory PF study of six disposable D/M respirators (13). Of particular interest was the inclusion of the 3M 8710 which is widely used in industry. In the study, respirators were tested on subjects who were selected by lip length and face length with a goal of achieving a wide range of facial sizes. There were ten categories of face sizes and these constituted the test panel. One subject was selected from each of the ten categories of face sizes; each one of the six different respirators was tested on each subject. Only one respirator of each type was tested on each subject. The subjects performed the exercises of normal breathing, deep breathing, turning the head from side-to-side, tilting the head up-and-down, talking, and normal breathing. The test aerosol was sodium chloride nebulized from a 1% NaCl water solution and dried with dilution air. Aerosol concentrations were determined with a sodium flame photometer connected to a strip chart recorder. Sodium chloride aerosol concentration in the test enclosure was $15 \pm 2.5 \text{ mg/m}^3$ and the aerosol had a MMAD of $0.70 \mu\text{m}$ and a GSD of 2.15. The GM of PFs for the 3M 8710 was 4.89 with a GSD of 1.47. The corresponding 5th percentile PF is 2.6. The NIOSH and ANSI APF for this category of respirator is 10 (6),(8).

This study conducted in 1977 has two main limitations which have been elucidated by post-1977 research. These limitations are, first, that only one fit test on each subject and mask was done, and second, the selection of a challenge aerosol with a MMAD of 0.70 μm . da Roza et al. reported in a 1983 paper that the distribution of replicate fittings of one facepiece on any one user is lognormal with a variance that can be large (22). This paper further notes that when comparing two fittings done on the same day to two fittings done several weeks apart, the reproducibility of two fittings done several weeks apart is 32% poorer. When comparing three fittings done on the same day to three fittings done several weeks apart, the reproducibility of three fittings done several weeks apart is 55% poorer. Therefore, Lowery et al.'s use of a single fitting of a respirator to predict the "average" fit for a subject / respirator combination cannot be judged reliable.

The use of a polydisperse 0.70 μm NaCl aerosol to determine the PFs poses problems. As discussed earlier, Ruuskanen et al. found that for a 0.8 μm particle filter penetration of the 3M 8715 was 7% at a flow through the mask of 30 LPM, a flow which approximates low to moderate work activity (17). Given this source of penetration into the respirator, it would not be possible for Lowery et al. to distinguish filter penetration from faceseal penetration.

PURPOSE OF THIS STUDY

Given the limitations in the previous laboratory PF study of the 3M 8710, the purpose of this study was to use the LPQNFT to validate the protection provided by the 3M 8710. Additionally, PFs obtained by male and female test subjects were tested for difference. PFs determined by the LPQNFT were compared to the outcome of a saccharin QLFT and the sensitivity and specificity of the saccharin QLFT were evaluated.

MATERIALS AND METHODS

Materials

The equipment used included the following:

1. A Model 3450 VOAG manufactured by TSI®, Inc.
2. Eight polonium ²¹⁰ strips as charge neutralizers.
3. A Model 3310 APS™ manufactured by TSI, Inc.
4. APS software and a personal computer.
5. The Dynatech® Model 223 Dynatent™ as the exposure chamber.
6. 3M 8710 disposable D/M respirators.
7. A 3M QLFT kit.
8. A sampling probe and train.
9. A filter holder.
10. A tripod.
11. Reagent-grade ethanol.
12. Reagent-grade corn oil.
13. A compressed air source.
14. An air dilution and exhaust system.

On the following page is a diagram of the equipment used for the QNFT.

Figure 1. Equipment Used for the QNFT

The VOAG produces solid or liquid aerosols uniform not only in size, but also in density, shape, and surface characteristics (23). The VOAG generates particles by controlling the breakup of a liquid jet via applying a periodic disturbance of an appropriate frequency. This process yields highly uniform drops with a standard deviation typically less than one percent of the mean droplet size. The generated aerosol has a high electrical charge, so a radioactive neutralizer is recommended when generating particles less than 5 μm in diameter. To produce a 2.5 μm QNFT challenge aerosol, a solution of 0.19% corn oil in ethanol was used as the liquid feed in a 60 mL syringe. Operating parameters for the VOAG were a 10 μm orifice, a frequency of 282.2 kHz, a liquid feed rate of 2.8×10^{-4} cm/sec, the amplitude at full setting, 70 LPM dilution air, and 1500 cc/min dispersion air.

For charge neutralization of the aerosol, eight Po 210 strips were used. The strips were attached to the acrylic drying column in a circular fashion approximately 10 cm above the liquid orifice cup. It is important to neutralize the high electrical charge as electrostatic capture is one means by which filtration on the 3M 8710 occurs and the goal is to best simulate "natural" conditions (24). The radioactive source creates charged ions in the gas which are attracted to charges of the opposite sign on the particles, reducing the particle charge distribution to a Boltzmann equilibrium.

The APS, which can detect and size single particles from 0.5 to 15 μm , was used as the aerosol detector (25). It operates by accelerating particles to a constant speed, then allowing them to decelerate in a sensing chamber. The rate of deceleration of each particle is dependent on its aerodynamic size. The velocity of each particle is measured by a laser split into two beams. The APS sampled at a rate of five LPM; of this five liters, four liters were used as sheath air and the remaining one liter was analyzed in the counting chamber. The APS sent data directly to a personal computer for on-line analysis.

The VOAG aerosol was combined with HEPA-filtered dilution air and routed into the Dynatent. Air was exhausted from the Dynatent to the outside of the building.

Dimensions of the Dynatent were an average width of 0.826 m, an average length of 0.826 m, and a height of 2.197 m. The volume of the Dynatent was approximately 1.5 m³.

The design of the sampling train was as follows. Two sampling lines were routed through the wall of the Dynatent. One line sampled the tent air and used a rounded sampling probe (26) with a smooth inner surface in order to minimize particle loss due to deposition. The second sampling line was used to sample inside the respirator or to pull air through the filter holder, depending on the phase of the experiment. Each sampling line exited the Dynatent and passed through its own stopcock; the sampling lines converged via a Y-adaptor and a single sampling line ran to the APS.

The respirator cavity concentration was sampled via a sampling probe of the design described by Liu et. al (26). The following is a diagram of the probe.

Figure 2. The Respirator Sampling Probe

The sampling probe was placed in each respirator so that it would be located between the respective subject's nose and mouth breathing area. The probe inlet has a tapered entrance and a smooth internal surface. For monodisperse particles of two μm and five μm and a sampling rate of four LPM, the probe showed zero percent particle deposition and is thus categorized as having a sampling efficiency of 100% (26). Accordingly, for the work of this experiment which involves a 2.5 μm monodisperse aerosol and a sampling rate of 5 LPM, it is reasonable to believe that the sampling efficiency of the probe approached 100%.

Figure 3 is a diagram of a subject wearing the respirator fitted with the sampling probe, line, and connector.

Figure 3. A Subject Wearing a Respirator Fitted with the Sampling Probe, Line, and Connector

Study Protocol

Test Subjects

The test subjects were fifteen healthy males and fifteen healthy females between the ages of 18 and 59 drawn from students, faculty, staff, and residents of the Birmingham area.

No attempt was made to select the test subjects on the basis of facial characteristics.

Filter Penetration Study

Experimental results from a previous study showed that a monodisperse corn oil aerosol of 2.5 μm aerodynamic diameter will result in average filter penetration of 0.1 percent (18). Filter penetration for this study was determined as follows. A circular section was cut from a respirator; all respirators used in this study were from lot #1703. This section was sealed via silicone caulking in a filter holder. The filter holder was attached at a height of approximately one meter to a tripod in the Dynatent. A Liu sampling probe (26) for sampling the aerosol concentration in the tent was mounted next to the filter holder. A 2.5 μm MMAD monodisperse corn oil aerosol was utilized as the challenge aerosol for the filter penetration assessments. The sampling procedure used involved taking a tent sample, followed by a filter holder sample, and then another tent sample. Filter penetration was calculated by:

$$\text{Filter Penetration} = \frac{\text{Filter Holder Particle Count}}{\text{Average of Tent Samples Before and After Filter Holder Particle Count}} \quad (1)$$

Ten penetration measurements were taken on each circular section of filter. This procedure was repeated for two other circular sections cut from respirators. Thus, a total of three circular sections were assessed in order to determine the filter penetration of the

8710 respirator. The overall filter penetration value for the 8710 was calculated as the arithmetic average of the filter penetration values for the three filters (n = 30 measurements; 3 filters tested).

Qualitative Fit Testing

The 30 test subjects were instructed as to how to put on the respirator and then were told to don the respirator. The respirator was fitted with a sampling probe and line which was sealed off during QLFT by having the subject place his or her thumb over the sampling line inlet. Testing proceeded according to the saccharin QLFT outlined in 29 CFR 1910.1025, Appendix D of the OSHA Lead Standard (27).

LPQNFT

After the saccharin QLFT, the subject entered the Dynatent, where the 2.5 μ m MMAD monodisperse corn oil aerosol had been accumulating for approximately 45 minutes, and seated him or herself in a chair that was in the Dynatent. The subject connected the sampling line of his or her respirator to the fitting in the wall of the Dynatent. QNFT began approximately five minutes after the subject entered the Dynatent to allow for reaccumulation of the challenge aerosol, which was diluted by the subject entering the Dynatent. Subjects performed the six exercises of 1.) normal breathing, 2.) deep breathing, 3.) turning ones head to the side, inhaling and exhaling, and then repeating on the other side, 4.) moving ones head up, inhaling and exhaling, then down, inhaling and exhaling, 5.) talking which was done by reading the Rainbow Passage, and 6.) normal breathing. Each exercise lasted sixty seconds. These exercises are commonly utilized during respirator fit tests and their origin is a 1976 publication by Hyatt of LASL who stated, "Based on experience and judgment, we believe that the five basic exercises are as representative as any exercises that can be done by a test subject during a laboratory

respirator man test. It is emphasized that this applies only to respiratory protective devices equipped with a quarter, half, or full facepiece." (28)

Each subject completed three QNFTs. Selection of three QNFTs per subject was based on research conducted by Harris which showed that performing three fit tests was as reliable as performing nine fit tests (29). Between tests, the subjects were told to remove the respirator, wipe his or her face, and then redon the respirator.

A PF was calculated for each exercise of each test using the following formula:

$$\text{Exercise PF} = \frac{\text{Avg. of Particle Count (outside) before the exercise and Particle Count (outside) after the exercise}}{\text{Particle Count (inside) during the exercise}} \quad (2)$$

A test PF was calculated using the following formula:

$$\text{Test PF} = 6 / (1/\text{NB1}_{\text{PF}} + 1/\text{DB}_{\text{PF}} + 1/\text{TH}_{\text{PF}} + 1/\text{UD}_{\text{PF}} + 1/\text{T}_{\text{PF}} + 1/\text{NB2}_{\text{PF}}) \quad (3)$$

where NB1_{PF} = the first normal breathing exercise PF

DB_{PF} = the deep breathing PF

TH_{PF} = PF while turning ones head side-to-side

UD_{PF} = PF while moving ones head up-and-down

T_{PF} = PF while one read the Rainbow Passage

NB2_{PF} = the second normal breathing exercise PF

The estimate of average fit for each individual was the arithmetic average of the three test PFs. The overall PF was adjusted by 0.6 to account for respiratory tract particle deposition of the 2.5 μm MMAD monodisperse corn oil aerosol.

The equation for the particle deposition correction factor (PDCF) used in this study was:

$$\text{PDCF} = \frac{\{ (P_I * t_I) + (P_E - P_D) * t_E \}}{t_I + t_E} \quad (4)$$

where P_I = fraction of particles inhaled = 1.00

t_I = inhalation time for a sedentary person = 1.6 s

P_E = fraction of particles exhaled = 1.00

P_D = fraction of particles deposited = 0.65

t_E = exhalation time for a sedentary person = 2.5 s

The origin of this equation was a paper by Danisch et al (30). However, the above equation differs from the Danisch et al. equation in that the above equation was amended to reflect that the time of inhalation for a sedentary person is 1.6 seconds (t_I) and the time of exhalation for a sedentary person is 2.5 seconds (t_E) (31). This time weighting necessitates the use in the denominator of the total residence time per breathing cycle. The Danisch et al. equation was (30):

$$\text{PDCF} = \frac{\{ P_I + (P_E - P_D) \}}{2} \quad (5)$$

This adjustment results in a PDCF of 0.6 versus a PDCF of 0.675 for Danisch et al.

According to Danisch (32), P_D is based on a total deposition during mouth breathing of 48% and a total deposition during nose breathing of 81% (33). To determine an average total deposition, Danisch assumes the breathing pattern is 50% through the mouth and 50% through the nose (32). Thus, average total particle deposition (P_D) is:

$$P_D = \frac{(48\% + 81\%)}{2} = 65\% \quad (6)$$

Statistical Analysis

For comparison purposes, a GM, GSD, fifth percentile, and a 95% lower tolerance level (LTL) of the fifth percentile for this study were calculated. The 95% LTL was the selected measure in assessing the overall PF of the respirator as this is a more conservative measure than the fifth percentile ⁽³⁴⁾. The normality of the PF data (n = 90) and the filter penetration data (n=30) was determined by reviewing a normality test value, a histogram, and a skewness plot as given by using SOLO Statistical Software ⁽³⁵⁾. A multiple regression analysis of the challenge concentration versus filter penetration was performed to test for an association between these parameters. An unweighted means ANOVA was performed to test for differences in the mean penetration between filters and between repetitions. Difference between mean PFs for males and females was tested by a two-sample t-test. The power of this two-sample t-test was calculated using NCSS-PASS Version 1.0 ⁽³⁶⁾. All tests of significance were to an alpha level of 0.05.

The pass / fail results of the saccharin qualitative fit test were compared to the overall PFs using a 2 X 2 table at a critical PF of 100. The specificity and the sensitivity of the saccharin QLFT were evaluated. On the following page, the general equations for specificity and sensitivity are given and their use illustrated.

	PF ≥ 100	PF < 100
Pass Saccharin	A	B
Fail Saccharin	C	D

$$\text{Sensitivity} = \{ A / (A + C) \} * 100$$

where sensitivity is the percentage of subjects who have a PF ≥ 100 and pass the saccharin QLFT

$$\text{Specificity} = \{ D / (B + D) \} * 100$$

where specificity is the percentage of subjects who have a PF < 100 and fail the saccharin QLFT

RESULTS AND DISCUSSION

Challenge Aerosol Particle Size Statistics and Concentration

As can be seen from Tables I and II, good control of challenge particle size was achieved for both the filter penetration and QNFT phases of this study.

TABLE I: Filter Penetration Study Particle Size Statistics

MMAD (μm)	
Average particle	2.50
Std. Dev. of particle	0.02
Range	2.49 $\rightarrow$ 2.54
n = 6 measurements	

TABLE II: QNFT Study Particle Size Statistics

MMAD (μm)	
Average particle	2.56
Std. Dev. of particle	0.08
Range	2.48 $\rightarrow$ 2.69
n = 57 measurements	

Table III presents the aerosol challenge concentration statistics for the filter penetration study.

TABLE III: Filter Penetration Study
Aerosol Challenge Concentration Statistics

Particles / cc	
Average Challenge	2.9
Std. Dev. of Challenge	1.0
Range of Challenge	3.5 → 7.8
n = 30 measurements	

For both the filter penetration study and the QNFT study, the tent concentration was measured before each exercise and after each exercise (six exercises per fit test; three fit tests per subject) thus assuring accurate challenge concentration data for each sample taken from the inside of the respirator. Please see Table IV for the aerosol challenge concentration statistics for the QNFT study.

TABLE IV: QNFT Study
Aerosol Challenge Concentration Statistics

Particles / cc	
Average Challenge	12.5
Std. Dev. of Challenge	1.2
Range of Challenge	9.5 → 14.3
n = 630 measurements; 30 subjects	

Filter Penetration

Table V, located on the following page, presents the filter penetration statistics. For the raw filter penetration data, please see Appendix A. Filter penetration was found to average 0.06% with a standard deviation of 0.02% ($n = 3$ filters). This result compares to a mean filter penetration of 0.1% determined in a previous study ($n = 3$ filters) (18). Given a mean penetration of 0.06%, a theoretical PF of 1670 is predicted for the average 8710 respirator. For the minimum penetration of 0.03%, a maximum theoretical PF of 3330 is predicted for the best performing 8710. For the maximum penetration of 0.1%, a minimum theoretical PF of 1000 is predicted for the poorest performing 8710.

To address the possibility of correlation between challenge concentration and filter penetration, a regression analysis was done with the average challenge concentration as the independent variable and the percent penetration as the dependent variable (35). The results were a $\beta = -6.4 \times 10^{-4}$, a p-value of 0.238 for $b = 0$, and a $r = -0.22$, and it was thus concluded that no association existed between challenge concentration and percent filter penetration.

An unweighted means ANOVA was performed to see if differences existed between the mean penetrations of filters one, two, and three and to see if differences existed between the mean penetrations of the ten repetitions (35). For the testing of difference between the mean penetrations of filters one, two, and three, the result was an F-ratio of 26.71 and a corresponding percent probability of 0.01 of observing a mean difference between the filters this large by chance alone. Thus, it was concluded that a significant difference exists between the mean penetrations of the three filters. For the testing of difference between the mean penetrations of the ten repetitions, the result was an F-ratio of 0.64 and a corresponding percent probability of 75% of observing a mean difference between the

ten repetitions this large by chance alone. Thus, it was concluded that no significant difference exists between the mean penetrations of the ten repetitions.

TABLE V: Filter Penetration Statistics

Avg. Penetration (n=3 filters; 10 penetration measurements per filter)	0.06%
Std. Dev. of Penetration	0.02%
Range	0.03 → 0.10%
Filter One	
Avg. Penetration	0.086%
Std. Dev.	0.018%
Range	0.06% → 0.10%
Filter Two	
Avg. Penetration	0.043%
Std. Dev.	0.013%
Range	0.03% → 0.07%
Filter Three	
Avg. Penetration	0.060%
Std. Dev.	0.009%
Range	0.04% → 0.07%
Max. PF Predicted Given	3330
Min. Penetration	
Max. PF Predicted Given	1670
Avg. Penetration	
Max. PF Predicted Given	1000
Max. Penetration	

Descriptive Statistics

The percent filter penetration values ($n = 30$) were found to be normally distributed as determined by review of the normality test value of 0.968 (reject if > 1.228 at $\alpha = 0.05$) (35). The test subjects' QNFT PFs ($n = 90$) were found to be not normally distributed as determined by review of the normality test value of 1.354 (reject if > 1.087 at $\alpha = 0.05$). Log transformations of the PFs resulted in a normal distribution as determined by review of the normality test value of 0.985 (reject if > 1.087 at $\alpha = 0.05$). The test subjects' QNFT PFs ($n=90$) adjusted for lung deposition were found to be not normally distributed as determined by review of the normality test value of 35.423 (reject if > 1.087 at $\alpha=0.05$). Log transformations of the PFs adjusted for lung deposition resulted in an approximately normal distribution with a normality test value of 1.0997 (reject if > 1.087 at $\alpha=0.05$).

Evaluation of Saccharin QLFT

Table VI presents the QLFT results. For the raw QLFT data, please see Appendix B. Twelve of thirty subjects passed the saccharin QLFT in comparison to twenty-eight of thirty subjects who passed the QNFT where passing the QNFT was defined as a PF of 100 or greater. The percent sensitivity of the saccharin QLFT was found to be 42.9% ($n = 30$). In contrast, Danisch et al. found the percent sensitivity of the saccharin QLFT to be 71.7% ($n = 200$) (30). The percent specificity of the saccharin QLFT was found to be 100% ($n = 30$), but this result is questionable due to only two subjects having a PF < 100 . In comparison, Danisch et al. found the percent specificity of the saccharin QLFT to be 85.1% ($n = 200$) (30).

Table VI: Saccharin QLFT vs. QNFT Results

	[--Pass QNFT--] [--Fail QNFT--]		
	PF $\geq$ 100	PF < 100	Total
Pass saccharin	12	0	12
Fail saccharin	16	2	18
Total	28	2	30

$$\text{Sensitivity} = (12 / 28) * 100 = 42.9\%$$

$$\text{Specificity} = (2 / 2) * 100 = 100\%$$

Table VII, located on the next page, compares the QLFT results of this study, the Danisch et al. study (30), and the Marsh study (37). OSHA accepted the saccharin QLFT based on this study by Marsh. While this study had good agreement with the sensitivity of the saccharin QLFT as determined by Marsh, there was poor agreement between the sensitivity measured in this study and that by Danisch et al (30). The much greater sensitivity found by Danisch et al. could be due to the larger sample size and / or to difference in test methodologies. If the saccharin taste was detected by a subject in this study, he or she then moved to the QNFT portion. In the Danisch et al. study, if the saccharin taste was detected by a subject, the subject was instructed to remove the respirator, leave the test area, and get a drink of water. Then, the saccharin QLFT was tried a second time. Saccharin QLFT protocols in 29CFR1910.1025 Appendix D do not mention allowing the test subject a second chance to pass the saccharin QLFT (27). Another possible reason for the lower sensitivity of the saccharin QLFT found in this study could be that the test subjects were graded as tasting saccharin when the subjects said, "I think I taste saccharin."

In this study, only two subjects were in the category used for calculating specificity. Thus, a comparison to the specificity determined by Danisch et al. (30), where the numerator was 86 subjects and the denominator was 101 subjects, or Marsh (37), where the numerator was 89 subjects and the denominator was 92 subjects, is of questionable use.

TABLE VII: Comparison of QLFT Results

Parameter	This Study	Danisch et al. (30)	Marsh (37)
n (number of test subjects)	30	200	40
Number of Brands of Disposable D/M Respirators Tested	1	4	6
Sensitivity	42.9%	71.7%	40.1%
Specificity	100.0%*	85.1%	96.7%
Passing QLFT	40%	43%	16.7%

* Very small sample size (n=2).

QNFT RESULTS

The results of the QNFT are summarized in Table VIII. The test subjects' raw QNFT data may be found in Appendices C, D, and E.

TABLE VIII: QNFT PF Statistical Summary

Arithmetic Mean	430
Range of PFs	20 → 1530
Mean log PFs	3.71
Std. Dev. of the log PFs	0.57
Geom. Mean	290
Geom. Std. Dev.	2.59
Exponent of the Fifth Percentile	60
Exponent of the 95% LTL of the fifth percentile of the log PFs	50
n (number of test subjects)	30
Number of QNFTs	90

As can be seen from the data in Table IX, located on the next page, the 8710 provides superior protection when compared to the best performing respirator (designated A) of a group of four disposable half-mask D/M respirators evaluated by Danisch et al (30). This study also found markedly greater protection for the 8710 than did Lowery et al (13).

TABLE IX: Comparison of PF Statistics

Parameter	This Study	Danisch et al. (30)	Lowery et al. (13)
n (number of test subjects)	30	50	10
Respirator	8710 D/M	A *	8710 D/M
Particle Deposition Correction Factor	0.6	0.675	Not Mentioned
Geom. Mean PF			
All Subjects	290	190	5
Pass saccharin	380	240	Not applicable
Geom. Std. Dev.			
All Subjects	2.59	2.34	1.50
Pass saccharin	2.29	1.87	Not applicable
Exponent of the 5th Percentile			
All Subjects	60	50	3
Pass saccharin	100	90	Not applicable
Exponent of the 95% LTL of the log PFs			
All Subjects	50	30	2
Pass saccharin	75	65	Not applicable
At or Above PF = 100	87%	82%	0%

*Where "A" was the designation of the best performing respirator of a group of four disposable half-mask D/M respirators evaluated by Danish et al (30).

No significant difference between the log PFs of male and female subjects was found utilizing a two-sample unpaired t-test (35). However, the power of this test was computed to be only 46 percent at the $\alpha = 0.05$ level (36). Assuming the difference between the mean log PFs of the male and female subjects remains unchanged, a sample size of 35 males and 35 females would boost the power to 81 percent.

However, close examination of the PFs measured in this study and that of Iverson et al. (18) shows some QNFT PFs exceeded the maximum PFs that would result from the filter penetration alone. The comparison of filter penetration and QNFT PFs for this study are shown in Table X. LPQNFT PFs in the study by Iverson et al. showed eight of twenty-four PFs greater than 1000, which is similar to the results found in this study.

TABLE X: Subjects Exceeding the Maximum Predicted PF for the Minimum, Average, and Maximum Filter Penetration

		# of Subjects with QNFT PF > Filter PF
Max. Predicted PF Given the Min. Filter Penetration	3300	0
Max. Predicted PF Given the Avg. Filter Penetration	1670	0
Max. Predicted PF Given the Max. Filter Penetration	1000	7

Since QNFT measures penetration through the filter and the faceseal, and given that faceseal penetration for half-mask respirators may be expected to be as high as 0.1 (PF = 10) (9),(16), it seems very unlikely that any subject would achieve a QNFT PF that would approach the maximum PFs resulting from filter penetration alone. This contradiction would indicate the LPQNFT method may not accurately measure true respirator fit.

Two explanations seem most likely for the PFs greater than 1000 obtained by the seven subjects. One possibility is that the particle count inside the respirator was low due to sampling bias. Myers et al. showed that for in-facepiece sampling of half-mask respirators, mean sampling bias was $-17 \pm 38\%$ (38). Factors showing the strongest influence on sampling bias were probe location, leak site, and the interaction between the leak site and the distribution of nose and mouth breathing. A negative sampling bias would result in an inflated PF. Myers et al. hypothesized that faceseal leakage was streamlining within the respirator cavity thus causing this negative bias.

A second possibility is that high particle deposition occurred at the leak site, thus reducing the particle count measured in the respirator cavity and inflating the PF. Hinds et. al. determined that for flow rates between 2 and 150 LPM through a 1.0 mm internal diameter X 10 mm long leak, losses of 2.5 μm AED particles were 8-35% (39). Another report stated that for D/M respirator leak sites with diameters less than 2.8 mm, aerosol deposition to the inner surface of the leak site may become significant, especially for supermicrometer-sized particles (40).

CONCLUSIONS

The results of the present study indicate that the 8710 D/M respirator provides a level of protection five times the ANSI APF as evaluated using the exponent of the 95% LTL of the fifth percentile of the log PFs (6). Thus, it can be said that the ANSI APF is a conservative measure of fit for this respirator. The Lowery et al. study which yielded an exponent of the 95% LTL of the fifth percentile of the log PFs of two had methodological limitations which render the study's PF rating of the 8710 invalid (13). These methodological limitations included (1) the use of a 0.7 μ m polydisperse challenge aerosol which would result in filter penetration of at least seven percent assuming low-to-moderate work activity (17), and (2) performing only one fit test for each subject and respirator which does not account for the finding that replicate fittings of one facepiece on any one user is lognormal with a variance that can be large (22).

This study found that the saccharin QLFT was not a good predictor of adequate fit for this respirator, where an adequate fit was defined as a $PF \geq 100$. The saccharin QLFT sensitivity was found to be only 43% ($n = 30$), where sensitivity was the percentage of subjects who have a $PF \geq 100$ and pass the saccharin QLFT. Results from the Marsh study support the general conclusion that the saccharin QLFT is not a good predictor of adequate fit for negative pressure half-mask respirators, when adequate fit was defined as a $PF \geq 100$ (37). The Marsh study found a saccharin QLFT sensitivity of only 40% ($n = 40$), when sensitivity was as defined above. In contrast, the Danisch et al. study found the saccharin QLFT to be a good predictor of adequate fit for disposable half-mask respirators, when an adequate fit was defined as a $PF \geq 100$ (30). The Danisch et al. study found a saccharin QLFT sensitivity of 72% ($n = 200$), when sensitivity was as defined above. Possible explanations for this difference include a larger sample size used by Danisch et al. and their allowance of a second attempt to pass the saccharin QLFT if

the subject failed on the first attempt. This second try at passing the saccharin QLFT is not mentioned in the saccharin QLFT protocols of 29CFR1910.1025 Appendix D (27).

However, interpretation of these results is conditional upon the apparent contradiction of measured QNFT PFs being greater than the maximum resulting from filter penetration alone. This would indicate that the LPQNFT method may be subject to particle deposition in leak sites (39), (40) and to the influence of conditions inside the facepiece that may lead to sampling bias (38). Further studies should be conducted to identify the cause of this contradiction.

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APPENDIX A: Filter Penetration Raw Data

F I L T E R	R E P E T	A V E R A G E	C I	P E N
1	1	2.848	0.00300	0.00105
1	2	2.901	0.00253	0.00087
1	3	2.902	0.00207	0.00071
1	4	2.883	0.00300	0.00104
1	5	2.886	0.00300	0.00104
1	6	2.873	0.00300	0.00104
1	7	2.849	0.00267	0.00094
1	8	2.854	0.00180	0.00063
1	9	2.854	0.00233	0.00082
1	10	2.875	0.00167	0.00058
2	1	2.874	0.00187	0.00065
2	2	2.810	0.00113	0.00040
2	3	2.865	0.00087	0.00030
2	4	2.971	0.00173	0.00058
2	5	3.004	0.00093	0.00031
2	6	3.031	0.00113	0.00037
2	7	3.001	0.00160	0.00053
2	8	2.980	0.00087	0.00029
2	9	2.962	0.00107	0.00036
2	10	2.953	0.00120	0.00041
3	1	2.805	0.00173	0.00062
3	2	2.810	0.00173	0.00062
3	3	2.779	0.00140	0.00050
3	4	2.776	0.00193	0.00070
3	5	2.786	0.00160	0.00057
3	6	2.786	0.00193	0.00069
3	7	2.779	0.00167	0.00060
3	8	2.781	0.00153	0.00055
3	9	2.761	0.00187	0.00068
3	10	2.751	0.00100	0.00036

APPENDIX B: Qualitative Fit Test Raw Data

S	G	S	Q
U	E	E	L
B	N	N	F
		S	T
1	2	14	0
1	2	14	0
1	2	14	0
2	2	12	0
2	2	12	0
2	2	12	0
3	2	2	0
3	2	2	0
3	2	2	0
4	2	2	0
4	2	2	0
4	2	2	0
5	2	3	0
5	2	3	0
5	2	3	0
6	2	4	1
6	2	4	1
6	2	4	1
7	2	4	0
7	2	4	0
7	2	4	0
8	2	3	1
8	2	3	1
8	2	3	1
9	2	4	1
9	2	4	1
9	2	4	1
10	2	12	0
10	2	12	0
10	2	12	0
11	2	7	0
11	2	7	0
11	2	7	0
12	2	5	0
12	2	5	0
12	2	5	0
13	2	3	1
13	2	3	1
13	2	3	1
14	2	3	1
14	2	3	1
14	2	3	1
15	2	2	1
15	2	2	1
15	2	2	1
16	1	5	1
16	1	5	1

S	G	S	Q
U	E	E	L
B	N	N	F
		S	T
16	1	5	1
17	1	2	1
17	1	2	1
17	1	2	1
18	1	9	1
18	1	9	1
18	1	9	1
19	1	3	0
19	1	3	0
19	1	3	0
20	1	2	1
20	1	2	1
20	1	2	1
21	1	2	0
21	1	2	0
21	1	2	0
22	1	4	1
22	1	4	1
22	1	4	1
23	1	7	0
23	1	7	0
23	1	7	0
24	1	4	0
24	1	4	0
24	1	4	0
25	1	3	0
25	1	3	0
25	1	3	0
26	1	3	1
26	1	3	1
26	1	3	1
27	1	12	0
27	1	12	0
27	1	12	0
28	1	3	0
28	1	3	0
28	1	3	0
29	1	3	0
29	1	3	0
29	1	3	0
30	1	2	0
30	1	2	0
30	1	2	0

APPENDIX C: Quantitative Fit Test Raw Challenge and Exercise Particle Counts Per Twenty Second Sample

S U B	G E N	T E S T	C O 1	N B 1	C O 2	D B	C O 3	S S	C O 4	U D	C O 5	T	C O 6	N B 2	C O 7
1	2	1	24950	47	23630	49	23304	54	22680	46	22785	36	23332	65	23097
1	2	2	23097	70	23452	41	23043	109	23516	156	21745	33	23550	70	21720
1	2	3	21720	98	24081	65	23642	206	23096	100	22768	37	23404	82	22876
2	2	1	23956	38	22740	63	22802	36	22462	32	21811	42	23095	35	22281
2	2	2	22281	36	22104	35	21915	22	21697	29	21264	19	22249	42	22768
2	2	3	22768	43	22854	16	22856	31	22441	23	22157	21	22806	50	23371
3	2	1	24177	110	22389	165	23260	59	21673	137	21151	62	22310	66	19732
3	2	2	19722	301	22618	166	22218	34	22315	287	22525	72	21871	50	21998
3	2	3	21998	286	21038	76	21945	152	22372	186	22535	58	22487	331	22464
4	2	1	23907	333	24183	450	23883	55	23636	297	23722	17	23132	23	22159
4	2	2	22159	24	21362	21	21044	33	22243	244	21833	20	21706	42	21748
4	2	3	21748	154	20084	311	20834	64	21196	173	21365	12	21715	64	21880
5	2	1	22121	51	22049	71	22056	87	22082	128	22333	43	22652	148	22272
5	2	2	22272	126	21926	172	21366	35	22820	114	22916	53	22443	216	22876
5	2	3	22876	111	22916	139	22160	67	21805	65	21184	41	22780	91	21993
6	2	1	18694	44	18589	41	18244	48	17405	132	19052	25	18314	19	19360
6	2	2	19360	24	19067	37	19134	33	18762	32	19597	8	19519	12	19401
6	2	3	19401	20	18848	48	18427	43	18859	39	19118	9	18914	15	19158
7	2	1	18823	22	19102	22	18687	18	17870	41	17028	23	17627	35	16624
7	2	2	16624	61	17875	18	18094	22	17793	50	17927	18	18000	35	18298
7	2	3	18298	27	16289	18	17948	14	18533	122	18471	6	18275	18	18887
8	2	1	17648	35	17236	38	15123	169	17029	62	16438	17	16793	23	17321
8	2	2	17321	11	17088	14	17243	13	17109	8	18044	11	17802	7	18209
8	2	3	18209	5	16745	9	17473	10	18219	10	17791	13	17735	14	17740
9	2	1	18345	86	18264	85	17847	123	17976	190	18179	48	17750	76	18100
9	2	2	18100	81	18988	96	18450	90	18845	92	18906	43	18814	73	19041
9	2	3	19041	134	19053	113	18541	94	19309	95	19250	42	19134	106	18475
10	2	1	22669	42	21834	30	21510	40	21830	62	20878	35	21629	35	21865
10	2	2	21865	74	21577	37	21041	44	20772	70	21082	47	21482	51	20893
10	2	3	20893	73	21808	48	21310	76	21972	62	21176	43	22025	55	22256
11	2	1	20938	498	21426	885	22119	1404	22008	657	22283	22	22129	319	22405
11	2	2	22405	285	22562	331	22846	512	22946	1136	22823	57	23395	363	23593
11	2	3	23593	458	23620	432	23469	374	20663	1067	23507	104	23506	564	23386
12	2	1	21701	95	21178	192	20815	145	20677	169	21501	57	21192	96	20510
12	2	2	20510	118	21788	245	21923	100	21181	171	21592	38	22055	287	22504
12	2	3	22504	80	22198	127	21484	74	21893	56	21819	29	22222	67	22181
13	2	1	23305	37	23959	43	23800	68	23888	58	23644	73	23551	24	22965
13	2	2	22257	24	22919	26	23479	20	22814	31	23229	60	23172	28	22846
13	2	3	21735	22	22985	16	22132	70	22947	103	22948	81	22947	64	22513
14	2	1	25492	8	22900	6	21787	12	21302	8	21440	10	20579	11	20924
14	2	2	20924	5	20676	12	20634	14	20730	10	20756	11	20637	10	20489
14	2	3	20489	7	20967	7	20766	13	20790	9	20418	9	21215	4	21727
15	2	1	24422	35	21142	59	21766	58	22782	50	23524	32	22619	79	23316
15	2	2	22948	32	23388	42	22919	36	22462	42	22769	23	22744	42	22957
15	2	3	22525	31	22054	16	23707	32	23624	23	22993	17	24077	17	23929
16	1	1	19483	34	19941	8	19825	7	20525	10	20595	7	20671	24	20796
16	1	2	20460	57	21012	26	21188	14	20747	6	20976	4	21310	23	21709

S U B	G E N	T E S T	C O 1	N B 1	C O 2	D B	C O 3	S S	C O 4	U D	C O 5	T	C O 6	N B 2	C O 7
16	1	3	21209	23	21850	9	22004	4	21851	3	21767	2	21280	18	22864
17	1	1	21176	66	19507	50	20127	52	19057	85	20248	47	20120	87	19823
17	1	2	19823	77	19560	40	19335	48	20257	48	20980	42	21018	56	20562
17	1	3	20562	84	21835	60	20082	36	21914	31	21365	38	20370	118	21178
18	1	1	22123	42	20988	30	20910	27	20281	40	20167	44	20794	30	20092
18	1	2	20092	30	20034	22	20464	35	20779	25	20010	27	21186	29	20644
18	1	3	20644	31	20991	82	19732	55	20212	21	20254	19	20770	18	20225
19	1	1	22640	88	22481	266	21439	364	22411	188	22476	107	22690	42	22017
19	1	2	22017	50	22258	113	20573	85	20865	53	22188	27	22418	19	22673
19	1	3	22673	18	22614	32	22099	68	22526	42	22627	21	23404	34	22537
20	1	1	23058	20	22179	30	23226	50	22147	48	22779	16	22881	26	23180
20	1	2	23180	38	23922	43	23660	47	23147	54	23454	18	24552	34	24564
20	1	3	24564	104	24837	143	24321	95	24421	77	24869	25	24796	55	24996
21	1	1	18968	63	18985	45	16957	31	17792	46	18186	58	18653	116	18820
21	1	2	18820	182	18467	34	17850	52	18225	21	17561	28	19368	100	18873
21	1	3	18873	124	18621	105	18897	57	19437	21	19551	9	19676	110	20232
22	1	1	21159	6	19908	11	19519	13	18993	7	18913	10	19031	9	19004
22	1	2	19004	14	18846	17	18992	21	19254	13	19435	8	19857	10	20226
22	1	3	20226	10	19631	11	20117	21	18630	12	20310	8	20143	11	20365
23	1	1	14535	10	14657	16	14655	24	15351	16	15588	11	15513	10	15921
23	1	2	15921	17	15924	7	15846	10	15910	9	16510	4	16193	12	15791
23	1	3	15791	16	16066	14	16358	19	16174	15	16718	14	17321	12	17313
24	1	1	17282	22	18645	30	19612	19	19537	22	19954	26	20053	30	20318
24	1	2	20318	17	20283	10	19206	24	20570	15	20672	8	20809	14	20830
24	1	3	20830	21	20606	14	20855	15	20697	23	20889	12	19916	26	21608
25	1	1	19567	72	19226	194	19196	205	18777	277	19499	55	19175	209	19430
25	1	2	19430	100	19513	113	19613	174	19558	168	19017	43	19447	274	19856
25	1	3	19856	40	19454	49	19855	63	19827	137	19431	49	19905	127	20555
26	1	1	20923	56	20896	157	20287	180	21268	126	20987	31	21017	65	20791
26	1	2	20679	59	19692	159	20095	141	18981	71	19983	24	20012	75	21467
26	1	3	20865	96	21109	152	20601	219	20785	222	21293	16	20969	136	20828
27	1	1	23304	19	22669	17	22296	14	22429	18	22815	9	22280	15	22373
27	1	2	22373	18	22817	19	19499	15	22695	19	22239	8	23614	13	23321
27	1	3	23321	11	23400	9	23247	13	23575	13	23908	4	22889	8	23405
28	1	1	17191	8	18032	9	18170	16	17516	21	17397	15	18704	5	18903
28	1	2	18903	8	18812	13	19158	24	18779	13	19045	26	19505	55	20058
28	1	3	20058	14	21106	27	20559	14	20245	11	20192	18	20672	12	20930
29	1	1	20173	17	19667	15	19526	14	19193	15	19185	12	19224	20	20293
29	1	2	20293	19	20642	19	18534	13	21333	17	21381	10	21213	22	21722
29	1	3	21722	15	21830	23	21244	26	20591	21	21496	17	19432	10	20789
30	1	1	23352	16	22110	39	21923	60	20889	26	21098	18	21478	39	21111
30	1	2	21111	23	21160	19	21160	29	21343	25	21258	13	21289	24	21330
30	1	3	21330	11	20474	13	21022	33	20434	21	20677	6	21361	14	21049

APPENDIX D: Quantitative Fit Test Exercise and Overall Protection Factors

S U B	G E N	T E S T	N B 1 P F	D B P F	S S P F	U D P F	T P F	N B 2 P F	P F	P F C O R R E C
1	2	1	517	479	426	494	641	357	470	282
1	2	2	332	567	214	145	686	323	287	172
1	2	3	234	367	113	229	624	282	237	142
2	2	1	614	361	629	692	535	648	553	332
2	2	2	616	629	991	741	1145	536	722	433
2	2	3	530	1428	731	970	1071	462	742	445
3	2	1	212	138	381	156	350	319	222	133
3	2	2	70	135	655	78	308	439	145	87
3	2	3	75	283	146	121	388	68	122	73
4	2	1	72	53	432	80	1378	985	122	73
4	2	2	907	1010	656	90	1088	517	342	205
4	2	3	136	66	328	123	1795	341	161	97
5	2	1	433	311	254	173	523	152	253	152
5	2	2	175	126	631	201	428	105	187	112
5	2	3	206	162	328	331	536	246	261	156
6	2	1	424	449	371	138	747	991	356	213
6	2	2	801	516	574	599	2445	1622	787	472
6	2	3	956	388	434	487	2113	1269	649	389
7	2	1	862	859	1015	426	753	489	664	399
7	2	2	283	999	816	357	998	519	522	313
7	2	3	641	951	1303	152	3062	1032	532	319
8	2	1	498	426	95	270	977	742	286	172
8	2	2	1564	1226	1321	2197	1629	2572	1635	981
8	2	3	3495	1901	1785	1801	1366	1267	1740	1044
9	2	1	213	212	146	95	374	236	178	107
9	2	2	229	195	207	205	439	259	237	142
9	2	3	142	166	201	203	457	177	195	117
10	2	1	530	722	542	344	607	621	532	319
10	2	2	294	576	475	299	453	415	395	237
10	2	3	292	449	285	348	502	403	364	218
11	2	1	43	25	16	34	1009	70	35	21
11	2	2	79	69	45	20	405	65	51	31
11	2	3	52	55	59	21	226	42	46	27
12	2	1	226	109	143	125	375	217	167	100
12	2	2	179	89	216	125	574	78	136	82
12	2	3	279	172	293	390	759	331	305	183
13	2	1	639	555	351	410	323	969	469	282
13	2	2	941	892	1157	743	387	822	732	439
13	2	3	1016	1410	322	223	283	355	384	230
14	2	1	3025	3724	1795	2671	2101	1887	2365	1419
14	2	2	4160	1721	1477	2074	1882	2056	2001	1201
14	2	3	2961	2981	1598	2289	2313	5368	2549	1529
15	2	1	651	364	384	463	721	291	432	259
15	2	2	724	551	630	538	989	544	632	379

S U B	G E N	T E S T	N B 1 P F	D B P F	S S P F	U D P F	T P F	N B 2 P F	P F	P F C O R R E C
15	2	3	719	1430	740	1013	1384	1412	1024	614
16	1	1	580	2485	2882	2056	2948	864	1346	808
16	1	2	364	812	1498	3477	5286	935	969	581
16	1	3	936	2436	5482	7270	10762	1226	2216	1330
17	1	1	308	396	377	231	429	230	309	185
17	1	2	256	486	412	430	500	371	389	234
17	1	3	252	349	583	698	549	176	343	206
18	1	1	513	698	763	506	465	681	583	350
18	1	2	669	920	589	816	763	721	732	439
18	1	3	672	248	363	963	1080	1139	540	324
19	1	1	256	83	60	119	211	532	126	76
19	1	2	443	190	244	406	826	1187	371	223
19	1	3	1258	699	328	538	1096	676	630	378
20	1	1	1131	757	454	468	1427	886	716	430
20	1	2	620	553	498	431	1334	722	607	364
20	1	3	238	172	257	320	993	453	296	178
21	1	1	301	399	560	391	318	162	308	185
21	1	2	102	534	347	852	659	191	267	160
21	1	3	151	179	336	928	2179	181	270	162
22	1	1	3422	1792	1481	2708	1897	2113	2073	1244
22	1	2	1352	1113	911	1488	2456	2004	1391	834
22	1	3	1993	1807	923	1623	2528	1841	1624	975
23	1	1	1460	916	625	967	1414	1572	1043	626
23	1	2	937	2269	1588	1801	4088	1333	1627	976
23	1	3	996	1158	856	1096	1216	1443	1098	659
24	1	1	817	638	1030	898	769	673	783	470
24	1	2	1194	1974	829	1375	2593	1487	1384	830
24	1	3	987	1481	1385	904	1700	799	1120	672
25	1	1	269	99	93	69	352	92	114	68
25	1	2	195	173	113	115	447	72	134	81
25	1	3	491	401	315	143	401	159	256	154
26	1	1	373	131	115	168	677	322	203	122
26	1	2	342	125	139	274	833	277	226	135
26	1	3	219	137	94	95	1321	154	149	89
27	1	1	1210	1323	1597	1257	2505	1488	1472	883
27	1	2	1255	1114	1406	1182	2866	1805	1444	867
27	1	3	2124	2592	1801	1826	5850	2893	2423	1454
28	1	1	2201	2011	1115	831	1203	3761	1446	868
28	1	2	2357	1460	790	1455	741	360	834	501
28	1	3	1470	772	1457	1838	1135	1733	1286	772
29	1	1	1172	1306	1383	1279	1600	988	1260	756
29	1	2	1077	1031	1533	1256	2130	976	1239	744
29	1	3	1452	936	805	1002	1204	2011	1127	676
30	1	1	1421	565	357	807	1183	546	653	392

S	G	T	N	D	S	U	T	N	P	P
U	E	E	B	B	S	D	P	B	F	F
B	N	S	1	P	P	P	F	2		C
		T	P	F	F	F		P		O
			F					F		R
										E
										C
30	1	2	919	1114	733	852	1636	888	958	575
30	1	3	1900	1596	628	979	3503	1515	1273	764

APPENDIX E: Log of the Quantitative Fit Test Exercise and Overall Protection Factors

S U B	G E N	T E S T	L N B 1 P F	L N D B P F	L N S S P F	L N U D P F	L N T P F	L N N B 2 P F	L N P F	L N P F C O R R
1	2	1	6.248	6.172	6.054	6.203	6.462	5.878	6.153	5.643
1	2	2	5.807	6.340	5.364	4.977	6.531	5.779	5.660	5.149
1	2	3	5.454	5.906	4.731	5.435	6.436	5.643	5.468	4.957
2	2	1	6.421	5.890	6.444	6.539	6.282	6.474	6.316	5.805
2	2	2	6.424	6.444	6.899	6.608	7.043	6.284	6.582	6.071
2	2	3	6.274	7.264	6.594	6.877	6.976	6.135	6.610	6.099
3	2	1	5.355	4.930	5.942	5.052	5.859	5.764	5.405	4.894
3	2	2	4.253	4.906	6.484	4.358	5.731	6.084	4.974	4.464
3	2	3	4.321	5.645	4.982	4.793	5.961	4.218	4.802	4.291
4	2	1	4.280	3.978	6.068	4.379	7.228	6.892	4.804	4.293
4	2	2	6.810	6.917	6.486	4.503	6.993	6.249	5.835	5.324
4	2	3	4.911	4.186	5.794	4.812	7.493	5.831	5.082	4.572
5	2	1	6.071	5.739	5.536	5.156	6.260	5.022	5.533	5.022
5	2	2	5.167	4.835	6.448	5.301	6.059	4.653	5.231	4.720
5	2	3	5.329	5.088	5.793	5.801	6.284	5.505	5.563	5.052
6	2	1	6.049	6.107	5.917	4.928	6.616	6.899	5.874	5.363
6	2	2	6.685	6.247	6.353	6.396	7.802	7.391	6.668	6.158
6	2	3	6.863	5.962	6.072	6.188	7.656	7.146	6.476	5.965
7	2	1	6.759	6.756	6.923	6.053	6.625	6.193	6.499	5.988
7	2	2	5.645	6.907	6.704	5.878	6.906	6.251	6.258	5.747
7	2	3	6.462	6.858	7.172	5.022	8.027	6.940	6.277	5.767
8	2	1	6.211	6.054	4.555	5.598	6.885	6.609	5.658	5.147
8	2	2	7.355	7.112	7.186	7.695	7.396	7.853	7.399	6.889
8	2	3	8.159	7.550	7.487	7.496	7.220	7.144	7.461	6.951
9	2	1	5.361	5.359	4.981	4.555	5.925	5.463	5.182	4.671
9	2	2	5.433	5.273	5.334	5.324	6.084	5.558	5.467	4.957
9	2	3	4.957	5.114	5.305	5.313	6.125	5.178	5.273	4.762
10	2	1	6.272	6.583	6.295	5.842	6.409	6.432	6.277	5.766
10	2	2	5.682	6.356	6.164	5.700	6.115	6.029	5.978	5.467
10	2	3	5.678	6.107	5.652	5.852	6.219	5.998	5.896	5.385
11	2	1	3.750	3.203	2.755	3.518	6.917	4.246	3.548	3.037
11	2	2	4.368	4.228	3.800	3.003	6.005	4.170	3.936	3.425
11	2	3	3.942	3.998	4.078	3.030	5.421	3.727	3.821	3.310
12	2	1	5.419	4.695	4.963	4.827	5.926	5.381	5.120	4.609
12	2	2	5.189	4.491	5.373	4.829	6.353	4.352	4.914	4.403
12	2	3	5.633	5.147	5.680	5.967	6.632	5.803	5.719	5.208
13	2	1	6.459	6.320	5.860	6.016	5.778	6.876	6.151	5.640
13	2	2	6.847	6.794	7.054	6.610	5.958	6.711	6.596	6.085
13	2	3	6.924	7.251	5.775	5.406	5.647	5.873	5.950	5.439
14	2	1	8.015	8.223	7.493	7.890	7.650	7.542	7.769	7.258
14	2	2	8.333	7.451	7.298	7.637	7.540	7.629	7.602	7.091
14	2	3	7.993	8.000	7.377	7.736	7.746	8.588	7.843	7.332
15	2	1	6.478	5.896	5.951	6.138	6.581	5.672	6.069	5.558
15	2	2	6.585	6.312	6.446	6.289	6.897	6.299	6.450	5.939

S U B	G E N	T E S T	L N B 1 P F	L N D B P F	L N S S P F	L N U D P F	L N T P F	L N N B 2 P F	L N P F	L N P F C O R R
15	2	3	6.578	7.265	6.606	6.921	7.233	7.253	6.931	6.421
16	1	1	6.363	7.818	7.966	7.629	7.989	6.761	7.205	6.694
16	1	2	5.897	6.699	7.312	8.154	8.573	6.841	6.876	6.365
16	1	3	6.842	7.798	8.609	8.891	9.284	7.112	7.704	7.193
17	1	1	5.731	5.982	5.932	5.443	6.062	5.436	5.733	5.222
17	1	2	5.544	6.187	6.022	6.063	6.215	5.917	5.964	5.453
17	1	3	5.531	5.856	6.369	6.548	6.308	5.171	5.839	5.328
18	1	1	6.241	6.549	6.637	6.226	6.143	6.524	6.369	5.858
18	1	2	6.505	6.825	6.379	6.704	6.637	6.581	6.595	6.084
18	1	3	6.510	5.515	5.895	6.871	6.984	7.038	6.291	5.781
19	1	1	5.547	4.413	4.098	4.782	5.352	6.277	4.836	4.326
19	1	2	6.093	5.244	5.496	6.007	6.717	7.079	5.917	5.407
19	1	3	7.137	6.549	5.793	6.287	6.999	6.516	6.445	5.935
20	1	1	7.031	6.629	6.118	6.148	7.263	6.786	6.574	6.063
20	1	2	6.429	6.316	6.210	6.067	7.196	6.582	6.409	5.898
20	1	3	5.470	5.147	5.547	5.769	6.901	6.115	5.691	5.180
21	1	1	5.708	5.990	6.329	5.969	5.761	5.085	5.729	5.218
21	1	2	4.629	6.281	5.849	6.748	6.491	5.253	5.589	5.078
21	1	3	5.019	5.185	5.818	6.833	7.687	5.201	5.598	5.087
22	1	1	8.138	7.491	7.301	7.904	7.548	7.656	7.637	7.126
22	1	2	7.209	7.015	6.814	7.305	7.806	7.603	7.237	6.727
22	1	3	7.597	7.499	6.827	7.392	7.835	7.518	7.393	6.882
23	1	1	7.286	6.820	6.438	6.874	7.254	7.360	6.950	6.439
23	1	2	6.842	7.727	7.370	7.496	8.316	7.195	7.394	6.884
23	1	3	6.903	7.054	6.752	7.000	7.103	7.275	7.001	6.491
24	1	1	6.705	6.458	6.938	6.800	6.646	6.512	6.663	6.152
24	1	2	7.085	7.588	6.720	7.226	7.860	7.305	7.233	6.722
24	1	3	6.894	7.300	7.234	6.807	7.439	6.683	7.021	6.510
25	1	1	5.596	4.595	4.528	4.235	5.862	4.526	4.734	4.223
25	1	2	5.272	5.154	4.723	4.743	6.103	4.273	4.900	4.389
25	1	3	6.197	5.994	5.752	4.965	5.995	5.071	5.545	5.034
26	1	1	5.923	4.876	4.749	5.122	6.518	5.773	5.315	4.804
26	1	2	5.835	4.829	4.931	5.615	6.725	5.622	5.419	4.908
26	1	3	5.387	4.921	4.548	4.551	7.186	5.035	5.004	4.493
27	1	1	7.098	7.187	7.376	7.136	7.826	7.305	7.295	6.784
27	1	2	7.135	7.015	7.249	7.075	7.961	7.498	7.275	6.765
27	1	3	7.661	7.860	7.496	7.510	8.674	7.970	7.793	7.282
28	1	1	7.697	7.606	7.017	6.723	7.093	8.232	7.277	6.766
28	1	2	7.765	7.286	6.672	7.283	6.608	5.885	6.727	6.216
28	1	3	7.293	6.648	7.284	7.516	7.034	7.458	7.160	6.649
29	1	1	7.066	7.175	7.232	7.154	7.378	6.896	7.139	6.628
29	1	2	6.982	6.938	7.335	7.136	7.664	6.883	7.122	6.612
29	1	3	7.281	6.842	6.690	6.910	7.093	7.606	7.027	6.516
30	1	1	7.259	6.336	5.877	6.694	7.076	6.303	6.481	5.970

S	G	T		L	L	L	L	L	L	L
U	E	E		N	N	N	N	N	N	N
B	N	S		N	D	S	T	N	P	P
		T		B	B	S	P	B	F	F
				1	P	P	F	2		C
				P	F	P		P		O
				F		F		F		R

30	1	2	6.823	7.015	6.597	6.748	7.400	6.789	6.865	6.354
30	1	3	7.550	7.375	6.443	6.886	8.161	7.323	7.149	6.639