NUREG/CR-5090
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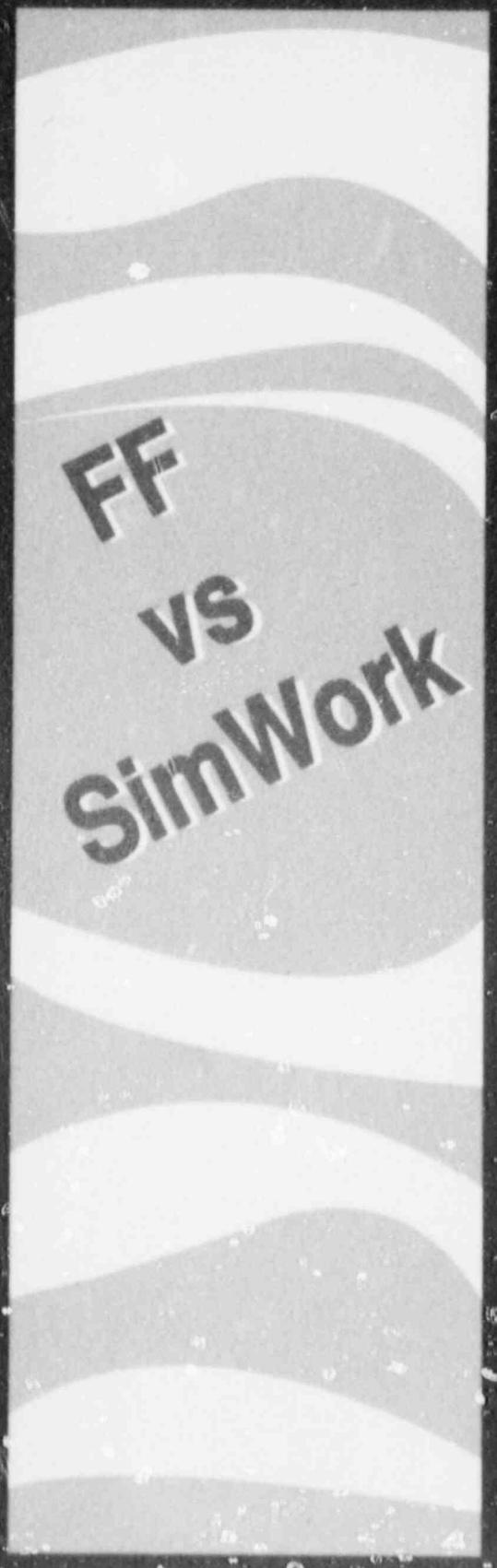
Effects of Temperature and Humidity on Respirator Fit Under Simulated Work Conditions



Los Alamos

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Effects of Temperature and Humidity on Respirator Fit Under Simulated Work Conditions

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GLOSSARY

ANSI	American National Standards Institute
APF	assigned protection factor
AP/NP	air purifying/negative pressure
CF	continuous flow
CT	core temperature
DF	Dynatec-Frontier
DEHS	di-2-ethylhexyl sebacate
EC	environmental chamber
FF	fit factor
FF/PD	full facepiece/pressure demand
H&S	health and safety
HEPA	high-efficiency particulate air
HP	Hewlett Packard
MSA	Mine Safety Appliance
MUC	maximum use concentration
MXT	maximum stress electrocardiogram
NIOSH	National Institute of Occupational Safety and Health
NRC	Nuclear Regulatory Commission
NP	negative pressure
OSHA	Occupational Safety and Health Administration
PAPR	powered air-purifying respirator
PD	pressure demand
PF	protection factor
PostWork	exercises done before leaving environmental chamber
PP	positive pressure
PreFit	exercises done in the Dynatec-Frontier chamber
PreWork	exercises done immediately upon entering environmental chamber
QFT	quantitative fit test
RH	relative humidity
SCBA	self-contained breathing apparatus
SimWork	simulated work
TLV	threshold limit value
YSI	Yellow Springs Instrumentation

EXECUTIVE SUMMARY

A study at the Los Alamos National Laboratory compared quantitative fit factors and simulated work factors under rigorous but controlled and reproducible conditions to determine the effects of temperature and humidity on respirator fit. This study used a commercially available two-man fit chamber and a 28.3-m^3 environmental chamber (EC) set at six conditions (0°C, 21°C, and 32°C each at 15% and 85% RH) that simulated U.S. work environments. Seven respirators were tested including two helmet powered air-purifying respirators (PAPRs), one half-mask PAPR, one full-facepiece pressure-demand (FF/PD) air-line respirator, one continuous-flow hood, one full-facepiece negative-pressure respirator (best fit of three sizes), and one half-mask negative-pressure respirator (best fit of three sizes).

A limited test panel of 10 subjects (22 to 48 years of age) was selected by specific fit factor (FF) criteria and a medical determination of physical well-being and work capability.

The test results indicate that the performance of one PAPR helmet is significantly degraded during the simulated work exercises at 32°C/85% RH EC condition. Eighty percent of the test subjects had FFs less than 1000 (80%). The half-mask PAPR performance was not affected.

The EC conditions and exercises had no effect on the performance of the continuous-flow hood. There was limited effect on the performance of the FF/PD air-line respirator at 32°C/85% RH (20% of subjects).

Poor reproducibility was noted for one helmet PAPR for six PreFit FFs determined at room temperature in the commercial fit chamber. This poor reproducibility was also observed for 6 of 10 subjects testing the negative-pressure half-mask and 7 of 10 testing the negative-pressure full-facepiece respirators.

The performance of the negative-pressure half-mask and full-facepiece respirators is degraded significantly during fit tests at high humidity and high temperature in the environmental chamber. The significant degradation of FFs for the negative-pressure half-mask at high humidity at both 21°C and 32°C is probably due to facepiece slippage caused by sweating during simulated and PostWork exercises.

Tight-fitting PAPRs provide higher protection than helmets or loose-fitting PAPRs. PAPRs should be divided into two classes: those with tight-fitting facepieces and those with helmets or loose-fitting facepieces. The ANSI Z88.2-1980 exercises for the determination of quantitative FFs for loose-fitting and tight-fitting respirators do not adequately simulate work situations. There should be more dynamic full-body movement exercises, especially those motions in which the individual bends over and stands up repeatedly.

The preselection criteria used for test subject selection for the negative-pressure respirators were not met during PreFit tests by most subjects.

The following information was obtained from test subjects' comments regarding respirator comfort:

(a) Continuous-flow respirators are more comfortable in hot and humid conditions than tight-fitting pressure-demand devices.

(b) Continuous-flow hoods are the most comfortable of all devices in hot and humid conditions.

(c) The half-mask facepiece is uncomfortable across the bridge of the nose for most test subjects. They also said that the half-mask facepiece seemed to slip on their faces when they sweated.

(d) The negative-pressure full-facepiece causes uncomfortable pressure across most subjects' foreheads. All subjects remarked about the large amount of moisture that accumulated in the facepiece from sweat and exhaled moisture.

A more extensive study should be conducted in hot and humid conditions and simulated work with a larger of number negative-pressure respirators from different manufacturers.

EFFECTS OF TEMPERATURE AND HUMIDITY ON RESPIRATOR FIT UNDER SIMULATED WORK CONDITIONS

by

B. J. Skaggs, J. M. Loibl, K. D. Carter, and E. C. Hyatt

ABSTRACT

A study conducted at the Los Alamos National Laboratory compared quantitative fit factors and simulated work factors and determined the effects of temperature and humidity on respirator fit. This study used a commercially available fit chamber and an environmental chamber set at six conditions to simulate U.S. work environments. Seven respirators were tested on a limited test panel of 10 subjects. The test results indicate that the performance of one powered air-purifying respirator (PAPR) helmet is significantly degraded during the simulated work exercises, whereas the half-mask PAPR performance was not affected. Tight-fitting facepiece PAPRs provide higher protection than loose-fitting PAPRs. The performance of the negative-pressure half-mask and full-facepiece respirators is degraded during fit tests at high humidity and high temperature. The degradation of the fit factors for the negative-pressure half-mask during high humidity at ambient and high temperatures is probably due to facepiece slippage caused by sweating. More dynamic exercises, including motions in which the individual bends over and stands up repeatedly, are recommended to develop quantitative fit factors that adequately simulate work factors. Tight-fitting facepiece PAPRs should not be classified with loose-fitting PAPRs.

I. INTRODUCTION

A. Background

The overall protection afforded by a given respirator design may be presented by its protection factor (PF), which is the ratio of the concentration of contaminant in the ambient atmosphere to that inside the facepiece. Originally, PFs were determined in an aerosol-filled chamber by conducting quantitative leak measurements on a group of test subjects wearing the specific respirator type. If one subject received a low PF, then the overall PF assigned to that type (half-mask, full facepiece, etc.) was decreased so that all wearers were protected. Hyatt[1] developed the assigned protection factors (APFs) listed in Table I. The PF was used to select the respirator type for an area where the hazard and its concentration were known. For example, a respirator with a PF = 10 may be selected for use where the maximum use concentration (MUC) is 10 times the threshold limit value (TLV) or the product of the hazard's ceiling concentration and the PF establish a MUC for short-time respirator use.

Table I. Assigned Protection Factors (APFs)[1]

Respirator Class	APF
Negative Pressure	
Half mask	10
Full facepiece	50
Positive Pressure, Atmosphere Supplying, or PAPR	
Half mask	1,000
Full facepiece or hood, helmet, or suit	2,000
SCBA, full facepiece	10,000

Later it became important to determine the respirator that best fits a wearer to protect him at his job, and the term fit factor (FF) was coined. The FF is an *individual* PF, unique for that wearer and respirator. Because an organization must invest in manpower and equipment to perform quantitative FFs, the question must be answered as to whether this factor based on laboratory testing actually predicts the on-the-job protection.

The effect of temperature and humidity on the performance of respirators has also been of concern to health and safety (H&S) personnel for many decades. The performance of self-contained breathing apparatus (SCBA) and gas masks at low temperatures during emergency use in industry and by fire fighters was of major concern by all users. Before World War II, the Army Chemical Corps was aware that a nose cup must be used inside the facepiece to prevent fogging caused by moist exhaled air striking the inside of the lens in a cold environment. All full-facepiece masks are now designed so that the incoming fresh air sweeps over the inside of the lens to reduce fogging.

In 1961, the Los Alamos National Laboratory conducted tests at temperatures ranging down to –30°F to determine the performance and reliability of SCBA and full-facepiece gas masks. The impetus for this study was a Navy experimental nuclear reactor excursion in Idaho in 1960, when temperatures were down to –20°F and entry by personnel wearing respirators was limited to 2 to 5 minutes because of reduced visibility caused by ice crystal formation on the lens. The primary purpose of the Los Alamos study was to learn how to provide good visibility at low temperatures. Personnel wore various commercial respirators in a 13- by 15-ft environmental test chamber while walking around the perimeter of the test chamber at approximately 3 miles per hour (mph) for approximately 20 to 30 minutes. Hyatt's report indicated that the three full-facepiece masks used with antifog compounds, but without nose cups, were satisfactory and provided adequate visibility at temperatures down to 0°F.[2] However, tests made with several subjects at temperatures of –10°F, –20°F, and –30°F showed that a properly fitted nose cup is essential to maintain satisfactory visibility for a minimum of 30 minutes. Antifog compound alone is of little help below 0°F. Freezing below 0°F of the exhalation valve was observed on some individuals. The SCBA regulator functioned properly at temperatures down to and including –30°F.

Respirator wearers have complained of discomfort and, in some cases, skin rash during the use of elastomeric half-mask respirators with dust and organic vapor/acid gas cartridges in high temperature/high humidity since they were approved in the 1930s. Another concern of H&S personnel and wearers was the instability of the facepiece, which would slip down a sweaty wearer's nose, resulting in facepiece leaks. During the period of 1972-1973,

the Los Alamos National Laboratory, Respirator Research and Development Section, quantitatively measured the leakage that occurred when an elastomer half-mask respirator actually slid down the nose of a volunteer test subject who sweated profusely while walking at 4 mph on a treadmill adjusted at a 5% grade.[3] Quantitative FFs were measured before and during the exercise. For a few subjects, the leakage increased from 10% to 20% (from an initial value of <0.1%) when the half-mask facepiece slipped down the nose because of perspiration. This slippage was observed in 1984 when the new environmental chamber (EC) was demonstrated to the project sponsor monitors early in the project.

In 1940, the Bureau of Mines approved dust and fume respirators with a cloth facelet that fit over the facepiece sealing edge where it contacted the wearer's face. The cloth facelet was used extensively on dust respirators worn by outdoor workers in hot and humid climates (for example, the Gulf Coast) and by workmen in smelters and the steel industry around furnaces and on coke ovens. Quantitative fit tests (QFTs) on respirators used with facelets demonstrated a leakage of 0.1% to 0.5%, which was of major concern when a potential exposure to carcinogens existed. For this reason, the approval of the facelets was discontinued in the early 1970s.

The problem of moisture condensation and liquid accumulation inside full-facepiece respirators and gas masks during use in high temperatures and/or high humidity has been known for years and reported by some investigators.[4] During a 1958 field evaluation in the South Pacific of the new experimental Army M17 gas mask, wearers would pour liquid from the M17 facepiece when they removed it after about one hour of use. No quantitative measurements were made of potential full-facepiece leakage during this evaluation other than bioassay samples where feasible.

The use of continuous-flow supplied-air respirators and hoods in hot and humid climates has been popular because of their cooling effect, which usually encourages the use of large volumes of airflow, generally above the minimum airflow required on the approval label. However, use of these devices in cold climates or working areas generally causes the wearer to reduce the airflow to prevent chilling (or frostbite). The reduced airflow in cold work areas may create a negative pressure in the facepiece or hood and cause inward leakage of contaminant. A solution to the above extreme temperatures for supplied-air hood and suit users is the Vortex tube cooling (or heating) system available since the early 1960s.

Although the initial objective of this study was to determine FFs under actual use conditions, it was evident to the funding organizations, the Nuclear Regulatory Commission (NRC) and Occupational Safety and Health Administration (OSHA), and the researchers, Los Alamos National Laboratory, that a necessary first step was the evaluation of FFs under more rigorous, but controlled and reproducible, conditions. It was decided that testing should be performed in an environmental chamber with the respirator wearer using more rigorous movements and with temperature-humidity extremes before performing extensive field studies. These environmental chambers tests would provide a better estimate of actual use performance than are provided by typical laboratory-measured FFs.

B. Problem Statement

The study was designed to simulate actual working environments while providing statistical data on the relationship of the FFs and the simulated work (SimWork) factors.

II. OBJECTIVES

Three primary objectives were established for this study:

Objective (1): Measure SimWork factors on respirator wearers (test subjects). A SimWork is a FF measured under simulated work conditions (in an environmental chamber).

Objective (2): Determine a relationship between FFs measured on the subject in the fit chamber and the SimWork factors measured on the subject in the environmental chamber (FF vs SimWork).

Objective (3): Determine if temperature and humidity affect the fit of a respirator.

III. APPROACH

As a precursor to a proposed field study, this study was designed to determine FF and SimWork factor in a simulated work situation. Ten test subjects were quantitatively fit tested in a standard test chamber before entering the environmental

chamber set at a temperature and humidity simulating working conditions. As the subjects performed work activities (exercises selected to duplicate many working body movements—shoveling, lifting and carrying loads for short distances, and swinging sledgehammers), additional quantitative fit measurements were made to determine how well the respirator maintained its original fit under these conditions. The temperature and humidity of the environmental chamber were varied to allow each respirator to be worn in different simulated work environments and to evaluate their effects on the fit of the respirators.

IV. METHODOLOGY

A. Subject Selection

A document describing the study was sent to all prospective subjects. Interested persons then attended a meeting in which the following items were discussed: (1) all medical screening tests used for acceptance, (2) work exercises to be performed, (3) length of each test, (4) amount paid for each test, and (5) safety equipment and safety precautions for subject protection. A demonstration of the donning and removal procedures for each respirator was presented, and each subject was given an opportunity to ask questions concerning the study.

A panel of 10 test subjects, 22 to 48 years of age, was selected after a medical determination of their physical well-being and of whether they could perform the required exercises under the study temperatures and humidities. Each subject also was required to achieve a minimum preselection FF (pp. 10, 14) with various respirators before participation in the study. Sixteen people had to be cleared through the selection procedures to provide a complete panel of 10 subjects for the two series of respirator tests. Only six subjects participated in both test series. Work schedule conflicts, automobile injuries, and family medical problems were some of the causes for the other subjects to drop out of the program.

1. Medical Screening Procedures

a. Step 1. A potential test subject was scheduled for a complete general physical with the Laboratory's Occupational Medicine Group if he were not a Laboratory employee. This physical was equivalent to the Laboratory's new-hire physical and included a computerized medical questionnaire, the physical examination, a resting electrocardiogram, an audiology test, and a pulmonary function test. If the person was a Laboratory employee and a prescribed length of time (determined by his age) had lapsed since his last physical, an update physical was conducted.

Upon receiving medical clearance from the Occupational Medicine Group to participate in the testing, the person was scheduled for a fit session, described later. He had to attain certain preselection minimum FFs (pp. 10, 14) with the test respirators to qualify as a study participant. The person also wore each test respirator for 30 minutes so he could determine whether the mask could be worn comfortably for the full test.

b. Step 2. If the person passed all criteria to this point, he participated in a maximal stress electrocardiogram (MXT) monitored by a cardiologist. Final subject approval was determined by the cardiologist and a Laboratory physician.

2. Anthropometric Representation. Each subject's facial dimensions (bizygomatic breadth and menton-nasal root depression length) were measured and recorded to determine his location on a standard anthropometric panel (Figure 1) used to represent 95% of the working population of the United States in face length and face width.[5]

The subjects were selected based on their availability, medical suitability, and ability to achieve certain minimum FFs on specified respirators. Anthropometric dimensions were not used in the selection procedures. The mandatory preselection criteria fits (pp. 10, 14) imposed by the funding-agency project managers greatly influenced the panel representation.

B. Test Chambers

1. Fit Chamber. A Dynatec-Frontier (DF) 222-8 two-man transportable fit chamber (Figure 2) was used for the performance of the quantitative fit tests (QFTs) to determine FFs.

2. Environmental Chamber. Vista Scientific Corporation (Ivyland, Pennsylvania) designed and built the environmental chamber according to Los Alamos specifications. The chamber (Figure 3) has

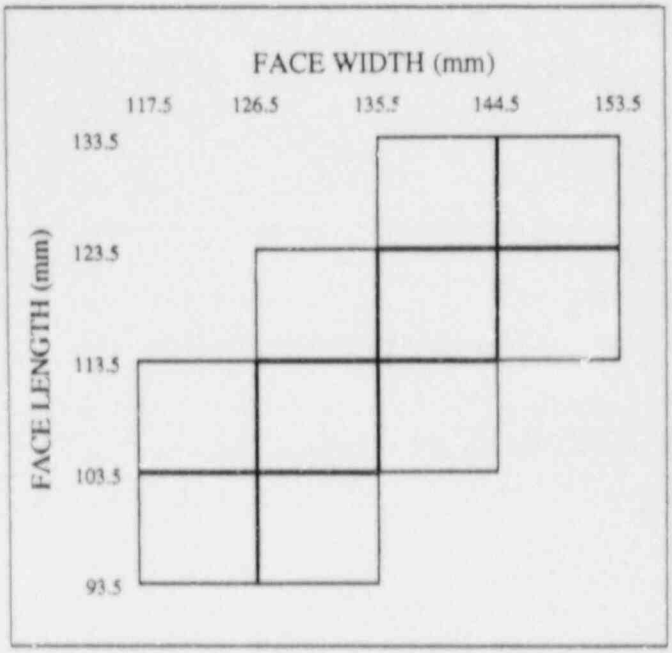


Figure 1. Study representation on anthropometric panel.

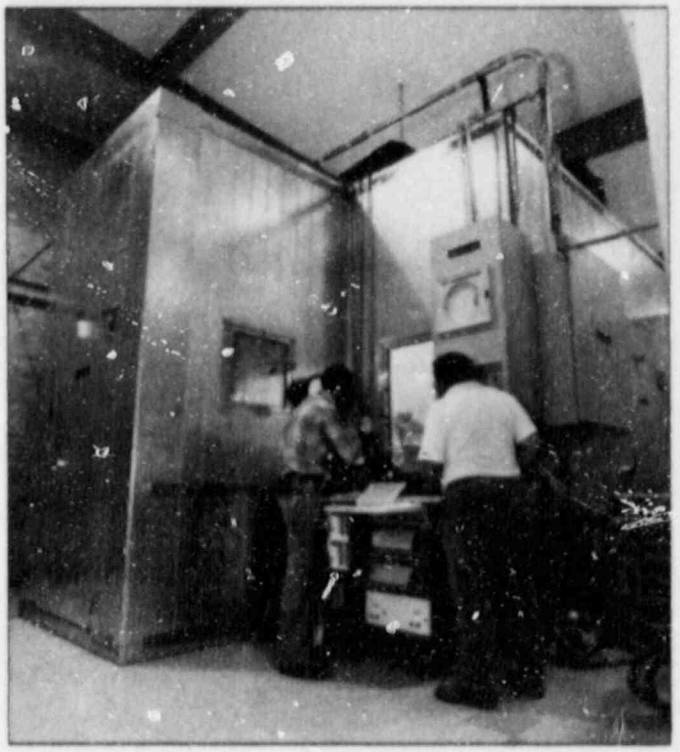


Figure 3. Vista Scientific Corporation environmental chamber.

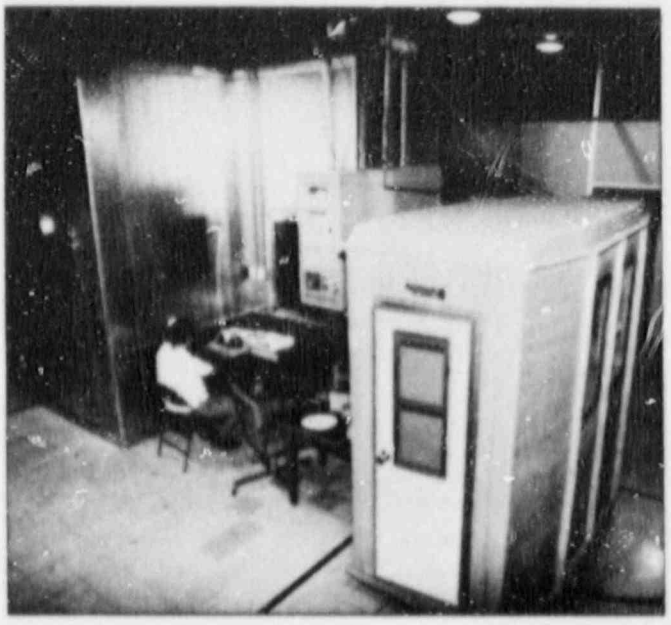


Figure 2. Dynatec-Frontier 222-8 ft chamber (foreground).

operating capabilities of –34.4°C to +51.7°C ± 2.7°C (–30°F to +125°F ± 5°F) and 10% to 95% ± 5% RH.

The chamber consists of a 28.3-m^3 (1000-ft^3) room with an attached 5.5-m^3 (200-ft^3) antechamber. The enclosures are constructed of urethane-insulated aluminum panels with tongue-and-groove construction with cam locks. One 90- by 120-cm (3- by 4-ft) heated window is located on the front of the environmental chamber so the test operator can observe most of the chamber activities. The facility has three doors (two for personnel and one for large equipment) that have heated gaskets. Personnel may safely exit from either chamber even if doors are accidentally locked from the outside. The chamber floor is covered with nonconductive, non-solid coverings. The chamber has grounded walls, vapor-proof electrical outlets, and dimmer-controlled incandescent lights that provide a maximum of 100-ft candle illumination.

Humidification of the chamber air is provided by a steam generator with control by a Vaisala Humicap capacitance-type humidity meter. A Dryomatic R300 rotary-drum silica-gel dryer dries the chamber

air. A 10-hp Carrier air-cooled refrigeration compressor and a condenser with two 24-inch fans provide chamber cooling. Two 4-kW electric heaters heat the chamber, with additional heat supplied from by-passing the hot Freon through the coils.

The chamber conditions can be manually controlled or automatically programmed and controlled by a two-channel Microstar microprocessor manufactured by Research, Inc. A Honeywell AR100 recorder-controller can be used to record the changes in humidity and temperature during all phases of the chamber operation.

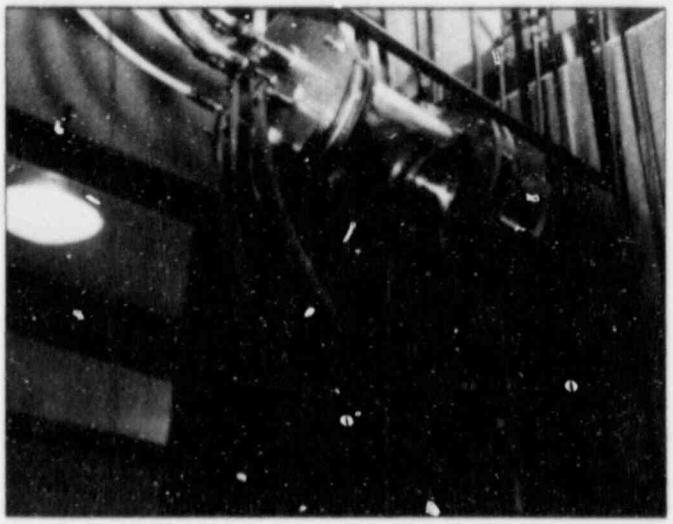
3. Aerosol

a. Generation. Two Naval Research Laboratory designed generators with Laskin nozzles produced a challenge aerosol of di-2-ethylhexyl sebacate (DEHS) in the DF fit chamber.[6] Both generators were used for quick concentration buildup; however, only one was used during a test to maintain the aerosol concentration.

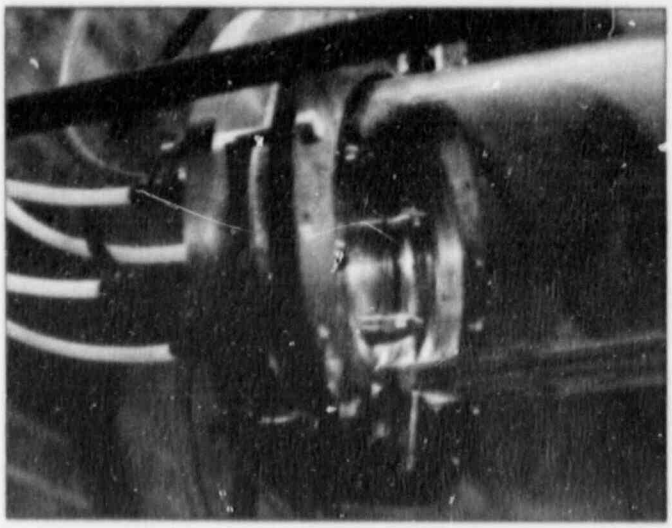
A sonic-nozzle aerosol system (Figure 4) was developed for the environmental chamber. Four Sonicore 035 (0.035-in.-diam orifice) sonic nozzles, operating at an air pressure of 25 to 90 psig, break the DEHS oil stream into fine particles as it passes through the orifice. A standing shock wave at the nozzle exit increases disintegration of the oil stream over that found in subsonic nozzles. This results in increased generation capacity when compared with the Laskin nozzles. Oil and air are fed to the nozzle through two separate inlet tubes and are mixed within the nozzle. The aerosol is mixed with air before exiting through the single-stage multihole impactor, which controls the product aerosol size distribution.

An aerosol concentration of 30 to 34 mg/m^3 with a mass median aerodynamic diameter of 0.67 ± 0.03 μm can be produced in the chamber with all four nozzles in operation. The concentration produced by each nozzle has also been characterized at several airflows. Any desirable aerosol concentration can be generated by using from one to four nozzles.[7] Small changes in aerosol size can be obtained by adjusting the dilution air to the aerosol ratio passing through the impactor.

Only 20% by mass of the aerosol particles generated by the sonic nozzles are in the desired size range of ≤1.0 μm before impaction. The excess oil from the impactor is recycled back to the oil supply reservoir by a pressurized oil recirculation system incorporated into the generator system.



(a) Generator impactor plate right of system.



(b) Four Sonicore 035 sonic nozzles.

Figure 4. Los Alamos National Laboratory sonic nozzle aerosol system.

b. Concentration. The aerosol concentration commonly used for quantitative fit testing is 25 mg/m^3. In any fit test program, it is desirable to minimize exposure to the challenge aerosol, even though the material is nontoxic. In a simple fit test,

Table II. EC Aerosol Concentration and Particle Size					
Condition		Concentration		Particle Size (MMAD)	
(°C)	(% RH)	(Mean mg/m^3)	(Std Dev)	(Mean μm)	(Std Dev)
32	85	19.6	2.4	0.65	0.10
0	15	16.1	0.8	0.74	0.07
32	15	19.6	2.4	0.73	0.04
0	85	27.3	2.8	0.73	0.03
21	85	21.3	4.9	0.71	0.002
21	15	21.4	8.7	0.76	0.04

the person being fit is surrounded by the fit chamber's challenge aerosol for 10 to 20 minutes maximum. However, in this study, each person is inside the fit and environmental chambers for approximately 90 minutes. The reduction of possible exposure to the subjects justified using a lower challenge concentration.

Aerosol samples were collected gravimetrically and with a cascade impactor during testing to track the aerosol concentration and size (Table II). Statistical analysis indicated no significant differences for particle size under the test conditions. A humidity effect was seen for the DEHS aerosol concentrations at the low (0°C) temperatures.

This lower concentration extended the life of the HEPA filters necessary for filtering the aerosol from both the fit chamber and the environmental chamber, reduced possible damage to the environmental chamber instrumentation and sensing elements, and extended the life of the environmental chamber's silica-gel dryer desiccant. This test concentration also requires a shorter time to stabilize, and a cost saving was realized over the duration of the study because of the reduction of oil and power requirements.

C. Test Instrumentation

1. Photometers. Two Los Alamos National Laboratory designed light-scattering photometers were used to determine the aerosol penetrations into the respirator facepieces.[8] Each photometer was connected by a set of sampling lines to both the DF fit chamber and the environmental chamber. By this design, one photometer was used to determine the FF on the subject wearing a respirator in the fit chamber, and then the same photometer was used to determine the SimWork factor for that subject still wearing the same respirator in the environmental chamber. Two photometers allow the simultaneous testing of two subjects.

2. Data Collection Systems. Integrating recorders were used for data collection in the initial stages of the study. The integrator gives the area under the curve, which is the most realistic prediction of exposure. These recorders were calibrated before each test.

A computerized data collection system, which also integrates the signal from the photometer and has been under development by this section for several years, had proved acceptable in field tests[9] on other studies. Comparison and evaluation tests were conducted on data collected by the integrating recorders and the new computer system. These comparison data were evaluated by the Laboratory statistician and found to be adequate for use in this study.

3. Subject Monitoring Equipment. An Exersentry heart rate monitor was used as a warning indicator of a change in the subject's physical condition during a test. The high alarm was set on 90% of the subject's predicted maximum heart rate determined in the MXT run by the cardiologists.

Primary monitoring of the subject's physical condition during the test was performed by continuously measuring the subject's core or rectal

temperatures by using Yellow Springs Instrument (YSI), Style 491, esophageal/rectal telethermometer probes. Each subject's temperature was recorded once each minute by a digital voltmeter (HP-3437A) connected to a Hewlett Packard microcomputer (HP-87). A digital print and graphics display (Figure 5) enabled the test operator to follow core temperature trends throughout the test. Alarms were provided by the computer if the core temperature rose too rapidly (0.5°C/min), exceeded 39°C, or if the probe slipped from place.

4. Aerosol Sampling Lines. Each respirator facepiece was fitted with a Liu[10] II design metal probe, which was attached by a Tygon tube (15-ft 1/8-in. i.d.) to the Los Alamos photometers.* The generator impactor was designed to select the optimum-sized particle to alleviate line losses to the photometer. If slight losses were realized, they were relative because the photometer detected the same losses for both 100% and the sample.

5. Other. In accordance with a special request by OSHA, pressure differences for the positive-pressure tight-fitting respirators were determined, and the temperature of the air to supplied-air respirators were measured. The Mine Safety Appliance (MSA) Company Comfo PAPR and Survivair facepieces were fitted with a second probe (located above the aerosol sampling probe) for the determination of in-mask pressure changes during inhalation and exhalation. Validyne DP45 pressure transducers and CD15 demodulators were used to measure the pressure changes with the data recorded on HP-7155B strip chart recorders. The Survivair also had an integrated-circuit temperature transducer placed at the bottom front of the facepiece to measure the temperature of the supplied air as it entered the mask. The HP-87 system was used to store and print in-mask air temperatures for the Survivair facepieces. The aerosol sampling line, heart rate monitor line, YSI core temperature cord, in-mask pressure sampling line, and integrated-circuit temperature cord were taped into a 15-ft cord packet that was color coded and attached to each subject. When two subjects were tested at the same time, experience and agility were necessary to keep the cord packets from getting fouled.

*A similar line allowed the photometer to sample each chamber's challenge concentration (100%).

Date: 11/25/85		Run Time: 900
Time	Subj-Red Core Temp	Subj-Green Core Temp
920	37.5	0.0
925	37.5	0.0
930	37.5	0.0
935	37.6	37.3
940	37.7	37.3
945	37.6	37.3
950	37.5	37.3
955	37.6	37.4
1000	37.8	37.4
1005	37.7	37.5
1010	37.8	37.6
1015	37.8	37.7
1020	37.1	37.7
1025	37.2	37.8
1030	37.2	37.9
1035	36.9	38.0
1040	37.0	38.2
1045	0.0	38.3
1050	0.0	38.4
1055	0.0	38.4

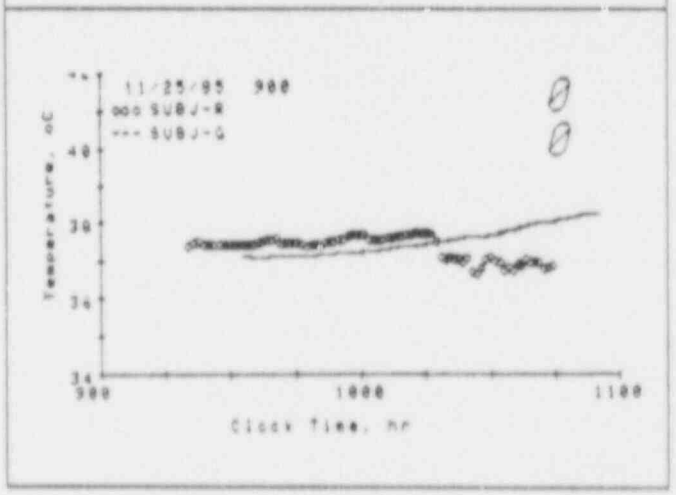


Figure 5. Core temperature graph.

D. Respirators

1. Series I Respirators. The following respirators were selected by the project managers of the

funding agencies. Comparison data developed by testing the two helmet PAPRs and the half-mask tight-fitting PAPR were of great interest to OSHA. The tight-fitting full-facepiece pressure-demand respirator and the continuous-flow hood were included in this series to provide comparative data of high-level-performance respirators. Series I respirators can be simply classified as devices with a forced airflow.

The following respirators were used in the Series I testing:

- 3M W344 Airhat PAPR, TC-21C-246, with HEPA filters;
- Racal AH3 Airstream PAPR, TC-21C-212, with HEPA filters;
- MSA PAPR with the medium Comfo II (neoprene) half-mask facepiece, TC-21C-186, with HEPA filters;
- Survivair Model 9811-02 (silicone) full-facepiece pressure-demand (PF/PD) supplied-air respirator, TC-19C-67/68; and
- Bullard 999 continuous-flow supplied-air hood, TC-19C-102.

2. Series II Respirators. Also selected by the representatives of the funding agencies were negative-pressure respirators commonly used at many U.S. work sites and available in multiple sizes.

The following respirators were used in the Series II testing:

- three sizes of MSA Comfo II half-mask respirators with HEPA filters, TC-21C-135; and
- three sizes of MSA UltraTwin full-facepiece respirators with HEPA filters, TC-21C-155.

3. Preliminary Inspection. All respirators and auxiliary equipment were purchased from New Mexico distributors. Section personnel carefully inspected the equipment to determine that the manufacturer's specifications were met.

a. MSA PAPR with Medium Comfo Half-Mask Facepiece (TC-21C-186). When the three MSA PAPRs were received, the batteries were charged according to manufacturer's instructions. One battery would not produce the 4-ft^3/min airflow specified by the manufacturer. The battery was discharged and recharged but still would not produce 4 ft^3/min. A replacement battery was obtained that did produce the required flow when [illegible]d.

b. 3M W344 PAPR (TC-21C-246). Upon exiting from the environmental test chamber, two subjects broke the plastic hinge that attaches the face shield to the helmet while attempting to position the face shield upward into the locking mechanism. The break occurred at the flex line of the hinge. We do not believe that the breaks were caused by temperature effects on the plastic because one test had been run at 21°C/15% RH and the second, at 0°C/15% RH. The 3M Company indicated the hinge material had just been changed because of this problem. At the suggestion of the company representative, a hinge from an older W344 was used as a temporary replacement until new parts were received. We do not know if the new hinges are more reliable because the test subjects did not attempt to unlock the face shield during the remaining tests.

c. Racal AH3 Airstream PAPR (TC-21C-212). Three Racal AH3 units were purchased. After four tests were conducted and compared, we observed that units 1 and 3 provided much lower FFs than unit 2. The FFs and SimWork factors were <1000 for units 1 and 3 and were >5000 for unit 2. Leaks were located at the point where the wires enter the battery compartment. Silastic was added to these areas and the problem was cured for unit 1. The problem with unit 3 was never determined, so the Racal testing was completed using units 1 and 2.

d. Pretest Inspection. Before each test, the respirator and its auxiliary equipment were again inspected according to manufacturer's instructions:

- The respirators were cleaned and examined for defects.
- The batteries were charged and airflow determinations were performed with manufacturer's equipment if supplied with the device. The 3M Company has a W-3008 flow test plate that is held in place by suction when the airflow is greater than 6 ft^3/min. Racal has a graduated airflow check tube containing a ball that is blown upward when the airflow is within the correct range of 6 ft^3/min or greater. MSA has an airflow kit, which was not supplied with the respirator. Airflow measuring equipment (Validyne manometer and flow transducer) available in the section was used to check the MSA airflow.

e. Sampling Probe. The probe was placed as near as possible to the breathing zone (midpoint between the mouth and nose) of all subjects. The actual locations of the probes for the Series I respirators are shown in Figure 6.

The probe location for the Series II respirators are shown in Figure 7. The Series I Survivair probe location is identical to the location of the probe for the UltraTwin shown in Figure 7.

The loose-fitting helmets and hoods were placed on several people with different head and face sizes. The location of each breathing zone was noted. This zone included the mouth and nose and was centered between them. This information was then used to place the aerosol sampling probes at a location as near as possible to the breathing zone for all subjects. The tight-fitting facepieces were also probed so that aerosol samples could be drawn from the subject's breathing zone.

Table III provides the location of the Liu design probe II[10] in each facepiece.

5. Preselection FF Criteria. The preselection FFs were specified by the project managers for the funding agencies. They were designed to provide a minimum FF that each test subject must obtain so that the effects of the study parameters would be documented by the test data.

a. Series I Preselection FF Criteria. Series I fit respirators were the MSA Comfo II half-mask and the Survivair full-face respirators in the negative-pressure mode. The test subject was required to obtain the following FFs:

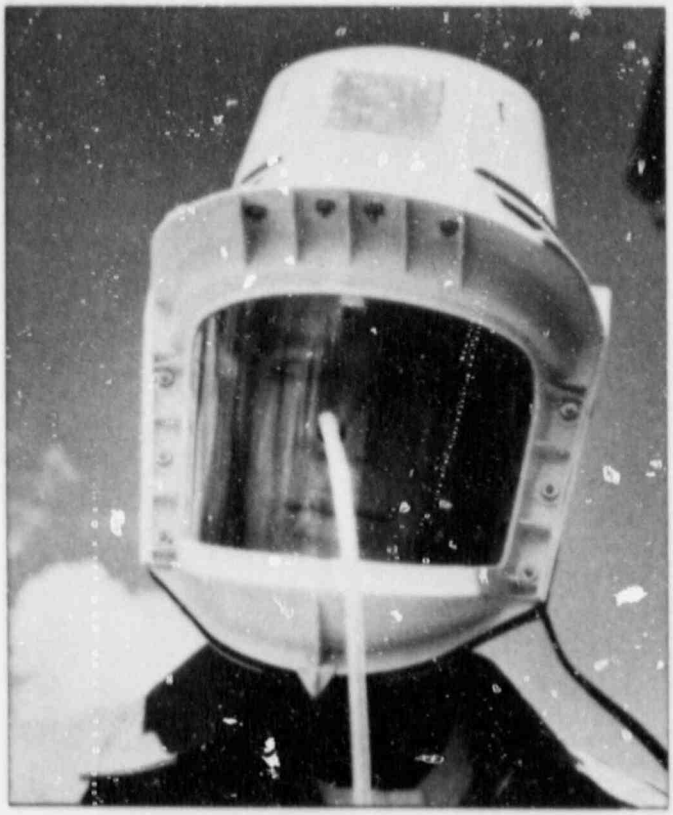
- FF $\geq$ 100 for the half-mask and
- FF $\geq$ 1000 for the full facepiece.

Table III. Facepiece Probe Location

Respirator		Measurement from Respirator Side (cm)	Measurement from Respirator Bottom (cm)
3M W344		13.0	6.4
MSA Comfo PAPR	Aerosol	2.5 above yoke snap	
	Pressure	3.8 above yoke snap	
Racal Airstream		11.4	3.2
Survivair Airline	Pressure	10.8	5.2
	Aerosol	10.8	4.4
	Temperature	10.8	0.6
Bullard 999		10.2	3.8
MSA Comfo II	Small	2.5 above yoke snap	
	Medium	1.9 above yoke snap	
	Large	2.5 above yoke snap	
MSA UltraTwin	Small	9.5	2.5
	Medium	9.5	2.5
	Large	9.5	2.5

(a)

(b)



(c)

Figure 6. Series I respirators:
(a) Racal AH3 Airstream PAPR.
(b) Bullard 999 continuous-flow supplied-air hood.
(c) 3M W344 Airhat PAPR.

(d)

(e)

Figure 6. (cont)
(d) MSA Comfo II half-mask.
(e) Survivair FF/PD supplied air.

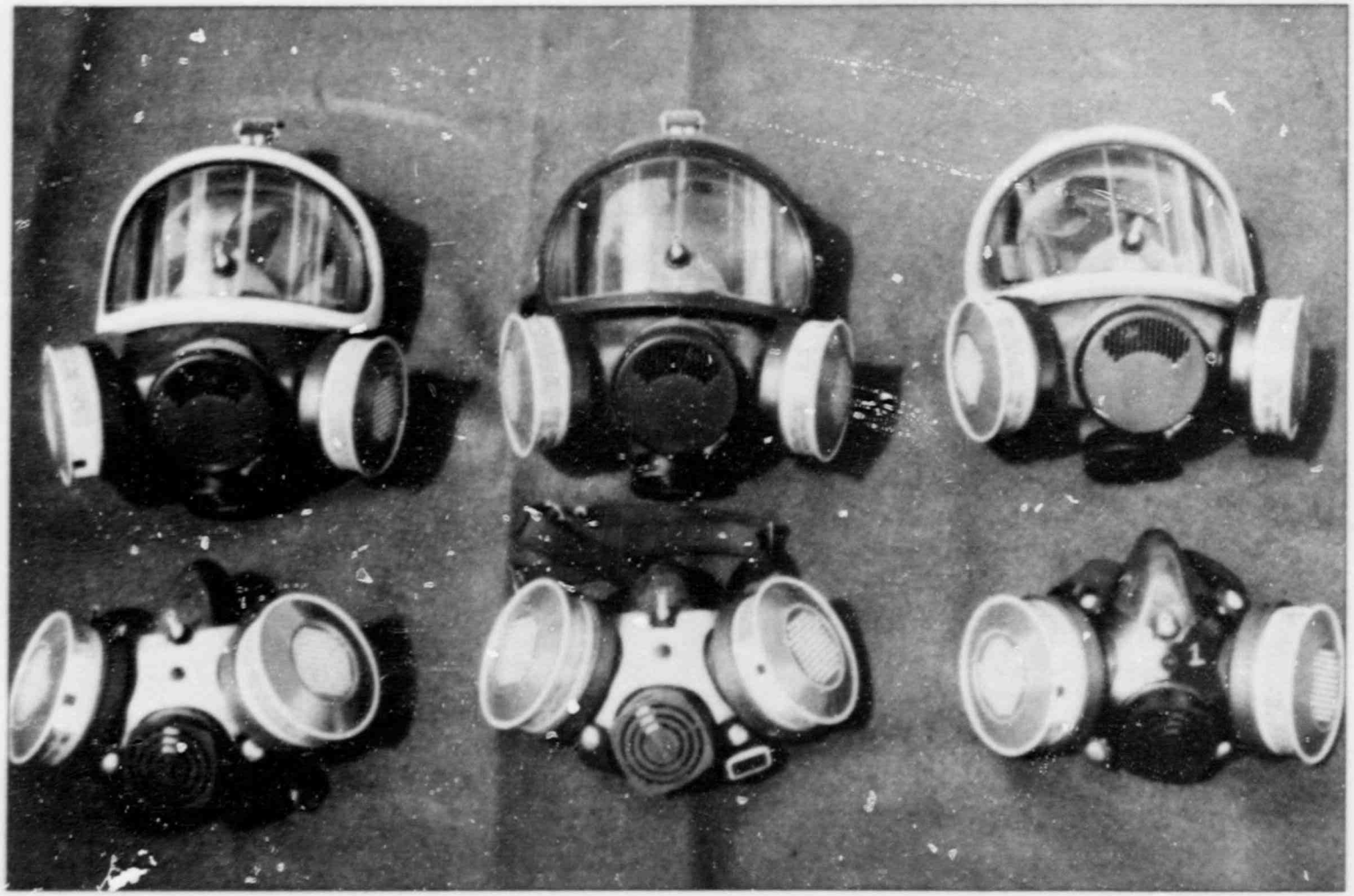


Figure 7. Series II Respirators.
Top: MSA UltraTwin facepieces—small, medium, and large (right to left).
Bottom: MSA Comfo II half-mask facepieces—small, medium, and large (right to left).

b. Series II Preselection FF Criteria. Series II respirator sizes were determined by conducting fit tests with the three sizes of the MSA Comfo and the MSA UltraTwin. The respirator size of best fit was chosen for the study. The Series II test subject was required to obtain the following FFs:

- FF ≥ 1000 for a half-mask respirator and
- FF ≥ 3000 for a full-facepiece respirator.

After receiving medical clearance, the person was scheduled for either a Series I or Series II fit session. He was instructed in the correct method of donning and removal according to manufacturer's instructions received with the respirators. The subject donned one of the respirators fitted with a sampling line, entered the DF fit chamber, and performed the following exercises:

- normal breathing,
- deep breathing,
- moving head side to side,
- moving head up and down,
- smiling (half-mask respirator) or frowning (full facepiece),
- reading, and
- normal breathing.

Each exercise was performed for a maximum of 2 minutes but was terminated after 30 seconds if no significant change of fit was observed. Had stability not been observed during that time, the exercise would have been continued for an additional 1.5 minutes for a total of 2 minutes.

During this session, the test subject also wore each tight-fitting respirator for 30 minutes to determine whether he could comfortably wear it for a test period of 1.5 to 2 hours.

If the subject could not obtain these preselected minimum FFs with any size respirator, he was *not* used in the study. Two male test subjects who obtained criteria fits for the Series I testing could not satisfy criteria for Series II with the Comfo II and could not participate in Series II tests. Each had a thin nasal bridge that allowed more aerosol penetration than the criteria permitted.

The preselection FF criteria are much higher than FFs proposed by Los Alamos, Z88.2-1980, OSHA, or NRC. For example, Los Alamos recommended a FF of 100 for a half-mask, and 500 for a full facepiece when a quantitative fit is determined.[1] Standard Z88.2-1980 recommends a FF of 100 for a half-mask and 1000 for a full facepiece.

E. Test Conditions

All test subjects wore each respirator in a series of tests at the following environmental conditions:

Test Number	Temperature (°C)	Temperature (°F)	Relative Humidity (%)
1	32	90	85
2	0	32	5
3	32	90	15
4	0	32	85
5	21	70	85
6	21	70	15

This order of the test conditions was selected by the NRC and Los Alamos statisticians to help alleviate possible acclimatization by the subjects.

F. Test Protocol

The test was arranged in the following four exercise groups:

- PreFit,
- PreWork,
- SimWork, and
- PostWork.

1. Loose-Fitting Respirator Exercises.[11] The following ANSI-Z88.2-1980 exercises for loose-fitting respirators were used for all Series I respirators as the PreFit, PreWork, and PostWork exercises:

- standing still, arms hanging downward along sides of body, normal breathing;
- bending forward and touching toes;
- raising arms above the head and looking upward;
- bending knees and squatting;
- standing while holding a 76-cm tubular rod with hands approximately 30 cm apart, twisting torso from side to side in an 180° arc, and slowly raising the arms from a downward direction to an upward direction in a 45° angle with the horizontal plane (sandblasting motion);
- running in place; and
- standing still, arms hanging downward along sides of body, normal breathing.

Each exercise was scheduled for 2 minutes, but the exercise was terminated after 30 seconds if no significant change in fit was observed.

2. Tight-Fitting Respirator Exercises.[11] The following ANSI Z88.2-1980 exercises for tight-fitting respirators were used for all Series II respirators as the PreFit, PreWork, and PostWork exercises: normal breathing, deep breathing, moving head side to side, moving head up and down, smiling/frowning, reading a prepared text (Rainbow Passage), and normal breathing.

Each exercise was scheduled for 2 minutes, but the exercise was terminated after 30 seconds if no significant change in fit was observed.

3. SimWork Exercises. The SimWork exercises performed by all test subjects wearing either of the Series I respirators follow:

SimWork Exercises	Time (min)
• Step up and back down a standard two-step platform[a] at a moderate rate holding to safety rail (Steps)	5.0
Rest	5.0
• Move oiled gravel from one bin to the other with a short-handled shovel (Gravel)	10.0
Rest	5.0
• Pick up nail and pound with claw hammer into a board located above the head; look back down for next nail (Nails)	10.0
Rest	5.0
• Pick up a cinder block from the floor, move it approximately 6 ft, and lay it in a typical pattern (Blocks)	10.0
Rest	5.0
• Pound continuously on a 4- by 4-in. board with 6-lb sledgehammer (Sledge)	5.0
Rest	5.0
Total	65.0

[a]Type used in physician's office.

The 5-minute seated rest periods were required by the Los Alamos National Laboratory's Human Studies Committee.

G. Subject Testing

1. Pretest Preparation. Two hours before a scheduled test, the EC microprocessor was programmed to attain stabilized test conditions.

All exercise equipment inside the chambers was checked and positioned; for example, new nail boards were installed at the correct height for the scheduled subjects. Data recording instrumentation was calibrated or checked. The telethermometers were checked, and the HP-87 core and air temperature program was initialized for test.

The respirators to be used that day were cleaned and inspected/checked according to manufacturer's specifications, and other equipment such as belts for supporting the respirator blowers/filters was prepared. The subject's coveralls, t-shirts, heart rate harnesses/sensors, individual core temperature probe boxes, and towels/washcloths were made ready for the subject. He picked up his equipment and proceeded to the dressing room. The helmets, ear plugs, gloves, and coats (for cold test) were arranged for the subjects to collect after they returned to the lab area.

Approximately 1 hour before the test, the aerosol generators for both chambers were turned on and the aerosol concentrations were allowed to stabilize.

2. Testing Procedure. Two subjects were scheduled for each session, which normally lasted about 2 hours. Upon arrival at the test facility, each subject changed out of street clothes, urinated, positioned the core temperature (CT) probe, heart rate monitor, and changed into the following test clothing: heart rate harness with sensors, t-shirt, coveralls, and safety shoes. We also provided gloves, ear plugs, helmets, safety glasses, and safety toe protectors. The subjects had full responsibility for inserting, removing, and cleaning their personal CT probes. Jackets were provided for the cold tests. Respirators and sampling line packets were color coded *red* and *green* to simplify communications to the two subjects and visual monitoring of the tests.

After the test operator checked each subject's heart rate monitor and CT probe, the subjects donned the respirators. The *red* subject entered the fit chamber and attached the aerosol sampling line to the *red* photometer port. He was instructed to perform the PreFit exercises appropriate for the respirator being worn while a respirator FF was determined. After the test, the aerosol sampling line was

disconnected, and the *red* subject exited the fit chamber without disturbing the respirator in any manner. Then the *red* subject and the test monitor entered the environmental chamber. The monitor's duties included attaching sampling lines and observing the subjects during the test. The test monitor attached the *red* cord packet to the *red* subject. Simultaneously, the *green* subject entered the fit chamber and attached the aerosol sampling line to the *green* photometer port. After the test operator checked both photometers, he instructed the *green* subject to perform the correct PreFit exercises while the *red* subject performed the PreWork exercises.

Next the *red* subject was directed to start the first work exercise, Steps. At the completion of the *green* fit test, that subject exited the fit chamber and entered the environmental chamber. The test monitor attached the *green* cord packet to the subject. At the end of the Steps exercise, the *red* subject was directed to rest (in one of the seats provided), and the *green* subject was instructed to perform the PreWork exercises. From this point, the subjects performed the work exercises, rests, and PostWork exercises with the *green* subject 5 minutes behind the *red*. Test duration was approximately 90 minutes from the time the *red* subject entered the fit chamber until the *green* subject exited the environmental chamber. Each subject was in the environmental chamber approximately 75 minutes.

After the PostWork exercises, all monitoring lines were detached from the *red* subject and he exited the environmental chamber. This subject removed the respirator and work equipment and then went to the change room to shower and change into street clothing. The *red* subject then returned to the chamber area to complete a debriefing form that had questions regarding his physical condition, the comfort of the respirator, and any comments about the test. When the *green* subject finished the test, he exited the chamber and followed the same procedure as the *red* subject above. This completed a test.

At least one person of the same sex as the test subjects was available for assistance in case of an emergency.

V. TESTING RESULTS

The study data sets and the number of subjects tested on each device are shown in Table IV. Each of the ten test subjects wore each device during six EC conditions (Table II) and four exercise groups as noted. This gave a total of 60 tests for each device and a total of 372 quantitative fit tests, which consisted of (1) PreFit, (2) PreWork, (3) SimWork, and (4) PostWork. The OSHA project manager agreed to test only two subjects on the Bullard continuous-flow hood because preliminary tests nominally gave FF $\geq$ 20,000.

Table IV. Study Data Sets and Number of Subjects on Each Device

Brand	Sets	Male	Female	Tests
Series I				
3M W344	10	8	2	60
Racal II	10	8	2	60
MSA Comfo II PAPR	10	8	2	60
Survivair	10	8	2	60
Bullard	2	1	1	12
Total				252
Series II				
MSA Comfo II	10	7	3	60
MSA UltraTwin	10	7	3	60
Total				120

A. Variation of Six Prefit FFs by Subject

Several factors must be considered when reviewing whether test subjects can obtain or achieve reproducible FFs with one type of respirator during three or more quantitative fit tests (QFTs). These include training, experience, motivation and attitude, physical condition, facial size and shape, and condition of the respirator tested. Facial size and shape are the main factors considered for tight-fitting negative-pressure respirators, but motivation and experience are also important.

To determine if temperature, humidity, and simulated work have an effect on the fit and/or performance of respirators, it is important to learn if each test subject has a wide variation in FFs measured by the six PreFit tests done at room temperature before entering the EC. One criterion is the FF recommended by Los Alamos based on test data available as a minimum FF.[1]

Respirator	FF
Series I	
PAPR	2,000
FF/PD supplied air	10,000
CF supplied-air hood	2,000
Series II	
Half-mask	10
Full facepiece	50

A logical second criterion can be the preselection criteria for Series I respirators, that is, FF ≥ 100 for the Comfo II facepiece and FF ≥ 1000 for the full facepiece. The preselection criteria for Series II are FF ≥ 1000 for the negative-pressure Comfo II and FF ≥ 3000 for the UltraTwin fitted with a high-efficiency filter.

1. Series I Respirators

a. PAPR PreFit FFs. The largest variation in the six FFs during Prefit tests was obtained for the Racal helmet for which 6 of 10 subjects had FFs varying by a factor of 10. Based on a criterion of a FF = 1000, 6 of 10 subjects testing the Racal achieved FF ≥ 1000 on all six tests. None of ten subjects wearing the 3M helmet achieved a FF ≥ 1000. For the MSA PAPR with Comfo, all 10 subjects achieved a minimum FF = 1000. For the MSA, 9 of 10 subjects had PreFit FFs > 10,000. The one value less than 10,000 was a FF = 8860. Five FFs were >20,000.

b. Supplied-Air Respirator PreFit FFs. For the Survivair FF/PD supplied-air respirator, 9 of 10 subjects had PreFit FFs > 10,000. The tenth subject had five FFs > 20,000 and one had a FF = 400 because of a faulty device for that test (p. 21). The two subjects wearing the Bullard hood obtained a PreFit FF > 18,000.

2. Series II Respirators. The MSA Comfo II and UltraTwin respirators used in Series II tests in the DF chamber showed wide variations in the six PreFit FFs obtained by each subject before entering the EC. The PreFit FFs for each subject wearing the Comfo II and UltraTwin are shown in Table V with the preselection criteria FFs and the number of times during the PreFit tests that each subject met the selection criteria that originally qualified the person as a test subject.

An observable difference existed among the 10 test subjects meeting the preselection criteria. Only four subjects met the preselection criteria during their six PreFit tests with the Comfo II. Only two subjects met the preselection criteria during their six PreFit tests with the UltraTwin.

Had the preselection criteria been lower (that is, FF ≥ 100 for the Comfo II and FF ≥ 1000 for the UltraTwin), then 5 of 10 subjects met these criteria for the Comfo II, and 8 of 10 subjects met these criteria for all six PreFits for the UltraTwin.

The PreFit FFs in Table V are listed in the order tested and indicate poor reproducibility. This assumes poor reproducibility is defined when three of six tests vary from the PreFit FFs obtained by a factor of 2 or more. Three subjects had very poor reproducibility for both the Comfo II and the UltraTwin. Six of ten subjects had poor reproducibility with the Comfo II. Seven of ten subjects had poor reproducibility with the UltraTwin.

Table V. PreFit FFs for the Comfo II and UltraTwin Respirators

Subject No. and Respirator	No. Met Selection Criteria	Preselection Criteria (x1000)	Prefit FF in DF Chamber (x1000)					
			1	2	3	4	5	6
1-Comfo II	6	1.0	20.00	12.00	3.80	17.00	2.10	2.30
1-UltraTwin	6	3.0	20.00	20.00	6.40	12.00	20.00	14.00
2-Comfo II	6	1.0	20.00	20.00	20.00	2.50	20.00	5.50
2-UltraTwin	5	3.0	5.70	13.00	7.00	5.30	19.00	***1.20***
9-Comfo II	3	1.0	***0.80***	20.00	***0.30***	20.00	2.70	***0.08***
9-UltraTwin	5	3.0	20.00	16.00	20.00	3.60	***2.10***	4.30
10-Comfo II	2	1.0	***0.06***	***0.04***	17.00	***0.50***	15.00	***0.06***
10-UltraTwin	1	3.0	***1.20***	20.00	***0.10***	***1.50***	***0.30***	***1.60***
15-Comfo II	2	1.0	***0.30***	***0.60***	14.00	1.70	***0.30***	***0.30***
15-UltraTwin	2	3.0	***0.20***	***0.90***	8.30	8.70	***1.40***	***1.00***
18-Comfo II	1	1.0	***0.06***	***0.04***	***0.09***	***0.01***	20.00	***0.30***
18-UltraTwin	5	3.0	3.20	12.00	***1.80***	11.00	4.30	20.00
19-Comfo II	6	1.0	20.00	19.00	7.50	18.00	20.00	20.00
19-UltraTwin	5	3.0	11.00	7.10	20.00	3.50	***2.50***	9.50
20-Comfo II	3	1.0	***0.05***	***0.10***	6.80	8.10	***0.05***	20.00
20-UltraTwin	5	3.0	20.00	20.00	4.20	20.00	***0.20***	3.7
21-Comfo II	6	1.0	20.00	20.00	20.00	20.00	20.00	5.7
21-UltraTwin	6	3.0	20.00	20.00	16.00	20.00	12.00	11.00
22-Comfo II	3	1.0	20.00	***0.07***	***0.03***	20.00	***0.10***	2.1
22-UltraTwin	3	3.0	20.00	***0.50***	***0.10***	8.00	4.00	***1.2***

B. Determination of Effects Based on FFs Obtained at All EC Conditions

1. Series I Respirators

a. PAPR Helmet Comparisons. The results of testing the Racal and 3M PAPR helmets, shown in Table VI for the four exercise groups and the EC conditions, are compared on the basis of a minimum FF of 1000 as recommended by Los Alamos and noted in Section Ia. Table VI compares the number out of ten test subjects that obtained FFs < 1000 for all EC conditions and exercises.

The variations of the Racal subjects during Pre-Fit exercises in the DF chamber are substantially different when compared with the 3M, showing one to two subjects obtained FFs < 1000 during four of the six tests before entering the EC chamber.

After adding the number of FFs < 1000 for both PAPR helmets, 61 for the Racal and 9 for the 3M,

Table VI. Number of Subjects Obtaining FFs < 1000 for PAPR Helmets

Device and Conditions (°C) (% RH)		DF Chamber	Environmental Chamber		
		Prefit	PreWork	SimWork	PostWork
Racal					
0	15	1	0	4	3
0	85	0	0	1	2
21	15	2	2	2	4
21	85	0	1	3	4
32	15	2	5	3	4
32	85	1	4	5	8
3M					
0	15	0	0	1	0
0	85	0	0	2	0
21	15	0	0	0	0
21	85	0	0	0	0
32	15	0	0	2	1
32	85	0	0	2	1

we made a statistical analysis. The p-value for this analysis is less than 0.001. (The smaller the p-value, the more certain one is that a difference exists. We determined significant p-value to be ≤0.05.)

We did see significant high-temperature (32°C) effects with the Racal; however, we saw no humidity effect. The effects of 32°/85% conditions on subjects testing the Racal were evident when 5 of 10 subjects had SimWork FFs < 1000, which increased to 8 of 10 subjects during PostWork exercises. The 32°/15% condition also effects performance, with 5 of 10 subjects having FFs < 1000 during PreWork exercises. From the Racal data in Table VI, it is evident that the high temperature (32°C) has more effect on the Racal performance than the SimWork exercises.

For the Racal helmet, the p-value for temperature is 0.005 and for the exercise the p-value is 0.006, indicating significant temperature and exercise effects. No humidity effect is evident; for example, SimWork has 9 FFs < 1000 for 15% RH and 9 FFs < 1000 for 85% RH. When the Racal PreFit data were not included in the analysis, we found temperature to still be significant with a p-value less than 0.0007, whereas exercises gave a p-value of 0.028. From this analysis, we conclude the performance of the Racal helmet degrades from the moment PreWork starts and continues to degrade. Also, there is a very significant temperature effect when the performance of the Racal helmet degrades as the temperature increases. There is no humidity effect.

The data at 0°C/15% for the Racal helmet suggest that SimWork has a greater effect than temperature, with 4 of 10 subjects achieving less than 1000 compared with none at PreWork. This is also indicated at 21°C/85%.

Although there is not enough failure data (FFs < 1000) to perform a statistical analysis on the 3M PAPR helmet, these data indicate no effect at any EC condition during PreWork exercises. There was some effect at 3 EC conditions during the SimWork exercises when 2 of 10 subjects obtained

Table VII. Comparison of Number of Subjects Obtaining FFs for Survivair FF/PD Supplied-Air and MSA Comfo PAPR

Device and Condition (°C)	(% RH)	PreFit FFs <20,000	PreFit FFs <10,000	PreFit FFs <1,000	SimWork FFs <20,000	SimWork FFs <10,000	SimWork FFs <1,000
Survivair FF/PD							
0	15	0	0	0	1	0	0
0	85	0	0	0	1	0	0
21	15	1	0	0	2	1	0
21	85	2	1	0	0	0	0
32	15	2	1	1	2	1	1
32	85	1	0	0	5	3	2
MSA Comfo II PAPR							
0	15	0	0	0	5	2	0
0	85	1	1	0	3	2	0
21	15	2	0	0	0	0	0
21	85	0	0	0	3	0	0
32	15	2	0	0	0	0	0
32	85	1	0	0	2	0	0

FFs < 1000 (Nos. 5 and 10 at 0°C/85%, Nos. 11 and 18 at 32°C/15%, and Nos. 9 and 18 at 32°C/85%). The 3M PAPR helmet had a performance degradation at three EC conditions for five subjects.

The following observations were made by the personnel conducting the tests and recorded on test subject statement debriefing forms:

(1) Racal AH3 Airstream PAPR Helmet (TC-21C-212). The Racal helmet was fitted with the Tyvek face seal. The subjects were instructed in the proper method of adjusting their headbands and assisted when necessary. As the subjects performed work exercises, such as shoveling gravel and moving the cinder blocks or pounding vigorously with the sledgehammer, the helmet bounced as much as ½ in. on some subjects' heads.

Frequently, the resting subjects would lean back and crush the Racal air supply hose, cutting off the filtered air. Several subjects also inadvertently shut off the blower with a brush of the hand or jacket. The Racal helmet provides little protection without an operating blower.

(2) 3M W344 PAPR Helmet (TC-21C-246). Most subjects mentioned neck fatigue caused by the weight of the blower motor mounted in the back of the helmet. The subjects also said that the chin strap would ride under the black face seal and felt looser after a test than when the device was initially donned. They thought that the elastic stretched after being soaked with sweat.

During the high-temperature tests, one subject said that sweat accumulated against the black plastic face seal and would run into and sting his eyes when he was bending over performing the work exercises, such as moving the cinder blocks.

b. MSA PAPR and Survivair Supplied-Air FF/PD Comparison. The results of testing the MSA PAPR with a Comfo II facepiece and the Survivair FF/PD supplied-air respirator are compared in Table VII. A comparison of the number out of 10 test subjects obtaining FFs less than 1,000, 10,000, and 20,000 is made at PreFit and SimWork exercises at all EC conditions. These three performance levels were chosen for reasons previously noted and to determine any effect on

performance of these devices at any EC condition for the two exercise groups listed in Table VII. Los Alamos has proposed a PF of 1000 for MSA PAPR and 10,000 for the Survivair supplied-air FF/PD respirator.

The MSA PAPR Comfo II data show all subjects obtaining a FF > 1000 during both PreFit and SimWork exercises at all six EC conditions.

There is no apparent temperature/humidity effect on the subjects testing the MSA Comfo II PAPR at 32°C/85% unless we compare 2 of 10 subjects with FFs < 20,000. These two subjects obtained FFs of 15,000 and 16,000. However, some temperature effect does appear to be at 0°C/15% where 5 of 10 test subjects had FFs < 20,000 and 2 of 10 subjects had PFs less than 10,000 at both 0°C humidity conditions with the MSA PAPR Comfo II.

The one subject (No. 10) with a FF < 1000 during the PreFit exercises with the Survivair actually had a FF = 400 before entering the EC chamber. The other five PreFit FFs for No. 10 were all 20,000. He obtained FFs = 700 during PreWork at 32°C/15%, FF = 250 during SimWork, and FF = 263 during PostWork exercises. As noted previously, these data indicate a faulty device.

There is a temperature-humidity effect on the performance of the Survivair at 32°C/85% with 2 of 10 subjects obtaining FFs < 1000 during the SimWork exercises. These two test subjects had actual SimWork FFs of 500 and 700 at this condition. They had FFs of 18,000 and 20,000 during PreWork exercises, but during the PostWork exercises obtained FFs of 432 and 735.

A statistical analysis was made only on the FFs < 20,000 in Table VII because there are not enough failures in the FFs less than 10,000 and 1000 to ascertain significant differences. We have significant temperature effects for SimWork for both respirators. In the case of Survivair, the 0°C and 21°C conditions are significantly different from the 32°C conditions. For the MSA PAPR, 0°C conditions are significantly different from the 21°C and 32°C results.

We have made the following observations on these two devices.

(1) MSA PAPR with Medium Comfo II Half-Mask Facepiece (TC-21C-186). Some test subjects found the MSA half-mask to be uncomfortable across the bridge of the nose. During the seated rest, the red switch on the belt-mounted blower/filter pack was inadvertently shut off by several subjects. With no airflow, the protection is reduced to the amount provided by a negative-pressure device.

(2) Survivair FF/PD Supplied-Air Respirator (TC-19C-67-/68). This type of respirator either as SCBA or supplied air provides the highest level of protection available for firemen or emergency entry (FF ≥ 10,000). However, careful maintenance and inspection procedures are important. For example, during a pretest inspection, an exhalation valve was found to be stuck open. All PD devices require good quality assurance programs by the manufacturers to ensure high performance when used by a customer.

c. Bullard 999 Continuous-Flow Supplied-Air Hood (TC-19C-102). Two Bullard hoods and air hoses were purchased. Preliminary tests run with this hood showed that the SimWork factor remained at ≥20,000 even if a subject reached into the hood to remove hair from the eyes. This observation was discussed with the OSHA monitor, who decided that testing the hood on the entire panel was not cost effective. Los Alamos then decided to test 2 subjects (1 female and 1 male) wearing the Bullard hood at all conditions for a total of 12 tests.

SimWork factors of 20,000 were recorded for all tests on the male subject. A test "abort" penetration (2% leak for 2 minutes) was observed during another test, and the female subject was removed from the chamber. The subject had dislodged the plastic facepiece from its square rubber grommet during the test. When the facepiece was repositioned, the hood provided good (FFs > 20,000) protection during the retest.

An aerosol mixing fan was located to the subject's left as she was pounding nails. During some of the Bullard tests, as the female subject reached up to position and pound the nails, the mixing fan billowed her cape and aerosol entered her hood through the neckband. This cape had a webbed belt on each side that was drawn through a D-ring and tightened. The belts secured the cape on the male adequately, so the hood did not blow around; however, there was no method to compensate for the smaller wearer.

Table VIII. Comparison of Number of Subjects Obtaining FFs for UltraTwin and Comfo II Respirators

Device and Condition (°C)	(% RH)	PreFit with FF Stated			SimWork with FF Stated		
UltraTwin		<50	<100	<1000	<50	<100	<1000
0	15	0	0	2	0	1	2
0	85	0	0	0	1	1	5
21	15	0	0	0	0	0	1
21	85	0	0	2	0	0	3
32	15	0	0	2	1	1	2
32	85	0	0	1	1	1	3
Comfo II		<10	<100	<1000	<10	<100	<1000
0	15	0	3	4	0	1	5
0	85	0	0	2	0	1	2
21	15	0	2	4	0	2	3
21	85	0	1	3	0	3	4
32	15	0	2	3	0	3	3
32	85	0	3	5	0	3	6

The female test subject did obtain FFs = 20,000 at all six EC conditions for both PreWork and PostWork.

To compare the Bullard FFs and the exercises during QFTs in this project with those obtained during an earlier Los Alamos project sponsored by the NRC, the following data are presented.

In 1979, Douglas (LA-6612-MS) reported the results of QFTs on the Bullard Model 77 continuous-flow hood, which has a high-pressure (80- to 95-psi) valve. Douglas made one test with 3 test subjects on 12 continuous flow hoods. The minimum air pressure recommended by the manufacturer was used with 25 ft of hose. The Model 999 has a low-pressure valve (12 to 25 psi). Douglas reported that his three test subjects obtained FFs = 20,000 on his five basic exercises. However, during the running-in-place exercise, the three subjects obtained FFs of 2400, 2800, and 7000.

2. Series II Respirators. The Series II respirators were air-purifying negative-pressure respirators. Three sizes of the MSA Comfo II and MSA UltraTwin facepieces were used.

a. Comparison of PreFit vs SimWork. A comparison of the number out of 10 test subjects obtaining FFs for all EC conditions with PreFit and SimWork exercises is shown in Table VIII. The three FFs of 10, 50, and 100 were based on FFs proposed by Los Alamos and the ANSI Z88.2-1980 standard. The FF = 10 for the Comfo II half-mask and the FF = 50 for UltraTwin was proposed by Los Alamos and is currently used by OSHA and NRC. The FF = 100 for the UltraTwin was proposed by ANSI Z88.2-1980. Also during routine QF testing of all respirator wearers by Los Alamos and others, the wearer must obtain a FF ≥ 1000 with full-facepiece respirators to be assigned a use FF = 100. The higher FF = 1000 was chosen to highlight effects of temperature/humidity and SimWork exercises in this table.

To demonstrate an effect on the performance of the respirators, the FFs obtained during SimWork at

various EC conditions must be compared with the PreFit FFs obtained before the EC is entered. An effect on the UltraTwin was seen when a single test subject of each 10 obtained a SimWork FF less than 200 for 4 of the 6 EC conditions. Comparison of the six EC conditions showed the greatest effect on the UltraTwin when five subjects received FFs < 1000 during the 0°C/85% condition. Humidity had more effect on UltraTwin performance than temperature when 3 of 10 subjects obtained FFs < 1000 at 0°C/85% condition.

A statistical analysis of the data in Table VIII for the UltraTwin indicates a significant difference (p-value = 0.04) between the 2 exercise groups with 7 FFs < 1000 for PreFit and 16 FFs < 1000 for SimWork. A *near significant* humidity effect is shown for the UltraTwin for SimWork with 5 FFs < 1000 at 15% RH and 11 FFs < 1000 at 85% RH.

The data for the Comfo II in Table VIII do not illustrate any definite effect by EC conditions or SimWork exercises compared with FFs obtained during the PreFit exercises. Based on FFs < 100, the data do illustrate some effect of humidity at 21°C/85% with three subjects attaining SimWork FFs of 51, 43, and 65.

A statistical analysis of the Comfo II FFs < 1000 indicated no significant differences. This result can be seen from the totals. For example, 21 FFs are less than 1000 for PreFit and 23 for SimWork. Analysis of SimWork exercises at three temperatures showed seven subjects had FFs < 1000 at 0°C; seven, at 21°C; and nine, at 32°C. No significant statistical differences were seen in a comparison of high and low humidity effects for the Comfo; 11 FFs > 1000 were observed for 15% RH and 12 for 85%.

b. FF Differences Among Exercise Groups. A detailed review of all data obtained with the Comfo II and UltraTwin shows some differences in the comparison of PreWork, SimWork, and PostWork at all EC conditions.

(1) Comfo II. The actual FFs obtained by the 10 test subjects at 3 EC conditions are shown in Table IX. A large difference exists in the FFs obtained by the different test subjects. Examples are test subjects 19 and 21, who obtained FFs > 14,000 at all six EC conditions during PreWork exercises compared with subject 10 with three of six FFs < 100 and subjects 18, 20, and 22 with two of six FFs < 100.

For most subjects, the largest degradations are for the higher temperatures and/or during SimWork, with several exceptions. Examples are test subjects 10, 15, 18, and 22 with significant increases in one or two FFs obtained during SimWork compared with FFs obtained during PreWork exercises.

The effect of high temperature and SimWork is clearly shown by the FFs obtained by subject 19. All FFs were above 300 for the 21°C/15% RH and both 0°C humidities. For some subjects, the FFs continued to degrade during the PostWork exercises, as shown by FFs obtained by subjects 1 and 21 at both low and high temperatures. Some subjects reported that the facepiece slid down the nose from sweat at higher temperatures and humidities.

(2) UltraTwin. The UltraTwin at 0°/85% under the SimWork vs PreWork column shows 5 of 10 test subjects had FFs during SimWork less than the FFs obtained during PreWork. To illustrate this in more detail, the FFs obtained by these five subjects with the UltraTwin follows:

Subject	UltraTwin Fit Factors 1	2	15	19	22
PreWork	20,000	6,000	2,700	5,000	20,000
SimWork	2,000	600	20	500	3,000

In addition to these five subjects, two other subjects had FFs during SimWork less than PreWork at 0°/85%. These data indicate the degrading effect of SimWork exercises on 7 of 10 test subjects. Note that the FF for subject 20 increased to 4300 during SimWork from 900 during PreWork.

The data for 0°/15% indicated a possible effect from SimWork exercises. The FF for subject 9 increased from 500 during PreWork exercises to 4500 during SimWork exercises. Because subject 9 had a PreFit FF = 16,000, the 0° temperature may have caused the exhalation valve to freeze partly closed, giving a FF = 500. During the hard work, the FF went up, suggesting that heavy breathing cleared the exhalation valve of ice.

The data for the 32° tests in the SimWork vs PreWork indicate some reduction of FFs, possibly

Table IX. FFs (x1000) Obtained with Comfo II at Exercise Groups							
Subject No.	Exercise	0°C		21°C		32°C	
		15%	85%	15%	85%	15%	85%
1	PreWork	19.0	18.0	19.0	4.2	20.0	20.0
	SimWork	15.0	18.0	18.0	16.0	5.6	19.0
	PostWork	9.2	0.8	0.2	0.3	0.4	14.0
2	PreWork	20.0	20.0	20.0	20.0	20.0	1.6
	SimWork	13.0	3.6	14.0	16.0	20.0	9.1
	PostWork	1.1	1.7	0.3	0.9	20.0	2.9
9	PreWork	20.0	20.0	0.10	20.0	0.20	1.80
	SimWork	20.0	20.0	0.10	3.7	0.09	0.56
	PostWork	20.0	20.0	0.06	0.7	0.08	0.07
10	PreWork	0.03	8.7	0.04	0.10	20.0	0.04
	SimWork	0.09	20.0	0.05	18.0	17.0	0.05
	PostWork	0.20	3.0	0.04	20.0	1.0	0.06
15	PreWork	0.40	8.20	8.50	0.30	3.9	0.50
	SimWork	0.30	0.06	0.05	0.05	17.0	0.10
	PostWork	0.30	0.05	0.05	0.05	8.0	0.60
18	PreWork	0.08	0.30	0.30	20.0	0.40	0.06
	SimWork	0.10	0.40	6.1	2.8	6.30	0.07
	PostWork	0.10	0.50	2.9	12.0	0.70	0.09
19	PreWork	20.0	16.0	20.0	20.0	20.0	20.0
	SimWork	11.0	10.0	20.0	0.30	0.04	0.10
	PostWork	1.1	0.50	20.0	0.50	18.0	0.30
20	PreWork	0.10	20.0	20.0	0.04	4.5	0.08
	SimWork	0.30	20.0	20.0	0.04	3.5	0.06
	PostWork	4.80	20.0	20.0	0.04	4.4	0.07
21	PreWork	20.0	20.0	14.0	17.0	20.0	20.0
	SimWork	15.0	20.0	19.0	18.0	20.0	18.0
	PostWork	5.7	19.0	2.2	0.50	12.0	2.5
22	PreWork	0.20	1.7	3.6	0.06	0.02	20.0
	SimWork	0.20	17.0	16.0	0.06	0.02	20.0
	PostWork	0.20	20.0	20.0	0.07	0.02	2.5

Table X. SimWork FFs for Comfo II Facepiece in NP/AP and PAPR Types										
Subject No.	Face Size Length (mm)	Width (mm)	Respirator Type	SimWork FF (x1000) 0°C 15%	0°C 85%	21°C 15%	21°C 85%	32°C 15%	32°C 85%
1	191	149	NP/AP	15.1	18.2	18.2	16.3	5.6	19.5
			PAPR	8.9	20.0	20.0	13.8	20.0	20.0
2	166	133	NP/AP	13.1	3.6	14.2	16.3	20.0	9.1
			PAPR	20.0	20.0	20.0	20.0	20.0	20.0
9	195	137	NP/AP	20.0	20.0	0.08	2.75	0.29	0.76
			PAPR	11.8	8.3	20.0	17.8	20.0	15.4
10	179	135	NP/AP	0.04	0.50	0.06	15.2	17.1	0.06
			PAPR	20.0	20.0	20.0	20.0	20.0	20.0
15	189	141	NP/AP	0.25	0.06	0.05	0.05	16.7	0.14
			PAPR	20.0	20.0	20.0	20.0	20.0	20.0
18	181	141	NP/AP	0.15	0.39	6.1	2.8	6.3	0.07
			PAPR	20.0	20.0	20.0	20.0	20.0	16.7

caused by mask movement from sweating. The 85% RH appears to degrade FFs more than 15% RH during SimWork. The 32° temperature during PreWork exercises also reduces the FF for three subjects at 85% RH and two subjects at 15% RH.

c. Comparison of SimWork FFs for Comfo II Facepiece as Air-Purifying and PAPR Respirators. Six test subjects tested both Series I and Series II respirators, allowing a comparison of the Comfo II facepiece used both as air-purifying negative-pressure (AP/NP) and PAPR positive-pressure respirators. Table X lists the actual FFs obtained by these six test subjects for each of these two devices with a Comfo II facepiece at all six EC conditions during the SimWork exercises. Also the test subjects' face lengths and widths are listed. Test subjects 2 and 15 are female and experienced test subjects. Subject 9 also is an experienced test subject and has shown poor reproducibility doing multiple QFTs with the same respirator in other studies.

The statistical analysis of the data in Table X shows a significant difference (p-value = <0.01) between the Comfo II facepiece used in the PAPR and in AP/NP respirators.

The data in Table X clearly demonstrate the high level of performance of the MSA PAPR with the Comfo II facepiece compared with the Comfo II AP/NP respirator during SimWork exercises at all EC conditions. Subjects 2, 10, and 15 had FFs = 20,000 for all six EC conditions while wearing the PAPR with Comfo II. The lowest FFs obtained with the PAPR with Comfo II were 8900 by subject 1 and 8300 by subject 9 during work at 0°C in the EC chamber.

The data show the effect of the 32°/85% condition on the Comfo II AP/NP respirator for four of six subjects with FFs < 1000 compared with FFs > 15,000 for six of six subjects wearing the PAPR with Comfo II. This work confirms the FF = 1000 for the MSA PAPR with Comfo facepiece proposed in 1976 by Los Alamos.

Table XI. Series I Respirators—Geometric Mean FFs and SimWork FFs (x1000)						
Brand	°C	RH%	PreFit FF	PreWork FF	SimWork FF	PostWork FF
3M W344 PAPR	0	15	14.3	7.1	5.6	8.3
	0	85	18.1	14.1	4.3	11.8
	21	15	12.4	14.3	3.4	11.5
	21	85	17.1	13.2	3.3	7.9
	32	15	18.8	18.2	4.3	8.6
	32	85	13.9	11.0	1.9	4.5
Racal AH3 PAPR	0	15	8.6	8.7	2.4	1.9
	0	85	7.1	6.2	3.5	3.5
	21	15	6.6	4.9	2.4	2.5
	21	85	8.2	3.6	2.4	1.7
	32	15	5.2	2.4	2.0	2.3
	32	85	4.4	1.9	1.2	0.9
MSA Comfo PAPR	0	15	20.0	17.1	14.2	13.8
	0	85	18.4	18.7	15.3	12.7
	21	15	19.3	20.0	20.0	13.2
	21	85	20.0	18.2	19.0	14.6
	32	15	19.8	20.0	20.0	18.9
	32	85	19.7	19.8	19.1	17.4
Survivair FF/PD Supplied Air	0	15	20.0	20.0	19.7	18.9
	0	85	20.0	20.0	19.1	13.6
	21	15	19.6	19.8	15.8	19.4
	21	85	17.7	19.9	20.0	20.0
	32	15	13.3	12.6	12.4	12.8
	32	85	19.8	19.8	8.5	7.9
Bullard 999 Type C, CF Supplied Air	0	15	20.0	20.0	20.0	20.0
	0	85	19.5	20.0	16.3	20.0
	21	15	20.0	20.0	13.7	20.0
	21	85	18.7	20.0	15.8	20.0
	32	15	20.0	20.0	7.5	20.0
	32	85	20.0	20.0	19.1	20.0

C. Geometric Mean FFs

The study statistical design was approved by a member of the Laboratory's statistical group and an NRC statistician during the study planning stage. Data from 372 Series I and Series II tests were used for this study.

All statistical analyses were conducted on complete data sets (Table IV) using the Statistical Analysis System by SAS Institute, Inc., Cary, North Carolina. A complete set is defined as test results derived from one respirator worn by one test subject in all six environmental conditions. Ten full sets of data were collected on all of the respirators tested with the exception of the Bullard continuous-flow hood.

1. Series I Respirators. Table XI presents the geometric mean FFs derived from the PreFit, PreWork, SimWork, and PostWork exercise groups.

Table XII. Series II Respirators—Geometric Mean FFs and SimWork FFs (x1000)						
Brand	°C	RH%	PreFit FF	PreWork FF	SimWork FF	PostWork FF
MSA Comfo	0	15	1.3	1.5	1.6	1.3
	0	85	4.8	8.4	5.7	2.5
	21	15	1.4	3.2	2.9	0.9
	21	85	2.8	2.1	1.5	0.5
	32	15	2.6	3.2	2.0	1.5
	32	85	1.6	1.5	0.8	0.6
MSA U -aTwin	0	15	8.1	5.6	5.3	3.1
	0	85	7.2	5.2	1.0	1.5
	21	15	4.1	3.7	5.0	5.8
	21	85	2.9	4.2	2.6	5.3
	32	15	3.6	3.7	3.5	4.4
	32	85	6.5	4.9	2.6	2.6

These geometric mean FFs calculated from FFs for all test subjects show a general trend of decreasing FFs from the PreFit to the PostWork.

The 3M W344 PAPR had significant differences in PreFit, PreWork, and PostWork vs SimWork. For the Racal AH3 exercise groups, PreFit vs PostWork had a significant difference. The MSA PAPR had no significant differences because of the low levels of the penetration for this device. The reportable level of detection of our photometer was chosen to be 20,000. With one exception, respirators with *forced airflow* are not affected by temperature and humidity.

2. Series II Respirators. Table XII presents the geometric mean FFs derived for Series II respirators from the Prefit, PreWork, SimWork, and PostWork exercise groups.

D. Results of Special Tests Requested

1. In-Mask Pressure Measurements. In-mask pressure differentials were measured for the MSA Comfo PAPR and the Survivair FF/PD air-line respirators in response to a special OSHA request. Complete data sets were collected on four subjects (two males and two females). The subjects' inhalation and exhalation pressure changes were measured with Validyne pressure transducers and recorded on HP strip chart recorders. Table XIII presents the subjects' inhalation (minimum) and exhalation (maximum) pressure measurements determined at each condition for the combined SimWork exercise set.

The highest individual exhalation pressure recorded for the MSA Comfo PAPR was +1.4 in. w.g. on subject 1 (largest subject) performing the Blocks SimWork exercise at 0°C/85%. The lowest inhalation pressure recorded was –0.1 inches w.g. also on this subject performing Blocks at 21°C/85%.

The Survivair PD air-line respirator in-mask pressures may be compared with the NIOSH-approved criteria for all PD devices. The three approval criteria are (1) the positive static facepiece pressure is not to exceed 1.5 in. w.g.; (2) during inhalation (4-ft^3/min machine test), the in-mask pressure must be greater than atmospheric or positive; (3) during exhalation (3 ft^3/min), the in-mask pressure shall not be more than 2 in. above the static pressure.

The highest exhalation pressure recorded for the Survivair air-line respirator was +3 in. w.g. on subject 1 performing the Steps SimWork exercise during the 0°C/85% condition (average = 2.78). The lowest inhalation pressure recorded was –0.8,

Table XIII. Facepiece Pressure Measurements for SimWork Exercises[a]						
Test Subject	32/85	0/15	32/15	0/85	21/15	21/85
MSA Comfo II PAPR						
No. 1						
Min[b]	0.16	0.08	0.12	0.14	0.06	0.07
Max[c]	0.70	0.71	0.64	0.86	0.68	0.76
No. 2						
Min	0.29	0.25	0.24	0.32	0.27	0.19
Max	0.64	0.52	0.60	0.65	0.65	0.56
No. 15 (Female)						
Min	0.18	0.25	0.25	0.36	0.23	0.23
Max	0.54	0.65	0.59	0.74	0.61	0.62
No. 18						
Min	0.20	0.15	0.17	0.12	0.16	0.21
Max	0.65	0.61	0.66	0.59	0.62	0.74
Survivair FF/PD Supplied-Air Respirator						
No. 1						
Min	0.51	0.13	-0.05	-0.30	-0.48	-0.40
Max	2.55	2.63	2.80	2.78	2.76	2.75
No. 2						
Min	-0.06	-0.23	0.49	-0.12	0.21	0.26
Max	2.63	2.39	2.55	2.56	2.62	2.54
No. 15 (Female)						
Min	0.51	0.19	0.48	0.32	0.33	0.43
Max	2.23	2.25	2.12	2.22	2.56	2.40
No. 18						
Min	0.28	0.11	-0.31	-0.25	0.24	-0.35
Max	2.50	2.57	2.69	2.57	2.49	2.63

[a]Inches w.g.
[b]Min = inhalation.
[c]Max = exhalation.

again on subject 1 performing Steps during the 21°C/85% condition. The average pressure for this EC condition for subject 1 was –0.40.

Statistical analysis of Table XIII shows significant differences among the maximum pressures but none for the minimum pressures. There is a p-value < 0.0001 for mask effects and no temperature or humidity effect.

The purpose of the PD (positive-pressure) mode on the Survivair air-line respirator was to achieve the highest possible FFs. Test subjects 2 and 15 achieved a FF = 20,000 at all six EC conditions with the Survivair PD air-line respirator. Subject 18 had 20,000 for four EC conditions, with 13,000 and 500 FFs at 32°F conditions. Subject 1 had 5 FFs = 20,000 and a FF = 6300 at 32°C/85%. These same four test subjects had very high FFs with the MSA Comfo PAPR as previously noted (Table X), and all had an average positive pressure in the facepiece. (Table XIII shows the facepiece pressure measurements.)

The performance of the Survivair PD air-line respirator on 10 test subjects doing SimWork at all EC conditions may be compared with the

Table XIV. Survivair FF/PD Supplied-Air Temperatures			
Chamber Conditions (°C)	(% RH)	Supplied Air (°C)	Average (°C)
32	85	32.[illegible]-37.7	35.3
32	15	31.8–35.6	34.0
21	85	27.0–30.5	28.9
21	15	25.3–29.9	27.0
0	85	12.1–17.5	15.1
0	15	14.8–17.4	16.4

performance of the same device on 25 test subjects, who achieved FFs = 20,000 in a QFT chamber at room conditions (reported by Hack[12]). The 10 test subjects doing SimWork during all 6 EC conditions achieved FFs > 10,000 during 55 of 60 tests (FF = 20,000 on 49 of 60 tests). However, subject 10 obtained FFs of 250 and 700 at 32°F humidities, and subject 20 had a FF = 2100 at 21°C/85% RH.

Hack reported pressure measurements with machine tests on two Survivair PD air-line respirators. The inhalation pressures were 0.4 and 0.6 in. w.g., whereas the exhalation pressures were 2.2 and 2.6 in. w.g.

2. Supplied-Air Temperature for Survivair FF/PD Air-Line Respirator. As part of the special OSHA request, the integrated-circuit temperature transducer, placed in the facepiece behind the clear plastic air-deflection shield, was used to measure the temperature of incoming air to the facepiece. The 25-ft air hose used in the Survivair tests was attached to a chamber manifold, and breathing air was supplied from the air trailer adjacent to the building. Table XIV gives the temperatures observed.

These results confirm supplied-air temperatures experienced in industry at various atmospheric working temperatures and reported to Los Alamos investigators. An example is a New England navy yard with many feet of exposed-surface metal pipes supplying cold (40°F–50°F) breathing air during winter conditions. At the other extreme, the Gulf coast and desert workers have heat problems (>90°F) when breathing-air lines are exposed.

VI. CONCLUSIONS

1. The tight-fitting half-mask PAPR provided higher protection than helmets or loose-fitting PAPRs.

2. Performance of the Racal PAPR helmet is degraded at high (32°C) temperature. At 32°C/85% RH condition, 8 of 10 subjects obtained FFs < 1000 compared with 3 of 10 subjects with FFs < 1000 during PreFit at room temperature. At 32°C/15% RH, 5 of 10 subjects for the Racal had similar effects.

Data at 0°C/15% RH suggest that SimWork has a greater effect on performance than temperature for 4 of 10 subjects.

3. The 3M PAPR helmet data showed no effect at EC conditions during PreWork exercises. During SimWork exercises, 2 of 10 subjects showed degradation of FFs.

4. The 32°C/85% RH condition had some, but nonsignificant, effect on the performance of the MSA Comfo II PAPR when 5 of 10 subjects obtained FFs < 20,000.

5. Tests at all EC conditions and exercises confirm the FF = 1000 for the MSA Comfo II PAPR proposed by Los Alamos in 1976.[1]

6. There is some effect, but nonsignificant, on the performance of the Survivair FF/PD supplied-air respirator at 32°C/85% RH for 2 of 10 subjects with FFs < 1000.

7. EC conditions and exercises had no obvious effect on the performance of the Bullard continuous-flow supplied-air hood.

8. All subjects testing the two Series I respirators with preselection criteria met the minimum on all six PreFit tests.

9. FFs developed with the exercises, presently recommended in ANSI Z88.2 1980 for loose-fitting respirators and used for Series I tests, do not adequately simulate work factors.

10. The NP high-efficiency half-mask and full-facepiece respirators degraded during fit tests at high humidity and high temperatures in the EC.

- FFs of the half-mask respirator degraded at high humidity (85% RH) at both 21°C and 32°C, in some cases, because of the facepiece sliding down the nose from sweating during SimWork and PostWork exercises (7 of 10 subjects).
- The SimWork exercises are more effective in degrading FFs for the half-mask and the full-facepiece respirators than the PreWork or PostWork exercises.

11. During SimWork exercises, the FFs of the NP full-facepiece respirator degraded at 0°C/85% for 50% of the subjects and at 0°C/15% for 30% of the subjects. Some data suggest it is possible that cold (0°C) temperature alone was the cause of an exhalation valve freezing partly closed, causing lower FFs.

12. QFTs with the NP full-facepiece respirator at 32°C show some apparent but nonsignificant reduction of FFs, possibly caused by mask movement from sweating during SimWork.

- The 85% RH appears to degrade the FFs more than the 15% RH by a ratio of 3 to 2 subjects.
- During PreWork exercises at 32°C, the FFs are also reduced compared with PreFit at room temperature for three subjects at 85% RH and two subjects at 15% RH.

13. FFs developed with the exercises, presently recommended in ANSI Z88.2-1980 for tight-fitting respirators and used for Series II tests, do not adequately simulate work factors.

14. The six PreFit FFs at room temperatures show poor reproducibility on some respirators tested. For example, we see poor reproducibility (defined on p. 17) for the following:

- most subjects testing the Racal PAPR helmet, which had the largest variation of Series I;
- six of ten subjects testing the Series II NP half-mask high-efficiency respirators; and
- seven of ten subjects testing the Series II NP full-facepiece high-efficiency respirator.

15. The preselection criteria originally used for subject selection for Series II respirators were not met during PreFit tests by most subjects.

- For the full-facepiece respirator, 2 of 10 subjects met the preselection criteria (FF ≥ 3000) on all 6 tests.
- For the half-mask respirators, 4 of 10 subjects met the preselection criteria (FF ≥ 1000).

16. Test subject's comments regarding comfort show the following:

- Respirator users are more comfortable using continuous-flow respirators in hot and humid conditions than using tight-fitting PD devices such as the Survivair.
- Continuous-flow hoods are the most comfortable of all devices in hot and humid conditions.
- Most test subjects commented that the MSA Comfo II facepiece was uncomfortable across the bridge of the nose. They also said that the half-mask facepiece seemed to slip on their faces when they sweated.
- The MSA UltraTwin was reported to cause uncomfortable pressure across most subjects' foreheads. The subjects all remarked about the large amount of moisture that accumulated in the facepiece from sweat and exhaled moisture.

VII. RECOMMENDATIONS

1. PAPRs should be divided into two classes—those with tight-fitting facepieces and those with helmets or loose-fitting facepieces. This classification change is being considered by the present ANSI Z88.2 committee.

2. More dynamic full-body exercises should be used for QFTs to better duplicate work situations, especially those motions in which the individual bends over and stands up repeatedly.

3. Efforts should be made to solve the problem of half-mask respirators sliding down the nose because of sweating in hot and humid conditions. Some currently commercially-available solutions to consider follow:

- A five-point suspension head harness with the fifth point connected to the half-mask nosepiece from above (used on Comfo for over 20 years by Canadian Atomic Power Plant workers).
- A hairnet-type head harness similar to one used by Scott to stabilize facepieces.

• The top headband split or divided over the crown of the head to form a yoke and help stabilize the half-mask (used for decades in Europe and currently available from most U.S. manufacturers on request.)

4. A more extensive study should be conducted with a larger number of different manufacturers' NP respirators, especially in hot and humid conditions and in simulated work.

5. The field study originally proposed for the third phase of this project should be conducted for a better understanding of the relationship between laboratory-developed FFs and actual work-use factors.

6. Studies of simulated work conditions can be used to determine the effects of field variables found in real work conditions. This information better prepares the field surveyor to obtain realistic data from well-planned and -executed field studies.

7. The study data seem to suggest that the negative-pressure full-facepiece respirator should be assigned a protection factor greater than the 50 presently recommended in 10 CFR Part 20 for NRC. However, more data must be collected to substantiate this change.

8. The Racal chin strap, offered as an auxiliary piece of equipment, should be an integral part of the respirator to improve the performance of the device. We understand that Racal has already acted on this suggestion and is now selling their device with the chin strap as standard equipment.

9. The MSA PAPR and Racal power switches should have a guard installed to protect the unit from being inadvertently switched off.

10. Diligent quality assurance control of all respiratory protective devices must be emphasized by all respirator manufacturers. A defective respirator, such as found among the new respirators purchased for this study, could be hazardous to an unsuspecting worker.

Careful cleaning, maintenance, and inspection with good employee training will help correct many problems and provide reliable use of respiratory protective devices.

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13 ABSTRACT (200 words or less)

A study conducted at the Los Alamos National Laboratory compared quantitative fit factors and simulated work factors and determined the effects of temperature and humidity on respirator fit. This study used a commercially available fit chamber and an environmental chamber set at six conditions to simulate U.S. work environments. Seven respirators were tested on a limited test panel of 10 subjects. The test results indicate that the performance of one powered air-purifying respirator (PAPR) helmet is significantly degraded during the simulated work exercises, whereas the half-mask PAPR performance was not affected. Tight-fitting facepiece PAPRs provide higher protection than loose-fitting PAPRs. The performance of the negative-pressure half-mask and full-facepiece respirators is degraded during fit tests at high humidity and high temperature. The degradation of the fit factors for the negative-pressure half-mask during high humidity at ambient and high temperatures is probably due to facepiece slippage caused by sweating. More dynamic exercises, including motions in which the individual bends over and stands up repeatedly, are recommended to develop quantitative fit factors that adequately simulate work factors. Tight-fitting facepiece PAPRs should not be classified with loose-fitting PAPRs.

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