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**Respirator Studies for the
National Institute for
Occupational Safety and Health**

July 1, 1974—June 30, 1975

by

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**RESPIRATOR STUDIES FOR THE NATIONAL
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ABSTRACT

Respirator studies carried out in FY 1975 for the National Institute for Occupational Safety and Health were concentrated in two major areas: (1) the development of respirator test equipment and methods to improve the means of evaluating the performance of respirators, (2) the testing of respirators to obtain quantitative data to permit recommendations to be made to upgrade respirator performance criteria. Major accomplishments included obtaining man-test results on several different respirators using an anthropometrically selected test panel, determination of respirator exhalation valve leakages under static and dynamic conditions, and determination of the effects of respirator strap tension on facepiece leakage.

I. INTRODUCTION

During 1975, the Respirator Research and Development Section, Industrial Hygiene Group of the Los Alamos Scientific Laboratory (LASL), continued to carry out studies in the field of respiratory protection for the National Institute for Occupational Safety and Health (NIOSH). These studies were made in two major areas of endeavor: (1) the development of respirator test equipment and methods to improve the means of evaluating the performance of respirators and respirator components, (2) the testing of respirators and respirator components to obtain quantitative data to permit recommendations to be made to upgrade the performance criteria for respirator components. The primary objective of the studies is an increase in the protection offered by respirators to workers who are exposed to air contaminants in work places.

II. DEVELOPMENT OF TEST EQUIPMENT AND METHODS

A. Introduction

During FY 1975, studies were conducted on the operating characteristics of the LASL Model I NaCl Aerosol System; development work was begun on a sulfur hexafluoride (SF_6) gas man test system; two respirator exhalation valve test systems were constructed and shipped to the NIOSH Engineering Branch; commercial strap tension meters were evaluated for ability to determine respirator head harness strap tension; and attempts were made to develop a method for determining respirator face-to-facepiece pressure.

B. Operational Characteristics of the LASL Model I NaCl Aerosol System

1. Introduction. Studies have continued on the operating characteristics of the LASL Model I NaCl Aerosol System.^{1,2} Investigations carried out during FY 75 included studies of the reproducibility of the NaCl aerosol size distribution produced by the system; a study of the stability of the system aerosol concentration; a study to determine if filter penetration results obtained at the NIOSH TCI and NIOSH EB laboratories agreed with results obtained at LASL; a study in which filter penetration results obtained at LASL were compared to filter penetration results obtained by the Physics Division, Chemical Defense Establishment, United Kingdom;

and a study to determine if exhaled breath affected the response of the system flame photometer.

2. Reproducibility of NaCl Aerosol Particle Size Distribution Produced by the Model I NaCl Aerosol System. Twelve size distribution determinations were made using two sets of single-stage round jet impactors. Impactors used were the four LASL 3-//min impactors² and four commercial 1-//min impactors. The 1-//min flow rate of the commercial impactors allows use of either the Model I Flame Photometer or a Thermal Systems Incorporated Particle Mass Monitor for determination of the mass percentage of incident NaCl aerosol passing the impactor stages.

Size distributions of aerosols generated by the Model I System were determined in a filter test chuck and in a man-test chamber. Aerosols were generated from a 1% NaCl solution using Wright nebulizers operated at 165-kPa (24-psi) air pressure. Aerosols were dried with 85 //min of dilution air having a temperature of approximately 20°C. Five different nebulizers were used, and in three of the 12 tests, two nebulizers were operated together.

A summary of test results is presented in Table I. All m_{mad} values were between 0.55 and 0.77 μm , and all σ_g values were between 1.90 and 2.33. Further studies would be necessary to establish the effects of this variability on filter-test and man-test results.

3. Aerosol Concentration Stability. A test was conducted to determine the stability of the NaCl aerosol concentration produced by the Model I System. Aerosol was generated from a 1% NaCl solution at 165-kPa (24-psi) air pressure supplied to the nebulizer. The resultant aerosol was diluted and dried with 35 //min of air at $\approx 21^\circ\text{C}$ and $\approx 20\%$ RH.

This diluted aerosol was delivered to an aerosol holding chamber and from this chamber 32 //min of aerosol was drawn through the filter-test chuck. A 0.3-//min sample from the test chuck was delivered through a peristaltic pump to the NaCl aerosol flame photometer. The photometer was interfaced to a strip chart recorder. Aerosol was continuously sampled for two hours with photometer response initially set to 85% of full scale. The largest deviation of the recorder trace throughout the two-hour period was $\pm 5\%$ of full scale, which was considered sufficiently stable for filter-testing purposes.

TABLE I

NaCl Aerosol Size Distribution Reproducibility for Aerosols Generated from a 1% NaCl - Water Solution at 165-kPa Gauge Pressure (24 psi) and Diluted with 85-ℓ/min air.

<u>Sizing Method</u>	<u>Location</u>	<u>Nebulizer</u>	<u>mmad (μm)</u>	<u>σ_g</u>
LASL 3-ℓ/min impactors	Filter test check	#10	0.69	2.32
LASL 3-ℓ/min impactors	Filter test check	#10	0.70	2.21
LASL 3-ℓ/min impactors	Filter test check	#10	0.76	2.03
LASL 3-ℓ/min impactors	Filter test check	#10	0.74	2.27
LASL 3-ℓ/min impactors	Filter test check	#7	0.68	2.06
LASL 3-ℓ/min impactors	Filter test check	#7	0.71	2.11
LASL 3-ℓ/min impactors	Large man-test chamber	#13 + #10	0.62	2.33
LASL 3-ℓ/min impactors	Large man-test chamber	#13 + #10	0.55	2.18
LASL 3-ℓ/min impactors	Large man-test chamber	#13 + #10	0.62	2.26
Commercial 1.0-ℓ/min impactors (TSI used for mass analysis)	Large man-test chamber	#13	0.73	1.90
LASL 3-ℓ/min impactors	Large man-test chamber	#13	0.77	2.14
Commercial 1.0-ℓ/min impactors (LASL flame photometer used for mass analysis)	Large man-test chamber	#13	0.76	1.97

Av = 0.69 Av = 2.15

Range = Range =
0.66 ± 0.11 2.15 ± 0.18

4. NaCl Aerosol Filter Penetrations Obtained by NIOSH TCL, NIOSH EB, and LASL. Four LASL Model I NaCl Aerosol Systems are now in operation; two at LASL, one at the NIOSH Engineering Branch (EB) in Cincinnati, Ohio, and one at NIOSH Testing and Certification Laboratory (TCL) in Morgantown, West Virginia. To determine how well results obtained with the different units agreed, twenty-three 100-cm²-area filter pads were tested at LASL for aerosol penetration, then retested at TCL and EB. LASL operators performed all tests. Original plans called for 11 of the pads to be retested at TCL and the remaining 12 to be retested at EB, but results obtained at TCL differed so much from results obtained at LASL that the operators decided to retest all 23 at EB to determine if the filter pads had been damaged. Filter penetrations obtained at TCL are compared to LASL-determined

penetrations in Table II and penetrations obtained at EB are compared to LASL-determined penetrations in Table III. Size distributions of test aerosols were determined with LASL-designed 3-ℓ/min impactors, and are reported in footnotes in the tables. EB results agreed well with LASL results, while TCL results were about double the LASL results. Again filters numbered 1 through 11 were tested at LASL, TCL, and at EB. The operators noted that the TCL unit displayed a very unstable zero-level reading ($\pm 0.1\%$), which probably contributed to the differences in penetration results.

5. Comparison of LASL NaCl Aerosol Filter Tests with the United Kingdom Chemical Defense Establishment NaCl Filter Test. Dust respirator filter approval schedules in the United Kingdom (UK) include a NaCl aerosol penetration

TABLE II

Comparison of Filter Penetrations Determined at LASL and NIOSH TCL for a Flow Rate of 32 ℓ/min through 100-cm² Effective Area

Filter	LASL % Pen ^a	TCL % Pen ^b
1	0.16	0.37
2	0.19	0.52
3	0.16	0.33
4	0.18	0.38
5	0.22	0.48
6	0.18	0.36
7	0.26	0.55
8	0.24	0.62
9	0.29	0.55
10	0.18	0.38
11	<u>0.17</u>	<u>0.32</u>
Av	0.20	0.44

^aAerosol $m_{\text{mad}} = 0.62 \mu\text{m}$, $\sigma_g = 2.01$.

^bAerosol $m_{\text{mad}} = 0.50 \mu\text{m}$, $\sigma_g = 1.80$.

test.³ To determine how the LASL NaCl penetration test compared to the UK test, six types of filter media were tested for NaCl aerosol penetration by LASL and by the Physics Division, Chemical Defense Establishment (CDE) in the UK. Of the six materials tested, five were 100-cm²-area glass paper discs supplied by the CDE, and one was a 100-cm²-area disc of American dust respirator filter media consisting of ultrafine glass fibers and coarse organic fibers, supplied by LASL. Five discs of each of the five materials supplied by CDE and one disc of the material supplied by LASL were tested for NaCl aerosol penetration at 5-cm/s face velocity at both LASL and CDE. Results of these tests are presented in Table IV. Both sets of results indicate decreasing penetration values for materials A through F; that is, the relative ranking was the same. This fact is important since it demonstrates that either test can be used to determine the relative merits of different filter materials. The difference in penetration results between LASL and CDE may be

TABLE III

Comparison of Filter Penetrations Determined at LASL and NIOSH Engineering Branch Laboratory for a Flow Rate of 32 ℓ/min through 100 cm² Effective Area

Filter ^a	LASL % Pen ^b	NIOSH Engineering Lab % Pen ^c
1	0.16	0.22
2	0.19	0.20
3	0.16	0.19
4	0.18	0.17
5	0.22	0.22
6	0.18	0.24
7	0.26	0.27
8	0.24	0.28
9	0.29	0.30
10	0.18	0.23
11	0.20	0.18
12	0.17	0.17
13	0.24	0.23
14	0.21	0.21
15	0.22	0.20
16	0.20	0.23
17	0.20	0.21
18	0.24	0.25
19	0.19	0.20
20	0.21	0.21
21	0.18	0.19
22	0.20	0.22
23	<u>0.15</u>	<u>0.15</u>
Av	0.20	0.22

^aFilters numbered 1 through 11 also tested at TCL (Table II).

^bAerosol $m_{\text{mad}} = 0.62 \mu\text{m}$, $\sigma_g = 2.01$.

^cAerosol $m_{\text{mad}} = 0.57 \mu\text{m}$, $\sigma_g = 2.05$.

due to differences in aerosol particle size distribution, but further studies would be necessary to con-

TABLE IV

Comparison of LASL NaCl Aerosol Filter Tests with the United Kingdom
Chemical Defense Establishment NaCl Filter Test

Material	Mean NaCl Aerosol Penetration (%)	
	CDE	LASL
1	77	87
2	13.8	8.4
3 ^a	3.7	1.9
4	2.75	1.1
5	0.028	0.008
6	0.014	0.003

^aAmerican material supplied by LASL.

firm this. The CDE has expressed an interest in exchanging additional filter materials for comparison studies using both DOP and NaCl aerosols. LASL will participate in these studies as soon as work schedules permit.

6. Comparison of Silica Dust and Silica Mist Tests with Sodium Chloride Aerosol Tests for Respirator Dust and Mist Filters. Two different types of fibrous filter materials were selected for a study to compare the results of silica dust and silica mist penetration tests with sodium chloride aerosol penetration tests. Raw filter material was obtained and cut into filter discs by LASL. These filters were then analyzed for weight, resistance to air flow, and sodium chloride penetration. The discs were then sent to four respirator manufacturers and NIOSH. With the exception of NIOSH, each concern will run silica dust and silica mist tests. NIOSH will run sodium chloride aerosol penetration tests. At this time, results have not been received from all participants.

7. Investigation of Possible Effect of Constituent in Breath on Response of Flame Photometer of NaCl Aerosol Apparatus and Determination of Lowest Feasible NaCl Aerosol Penetration.

a. Introduction. The LASL NaCl Aerosol System and a hood-type chamber were used to evaluate the performance of the sealing of respirator facepieces to faces of human test subjects. During a performance test, the quantitative penetration of NaCl aerosol particles into the interior of the respirator facepiece is measured.

The Annual Report of Studies for NIOSH carried out by LASL for FY 1973 (LA-5620-PR) mentions that there may be some doubt about the accuracy of NaCl aerosol penetration readings made during performance testing of respirators due to some constituent in the exhaled breath of human test subjects affecting the photometer reading. The above-mentioned report questioned the accuracy of aerosol penetration measurements of less than 0.1 percent.

During FY 75 studies were performed to determine the effect of exhaled breath on the accuracy of the measurement of aerosol penetration into facepieces. Tests were carried out in which the test subjects wore a full-facepiece air-purifying respirator equipped with a high-efficiency filter cartridge. The respirators were tested inside a chamber which contained clean air (no NaCl aerosol present). The test subjects carried out normal breathing and deep breathing while wearing the respirators. Air from within the interior of a respirator facepiece during a test was sampled at 1.0 l/min and fed into the flame photometer burner. The photometer has scales of 0-100, 0-10, 0-1.0, and 0-0.1%. One series of tests was carried out at the 0-1.0% setting and another at the 0-0.1% scale.

An air-purifying respirator (Respirator KS) with full facepiece and high-efficiency filter (which permits no more than 0.03% penetration of a 0.3- μ m DOP aerosol) was used in all tests.

LASL also carried out tests to determine the stability of NaCl penetration measurements using the 0-0.1% scale on the photometer. These tests used clean air at flow rates of 1.0 l/min and 0.3 l/min. Tests were also made to determine the lowest aerosol penetration which could be measured when either of the two mentioned air-sampling flow rates are used.

b. Procedures. During a test, the gain setting on the electronics unit was adjusted to 8.37 which is the setting used for a full-scale meter deflection for the 0-100% scale when air containing NaCl aerosol at 15 mg/m³ is fed into the photometer burner. It must be remembered that the tests were carried out without any NaCl aerosol being present in the test atmosphere. The stray light control was adjusted to give a mid-scale meter reading. Each test subject provided information about his most recent meal and smoking habits.

Air at a flow rate of 1.0 l/min was sampled from within the facepiece and fed to the photometer during the time that the test subject wore the respirator. The test subject was required to first breath normally and then deeply for a few minutes. Results for these two settings are presented in Tables V and VI.

TABLE V

DEPRESSION OF SODIUM CHLORIDE AEROSOL SYSTEM PHOTOMETER ZERO READING BY HUMAN BREATHING

Test Unit: Human subject wearing full-facepiece type air-purifying respirator equipped with high-efficiency type particulate-filter cartridge.

Air-Sampling Flow Rate: 1.0 l/min Photometer Scale: 0 to 1.0%

Stability of Photometer Zero: $\pm 0.01\%$.

Test Subject	Time After Last Meal (hr)	Most Recent Meal	Does Test Subject Smoke	Depression of Photometer Reading (%)
A	1.5	Toast, Coffee	Yes	0
B	1	Chili Hamburger, Coffee	Yes	0
C	3	Cheese Sandwich, Coke	Yes	0.05
D	2	Hamburger, Malted Milk	Yes	0
E	1.5	Orange Juice, Cereal, Tea	No	0
F	1.5	Ham, Peas, Carrots, S. Potatoes, Coffee	Yes	0.02
G	1.5	Fr. Potatoes, Eggs, Toast, Coffee	No	0
H	4.5	BBQ Beef, Beer	Yes	0.02
I	2	Toast, Coffee	Yes	0
J	3	Gr. Cheese Sandwich, Orange Juice	Yes	0
K	1.5	Apple Pie, Cake	Yes	0

Tests were carried out to determine both the stability of the aerosol penetration measurements and the lowest penetration which could be measured accurately with the 0-0.1% scale setting. Tests were made at a sampling rate of 1.0 l/min and at 0.3 l/min. Table VII shows the results of these tests.

c. Analysis of Test Results. A review of Table V shows that, in 3 of 11 tests, there was a depression of the flame photometer reading. The largest depression was found to be 0.05%. Each of the two other depressions was 0.02%. Table V also indicates that the photometer zero reading can vary up to $\pm 0.01\%$ or a total of 0.02%. Thus, the largest depression of the photometer reading, 0.05%, is about 2.5 times the random fluctuation of the photometer zero reading. The other two depressions of the photometer, which are equal to 0.02%, are

equivalent to the random fluctuation of the photometer zero reading. Therefore, only a single significant depression of the photometer reading occurred in eleven tests carried out with the 0-1.0% scale setting of the photometer.

A study of the test results given in Table VI indicates that in two of the eight tests there was depression of the photometer reading. The depression of the reading in one test was 0.01% and in the other 0.005%. Table VII shows that the photometer zero reading can range up to $\pm 0.005\%$ or a total of 0.01%. Thus, the largest depression of the photometer reading, 0.01%, is equivalent to the random fluctuation of the photometer zero reading, and the other small depression of the photometer, 0.005%, is only half the value of the random fluctuation of the photometer zero reading.

TABLE VI

DEPRESSION OF SODIUM CHLORIDE AEROSOL SYSTEM PHOTOMETER ZERO READING BY HUMAN BREATHING

Test Unit: Human subject wearing full-facepiece type air-purifying respirator equipped with high efficiency type particulate-filter cartridge.

Air-Sampling Flow Rate: 1.0 l/min Photometer Scale: 0 to 0.10%

Stability of Photometer Zero: $\pm 0.005\%$.

Test Subject	Time After Last Meal (hr)	Most Recent Meal	Does Test Subject Smoke	Depression of Photometer Reading (%)
A	4	Eggs, Toast, Coffee	Yes	0
B	2	Toast and Coffee	Yes	0.01
C	2	Eggs, Beef Patty, Coffee	Yes	0
D	4.5	Eggs, Beef Patty, Coffee	Yes	0.005 ^a
E	17	Pork Chops, Chili, Beer	No	0
F	3	Orange Juice, Cereal, Tea	Yes	0
G	2	Eggs, Bacon, Toast, Milk	No	0
H	2.5	Eggs, Bacon, Chili, Coffee	Yes	0

^aPhotometer gain adjusted to maximum value.

The information given in Table V and VI indicates that there is no apparent relationship between the food consumed by test subjects or the smoking habits of these test subjects and the depression of the flame photometer reading.

The results given in Table VII show that when the NaCl aerosol photometer scale setting is 0.1%, the total fluctuation range for zero reading was found to be 0.004 to 0.014% for flows of 1.0 l/min and 0.007 to 0.016% for 0.3 l/min. The average of the total fluctuation range for the photometer zero reading at the 1.0-l/min air-sampling rate was 0.009% and at the 0.3-l/min rate was 0.010%.

d. Conclusions. A significant depression of the photometer reading given by the NaCl aerosol system occurred in only one of the 19 tests carried out with test subjects in clean air. This depression was only 2.5 times the random fluctuations. Thus, it is concluded that the accuracy of the measurement of NaCl aerosol particulate penetrations into the interior of respirator facepieces worn by human test subjects is not affected by any constituent in the breath of the subjects.

Since the average of the total fluctuation range of the photometer zero reading was found to be 0.009 to 0.010% for flow rates of 1.0 l/min and 0.3 l/min when the scale setting is 0.01%, it is concluded that the NaCl aerosol system should not be used to measure penetrations of respirators and filters that are smaller than 0.010%.

C. Gas Man-Test System

1. Introduction. NIOSH requested that LASL develop a man-test system using a gaseous atmosphere rather than an aerosol. LASL reviewed gas detector systems for applicability. The system chosen for development was sulfur hexafluoride as the gas, and a hydrogen flame photometer, set to detect sulfur emission lines, as the detector. A bench test set up has been fabricated and preliminary tests performed.

2. System Criteria. LASL developed the following criteria for a gas man-test system:

TABLE VII

TOTAL RANDOM FLUCTUATION OF SODIUM CHLORIDE
AEROSOL SYSTEM

Test Conditions: Clean air (passed through high-efficiency type particulate-filter cartridge) fed into flame photometer burner.

Photometer Scale Setting on Electronic Unit: 0-0.1 percent scale.

Total Random Fluctuation for Air-Sampling Rate of			
1.0 l/min		0.3 l/min	
Test	Total Fluctuation Range of Photometer Zero Reading (%)	Test	Total Fluctuation Range of Photometer Zero Reading (%)
1	0.004	1	0.012
2	0.010	2	0.008
3	0.014	3	0.007
4	0.005	4	0.016
5	0.012	5	0.009
6	0.010	6	0.008
7	0.008	7	0.010
8	0.007	8	0.009

a. Challenge gas must be inert at normal conditions and nontoxic.

b. Detector must be real time (event now - signal now).

c. Detector operation should be relatively insensitive to high humidity and normal constituents of human breath.

d. Detector operation should provide greater sensitivity than that provided by present aerosol systems.

The criteria are based on LASL's use of aerosol man-test systems, and test results for a gas system need to be correlated to aerosol system results.

3. System Chosen for Development. LASL reviewed various combinations of gases and detectors. After discarding explosive, corrosive, or toxic gases, slow time-averaging detectors, and detectors seriously affected by humidity, carbon dioxide, or hydrocarbons found in normal breath, the best available gas was sulfur hexafluoride, (SF_6), as a challenge atmosphere. SF_6 is a synthetic inert gas, listed as a common asphyxiant, with a TLV of 1000 ppm. The detector is a Tracor hydrogen flame

photometer, using a photomultiplier tube filtered to detect sulfur emission lines.

4. System Development. LASL set up a bench test gas system. The system includes the Tracor flame photometer, LASL model 72A photometer electronics (same as used on NaCl flame photometer), flowmeters, gas flow control valves, and gas bottles. The system uses H_2 , O_2 , N_2 , and air for the flame supply.

After some experience in the use of the detector was obtained, a thermocouple was installed in the detector to signal when the flame is on. Because an incorrect gas mixture will extinguish the flame, a positive flame detector is needed.

A test was run using $\approx 10\,000$ ppm SF_6 introduced with combustion air. The flame was not extinguished, but thick white smoke issued from the exhaust. The residue left in the burner chamber had to be burned off, taking three days. During the first two days, the photometer response was off scale on the 100% range with the gain set as low as possible. The sensitivity of the detector seems promising. Work on this system will be continued into FY 1976.

D. Valve Test Unit Fabrication

1. Introduction. Fabrication of two respirator exhalation valve test units for NIOSH was a carry-over project from FY 74, completed during FY 75.

The valve test units met all the design criteria listed in the FY 74 NIOSH-AEC letter of agreement. Several other functions besides those listed in the FY 74 letter of agreement were included by LASL.

The units were ready for calibration and final check-out in December 1974 and were shipped in May of 1975.

2. Valve Test Unit Functions. Exhalation air may be any of the following:

1. Ambient air.
2. Ambient temperature air at $\approx 98\%$ RH.
3. Heated and humidified air; temperatures between ambient and 93°C (200°F), humidity between 90% and 100% RH.
4. Cycles that simulate human breathing.
5. Intermittent blasts of air, of variable flow rate, to simulate coughing.
6. A continuous blast of air, of variable flow rate.

Inhalation Leak Testing may be any of the following:

1. Static air leakage at test suction from 125- to 1000-Pa gauge (1/2 in. to 4 in. of water column).
2. Static aerosol leakage at test suction from 125- to 1000-Pa gauge (1/2 in. to 4 in. of water column).
3. Dynamic air leakage at test suction from 125- to 1000-Pa gauge (1/2 in. to 4 in. of water column).
4. Dynamic aerosol leakage at test suction from 125- to 1000-Pa gauge (1/2 in. to 4 in. of water column).

LASL designed the valve test units to test exhalation resistance pressure continuously during each normal exhalation. During the unit check-out, it was discovered that the higher exhalation flows would cause a negative resistance pressure. Investigation showed that the pressure tap, which is the aerosol leak detector connection, was located at a small i.d. connection. High flow rate air caused a Venturi effect at the pressure tap, consequently producing a negative pressure signal. Correction of the pressure tap location would cause errors in pressure reading and increased aerosol delivery time to the detector. Because no long-term experience had been attained in the use of the unit, design modification was postponed until routine use experience was obtained. The modification would be simple: either a new location for the pressure tap, or one valve holder for pressure measurement and one for aerosol leak testing.

3. Training of NIOSH Personnel. Training of NIOSH personnel to operate the valve test units was completed during the week of June 23, at NIOSH EB, Cincinnati. LASL personnel trained NIOSH EB personnel and NIOSH TCL personnel at that time.

The LASL Exhalation Valve Test System has been modified to allow determination of the fraction of the total respirator aerosol leakage contributed by an exhalation valve under actual use conditions. This modification is described in section III. C of this report.

E. Head Harness Strap Tension Meter

1. Project Description. Title 30 CFR Part 11, Section 11.78 (a), requires respirator head harness "to provide adequate tension during suspension and an even distribution of pressure over the sealing area." The ERDA-NIOSH letter of agreement for FY 1974 requested LASL to perform research, and develop instruments to measure head harness tension, and this work was continued in FY 1975.

Adequate instrumentation for measuring head harness tension was required as soon as possible for certification testing and for checking tension prior to man tests. Because of the immediate need, LASL first searched for commercially available instruments. Head harness tension meter criteria were: small and light enough to be held in one hand, easily operated by one operator, reasonable accuracy and reproducibility.

The instruments to be developed for future use would be more accurate than those for immediate use, providing continuous readings while a subject performs test exercises. Hopefully, such instruments would be small enough to be worn by a test subject.

2. Immediate Use Instruments. LASL began an extensive search of recent literature for strap tension meters that satisfied the basic criteria.

In the FY 74 Annual Report¹ to NIOSH, LASL reported an investigation of two strap tension meters, both produced by the Electromatic Equipment Company. One of these meters, the Check-Line BXL-200, gave accurate and reproducible results when used to measure the tension in a strap from which a known weight was suspended.¹

During FY 75, three other strap tension meters have been investigated. They were a Tensitron, Inc., Electronic Displacement meter, a Tensitron, Inc., spring-operated meter, and an Electromatic Equipment Company special order spring-operated meter.

For each instrument, accuracy and reproducibility were tested by measuring the tension on a suspended strap, with known weights creating the strap tension. Also, the meter's usability in measuring head harness strap tension was evaluated on a respirator worn by a test subject.

a. *Tensitron Electronic Tension Meter.* Figure 1 shows the Tensitron model FT-2000 transducer. Price of this unit is about \$1500. The unit tested was on loan to LASL from the American Optical Corporation.

During the bench tests at LASL the FT-2000 meter gave erratic, inaccurate readings, and had a zero-point drift. However, when the same unit was bench tested at the Tensitron laboratory at Harvard, Cambridge, MA, with LASL personnel present, the unit was extremely accurate with steady readings, and no zero-point shift. No good, provable reason has been suggested for this discrepancy. The test results must be taken as inconclusive.

When the unit was used to test head harness strap tension on a respirator being worn by a subject, the sensor was usable but produced some operator complaints. The sensor spring tension was high enough to quickly cause operator fatigue. The strap acquisition device consisted of chromed steel plates which held the strap in place in the sensor, Fig. 2. If the strap is not allowed to move freely through the acquisition device, small changes in sensor position will cause incorrect tension reading.

The Tensitron unit was returned to the American Optical Corporation at the end of the 90-day loan period.

Fig. 1.
Tensitron Model FT-2000,

Fig. 2.
Tensitron Strap Acquisition Device.

b. *Tensitron Spring-Operated Tension Meter.* Figures 3 and 4 show a Tensitron model TM-200 hand-held, spring-operated tension meter. The trigger separates the three rollers. To measure strap tension, the rollers are separated, the strap to be measured is placed between the rollers, and the rollers come back to their normal position. The displacement of the center roller produces a meter read-out of strap tension.

Two TM-200 meters were purchased for evaluation, one with 0-2000-g range, calibrated for elastic fabric straps, and the second with 30-5000 g, calibrated for rubber straps. The instruments cost \$270 each.

During the suspended strap testing the Tensitron meters showed good accuracy and excellent reproducibility.

During the actual use test, the Tensitron meters were difficult to use, due to the arrangement of rollers. The operator usually had to take a reading

Fig. 3.
Top View, Tensitron Model TM-200.

Fig. 4.
Bottom view, Tensitron Model TM-200.

while the head harness strap was pulled away from the subject's head, causing an inaccurate reading. This error could be minimized on some masks, where the strap-adjusting clip was mounted away from the head, by taking the reading as close as possible to the facepiece. This major problem was the only one encountered.

c. **Check-line, Special-Order, Spring-Operated Tension Meter.** Figure 5 shows a Check-line, master series, model BXL-200-20L, special order, spring operated tension meter, sold by Electromatic Equipment Company. The special model has two modifications:

1. A lever replaces the thumb switch, providing easier operation.
2. The rollers on the strap acquisition device are very thin, to reduce the distance that the strap is held away from the subject's head. Each instrument costs \$335.

LASL purchased two special order meters with different ranges. One has a range of 20 to 2000 g. for use on elastic fabric straps. The second has a range of 50 to 5000 g. for use on rubber straps.

These meters showed good accuracy and reproducibility when testing a suspended strap.

The special order meters were very easy to use measuring head harness strap tension on a subject. The thin rollers kept the section of strap being measured very close to the subject's head.

3. **Continuous Read-Out Strap Tension Meter.** The most promising continuous read-out head harness tension instrument uses a conductive elastomer as the tension sensor. A conductive elastomer strap changes electrical resistance as it is elongated. A specific electrical resistance would be calibrated to a known tension in the strap. A calibrated conductive elastomer strap attached in line, or in parallel, with the actual head harness strap would produce continuous signals of instantaneous head harness strap tension. The resistance of the conductive strap would be measured by an ohmmeter. The connection between the ohmmeter

Fig. 5.
Checkline Master Series, Model BXL-200-20L.

and the strap would be two fine low-resistance wires. The ohmmeter reading could be transferred to a recording instrument. The LASL plastic fabrication group has been unable to produce a satisfactory conductive elastomer using a formula published by NASA. LASL has located a commercial manufacturer of conductive elastomers, Technical Wire Products, Inc., and has purchased several sheets of different materials.

Tests at LASL showed that the commercial conductive elastomer will signal a change in length, but will not return to the original zero reading after tension is removed, and the signal produced by change in length is not reproducible. LASL feels that using a conductive strap is feasible, but time will have to be spent developing the proper conductive elastomer.

F. Face-to-Facepiece Pressure Sensor Development

1. **Project Description.** Title 30 CFR Part 11, Section 11.78 (a), requires respirator head harness "to provide adequate tension during suspension and an even distribution of pressure over the sealing area." As of June 1974, NIOSH TCL had no instruments to check facepiece pressure. The ERDA-NIOSH letter of agreement for FY 1975 requested LASL to perform research and develop design criteria for an instrument to measure facepiece pressure.

The criteria for a face-to-facepiece pressure measuring instrument were: small and light enough to be held in one hand, easily operated by one operator, producing reasonably accurate and reproducible pressure readings, and a pressure sensor thin enough to cause a minimum of disturbance to the facepiece seal when inserted between the face and the facepiece.

2. **Investigations.** LASL searched recent literature for pressure meters that would satisfy the basic criteria for the face-to-facepiece pressure meter.

No satisfactory pressure meter was found. Load cells are too big. Catheter blood pressure sensors were the right size, but only measure fluid pressure. The smallest adequate pressure sensor was 0.9 mm (0.035 inches) thick, much too thick for the intended use. Several vendors commented on the difficulty of solid surface-to-solid surface pressure measurements.

After determining that a satisfactory pressure meter was not commercially available, LASL investigated instrument development from available products.

The development planning showed two promising approaches: a) a Validyne⁴ very low differential

pressure transducer monitoring the air pressure in a small plastic bulb inserted between the face and facepiece; and b) pressure-sensitive liquid crystals which change color with pressure, used as the sensor for face-to-facepiece pressure. Both approaches proved unsuccessful.

a. *Use of a Validyne Differential Pressure Transducer.* During FY 1975, a plastic bulb Validyne pressure transducer system, described in the FY 1974 annual report to NIOSH¹ and illustrated in Fig. 6, was constructed. A preliminary investigation revealed that, when the sensor was moved as an operator would have to move it during a test, high transducer output voltages (2 to 3 volts) occurred. When the plastic bulb sensor was completely collapsed, maximum output voltage was only about one volt. Since background voltage signals caused by moving the sensor were higher than the maximum voltage resulting from a collapsed sensor, the system can not be used for measuring face-to-facepiece pressure. Any fluid pressure-measuring instrument used for this purpose will have the same problem. Work on this project has been terminated.

b. *Use of Pressure-Sensitive Liquid Crystals.* Liquid crystals are, generally, synthetic, viscous liquids which change colors due to changes in

Fig. 6.
Plastic Bulb Air Pressure Sensor for Face-to-Facepiece Pressure Measurement.

molecular arrangement when subjected to heat, pressure, or electrical fields.

LASL purchased, from Varilight Corp., a quantity of pressure-sensitive, temperature-insensitive, liquid crystal. A thin film of the liquid crystals between clear Plexiglass sheets easily showed pressure points and gradients by color shifts through the visible spectrum. The liquid crystal exhibited good sensitivity and discrimination, but the recovery time (color shift when full pressure was reduced instantly to zero pressure) was about 0.25 sec. to 0.5 sec.

Three methods of measuring molecular arrangement change which LASL investigated were; 1) optical transmission, 2) electrical resistance, and 3) electrical capacitance.

Optical transmission is the most obvious, but fiber optics would have to be used for sensor-to-amplifier connections. LASL investigated the problems (optical coupling, probable sensitivity, fragility) and decided that the probable sensitivity of this method did not justify further investigation.

Electrical resistance would be the easiest measurement to perform. Several test geometries showed the liquid crystal to be an excellent resistor at all normal temperatures and expected pressures. Similar results from tests by the LASL Electronics Division showed that any electrical resistance change accompanying liquid crystal color change could not be measured.

Electrical capacitance change accompanying the liquid crystal color change would be caused by a change of dielectric strength, because the change of color is caused by a change in physical structure. Attempts were made to measure capacitance change by arranging a plastic envelope containing a thin film of the liquid crystal between two pieces of metal foil and placing the device under pressure.

Initial results were inconclusive due to leaks and air bubbles in the plastic envelope. After fabricating a good envelope, test results showed little or no capacitance change with color change.

3. Conclusions. During FY 1975, LASL investigated commercial pressure sensors. LASL also investigated different experimental methods of measuring face-to-facepiece pressure, as described in this report. No suitable commercial instruments were located. None of the three experimental methods are feasible as instruments to be used to measure face-to-facepiece pressure prior to a respirator man test.

LASL recommends that no further effort be expended on the experimental methods described.

LASL's only positive recommendation is that concerned personnel should continue to scan technical advertisements for new types of miniature pressure sensors.

III. RESEARCH DIRECTED TOWARD ESTABLISHING IMPROVED RESPIRATOR PERFORMANCE CRITERIA

A. Introduction

During FY 75, major efforts included studies of the effects of flow rate, aerosol loading, humidity, and elevated temperatures on respirator dust and mist filter performance; a comparison of respirator exhalation valve performance under static and dynamic conditions; a study of the effects of strap tension on respirator performance; a study of the performance of several commercially available single-use dust respirators; and an evaluation of respirator performance with anthropometric test panels.

B. Dust and Mist Filter Studies

1. Introduction. Work has continued on the functional characteristics of respirator dust and mist filter media. Investigations completed during FY 75 included studies of the effects of flow rate on aerosol penetration and resistance to air flow, effects of aerosol loading on filter penetrations and resistance to air flow, effects of storage in a high-humidity atmosphere on aerosol penetration, and effects of exposure to elevated temperatures on aerosol penetration.

2. Effects of Flow Rate on Aerosol Penetration and Resistance to Air Flow. At the present time, a respirator dust and mist filter used in a single-filter respirator is tested for aerosol penetration at an air flow rate of 32 l/min and for resistance at a flow rate of 85 l/min . Currently, a respirator dust and mist filter used in a double-filter respirator is being tested for aerosol penetration at 16 l/min and for resistance at 42.5 l/min . It has been suggested⁵ that these tests be carried out for flow rates equivalent to those occurring at the medium work rate of 622 kg-m/min . This would mean that a respirator dust and mist filter used in a single-filter respirator would be tested for aerosol penetration at 77 l/min (to represent average inhalation flow rate) and for resistance at 100 l/min (to represent maximum inhalation flow rate). Also, this would mean that a respirator dust

and mist filter for use in a double filter respirator would be tested for aerosol penetration at 38 //min and for resistance at 50 //min.

Tests have been carried out on respirator dust and mist filters, composed of both mechanical and electrostatic type filter materials, to compare the penetration of filters by NaCl aerosol at 16, 32, 38, and 77 //min and to compare the resistance offered by filters at 42.5, 50, 85, and 100 //min.

Figure 7 shows the effects of increasing flow rate on NaCl aerosol penetration. Filters tested included four resin felt electrostatic type filters and one mechanical type nonwoven material. The electrostatic type filters showed a steady increase in aerosol penetration with increased flow, while the mechanical type filters showed less change, due probably to the increased effects of impaction on particle collection.

Figure 8 illustrates the effects of increased flow rate on resistance to air flow. Again, four electrostatic felt type filters and one mechanical filter were evaluated. All filters showed a steady increase

Aerosol: Polydisperse NaCl, $\text{mmad} = 0.6 \mu\text{m}$, $\sigma_g = 2$
Concentration = $15 \mu\text{g}/\text{m}^3$
35 cm^2 area for all filters

A - Resin-impregnated pressed felt, 100% wool
B - Resin-impregnated needled felt, 50% wool, 50% orlon
C - Resin-impregnated needled felt, 50% wool, 50% acrylic
D - Resin-impregnated needled felt, wool-acrylic mixture
E - Air-laid nonwoven, coarse organic & ultrafine glass fibers

Fig. 7.

Effects of increasing flow rate on NaCl aerosol penetration.

A - Resin-impregnated pressed felt, 100% wool
B - Resin-impregnated needled felt, 50% wool, 50% orlon
C - Resin-impregnated needled felt, 50% wool, 50% acrylic
D - Resin-impregnated needled felt, wool-acrylic mixture
E - Air-laid nonwoven, coarse organic & ultrafine glass fibers

Fig. 8.

Effects of air flow rate on resistance to air flow.

in resistance with increase in air flow.

Results of these studies indicate electrostatic type filter materials show a steady increase in aerosol penetration with increased flow rate, while mechanical type filter materials show an initial increase in penetration with increased flow, and as flow is increased penetration tends to level off. Both types of materials show a steady increase in resistance to air flow as flow rate is increased.

3. Effects of Storage of Respirator Dust and Mist Filters in Highly Humid Air. A study to determine the effect of storage of respirator dust and mist filters composed of three types of electrostatic felt (100% wool, 50% wool-50% orlon, 50% wool-50% acrylic) in highly humid air (90% RH at 32°C) has been completed. The filters were tested for NaCl aerosol penetration at 32 and 77 //min prior to exposure to the humid atmosphere, and then at 7-day intervals, up to 28-days total exposure. Figures 9 and 10 illustrate the results of this study.

Concentration = 15 mg/m³

Air flow through filter during penetration measurement: 32 l/min
Filters stored in chamber maintained at 30°F, 90% relative humidity

- A - Resin-impregnated pressed felt, 100% wool, 35-cm²-area filter
- B - Resin-impregnated needled felt, 50% wool, 50% orlon, 35-cm²-area filter
- C - Resin-impregnated needled felt, 50% wool, 50% acrylic, 35-cm²-area filter

Fig. 9.

Effects of storage at 32°C, 90% relative humidity on NaCl aerosol penetration for a 32 l/min test flow rate.

Aerosol: Polydisperse NaCl, $\text{mmad} = 0.6 \mu\text{m}$, $\sigma_g = 2$

Concentration = 15 mg/m³

Air flow through filter during penetration measurement: 77 l/min
Filters stored in chamber maintained at 90°F, 90% relative humidity

- A - Resin-impregnated pressed felt, 100% wool, 35-cm²-area filter
- B - Resin-impregnated needled felt, 50% wool, 50% orlon, 35-cm²-area filter
- C - Resin-impregnated needled felt, 50% wool, 50% acrylic, 35-cm²-area filter

Fig. 10.

Effects of storage at 32°C, 90% relative humidity on NaCl aerosol penetration of electrostatic felt filters for a 77-l/min flow rate.

penetrations were initially in the 10-25% range and, at the end of the 28-day exposure period, were in the 60-65% range. There was no appreciable change in resistance to air flow. The large increase in aerosol penetration after exposure to high temperatures and high humidity suggest that while freshly manufactured resin felt filters may be efficient, by the time they are used, they may offer very little protection. LASL has previously suggested¹ that this type filter be stored in a hot humid environment (32°C, 90% relative humidity) for 30 days before TCL performs approval tests. This storage period would help assure adequate protection for users of dust and mist respirators.

4. Effect of Exposure of Respirator Dust and Mist Filters to Elevated Temperatures. A study of the effects of exposure to elevated temperatures of three types of electrostatic felt dust and mist filter material (100% wool, 50% wool-50% orlon, 50% wool-50% acrylic) has been completed. Eight discs of each material were exposed for four hours to temperatures of 50, 88, 116, and 143°C in a dry oven. For each temperature, four discs were tested both initially and after exposure for resistance to air flows at 42.5 and 50 l/min and NaCl aerosol penetration at 16 and 38 l/min. The remaining four discs of each material were tested both initially and after exposure for resistance to air flows of 85 and 100 l/min and for NaCl aerosol penetration at 32 and 77 l/min. NaCl aerosol penetrations as a function of exposure temperatures are presented in Table VIII, IX, and X.

Results indicate that high temperatures cause some loss of electrostatic charge, and a consequent increase in aerosol penetration. There was no appreciable effect on resistance to air flow. The 100% wool material showed an increase in aerosol penetration after four-hours exposure to temperatures of 116°C and higher, while the 50% wool-50% orlon material and the 50% wool-50% acrylic material showed increased NaCl aerosol penetrations after four-hours exposure to temperatures of 88°C and higher.

5. Effects of Aerosol Loading on Penetration and Resistance to Air Flow of Respirator Dust and Mist Filters. An investigation of the effects of NaCl and DOP aerosol loading of dust and mist respirator filters on resistance to air flow and aerosol penetration has been completed. Figure 11 illustrates the effects of DOP aerosol loading on resistance to air flow for a mechanical and an electrostatic type dust filter. The DOP load caused very little increase in resistance to air flow for either

TABLE VIII
EFFECTS OF EXPOSURE TO ELEVATED TEMPERATURES
ON AEROSOL PENETRATION

Filter Material: A - Resin-Impregnated Pressed Felt, 100% Wool

35-cm² Area

Aerosol: Polydisperse NaCl, mmad = 0.6 μ m, σ_g = 2

Concentration = 15 mg/m³

% of Incident Aerosol Mass

Passing Filter After 4 Hours

Exposure to Indicated Temperature

Test Flow Rate (l/min)	22°C (72°F)	50°C (122°F)	88°C (190°F)	116°C (240°F)	143°C (290°F)
16	5	5	5	27	30
32	10	10	12	44	44
38	10	10	11	42	47
77	16	16	20	55	60

TABLE IX
EFFECTS OF EXPOSURE TO ELEVATED TEMPERATURES
ON AEROSOL PENETRATION

Filter Material: B - Resin-Impregnated Needled Felt, 50% Wool

50% Orlon, 35-cm² Area

Aerosol: Polydisperse NaCl, mmad = 0.6 μ m, σ_g = 2

Concentration = 15 mg/m³

% of Incident Aerosol Mass

Passing Filter After 4 Hours

Exposure to Indicated Temperature

Test Flow Rate (l/min)	22°C (72°F)	50°C (122°F)	88°C (190°F)	116°C (240°F)	143°C (290°F)
16	1.0	1.0	9.0	25	30
32	3.5	3.5	27	44	44
38	3.5	3.5	22	41	43
77	10.0	10.0	40	55	55

TABLE X

EFFECTS OF EXPOSURE TO ELEVATED TEMPERATURES ON AEROSOL PENETRATION

Filter Material: C - Resin-impregnated Needled Felt, 50% Wool

50% Acrylic, 35-cm² AreaAerosol: Polydisperse NaCl, mmad = 0.6 μ m, σ_g = 2Concentration = 15 mg/m³

% of Incident Aerosol Mass

Passing Filter After 4 Hours

Exposure to Indicated Temperature

Test Flow Rate (l/min)	22°C (72°F)	50°C (122°F)	88°C (190°F)	116°C (240°F)	143°C (290°F)
16	5	5	30	31	37
32	10	12	45	48	51
38	12	13	49	51	51
77	22	24	56	58	61

Aerosol: Monodisperse DOP, particle size = 0.3 μ mConcentration = 160 mg/m³Filters: C - Resin-impregnated needled felt, 50% wool,
50% acrylic, 35-cm²-area discF - Air-laid nonwoven, coarse organic & ultrafine
glass fibers, 35-cm²-area disc

Air flow conditions:

Air flow through filter during particulate loading 38 l/min

Air flow through filter during resistance
measurement 50 l/min

Fig. 11.

Effects of DOP loading on resistance to air flow.

filter. Figure 12 illustrates the effects of NaCl aerosol loading on resistance to air flow for a mechanical and an electrostatic type dust and mist respirator filter. Both filters showed an increase in resistance to air flow. The NaCl load was much less than the DOP load, but resistance increased more. These results show that solid particles load filters much more quickly than liquid particles.

Figure 13 shows the effects of DOP aerosol loading on aerosol penetration. A mechanical and an electrostatic type dust filter were tested, as well as a commercial filter approved for protection against metal fumes. The electrostatic dust filter (D) showed a sharp increase in penetration with increased load. This is due to the collected DOP forming a film around the filter fibers which allows leakage of electrostatic charge from the resin particles to the fibers. Filters G and K are both mechanical type filters, and both showed very little change in penetration with increased load.

Filter D, which showed an increase in penetration from ~10% to ~80%, is approved for protection against mists having an air contamination level of not less than 0.05 mg/m³ or two million particles per cubic foot. DOP falls in this category, but clearly this filter would offer very little protection against DOP. LASL has recommended² that a DOP mist replace the silica mist test now used for approval testing of filters designed for protection against mists having air contamination levels greater than 0.05 mg/m³.

Particulate Loading of Filters

Aerosol: Polydisperse NaCl, MMAD = $0.6 \mu\text{m}$, $\sigma_g = 2$
Concentration = 15 mg/m^3

Air flow down through filter during particulate loading:
 $6.33 \times 10^{-4} \text{ m}^3/\text{s}$ (38 l/min)

Air flow through filter during resistance measurement:
 $8.33 \times 10^{-4} \text{ m}^3/\text{s}$ (50 l/min)

C - Resin-impregnated needled felt, 50% wool, 50% acrylic,
35-cm²-area disc

F - Air-laid nonwoven, coarse organic & ultrafine glass
fibers 35-cm²-area disc

Fig. 12.

Effects of NaCl aerosol loading on 35-cm²-area electrostatic and mechanical type filters.

Figure 14 illustrates the effects of NaCl aerosol loading on filter penetration. Again, a mechanical and an electrostatic type dust filter were tested, as well as a commercial filter approved for protection against fumes. Filter D showed some increase in penetration (from ~1% to ~7%) but the solid particulate did not cause the rapid degradation observed with the liquid DOP aerosol. Filter G and K both showed a slight decrease in penetration with increased NaCl load.

C. Respirator Exhalation Valve Testing

1. General. A program to test respirator exhalation valves was planned for FY 75. The valve testing was planned to begin after the construction of the NIOSH valve test units was completed. The planned test program was to have tested 100 each of valves donated by six manufacturers. Both static and dynamic tests were involved with air and aerosol, using both ambient exhaled air and heated and humidified exhaled air. The test would have used the type of test system which LASL built for NIOSH.

The original program was revised for two reasons. First, NIOSH needed, as soon as possible,

Aerosol: Monodisperse DOP, particle size = $0.3 \mu\text{m}$

Concentration = 160 mg/m^3

Air flow through filter during particulate loading: 38 l/min

Fig. 13.

Monodisperse DOP aerosol penetration as a function of load for three types of filters.

recommendations on changes to 30 CFR II. Second, preliminary tests at LASL showed little correlation between dynamic air leakage and dynamic aerosol leakage, and valve and cover combinations showed very little aerosol leakage.

LASL decided that the necessary testing program should use the seven available types of valves, testing four of each type. The program would be simplified by testing the valves for dynamic aerosol leakage only, with heated and humidified exhaled air, using a negative pressure, simulating breathing, and having the valve under test mounted on a facepiece. This program could be completed in a short amount of time, and would show the fraction of the total respirator aerosol leak contributed by the exhalation valve under actual use conditions.

In order to make such a study, LASL set up a new type of test system which simulated actual use con-

Aerosol: Polydisperse sodium chloride, MMAD = $0.6 \mu\text{m}$, $\sigma_g = 2$
 Concentration = 15 mg/m^3
 Air flow rate during particulate loading: 38 l/min

Fig. 14.

NaCl aerosol penetration as a function of load for three types of filters.

ditions but removed all sources of aerosol leakage other than the exhalation valve.

2. Equipment. Seven different types of respirator exhalation valves were tested, four valves of each type. The valves tested are commercially available and were donated for the study by six participating manufacturers.

The valves were tested while in place on a facepiece. The MSA Custom Comfo facepiece was used for all valves because the snap fasteners on the straps speeded up the testing procedure by allowing quick facepiece changes. Figure 15 shows a test system schematic. The valve-and-facepiece combination was sealed onto a head form, inside of a test chamber. Empty filter cartridges were sealed into the filter receptacles. The empty filter cartridges were connected to HEPA filters located outside of the test chamber. For this study a polydisperse DOP challenge aerosol was used. The detector was a LASL 69B light-scattering photometer, which reads percentage penetration of the DOP aerosol. Shown are the 100% and sample lines. Exhalation air comes from a breathing pump using a 622 kg-m/min cam operated at 27 cycles/min. The exhalation air passes through a heater/humidifier, then past wet and dry bulb thermometers, into the mask and out the exhalation valve. The exhalation air is at $35 \pm 1.7^\circ\text{C}$ ($95 \pm 3^\circ\text{F}$) and $94 \pm 3\%$ RH as it enters the mask.

Fig. 15.

Line diagram of LASL Dynamic Exhalation Valve Test System.

Inhalation air is drawn through the HEPA filters external to the test chamber, through the facepiece, through a condenser used to protect the breathing pump from water vapor, and into the breathing pump.

3. Procedure. The first step in the actual test procedure was to test for system aerosol leakage. An impervious piece of plastic was sealed over the exhalation valve, and the exhalation line was disconnected from the test head. The breathing pump was operated to create a normal negative pressure in the facepiece during each inhalation. The allowable aerosol leakage was usually 0.01% penetration. If, for any reason, a system leak could not be sealed, the leak was reduced to a minimum and this minimum leak rate subtracted from test results.

After ascertaining system leakage, the exhalation valve seal was removed, the exhalation line connected to the system, and the valve tested for five minutes without a valve cover.

After five or six minutes of testing, the valve cover was put in place over the valve, and the combination tested for one minute.

When the dynamic testing was done, each valve under study was static leak tested, using a leak test system on loan from the American Optical Corporation.

4. Results. Table XI is a summary of the test results for the seven types of valves. Penetration results without valve cover are the averages at five minutes of testing. Two things were immediately obvious; first, there was no obvious correlation between static air leakage results and dynamic aerosol leakage results; and second, all of the valves tested

TABLE XI

SUMMARY OF RESPIRATOR EXHALATION VALVE TESTS

Valve Identification	Average Air Leakage Thru Valve Under Static Conditions Differential Pressure of 2.5×10^2 Pa (ml/min)	Average Penetration of Aerosol Into Interior of Respirator Contributed by Valve Leakage for Breathing at Work Rate of 622 kg-m/min			
		Without Valve Cover (%)	With Valve Cover Type 1 (%)	With Valve Cover Type 2 (%)	With Valve Cover Type 3 (%)
A	9.2	0.04	<0.01	<0.01	
B	13	0.07	0.05	<0.01	<0.01
C	2.9	<0.01	<0.01		
D	16.6	0.05	<0.01		
E	11.4	<0.01	<0.01		
F	39.8	0.01	<0.01		
G	>50	0.02	<0.01		

provided excellent protection with a valve cover in place.

Figure 16 shows valve A, a convex rubber valve, flat-beveled plastic seat, with two types of cover.

Table XII gives the test results for valve A. The static air leak results are all well under the 30 ml/min allowed by 30 CFR II. The dynamic results vary from valve to valve, and sometimes, for one valve, the results vary with time. Whether the time variation is due to wetting, increased temperature softening the valve, or continuous flexing of the valve, is uncertain at this time.

Figure 17 shows valve B, a convex rubber valve, flat-beveled plastic seat, with three types of covers.

Table XIII gives the test results for valve B. The static leak results are all under 30 ml/min. No correlation is seen between dynamic and static results. Most striking here are the dynamic results, which show that a relatively deep, solid cover reduces leakage to the limit of detectability.

Figure 18 shows valve C, a convex rubber valve, flat-beveled plastic seat, with one cover. In design and construction, valve C is very similar to valves A and B.

Table XIV shows the test results for valve C. The static and the dynamic leak test results are both quite low; however, the valve with the lowest static leak value has the highest dynamic leak value and vice versa. The scope of the study was too limited to determine why valve C performed better than valve A or B when tested without covers.

Figure 19 shows valve D, a concave rubber valve, ridged plastic seat, with one cover.

Table XV displays the results for valve D. One of the D-type valves was slightly over the 30 ml/min static leak limit. Again, there is no correlation between static air leakage and dynamic aerosol leakage. These results also show that the relatively deep, solid-sided cover reduces valve aerosol leakage to below detectable limits.

Figure 20 shows valve E, a convex rubber valve and flat metal seat. The seat forms a cylindrical

Fig. 16.
Valve A.

TABLE XII

TEST RESULTS FOR RESPIRATOR EXHALATION VALVE A

Test No.	Air Leakage Thru Valve Under Static Conditions with Downstream Air Differential Pressure of 2.5×10^2 Pa (ml/min)	Penetration of Aerosol Into Interior of Respirator Contributed by Valve Leakage for Breathing at Work Rate of 622 kg-m/min								
		Without Valve Cover							With Valve Cover No. 1 (%)	With Valve Cover No. 2 (%)
		0 min (%)	1 min (%)	2 min (%)	3 min (%)	4 min (%)	5 min (%)	6 min (%)		
1	1.75	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	<0.01
2	8	0.03	0.02	0.02	0.01	0.01	0.01	---	<0.01	<0.01
3	19	0.08	0.09	0.08	0.09	0.08	0.09	0.01	<0.01	<0.01
4	8	0.02	0.03	0.04	0.04	0.03	0.03	---	0.01	0.01
Average	9.2						0.04		<0.01	<0.01

enclosure around 1/2 to 2/3 of the valve. The valve has one type of cover.

Table XVI shows the test results for valve E. The static air leak results were all under 30 ml/min. There is no apparent correlation between static air and dynamic aerosol leakage. All type E valves tested showed <0.01% penetration (lower limit of the detector) without covers.

Figure 21 shows valve F, a flat rubber valve with four "leg" connectors, with a plastic seat and one cover. The seat edge forms a cylindrical enclosure completely around the valve.

Table XVII gives the test results for valve F. These results dramatically show the lack of correlation between static air leakage and dynamic aerosol leakage. Tests 2 and 4 were at the extremes of the range for static air leakage, but both tests showed <0.01% penetration at the start of testing, and maintained that level of protection throughout testing, without valve covers.

Figure 22 shows valve G, a flat rectangular valve on a metal seat, with one valve cover. The seat forms a disc in which the valve is seated.

Table XVIII lists the test results for valve G. These results were surprising. As expected, all of the type G valves showed high static air leakage. The first surprise was the dynamic aerosol leakage, done without cover, which was very low, never over 0.02%. The second surprise was that the valve cover, a half-cylinder of perforated metal, open at the ends, reduced any leakage to the detectable limit.

5. Conclusions. To summarize and conclude, LASL feels that this study shows that there is no correlation between static air leakage and dynamic aerosol leakage.

The test system described is a good simulation of the conditions encountered in respirator use by a human. The test results show that commercially available respirator exhalation valve-and-cover systems contribute little or nothing to the total leakage into a respirator facepiece.

This study used an aerosol challenge atmosphere. Mr. Dudley Watkins, Scott ATO Company, reported in a personal correspondence, testing his company's respirator exhalation valves using a dynamic test system and a helium challenge atmosphere. Mr. Watkins' results were similar to LASL's results. LASL expects that the type of results reported here will hold for aerosol or gas challenge atmospheres.

Fig. 17.
Valve B.

TABLE XIII

TEST RESULTS FOR RESPIRATOR EXHALATION VALVE B

Test No.	Air Leakage Thru Valve Under Static Conditions with Downstream Air Differential Pressure of 2.5×10^2 Pa (ml/min)	Penetration of Aerosol Into Interior of Respirator Contributed by Valve Leakage for Breathing at Work Rate of 622 kg-m/min									
		Without Valve Cover							With Valve Cover No. 1	With Valve Cover No. 2	With Valve Cover No. 3
		0 min (%)	1 min (%)	2 min (%)	3 min (%)	4 min (%)	5 min (%)	6 min (%)	(%)	(%)	(%)
1	5	0.16	0.14	0.14	0.14	0.14	0.14	---	0.12	0.01	<0.01
2	5	0.06	0.07	0.06	0.06	0.05	0.03	0.03	0.02	<0.01	<0.01
3	24	0.08	0.10	0.10	0.09	0.09	0.09	---	0.06	<0.01	<0.01
4	18	0.01	0.03	0.05	0.02	<0.01	<0.01	---	---	---	---
Average	13						0.07		0.05	<0.01	<0.01

Fig. 18.
Valve C. Fig. 19.
Valve D.

TABLE XIV

TEST RESULTS FOR RESPIRATOR EXHALATION VALVE C

Test No.	Air Leakage Thru Valve Under Static Conditions with Downstream Air Differential Pressure of 2.5×10^2 Pa (ml/min)	Penetration of Aerosol Into Interior of Respirator Contributed by Valve Leakage for Breathing at Work Rate of 622 kg-m/min							
		Without Valve Cover							With Valve Cover No. 1 (%)
		0 min (%)	1 min (%)	2 min (%)	3 min (%)	4 min (%)	5 min (%)	6 min (%)	
1	<1.5	0.03	0.02	0.02	0.01	0.01	0.01	---	<0.01
2	3.3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	---	<0.01
3	1.8	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	---	---
4	5	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	---	---
Average	2.9						<0.01		<0.01

TABLE XV

TEST RESULTS FOR RESPIRATOR EXHALATION VALVE D

Test No.	Air Leakage Thru Valve Under Static Conditions with Downstream Air Differential Pressure of 2.5×10^2 Pa (ml/min)	Penetration of Aerosol Into Interior of Respirator Contributed by Valve Leakage for Breathing at Work Rate of 622 kg-m/min							
		Without Valve Cover							With Valve Cover No. 1 (%)
		0 min (%)	1 min (%)	2 min (%)	3 min (%)	4 min (%)	5 min (%)	6 min (%)	
1	18	0.03	0.04	0.04	0.04	0.04	0.05	---	<0.01
2	8	0.11	0.07	0.06	0.05	0.04	0.03	---	<0.01
3	3.5	0.05	0.08	0.11	0.12	0.08	0.08	0.07	<0.01
4	37	0.06	0.06	0.05	0.06	0.04	0.04	---	<0.01
Average	16.6						0.05		<0.01

Fig. 20.
Valve E.

Fig. 21.
Valve F.

TABLE XVI

TEST RESULTS FOR RESPIRATOR EXHALATION VALVE E

Test No.	Air Leakage Thru Valve Under Static Conditions with Downstream Air Differential Pressure of 2.5 x 10 ² Pa (ml/min)	Penetration of Aerosol Into Interior of Respirator Contributed by Valve Leakage for Breathing at Work Rate of 622 kg-m/min							
		Without Valve Cover							With Valve Cover No. 1 (%)
		0 min (%)	1 min (%)	2 min (%)	3 min (%)	4 min (%)	5 min (%)	6 min (%)	
1	19	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	---	---
2	20	0.03	0.03	0.03	0.02	0.01	< 0.01	---	---
3	2.5	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	---	---
4	4	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	---	---
Average	11.4						< 0.01		< 0.01

TABLE XVII

TEST RESULTS FOR RESPIRATOR EXHALATION VALVE F

Test No.	Air Leakage Thru Valve Under Static Conditions with Downstream Air Differential Pressure of 2.5×10^2 Pa (ml/min)	Penetration of Aerosol Into Interior of Respirator Contributed by Valve Leakage for Breathing at Work Rate of 622 kg-m/min							
		Without Valve Cover							With Valve Cover No. 1
		0 min (%)	1 min (%)	2 min (%)	3 min (%)	4 min (%)	5 min (%)	6 min (%)	
1	50	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	—	<0.01
2	> 50	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	—	—
3	9	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	—	—
4	> 50	0.02	0.02	0.02	0.02	0.02	0.02	—	0.01
Average	39.8						0.01		<0.01

Fig. 22.
Valve G

G

TABLE XVIII
TEST RESULTS FOR RESPIRATOR EXHALATION VALVE G

Test No.	Air Leakage Thru Valve Under Static Conditions with Downstream Air Differential Pressure of 2.5×10^2 Pa (ml/min)	Penetration of Aerosol Into Interior of Respirator Contributed by Valve Leakage for Breathing at Work Rate of 622 kg-m/min							
		Without Valve Cover							With Valve Cover No. 1 (%)
		0 min (%)	1 min (%)	2 min (%)	3 min (%)	4 min (%)	5 min (%)	6 min (%)	
1	>50	0.02	0.02	0.02	0.02	0.02	0.02	---	<0.01
2	>50	0.02	0.02	0.02	0.02	0.02	0.02	---	<0.01
3	>50	0.01	0.01	0.01	0.01	0.01	0.01	---	<0.01
4	>50	0.01	0.01	0.01	0.02	0.02	0.02	0.02	<0.01
Average	>50						0.02		<0.01

D. Study of Respirator Performance Versus Head Harness Strap Tension

A study of respirator performance versus head harness strap tension was done, using the 20-to 2000-g range, special-order, Check-Line tension meter. A commercially available half-mask was used for this study. This respirator was picked because it is available with either four-point or two-point suspension harness. During FY 1975, only the four-point suspension was studied.

1. Procedure. The test was run using an abbreviated anthropometric test panel. Figure 23 shows the setup for a full anthropometric test panel. The numbers in each box refer to the number of subjects needed in that particular face size for a complete panel. The abbreviated panel used for this test had one person for each face size, or box.

Each subject was tested seven times using the six standard exercises with the same facepiece, but with seven different strap tensions. The six exercises used were as follows:

1. normal breathing.
2. deep breathing.
3. head side to side.
4. head up and down.
5. talking.
6. normal breathing.

The seven strap tensions were as follows:

1. top strap, 226 g (1/2 pound); bottom strap, 226 g (1/2 pound).
2. top strap, 453 g (1 pound); bottom strap, 226 g (1/2 pound).
3. top strap, 226 g (1/2 pound); bottom strap, 453 g (1 pound).
4. top strap, 453 g (1 pound); bottom strap, 453 g (1 pound).

Fig. 23.
Panel for testing half-mask.

- (1 pound),
5. top strap, 680 g (1-1/2 pound); bottom strap, 453 g (1 pound),
6. top strap, 453 g (1 pound); bottom strap, 680 g (1-1/2 pound).
7. top strap, 680 g (1-1/2 pound); bottom strap, 680 g (1-1/2 pound).

2. Results. Figure 24 shows the test results for each test subject. A "B" instead of a number indicates that either the exhalation or inhalation valves were completely blocked at the given strap tension, due to the subject's face touching the valve. Generally, the average percentage penetration decreases with increased strap tension.

		LIP LENGTH (mm)							
		34.5		43.5		52.5		61.5	
FACE LENGTH (mm)	133.5			TENSION AV		TENSION AV			
		1	20 %	1	43 %	1	44 %		
		2	1.3 %	2	0.06%	2	5 %		
		3	21 %	3	25 %	3	38 %		
		4	0.01%	4	0.05%	4	1.2 %		
		5	0.01%	5	0.01%	5	0.01%		
		6	0.01%	6	2.4 %	6	2.7 %		
		7	0.01%	7	0.48%	7	0.01%		
	123.5	TENSION AV		TENSION AV		TENSION AV			
		1	20 %	1	37 %	1	0.96%		
		2	1.3 %	2	30 %	2	0.35%		
		3	21 %	3	32 %	3	7.5 %		
		4	0.01%	4	0.5 %	4	0.31%		
		5	0.01%	5	24 %	5	0.23%		
		6	0.01%	6	6.1 %	6	0.27%		
		7	0.01%	7	3.5 %	7	0.22%		
113.5	TENSION AV		TENSION AV		TENSION AV				
	1	27 %	1	42 %	1	3.2 %			
	2	22 %	2	1.7 %	2	5.7 %			
	3	9.3 %	3	18 %	3	6.4 %			
	4	8 %	4	0.14%	4	1.6 %			
	5	8 %	5	0.01%	5	6 %			
	6	8 %	6	0.03%	6	1.6 %			
	7	8 %	7	0.01%	7	3.9 %			
103.5	TENSION AV		TENSION AV		STRAP TENSION (g) TOP		BOTTOM		
	1	59 %	1	8 %	1	226	226		
	2	51 %	2	7 %	2	453	226		
	3	51 %	3	0.24%	3	226	453		
	4	50 %	4	0.01%	4	453	453		
	5	3.5 %	5	0.01%	5	680	453		
	6	4.8 %	6	0.23%	6	453	680		
	7	13 %	7	0.01%	7	680	680		
93.5									

Fig. 24.
Effects of respirator head harness strap tension
on respirator leakage.

The effect of an anthropometric test panel is illustrated in Fig. 24. The lower left boxes show high leakages even with high strap tensions. The respirator seems to fit large faces better than small faces.

The data can be broken down into three strap tension configurations:

1. top strap and bottom strap tension equal.
2. top strap tension greater than bottom strap tension.
3. top strap tension less than bottom strap tension.

Figure 25 shows the results for 226 g (1/2 pound) of tension in top and bottom straps. The penetrations are generally high, except for the lower right boxes, showing a natural fit for short, broad faces.

Figure 26 shows the results for 453 g (1 pound) of tension in top and bottom straps. This test panel shows a protection factor of 50, except for the lower left boxes, which are the face sizes most difficult to fit for this facepiece.

Figure 27 shows the results for 680 g (1-1/2 pound) of tension in both the top and bottom straps. Out of

Fig. 25.
Ten-person panel results for 226-g tension in both top and bottom straps.

ten test subjects, six showed protection factors of 200 or better, two showed protection factors of ten, and two showed less than ten. Out of ten subjects, two felt a great deal of pain, one had partial blockage, and one had total blockage. The poor results for the lower-left boxes is expected, but the higher penetrations for the central box and the lower-right box is surprising. The central box subject commented that the exhalation valve cover dug into his throat at all times, and that the inhalation valve was blocked during the head up and down exercise. The lower-right box subject commented on extreme pain across the nose.

Figure 28 shows the results for top strap tension of 453 g (1 pound) and a bottom strap tension of 226 g (1/2 pound). The results are extremely erratic.

Figure 29 shows the results for top strap tension of 680 g (1 1/2 pound) and a bottom strap tension of 453

Fig. 26.
Ten-person panel results for 453-g tension in both top and bottom straps.

g (1 pound). The results are generally improved, but still very erratic. It appears that, for this facepiece, a top strap tension greater than the bottom strap tension distorts the facepiece seal.

Figure 30 shows the test results for a top strap tension of 226 g (1/2 pound) and a bottom strap tension of 453 g (1 pound). The readings are generally high, with the lower right face sizes showing relatively low penetrations.

Figure 31 shows the test results for a top strap tension of 453 g (1 pound) and a bottom strap tension of 680 g (1-1/2 pound). The readings are all lower. The panel indicates a protection factor of ten except for the one subject who had blocked inhalation valves.

3. Conclusions. The study described here had a very narrow scope, using one mask and a ten-person

Panel for Half-masks

Strap Tension (g)

Top = 680 Bottom = 680

Fig. 27.

Ten person panel results for 680-g tension in both top and bottom straps.

test panel; however, LASL feels that it shows three things:

1. The strap tension meter described is usable for measuring head harness strap tension prior to a respirator man test.
2. The amount and configuration of head harness strap tension definitely affect the results of respirator man tests.
3. If a respirator is a poor fit for a certain face size, increasing the head harness strap tension will not by itself produce a good face-to-facepiece fit.

Panel for Half-masks

Strap Tension (g)

Top = 453 Bottom = 226

Fig. 28.

Ten-person panel results for 453-g tension in top strap and 226-g tension in bottom strap.

Panel for Half-masks

Strap Tension (g)

Top = 680 Bottom = 453

Fig. 29.

Ten-person panel results for 680-g tension in top strap and 453-g tension in bottom strap.

Fig. 30.

Ten-person panel results for 226-g tension in top strap and 453-g tension in bottom strap.

Fig. 31.

Ten-person panel results for 453-g tension in top strap and 680-g tension in bottom strap.

E. Performance of Single Use Dust Respirators

1. Introduction. An evaluation of six different single-use respirators has been completed. Three series of tests were performed on each respirator. In the first series of tests, the respirators were tested on test subjects having a wide range of facial sizes (using lip length and face length to characterize facial dimensions). In the second series of tests, the respirators were tested on a single test subject before and after storing the respirators for 21 days in an environmental chamber at 32°C and 90% relative humidity. In the third series of tests, the respirators were worn by two test subjects for a simulated six-hour work shift, and NaCl aerosol leakages were determined immediately after the respirators were donned, and then at one-hour intervals. A general description of each respirator tested is given in Appendix A.

Aerosol leakage into respirators worn by human test subjects was determined using a LASL-designed NaCl aerosol test apparatus. NaCl aerosol was nebulized from a 1% NaCl solution and dried with dilution air.

2. Evaluation of Single-Use Respirators On a Wide Range of Facial Sizes. LASL has developed an anthropometrically selected test panel for evaluating the ability of half-mask respirators to fit a wide range of facial sizes.⁶ Facial dimensions used for selecting subjects are face length (menton-nasal root depression length) and lip length. Figure 23 is a diagram of the panel showing facial dimensions and distribution of subjects. The test panel shown in Fig. 23 is roughly representative of the facial size distribution of 95% of the American working population, based on the facial dimensions of 4208 Air Force men and women.⁷ In the study described here, a modification of this test panel was used whereby one subject was selected from each of the ten boxes, and each subject wore each of the six different types of single-use respirators. A new respirator was used for each test, that is, after a respirator had been worn by a test subject, it was discarded. The approximate test panel position of each subject is illustrated in Fig. 32.

Aerosol leakages were monitored while subjects performed the following exercises:

1. Normal Breathing.
2. Deep Breathing.
3. Turning Head From Side-to-Side.
4. Tilting Head Up and Down.
5. Talking.
6. Normal Breathing.

		LIP LENGTH (mm)									
		34.5		43.5		52.5		61.5			
FACE LENGTH (mm)	133.5			A		1	5	B		1	5
						2	5			2	5
						3	5			3	5
						4	5			4	5
						5	5			5	5
123.5					6	5			6	5	
	C	1	5	D	1	5	E	1	5		
		2	5		2	5		2	5		
		3	5		3	5		3	5		
		4	5		4	5		4	5		
		5	5		5	5		5	5		
113.5		6	0		6	5		6	5		
	F	1	5	G	1	5	H	1	5		
		2	0		2	0		2	5		
		3	5		3	5		3	5		
		4	5		4	5		4	5		
		5	5		5	5		5	5		
103.5		6	5		6	5		6	5		
	I	1	0	J	1	5					
		2	5		2	5					
		3	5		3	5					
		4	0		4	5					
		5	5		5	5					
93.5		6	5		6	5					

Fig. 35.

Results in terms of a protection factor of five or better.

jects achieved protection factors of at least five on which respirators. A 5 next to a mask number indicates a protection factor of five or better, and 0 indicates a protection factor of less than five.

For masks No. 1 and No. 4, the only subject failing to achieve a protection factor of five is in a box in which only 7.3% of 4208 Air Force men and women fell. Of the 2359 men measured in the Air Force survey none fell in this box.⁷

For mask No. 2, the test subjects failing to achieve a protection factor of five occur in boxes in which 28.3% of the Air Force population fell. Of the 2359 men measured, only 6.6% fell in these two boxes.

For mask No. 6, the only subject failing to achieve a protection factor of five occurs in a box in which only 2.4% of the Air Force men and women were found. Of the 2359 men measured, only 0.7% occurred in this box.

Even though the quantitative aerosol leakage tests reported here were performed using only ten test subjects, the results seem to indicate single-use respirators can be expected to provide a protection factor of at least five for most facial sizes, and the masks seem to fit male facial sizes better than female facial sizes.

3. Effects of Storage in a High-Humidity Atmosphere on the Performance of Single-Use Respirators. It has been established that exposure to high-humidity atmospheres can cause a decrease in the particulate removal efficiency of resin-impregnated electrostatic filter materials.² Since some single-use respirators use this type media, tests were conducted in which five each of the six different single-use respirators were stored for 21 days in an environmental chamber maintained at 32°C and 90% relative humidity. Before storage, each respirator was evaluated for aerosol leakage while worn by a test subject (same test subject for all tests) using the test procedures described above, except only the normal breathing exercise was performed. The masks were again tested after removal from the humidity chamber, then allowed to dry for three days at 70°F and 20% relative humidity, then again tested.

Of the six masks, only mask No. 4 showed a decrease in the level of protection offered after exposure to the humid atmosphere. Leakages before exposure, after exposure, and after drying for the five No. 4 masks tested are presented in Fig. 36. Leakages increased sharply after the high-humidity exposure, then decreased slightly after drying. The decrease in leakage after drying was unexpected and so far the cause of this decrease is unexplained.

4. Consistency of Protection Provided by Single-Use Respirators for a Six-Hour Work Shift. Since high humidity is known to degrade the efficiency of electrostatic felt filter materials, and since exhaled breath is very humid, tests were performed to determine what effects long-term wearing of single-use respirators have on the level of protection offered. Two test subjects wore single-use respirators for three hours, removed the respirators and redonned after one hour, then wore them for another three hours. NaCl aerosol leakage was determined immediately after the respirator was donned, and then at one-hour intervals. Only the normal breathing exercise was performed. Time required to determine aerosol leakage was approximately ten minutes, so that during the seven hours required for a test, the subjects wore the respirators in the 15 mg/m³ NaCl aerosol for approximately one hour 20 minutes. For the remainder of the seven hours, the subjects worked in a dust-free lab.

Five each of the six different single-use respirators were tested. Of the six, only mask No. 2 and Mask No. 5 showed varying levels of protection during the test period. Figures 37 and 38 show results for mask No. 2 and mask No. 5. Mask No. 2 seemed to fit test

Fig. 36.
 Effects on man-test results of storing mask No. 4 at 32°C, 90% relative humidity for 21 days.

Fig. 37.
 NaCl aerosol leakage as a function of number of hours worn for mask No. 2.

Fig. 38.
NaCl Aerosol leakage as a function of number
of hours worn for mask No. 5.

subject "X" better than subject "Y". The positions of these two subjects in the test panel are shown in Fig. 39. Neither of these subjects was used in the evaluation of fit on a wide range of facial sizes, described in III.E.2. above.

The level of protection provided by mask No. 5 varied for both test subjects. The variations in leakage observed for mask No. 2 and mask No. 5 could not be attributed to degradation of the filter materials by exhaled breath, since there is no trend toward lower levels of protection with increased time of wearing, and both of these masks use mechanical filter material which is not degraded by exposure to humid air. Mask No. 4, the only mask shown to lose efficiency after 21-days exposure to a high-humidity atmosphere, did not lose efficiency during the 6-hour test. Mask No. 4 is equipped with both an inhalation and an exhalation valve which protect the filter material from the user's exhaled breath.

5. Summary. Only two of the six single-use respirators tested provided a protection factor of five to all ten test panel subjects having a wide range of facial sizes. One of the six single-use respirators tested was shown to be adversely affected by storage in a humid environment, and two of the six showed widely varying levels of protection when worn for a six-hour workday.

Fig. 39.
Test panel positions of subjects X and Y.

F. Evaluation of Respirator Performance with Anthropometric Test Panels

1. Introduction. Respirator research during the past few years has revealed information which indicates a need to revise the regulations currently used in the NIOSH respirator certification program. The regulations currently do not require respirator fit testing as a certification requirement. This study is to examine the use of an anthropometric quantitative fit test panel as a certification tool and to perform tests utilizing this panel on presently approved respirators.

Respirator Test Panels representative of 90 to 95% of the working population were established as part of this program.

(For detailed information on test panels, see LASL Report LA-5488 by A. Hack et al, on "Selection of Respirator Test Panels Representative of U.S. Adult Facial Sizes.")

The program includes the relationship of respirator dimensions to facial fit and respirator efficiency, and the establishment of pass-fail criteria for respirators.

The quantitative man tests are used to determine respirator efficiency and face fit. Respirator comfort is determined subjectively. The test procedures for conducting quantitative man tests are outlined in Section 3 of this report.

2. Establish a Respirator Fit Test Panel. The first phase of the program was to recruit test subjects. Advertisements were placed in the news media in the area of Los Alamos, New Mexico. There was a shortage of small faces in the first 90 test subjects measured. To correct this, further advertisements were placed requesting volunteers with small faces.

NIOSH requested that fit test procedures be verified by use of more than one test panel; therefore, 146 men and women were recruited to allow the establishment of multiple test panels.

The test subjects were informed concerning the tests in which they would participate and, in addition, were approved by a LASL medical panel cognizant of the study details. A NIOSH human studies committee approved the test program.

The test subjects were given a 30-minute orientation on quantitative man testing starting on August 23, 1974. The last orientation was held December 16, 1974. They were shown the respirators they would be testing. The test subjects were told they would enter

test chambers or hoods filled with one of two aerosols, either sodium chloride or dioctyl phthalate (DOP).

They were informed that sodium chloride, a solid aerosol, and DOP, an oil mist, both have maximum concentrations to which a person should be exposed and that they would normally be exposed to a concentration lower than the maximum allowable safe exposure. They were asked to sign forms consenting to act as human test subjects, and authorizing their physician to release such medical information about themselves as might be necessary for LASL physicians to review. Of the 140, 130 were referred for medical approval.

In order to be certain the subjects were in good health and that wearing a respirator for brief periods would not be injurious to their health, the 130 test subjects completed a questionnaire containing 17 medical questions and signed medical release forms.

Blood and urine samples were collected for analysis. The questionnaires, urine analysis, blood chemistry screen, and medical records were reviewed by LASL physicians to determine the fitness of each test subject to engage in the respirator study.

Approval for experimentation on Human Test Subjects was required, both from the LASL Human Studies Review Committee, and from the Human Subjects Review Board, Communicable Disease Center, DHEW. Such permission was granted by both organizations.

The procedure followed was to review applicable regulations of the University of California and NIOSH, and consult with LASL medical and legal personnel. The toxicity of DOP and NaCl was reviewed, and an abstract of the information obtained was included with a test protocol outlining procedures.

The LASL Human Studies Review Committee's only major objection was to stressing of test subjects. Part of the original test procedure called for test subjects to be stressed by treadmill, while undergoing a quantitative respirator leak evaluation. The purpose of this stressing was to simulate actual workplace use of the respirators. We accordingly abandoned the "stress" portion of the exercises, and substituted a period to be spent in a hot humid chamber, to work up a sweat, as a substitute for physical activity. The revised test protocol was resubmitted to the LASL committee. Additional paper work involved the preparation of a medical questionnaire, and the establishment of blood chemistry screening and other test procedures by the LASL medical group for potential test subjects. Due to changes in personnel and the pressure of other assignments we did not receive approval from the LASL committee until August 1974.

After approval was granted by the LASL Committee, all relevant information was sent to our NIOSH Project Officer for transmittal to the DHEW Human Studies Review Board. Minor questions raised by members of the Board were answered to the satisfaction of all members, and we were granted permission to proceed with the experiments in November 1974.

The use of the humid chamber was abandoned because of the time pressure on completion of the required number of tests.

a. *Selection of Test Panels and Respirators.* The selection of test panels for half-mask and full-face respirators involved men and women who were measured for 14 standard facial dimensions. The test panel concept is described in Ref. 6. The panel for testing full facepiece respirators is based on face length and face width and is shown in Fig. 40. The panel used for testing half-mask respirators was based on face length and lip length and is shown in Fig. 41. The 130 test subjects were divided into ten subdivisions for each panel based on the two key dimensions (face width and face length or lip width and face length). The other 11 facial dimensions have been retained for future study.

For the purpose of this study no distinction has been made concerning sex. Each box has in it a certain number of persons who are selected without regard to sex. It is possible that factors such as skin texture and facial hair differences in the sexes may be significant for investigation; however, these factors are not reported on here. Male and female representation as related to population distribution is shown in Appendix B.

Our investigation of the test panel concept has involved approximately 600 tests to date. At least twice the required number of test subjects were tested in each panel size box.

The protection provided by respirators is affected by peripheral seal design, and differences in respirator suspension, structural materials, and dimensions. The tabulation of these features for the respirators tested is shown in Table XIX.

While not a part of quantitative testing, the relationship of comfort and the compatibility of wearing eyeglasses with respirators cannot be ignored.

Respirators chosen for this test program were with one exception approved devices in wide use. The exceptions are masks 5, 6, 7, (a related series) which are not approved in this country.

b. *Reproducibility of Data Obtained in Investigation of the Test Panel Concept.* To determine reproducibility of respirator performance for

Fig. 40
25-Person Panel for Full-Face Masks.

Fig. 41
25-Person Panel for Half-Masks.

different tests, two half-mask and two full-face respirators used to examine the test panel concept were retested on one person selected from each block of the half-mask panel and the full facepiece panel. Four quantitative man tests were conducted on each test subject. A total of 160 tests were used to determine reproducibility of respirator efficiency.

TABLE XIX
RESPIRATORS SELECTED FOR VALIDATION OF PANEL

<u>No.</u>	<u>Type of Respirator</u>	<u>Respirator Circumference (cm)</u>	<u>Peripheral Seal Design</u>	<u>Respirator Headband Design</u>	<u>Structure Material</u>
<u>Half-Mask</u>					
1	Welsh 7500	35.9	Internal roll w/o chin cup	4 Pt; woven elastic	Polyvinyl chloride
2	MSA Custom Comfo	33.8	Internal roll with chin cup	4 Pt; woven elastic	Rubber
5	Drager, Small R27-203	31.9	Internal roll with chin cup; interior lateral support strap	2 Pt; rubber, double loop	Neoprene/natural rubber mixture
6	Drager, Medium R27-202	34.4	Internal roll with chin cup; interior lateral support strap	2 Pt; rubber, double loop	Neoprene/natural rubber mixture
7	Drager, Large R27-201	36.6	Internal roll with chin cup; interior lateral support strap	2 Pt; rubber, double loop	Neoprene/natural rubber mixture
8	Willson 1200		Internal roll with chin cup	4 Pt; woven elastic	Rubber
<u>Full-Facepiece</u>					
3	MSA Ultravue	55.0	Flat with inner flap	5 straps	Soft rubber
4	Welsh 7600-S	51.5	Flat with inner flap	5 straps	Silicone rubber

3. Quantitative Man Tests. a. Respirator Test Procedures. In setting up quantitative man-test procedures for this project, proposed revisions to the present respirator certification requirements were considered. Project guidelines for conducting quantitative man tests were written for use prior to initiation of testing. The essential portions of these guidelines are given in this section.

The respirators were accepted for quantitative man tests after being evaluated for durability and mechanical construction. A minimum of five respirators of each type were selected and identified by sequential numbers for the respirator model and size, and alphabetical identification for each respirator of the same model and size. The necessary

items for checking and identifying each respirator in detail were included in a respirator record data sheet.

A physical check was made of the respirators for damage or impairment that may have occurred in shipping and handling. This included (a) checking conditions of facepiece body for cracking, and holes or tears in the rubber, especially around attachment points; (b) checking integrity of headstraps for breaks or tears in material and condition of attachments or adjusting devices; (c) checking inhalation and exhalation valve assemblies for cracks or tears in valve material; (d) checking for foreign material between valve and seat, and proper installation of valve body in facepiece.

A sampling probe was installed in each respirator that would permit 0.3 #/min of air to be drawn from

within the facepiece midway between the wearer's nose and mouth. The sampling probe was 1/4-20 x 1 inch nylon screw with a 2.65-mm hole drilled through the screw. Attached to the probe was a 1/8-inch i.d. x 1/32-inch wall amber latex surgical tubing 24 inches in length.

Respirators were cleaned and disinfected after each use, using the best method suited to the respirator material as suggested by the manufacturer. If a method was not specified then the respirators were cleaned with detergent and lukewarm water, 101 Germicidal Detergent, or wiped thoroughly with ethyl alcohol.

High-efficiency filters tested for pressure drop and NaCl aerosol penetration were used. Filters were labeled with the same number assigned the respirator model and size, followed by a dash and a sequential number for each filter.

b. Fit-Testing Procedures. Before performing the qualitative fitting test, a physical check-out was made of the respirators for damages or impairments that may have occurred in labeling or installing the probes.

The respirator facepiece body and inhalation and exhalation valves were checked out for cleanliness which included checking for foreign material between valve and seat, checking sampling probes for condition and integrity of seal, and checking for proper installation of filter elements on respirators and conditions of gaskets in filters or cartridge holder.

Prior to performing qualitative and quantitative tests, all test subjects were trained in the procedures necessary to wear a respirator and attain satisfactory fit. The test subjects were given brief oral instructions concerning orientation of the facepiece and location of head harness straps before proceeding with the qualitative test. The manufacturer's instructions for putting on and adjusting the respirator were given to the test subjects either orally or in writing.

The sequential test number, the subject's name and measurement number taken from the anthropometric data sheet, and respirator information taken from the respirator data sheet were recorded. A subjective evaluation was made on the feasibility of wearing glasses with the respirator. In addition, strap tensions were recorded on the data sheet.

The wearer performed one or more of the following qualitative fitting tests:

(1) Positive pressure test — closing the exhalation valve cover with fingers or palm of hand and puffing lightly. Escaping air between facepiece and face indicated leakage. If the exhalation valve cover could

not be closed with fingers, the exhalation valve cover was removed and the exhalation valve was covered with the palm of the hand or fingers, and the test subject puffed lightly. If the exhalation valve cover was removed for this test, it was replaced without disturbing the facepiece fit or requiring removal and replacement of the respirator.

(2) Negative pressure test — closing openings in filters or filter covers and inhaling lightly. Inward leakage of air between facepiece and face indicated leakage.

(3) If leakage was observed between facepiece and face when tests were performed in accordance with paragraphs (1) and (2), the wearer then adjusted the facepiece fit and repeated the tests prescribed in this paragraph. No adjustment of facepiece fit was allowed during quantitative testing.

c. Quantitative Fitting Tests. This test immediately followed the Qualitative Fitting Test.

The TDA-60 NaCl Aerosol Test System designed for quantitative fitting tests was used. This is a commercial version of a LASL design. The general method used in this project to determine the leakage into the facepiece of the respirator is not new. While the use of sodium chloride aerosols is now well established, the data reduction and the exercise procedures used are not. The exercises used for this project are standard and consist of (a) normal breathing, (b) deep breathing, (c) turning head from side to side, (d) moving head up and down, (e) talking, (f) smiling/frowning, and (g) repeating normal breathing. Differences occur in the analysis of the penetrations recorded during these exercises. One method is to utilize only the first five exercises and determine the average penetration of the mask on these alone. A second method uses all seven exercises; however, the penetrations recorded during the smile/frown are not included in the averages. This latter method indicates if the mask seal is broken during a smile/frown and, by including the repeat of the normal breathing exercise, the measure of resealing will be noted. In most cases the average penetration recorded in utilizing five exercises will be lower than with seven.

After determining the exercises to be used it is necessary to decide how the average penetration will be calculated. There are two methods for doing this. The first is the so-called average penetration method which in essence utilizes the area under the curve. The second records only the peak values found for penetration during inhalation. Peak values are recorded and averaged for each exercise. The second method, using peak values alone, provides higher penetration results and it is considered more conservative.

For this project the most conservative method of reporting average penetration has been chosen. Seven exercises are used and the peak penetration is calculated averaging the six results without the smile/frown.

Procedures for recording the exercises on the strip chart and entering the data on the Quantitative Fitting Test data sheet were as follows.

After the test subject entered the hood and the test aerosol was stabilized, the photometer was set at 100% while sampling the aerosol concentration. Then clean air was used to set a zero reading. The probe of the mask was connected to the photometer and the exercises were started. Photometer signals were recorded on the strip chart to a sensitivity of 0.01%.

d. *Determine the Relation of Respirator Comfort to Respirator Efficiency.* Evaluations were made related to respirator comfort. While conducting the quantitative man tests, observations on evenness of facepiece peripheral pressure were also made.

The comfort ratings used are as follows:

1. **Very Comfortable.** Mask can be worn for an indefinite period of time without its becoming unbearably bothersome or painful. No pain points; mask feels comfortable.
2. **Comfortable.** Mask can be worn for a reasonable length of time, approximately 2 to 4 hours without undue discomfort. Some pressure points with slight discomfort.
3. **Barely Comfortable.** Mask can be worn for a shorter period of time, approximately 1/2 hour to one hour without intolerable discomfort. Some discomfort from pressure.
4. **Uncomfortable.** Mask can be tolerated for the period of the test only.
5. **Intolerable.** Mask cannot be worn without discomfort for any period of time.

The results of comfort evaluations on two half-masks are shown in Figs. 42 and 43. Respirator No. 2 is softer, more pliable, and smaller than respirator No. 1. The test results show No. 2 to be more comfortable and provide a better fit.

Leakage between mask body and face fluctuates with the sealing tightness of the respirator. To avoid such fluctuations, strap tension was restricted to a range of 340 to 450-g tension for all half-mask quantitative man tests. The strap tension of half-mask respirators was measured with a Check-Line Tension-Meter. For full face respirators strap tension could not be measured with the tension meter but was estimated by feeling.

Such measurements eliminated extremes of strap tension that created facepiece seal failures. Also recorded were facial characteristics, such as malfor-

		LIP LENGTH (mm)				
		34.5	43.5	52.5	61.5	
FACE LENGTH (mm)	133.5	A 2 5 2 3		B 5 3 3 2		
	123.5	C 3 2	D 3 4 3 1 ② 2 3 3 2 3		E 2 2 2 2 3 2	
	113.5		G ③ 1 2 4 ⑤ 2			
	103.5	F ③ 1 2 4 ⑤ 2		H 2 2		
	93.5	I ④ 4 ⑤ ⑤		J ④ ④ ⑤ 3 ④		

Fig. 42.

Comfort Rating, Respirator No. 1.

		LIP LENGTH (mm)				
		34.5	43.5	52.5	61.5	
FACE LENGTH (mm)	133.5	A 2 3 2 2		B 2 2 3 5		
	123.5	C 2 3	D 1 2 1 2 3 3 3 2 1 2		E 2 2 2 3 2 1	
	113.5		G 3 2 1 3 2 2 ② 2			
	103.5	F 2 2 2 2 3		H 2 3		
	93.5	I 2 4 5 4		J ① 2 2		

Fig. 43.

Comfort Rating, Respirator No. 2.

mations of the nose, chin, and hollow cheeks for half-masks, and malformations around the sealing surfaces of the full-face masks. No work has been done at this time in this area.

e. **Multiple-Size Respirator Studies.** The effective use of respirators depends on a proper fit for all faces, and one way to accomplish this is by using

multiple-size respirators. As it is unlikely that one mask can fit all faces, respirator program administrators now must provide several brands of respirators to cover different sizes of faces since few manufacturers supply multiple sizes. In order to evaluate the use of multiple-size half-mask respirators, a foreign half-mask respirator was tested using the 35-person panel. It was available in small, medium, and large sizes as shown on Table XIX as No. 5, No. 6, and No. 7. The results of the resulting quantitative man tests are discussed Sec. 5.c.

4. NaCl Aerosol Size and Concentration Specifications. The LASL Respirator Research and Development Section of the Industrial Hygiene Group has conducted a study on several types of sodium chloride (NaCl) aerosol generators, for use in a compact system, to test particulate filter penetration and respirator performance. The NaCl aerosol has to be reproducible with an aerosol mass median aerodynamic diameter (mmad) of $0.6\ \mu\text{m}$, σ_g of 2.0 ± 0.5 , and concentration of $15\ \text{mg}/\text{m}^3$.

The behavior of sodium chloride aerosol exposed to different humidities is not completely known; however, data from past studies indicate that low humidity levels have little effect on the size of the aerosol. Our compressed air supply used is in the humidity range of $12 \pm 4\%$. The Wright nebulizer was checked using double distilled water and the humidity was found to be $29 \pm 4\%$. This humidity range has little effect on crystal growth.

5. Quantitative Fit Testing Results. a. Test Panel Size. The number of test subjects used to represent the faces of the working population is 25. This is a number that we believe can be economically tested. The 25 subjects are arranged in 10 size categories (or boxes) as shown previously in Figs. 40 and 41.

Our initial task was to determine how a mask would perform on more than one test panel in order to develop some confidence in our results. It soon became apparent that there were two distinctly different ways of dealing with the test data. The simpler way was to create two different panels of 25 persons each, and then compare the test results between the two panels. However, we do not expect the test results to be identical between people of the same facial dimensions in the different panels because the facial dimensions chosen, though important, are far from complete in describing the faces. The alternate analysis is to pool all of the test results on all of the subjects and then summarize the tests

as a probability of the persons in a box either passing or failing. It is this latter method of data analysis that was chosen.

For the first four respirators tested, 70 subjects constituted our sample population. The size of the population was reduced to 35 for masks 5 through 8, when it became apparent that we could not finish all tests and data analyses in time without reducing the number of tests. The 35 subjects consisted of the 25-person panel plus one additional person per box.

b. Probability Determination of Respirator Success or Failure when Tested with the Panel. To analyze the data, a mask leakage rate was established above which the subject would be considered to have failed. For half-masks this was 10%, and 2% for full-face masks. In the case of masks that did very well at one of these levels, additional lower leakages were also examined. The probability of a subject's passing if one failed in the tests is $2/3$ for each subject.

If three subjects are required to be tested in a box, according to the 25-person panel scheme, and if each subject has a $2/3$ chance of passing, then the probability of their all passing is $2/3 \times 2/3 \times 2/3$ or 30%.

To determine the overall probability of the mask's passing or failing for the entire panel of ten boxes, the probability of passing in all of the boxes must be combined. A more detailed explanation of the probability determination is given in Appendix C. Ideally a mask should pass the entire panel of ten boxes to be considered a success. Our test results to date indicate that most masks have little chance of passing the entire panel without failure. Following the methods of Hyatt⁸ in determining protection factors, we have decided to consider a mask to have passed successfully if 95% of the 25 persons, or 24 subjects, pass. For test panels of 20 to 25 persons, one failure will be allowed. Panels containing less than 20 persons, discussed under truncated panels below, will require all of the subjects to pass. The results are reported in Table XX under the column headed "Predicted Probability of 95% of Panel Passing." For example, in Table XXI, Mask 3 has a 98% probability of passing. This mask is predicted to fit the working population represented by the test panel. In contrast, a mask such as No. 1 is shown in Table XX to have only 0.2% probability of fitting the panel.

We also report the predicted probability of a mask passing when no failures are allowed (all 25 subjects pass), and when two failures are allowed (23 subjects pass). The values are shown in the individual tables describing the test results on each mask, beginning with Table XXII.

TABLE XX
RESPIRATOR FIT TEST RESULTS, HALF-MASKS

<u>Respirator</u>	<u>Protection Factor/Penetration</u>	<u>No. Subject Tested</u>	<u>No. Pass (%)</u>	<u>No. Fail (%)</u>	<u>Predicted^a Probability of 95% of Panel Passing</u>	<u>Comments</u>
1	10/10%	70	$\frac{52}{(74\%)}$	$\frac{18}{(26\%)}$	0.2%	Failures mostly in shorter faces
2	10/10%	72	$\frac{68}{(94\%)}$	$\frac{4}{(6\%)}$	57%	All failures in shorter faces
	20/5%	72	$\frac{65}{(90\%)}$	$\frac{7}{(10\%)}$	24%	One failure in longer face
	50/2%	72	$\frac{60}{(83\%)}$	$\frac{12}{(17\%)}$	4%	Failures in long & short faces. Mid-size male faces pass
5	10/10%	35	$\frac{31}{(89\%)}$	$\frac{4}{(11\%)}$	13%	Three failures in short, one in long face
	20/5%	35	$\frac{28}{(80\%)}$	$\frac{7}{(20\%)}$	0.0%	Additional fail- ures in short faces
	50/2%	35	$\frac{26}{(74\%)}$	$\frac{7}{(26\%)}$	0.0%	Additional fail- ures in short and long faces
6	10/10%	35	$\frac{30}{(86\%)}$	$\frac{5}{(14\%)}$	5%	Failures only in short faces
	20/5%	35	$\frac{27}{(77\%)}$	$\frac{8}{(23\%)}$	0%	Failures only in short faces
	50/2%	35	$\frac{25}{(71\%)}$	$\frac{10}{(29\%)}$	0%	Two failures in long faces. Mid- size male faces pass
7	10/10%	35	$\frac{15}{(43\%)}$	$\frac{20}{(57\%)}$	0%	Only very long and wide faces can fit
8	10/10%	35	$\frac{34}{(97\%)}$	$\frac{1}{(3\%)}$	89%	Best half-masks, 1 failure in short- est face
	20/5%	35	$\frac{32}{(91\%)}$	$\frac{3}{(9\%)}$	35%	2 failures in long- est, 1 failure in shortest, longest mid-size faces pass
	50/2%	35	$\frac{28}{(80\%)}$	$\frac{7}{(20\%)}$	0%	More failures in longest & short- est
	100/1%	35	$\frac{26}{(74\%)}$	$\frac{9}{(26\%)}$	0%	Mid-length male faces pass

Note: 95% of a panel of 25 subjects = 23.75 or 24 subjects

^aBased on the large number of subjects tested, the following are the predicted probabilities of a panel of 25 persons having 1 or fewer failures.

TABLE XXI
RESPIRATOR FIT TEST RESULTS, FULL-FACE MASKS

Respirator	Protection Factor/Penetration	No. Subjects Tested	No. Pass (%)	No. Fail (%)	Predicted Probability of 95% of Panel Passing	Comments
3	50/2%	71	$\frac{70}{(99\%)}$	$\frac{1}{(1\%)}$	98%	One failure smallest face
	100/1%	71	$\frac{69}{(97\%)}$	$\frac{2}{(3\%)}$	84%	Additional failure mid-size
	200/0.5%	71	$\frac{68}{(96\%)}$	$\frac{3}{(4\%)}$	71%	Additional failure large face
	250/0.4%	71	$\frac{67}{(94\%)}$	$\frac{4}{(6\%)}$	55%	Additional failure in mid-size. Mid-width females pass
	333/0.3%	71	$\frac{64}{(90\%)}$	$\frac{7}{(10\%)}$	24%	Additional failures small & mid-size
	500/0.2%	71	$\frac{57}{(80\%)}$	$\frac{14}{(20\%)}$	2.2%	Scattered failures in 9 out of 10 boxes
4	50/2%	72	$\frac{60}{(83\%)}$	$\frac{12}{(17\%)}$	6%	Failures in 6 out of 10 boxes scattered
	100/1%	72	$\frac{56}{(78\%)}$	$\frac{16}{(22\%)}$	1%	Additional failures in the same 6 boxes

TABLE XXII
Mask Performance Summary, No. 1

Mask # 1 Number of Test Subjects 70
Protection Factor 10 Penetration 10%

Subjects Passing Number 52 Percent 74		Subjects Failing Number 18 Percent 26	
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LIP LENGTH (mm)

	34.5	43.5	52.5	61.5	43.5	52.5	61.5
133.5		A	B		A	B	
		7	4		0	0	
123.5	C	D	E	C	D	E	
	2	15	6	0	3	0	
113.5	F	G	H	F	G	H	
	4	9	2	2	3	0	
103.5	I	J		I	J		
	2	1		6	4		
93.5							

Probability of a Panel of 25 Subjects Passing (Recommended pass criteria is 24 or more) ≥ 23 pass 1.4%; ≥ 24 pass 0.2%; 25 pass 0.0%.

c. *General Test Results.* Table XX shows the results of each of the six half-masks tested. A wide variation among the six half-masks is apparent. Clearly, No. 1 does not fit the test panel, although the comments indicate that wide faces do better than the narrow faces. A truncated panel including only the wide faces would increase the probability of passing. First listed are the protection factor and average penetration for which the results were tested. Test subjects who achieved penetration less than or equal to that listed on the table were counted as passing, all others became failures. The numbers of subjects who passed and failed are shown along with the percentages. For example, Respirator No. 1 was tested on 70 people for a protection factor (PF) of 10. Fifty-two passed (74%), 18 failed (26%). The probability of 95% of a panel of 25 subjects (24 out of 25) passing is only 0.2%. (See Appendix C for a description of the probability determinations.) Respirator No. 8 is the best mask for the entire panel with 1 failure out of 35 test subjects for a PF of 10.

We can predict that 89% of the time, No. 8 will achieve a PF of 10 on the entire panel. The three respirators related by size, No. 5, No. 6, and No. 7, do not do as well together as does No. 8 alone, showing that design, size, and strap configuration are more important than multiple sizes. The two worst performing masks are No. 1 and No. 7.

Table XXI reports the results on the two full face masks tested. Number 3 performs better than No. 4 since 84% of the time No. 3 will achieve a PF of 100, while No. 4 can achieve a PF of 100 only 1% of the time.

d. Truncation of Test Panels. As described in Ref. 6, we do not expect most respirators to fit all the members of the test panels. The panels represent a greater variation in facial sizes than the masks were designed to fit. At the present time most of the commercially available respirators are designed to fit men, while women are also represented in the facial size of the test panels. Therefore, it is unlikely that the presently approved masks could pass an approval schedule requiring that they fit the entire test panel. We believe that it is appropriate to reduce the number of facial sizes represented by the entire test panel to some smaller percentage of the population. Then respirators that fit the members of this reduced or truncated panel could be approved for that portion of the population represented by the truncated panel. Such respirators would be labeled as approved for certain facial sizes, i.e., longer than 113 mm and wider than 125 mm. A method of measuring the faces of the potential respirator user would have to be supplied by the manufacturer. The details of such measuring instruments are beyond the scope of this work, except that we believe that needed measurements could be made with inexpensive devices, and this does not present a major obstacle to the use of such a scheme.

A variety of different truncated panels are discussed below. All such truncated panels have been created by deleting boxes along the straight lines defining the major measurements of length and width of the test panel boxes. Consistent lines along which test panels are truncated will ensure the respirator wearer a reasonable chance of a good seal, provided that he selects a device approved for his facial size. Qualitative fit tests, as recommended by the manufacturer, will of course still be required to prove the fit on the user.

e. Performance of Individual Respirators.

i. Respirator 1. This half-mask is made of vinyl and has a four-point suspension. It is currently ap-

proved by NIOSH/MESA with a variety of different filters and sorbents. The mask is wide and only fits wide faces well. Table XXII shows the performance of Mask I on the entire panel of 70 test subjects. The number of subjects who passed or failed in each box of the panel is shown for a PF of 10, or 10% leak. Fifty-two subjects pass (74%) and 18 subjects fail (26%). For a panel of 25 subjects the probability of meeting the requirement of one or fewer failures is less than 1%.

In order to allow this mask to be acceptable for a limited percentage of the population we will have to truncate the panel. The panel may be cut in half along the line of face length 113-114 mm. Table XXIII shows such a truncated panel with only the longer faces represented and 13 test subjects used. In box D 18 subjects were tested. Three of the 18 failed and the remaining 15 passed. The predicted probability of a subject in that size range (Box D) passing is 15 over 18. The predicted probability of all 5 of the subjects in that box passing is (15 over 18)⁵ or 40%. All other boxes have a 100% chance of passing. Therefore, we may predict that the entire truncated panel of 13 persons will have no failures 40% of the time. If we wish to increase the probability of this panel's passing we may allow up to one failure. The predicted probability of the panel's passing with one or fewer failures increases to 80%. Another truncation would be to allow only the widest boxes to be included, Table XXIV. Here only six test subjects are available, but the probability of all of them having a PF of 10 is 100%. This mask would then be approved for a small percentage of the population, but additional sizes by the manufacturer could fit the other facial sizes.

ii. Respirator 2. This mask is made of natural rubber, and has a metal yoke and four point suspension. It is currently approved with a variety of filters and sorbents. The mask is narrower than No. 1 which may account for its better performance. Test results for a PF of 10, 20, and 50 are shown in Table XXV.

At a PF of 10, only four subjects failed out of 72. These occurred in faces shorter than 113 mm, which is the size range for the majority of the women. The entire panel can only be expected to pass with one or fewer failures 57% of the time; however, if the panel is truncated along the line of face length 113 mm, Table XXVI, the predicted probability of passing for a PF of 10 is 100%. Such a panel would contain about 85% of the men and only 12% of the women, which is what we would expect from a mask designed for men.

Higher protection factors are shown for study purposes in Table XXV. At a PF of 20, three more subjects failed, two below 113 mm and one above. At a PF of 50 there were 5 more failures for a total of 12 with all faces between 113 and 123 face-length mm still provided protection.

iii. *Respirators 5, 6, and 7.* The small half-mask No. 5 is one of three sizes tested to determine how multiple-size half-masks perform. None of these masks are now approved for use in the United States. They are made of natural rubber with double straps connected to a two-point suspension. Table XXVII shows the performance of the No. 5 half-mask with 35 test subjects. At a PF of 10, this mask performs between No. 1 and No. 2. Thirty-one subjects pass (89%), and four fail (11%), but they are scattered about the panel. Examining the results at

TABLE XXV
Mask Performance Summary, No. 2

Mask # 2 Number of Test Subjects 72
Protection Factor 50 Penetration 2%

Subjects Passing		Subjects Failing	
Number 60	Percent 83%	Number 12	Percent 17%

LIP LENGTH (mm)

FACE LENGTH (mm)	LIP LENGTH (mm)			LIP LENGTH (mm)			
	34.5	43.5	52.5	61.5	43.5	52.5	61.5
133.5		A 6	B 2		A 1	B 2	
123.5	C 2	D 18	E 6		C 0	D 0	E 0
113.5	F 5	G 10	H 2		F 2	G 3	H 0
103.5	I 6	J 3			I 2	J 2	
93.5							

Probability of a Panel of 25 Subjects Passing
23 or more pass 14%; 24 or more pass 4%; 25 pass 0.5%
(The recommended pass criteria is 24 or more.)

TABLE XXIII Truncated Test Panel, No. 1

		LIP LENGTH (mm)			
		34.5	43.5	52.5	61.5
FACE LENGTH (mm)	133.5		A 2		B 2
	123.5	C 1	D 5		E 3
	113.5	F	G		H
	103.5	I	J		
	93.5				

TABLE XXIV Truncated Test Panel, No. 1

LIP LENGTH (mm)

FACE LENGTH (mm)	LIP LENGTH (mm)					
	34.5	43.5	52.5	61.5		
133.5		A		B	2	
123.5	C		D		E	3
113.5	F		G		H	1
103.5	I		J			
93.5						

Mask # 2 Number of Test Subjects 72
Protection Factor 20 Penetration 5%

Subjects Passing		Subjects Failing	
Number 65	Percent 90%	Number 7	Percent 10%

LIP LENGTH (mm)

FACE LENGTH (mm)	LIP LENGTH (mm)			LIP LENGTH (mm)			
	34.5	43.5	52.5	61.5	43.5	52.5	61.5
133.5		A 7	B 3		A 0	B 1	
123.5	C 2	D 18	E 6		C 0	D 0	E 0
113.5	F 7	G 10	H 2		F 0	G 3	H 0
103.5	I 7	J 3			I 1	J 2	
93.5							

Probability of a Panel of 25 Subjects Passing
23 or more pass 53%, 24 or more pass 24%, 25 pass 5%
(The recommended pass criteria is 24 or more.)

Mask # 2 Number of Test Subjects 72
Protection Factor 10 Penetration 10%

Subjects Passing		Subjects Failing	
Number 68	Percent 94%	Number 4	Percent 6%

LIP LENGTH (mm)

FACE LENGTH (mm)	LIP LENGTH (mm)			LIP LENGTH (mm)			
	34.5	43.5	52.5	61.5	43.5	52.5	61.5
133.5		A 7	B 4		A 0	B 0	
123.5	C 2	D 18	E 6		C 0	D 0	E 0
113.5	F 7	G 11	H 2		F 0	G 2	H 0
103.5	I 8	J 3			I 0	J 2	
93.5							

Probability of a Panel of 25 Subjects Passing
23 or more pass 86%; 24 or more pass 57%; 25 pass 19%
(The recommended pass criteria is 24 or more.)

TABLE XXVI Truncated Test Panel, No. 2
LIP LENGTH (mm)

	34.5	43.5	52.5	61.5
133.5		A	B	
		2	2	
123.5	C	D	E	
	1	5	3	
113.5	F	G	H	
103.5				
93.5				

TABLE XXVII

Mask Performance Summary, No. 5

	34.5	43.5	52.5	61.5		34.5	43.5	52.5	61.5
133.5		A	B				A	B	
		3	3				0	0	
123.5	C	D	E			C	D	E	
	2	5	4			0	1	0	
113.5	F	G	H			F	G	H	
	3	5	2			1	0	0	
103.5	I	J				I	J		
	1	3				2	0		
93.5									

Probability of a Panel of 25 Subjects Passing
23 or more pass 35%; 24 or more pass 10%; 25 pass 2%
(The recommended pass criteria is 24 or more.)

Mask # 5 Number of Test Subjects 35
Protection Factor 20 Penetration 5%

Subjects Passing Number 28 Percent 80%
Subjects Failing Number 7 Percent 20%

	34.5	43.5	52.5	61.5		34.5	43.5	52.5	61.5
133.5		A	B				A	B	
		3	3				0	0	
123.5	C	D	E			C	D	E	
	2	5	4			0	1	0	
113.5	F	G	H			F	G	H	
	3	5	1			1	0	1	
103.5	I	J				I	J		
	0	2				3	1		
93.5									

Probability of a Panel of 25 Subjects Passing
23 or more pass 3.8%; 24 or more pass 0%; 25 pass 0%
(The recommended pass criteria is 24 or more.)

Mask # 5 Number of Test Subjects 35
Protection Factor 50 Penetration 2%
Subjects Passing Number 26 Percent 74%
Subjects Failing Number 9 Percent 26%

	34.5	43.5	52.5	61.5		34.5	43.5	52.5	61.5
133.5		A	B				A	B	
		3	2				0	1	
123.5	C	D	E			C	D	E	
	2	5	4			0	1	0	
113.5	F	G	H			F	G	H	
	3	5	0			1	0	2	
103.5	I	J				I	J		
	0	2				3	1		
93.5									

Probability of a Panel of 25 Subjects Passing
23 or more pass 0%; 24 or more pass 0%; 25 pass 0%
(The recommended pass criteria is 24 or more.)

PFs of 20 and 50 shows a preponderance of failures in the faces shorter than 113 mm.

The medium size half-mask No.6 was tested on the same 35 people as the small (and large size) masks. Compare the results in Table XXVIII with those in Table XXVII. The two masks performed complementally, with the small No. 5 fitting the longer faces. If the faces fitting each of the masks are combined, the only faces not protected are the smallest and narrowest faces in Box I, see Table XXIX. These two masks together would provide good coverage of most of the faces in the panel. At a PF of 20, the small mask increases failures from four to seven, with all new failures occurring in the shorter faces. The medium mask increases failures from five to eight, with all new failures in the same boxes as occurred at PF of 10. At a PF of 50, failures are widely scattered about the panels.

The small mask No.5 may be tested on a truncated panel, Table XXX, which will represent about half the males and has a 100% chance of passing.

The medium size mask No.6 can also be tested on a truncated panel, Table XXXI, with 86% of the males and 12% of the females represented.

The larger half-mask No.7 shown in Table XXXII is the worst performing mask tested. Twenty subjects failed out of 35 tested for a PF of 10. This mask is just too wide to obtain a good seal. The small and medium masks do a credible job if used together to cover the working population but the large mask should not be included in the set.

iv. *Respirator 8.* Mask No.8 is a natural rubber mask with four-point suspension, and is approved with a variety of filters and sorbents. It was the best performing half-mask tested, and Table XXXIII shows test results for PFs from 10 through

TABLE XXVIII
Mask Performance Summary, No. 6

TABLE XXIX
Mask Performance Summary, No. 5 and No. 6

	A	B
	0/0	0/0
C	D	E
0/0	1/0	0/0
F	G	H
1/0	0/1	0/0
I	J	
2/2	0/2	

TABLE XXX Truncated Test Panel, No. 5

TABLE XXXI Truncated Test Panel, No. 6

TABLE XXXII

Mask Performance Summary, No. 7

Mask # 7 Number of Test Subjects 35
Protection Factor 10 Penetration 10%

Subjects Passing Number 10 Percent 42%
Subjects Failing Number 20 Percent 58%

		LIP LENGTH (mm)						
		34.5	43.5	52.5	61.5	43.5	52.5	61.5
FACE LENGTH (mm)	133.5		A	B		A	B	
	123.5		3	2		0	1	
	113.5	C	D	E		C	D	E
	103.5	0	4	4		2	2	0
	93.5	F	G	H		F	G	H
		1	0	1		3	5	1
		I	J			I	J	
		0	0			3	3	

Probability of a Panel of 25 Subjects Passing
23 or more pass 0%; 24 or more pass 0%; 25 pass 0%
(The recommended pass criteria is 24 or more.)

Mask # 8 Number of Test Subjects 35
Protection Factor 20 Penetration 5%

Subjects Passing Number 32 Percent 91%
Subjects Failing Number 3 Percent 9%

		LIP LENGTH (mm)						
		34.5	43.5	52.5	61.5	43.5	52.5	61.5
FACE LENGTH (mm)	133.5		A	B		A	B	
	123.5		2	2		1	1	
	113.5	C	D	E		C	D	E
	103.5	2	6	4		0	0	0
	93.5	F	G	H		F	G	H
		4	5	2		0	0	0
		I	J			I	J	
		2	3			1	0	

Probability of a Panel of 25 Subjects Passing
23 or more pass 68%; 24 or more pass 35%; 25 pass 9%
(The recommended pass criteria is 24 or more.)

TABLE XXXIII

Mask Performance Summary, No. 8

Mask # 8 Number of Test Subjects 35
Protection Factor 10 Penetration 10%

Subjects Passing Number 34 Percent 97%
Subjects Failing Number 1 Percent 3%

		LIP LENGTH (mm)						
		34.5	43.5	52.5	61.5	43.5	52.5	61.5
FACE LENGTH (mm)	133.5		A	B		A	B	
			3	3		0	0	
	123.5	C	D	E		C	D	E
		2	6	4		0	0	0
	113.5	F	G	H		F	G	H
	4	5	2		0	0	0	
103.5	I	J			I	J		
	2	3			1	0		
93.5								

Probability of a Panel of 25 Subjects Passing
23 or more pass 100%; 24 or more pass 89%; 25 pass 44%
(The recommended pass criteria is 24 or more.)

Mask # 8 Number of Test Subjects 35
Protection Factor 50 Penetration 2%

Subjects Passing Number 28 Percent 80%
Subjects Failing Number 7 Percent 20%

		LIP LENGTH (mm)						
		34.5	43.5	52.5	61.5	43.5	52.5	61.5
FACE LENGTH (mm)	133.5		A	B		A	B	
	123.5		2	0		1	3	
	113.5	C	D	E		C	D	E
	103.5	2	6	4		0	0	0
	93.5	F	G	H		F	G	H
		4	5	2		0	0	0
		I	J			I	J	
		1	2			2	1	

Probability of a Panel of 25 Subjects Passing
23 or more pass 2%; 24 or more pass 0%; 25 pass 0%
(The recommended pass criteria is 24 or more.)

100. For a PF of 10, there were 34 passing out of 35. The single failure occurred in the smallest and narrowest face. We can predict that 24 of 25 subjects will pass 89% of the time. At a PF of 20, 3 failures occur with the additional failures in the longest faces. At a PF of 50, four additional failures occur, all in the longest and shortest categories. All faces between 103 and 123 mm length are still protected. Table XXXIV shows a truncated panel for Mask No.8 at a PF of 50. Seventeen test subjects were used, which represent about 70% of the males and females in the working population. Based on our test results, we estimate the users with face length of 103 to 123 mm have a 100% chance of passing at a PF of 50.

v. *Respirator 3.* This full-face mask was the better performing of the two full facepieces tested. It is made of natural rubber, has five head straps, and is relatively narrow. Table XXXV shows the performance of No.3 at several different protection factors. Out of 71 subjects tested, there was a single failure at a PF of 50 in the smallest size box. At a PF of 100, there is an additional failure in a mid-size length and width face. At 200, there was a third failure in a large face. At 250 (0.4% penetration) there is another failure in a mid-size face. Seven failures occur at a PF of 333, and 14 failures occur at 500. These failures are scattered about the panel with no apparent pattern.

Two truncations of the panel for No.3 are suggested. In Table XXXVI, Box 9 has been deleted, the smallest facial size. At a PF of 50, no failures are predicted, and at 100, 22 out of 23 sub-

TABLE XXXIV Truncated Test Panel, No. 8
LIP LENGTH (mm)

TABLE XXXV
Mask Performance Summary, No. 3

Probability of a Panel of 25 Subjects Passing
23 or more pass 92%; 24 or more pass 71%; 25 pass 22%
(The recommended pass criteria is 24 or more.)

Probability of a Panel of 25 Subjects Passing
23 or more pass 85%; 24 or more pass 21%; 25 pass 0.0%
(The recommended pass criteria is 24 or more.)

TABLE XXXVI Truncated Test Panel, No. 3

Probability of a Panel of 25 Subjects Passing
23 or more pass 90%; 24 or more pass 51%; 25 pass 20%
(The recommended pass criteria is 24 or more.)

Probability of a Panel of 25 Subjects Passing
23 or more pass 52%; 24 or more pass 24%; 25 pass 0%
(The recommended pass criteria is 24 or more.)

jects will pass 93% of the time. For a PF of 200, Table XXXVII shows two boxes deleted, Box 2 and 9. Here, 20 out of 21 subjects are predicted to pass 93% of the time.

vi. *Respirator 4.* This full-face mask is made of silicone rubber with five head straps. It is considerably wider than No.3, which may account for its increased failures. Table XXXVIII shows failures scattered about the panel without any obvious pattern at a PF of 50. Truncation was not attempted.

TABLE XXXVII Truncated Test Panel, No. 3

		FACE WIDTH (mm)				
		117.5	126.5	135.5	144.5	153.5
FACE LENGTH (mm)	133.5			1	2	2
	123.5		3	2	4	5
	113.5		2	5	2	
	103.5	6	7	8	2	
	93.5	2	4	2		

TABLE XXXVIII

Mask Performance Summary, No. 4

		FACE WIDTH (mm)				
		117.5	126.5	135.5	144.5	153.5
FACE LENGTH (mm)	133.5			1	2	6
	123.5		3	9	10	4
	113.5		2	7	0	8
	103.5	6	7	8	2	
	93.5	2	4	2		

Mask #4 Number of Test Subjects 72
Protection Factor 50 Penetration 2%

Subjects Failing
Number 50
Percent 69%

Subjects Failing
Number 12
Percent 17%

Probability of a Panel of 25 Subjects Passing
23 or more pass 20%, 24 or more pass 6%; 25 pass 0.6%
(The recommended pass criteria is 24 or more.)

6. Reproducibility of Respirator Tests. We believe that respirator leak tests give an accurate representation of the mask efficiency on a given test subject. Variations from test to test on the same subject and the same respirator are most likely to be caused by differences in the mask seal. In order to further examine this question we selected one subject in each test panel box and ran three additional tests on the same four masks run previously. For each mask we then have a total of four tests in which the facial dimensions were held constant. The

results achieved are presented in Tables XXXIX through XLII. Mask No. 1, at a PF of 10, showed complete agreement in 7 out of 10 boxes. Two had two failures and two passes. These three boxes with inconsistent results occurred in the smallest and narrowest faces, and indicate that a wide and long mask has trouble achieving a good fit on the smaller faces.

Mask No.2, a smaller and narrower mask, has all tests "pass" at a PF of 10.

Mask No. 3 has consistent results with all subjects passing at a PF of 100 (1% leak).

Mask No. 4 has consistent results in seven out of ten boxes for a PF of 50. The remaining three boxes, again in shorter and narrower faces, have three failures and one pass in one box, and two passes and two failures in two of the boxes. This mask is wide and does not give consistent results on very narrow faces.

TABLE XXXIX Mask 1, Multiple Tests

		LIP LENGTH (mm)				
		34.5	43.5	52.5	61.5	
FACE LENGTH (mm)	133.5		A	B		
	123.5		4P	4P		
	113.5	C	D	E		
	103.5	F	G	H		
	93.5	I	J			

Protection Factor 10, 10 Test Subjects
Number Pass or Fail Average Penetration
Four Tests Each

		LIP LENGTH (mm)				
		34.5	43.5	52.5	61.5	
FACE LENGTH (mm)	133.5		A	B		
	123.5		.02 .34 1.3 .33			
	113.5	C	D	E		
	103.5	F	G	H		
	93.5	I	J			

TABLE XL Mask 2, Multiple Tests

		LIP LENGTH (mm)				
		34.5	43.5	52.5	61.5	
FACE LENGTH (mm)	133.5		A	B		
	123.5		4P	4P		
	113.5	C	D	E		
	103.5	F	G	H		
	93.5	I	J			

Protection Factor 10, 10 Test Subjects
Number Pass or Fail Average Penetration
Four Tests Each

		LIP LENGTH (mm)				
		34.5	43.5	52.5	61.5	
FACE LENGTH (mm)	133.5		A	B		
	123.5		.24 .03 .81 4.0			
	113.5	C	D	E		
	103.5	F	G	H		
	93.5	I	J			

TABLE XLI Mask 3, Multiple Tests

		Protection Factor 100, 10 Test Subjects Number Pass or Fail Average Penetration Four Tests Each									
		FACE WIDTH (mm)									
FACE LENGTH (mm)		117.5	126.5	135.5	144.5	153.5	126.5	135.5	144.5	153.5	
	133.5			1	2				1	2	
	122.5			4P	4P				.74	.02	.02
	111.5		3	4P	4P	5	3	4	.02	.02	.18
	103.5						.02	.03	.02	.10	.03
FACE LENGTH (mm)	93.5						.17	.32	.54	.31	.02
		6	7	8			6	7	8		
		4P	4P	4P			.02	.02	.10	.02	.40
							.02	.08	.03	.03	.75
		9	10				9	10			
FACE LENGTH (mm)	83.5						.09	.05	.05	.78	
							.04	.81	.13	.85	

TABLE XLII Mask 4, Multiple Tests

		Protection Factor 50, 10 Test Subjects Number Pass or Fail Average Penetration Four Tests Each									
		FACE WIDTH (mm)									
FACE LENGTH (mm)		117.5	126.5	135.5	144.5	153.5	126.5	135.5	144.5	153.5	
	133.5			1	2				1	2	
	123.5			4P	4P				.04	.09	.03
	113.5		3	4P	4P	5	3	4	.64	.03	.02
	103.5						.05	.38	.04	.08	.02
FACE LENGTH (mm)	93.5						.23	.09	.19	.06	1.3
		6	7	8			6	7	8		
		3P	4P	4P			3.0	3.3	.11	.39	.09
							.43	2.7	.05	.18	.02
		9	10				9	10			
FACE LENGTH (mm)	83.5						1.0	3.0	4.3	.57	
							6.7	.83	6.9	.49	

It should be noted that the two masks with inconsistent results involve panels that we truncated elsewhere, and the boxes deleted will include those in which the results were inconsistent. We believe that the data presented here tend to support the conclusion that a mask will give consistent fit-test results when tested on the faces that it is clearly designed to fit. Inconsistency itself is an indication of poor fit and should be cause for nonapproval of a respirator.

7. Conclusions. *a.* Anthropometric Test Panels for determining the efficiency of respirators can be established by screening a reasonable number of people. For our panel, screening less than 150 people provided sufficient subjects of the required sizes to supply more than two panels for both full facepiece and half-masks.

b. Our test results show differences in respirator performance on masks now "NIOSH approved" for identical purposes. Such differences can be accounted for by the fact that our quantitative tests are more sensitive than the qualitative tests now in use. In addition our panels include women, for whom present masks are not designed.

c. The masks tested during this year offer reasonable protection for men. The worst performing approved mask, No.1, protects ten times as many men as women, while the best half-mask, No. 8, protects all of the men represented on the panel, and 83% of the women.

d. The present designs of masks are made using the designers' best available information including military anthropometry and intuition. Existing certification procedures utilize the faces of the testing personnel themselves, with less than a wide variety of facial sizes and shapes. We believe that masks approved using the anthropometric panel system should provide better protection than devices approved under current regulations.

e. The better performing half-masks appear to be smaller and, especially, narrower than the poorer performers. It appears to be a fact of mask design that narrow half-masks can deform to accommodate wide faces, but the converse is not true, i.e., wide masks cannot be adjusted to seal on narrow faces. This confirms findings of the USAF reported in Anthropometric Sizing and Fit-Test of the MC-1 Oral-Nasal Oxygen Mask, Emanuel, Alexander and Churchill, WADC Report 58-505, p.12.

f. Four-point strap suspension again appears superior to two-point, which confirms the recommendations that LASL made to the AEC against two-point suspension.

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APPENDIX A

DESCRIPTION OF THE SIX SINGLE-USE RESPIRATORS TESTED

Mask No. 1 is constructed from thin mechanical type filter material, shaped in a hemisphere. It has no inhalation or exhalation valves. A thin aluminum strip across the nose area of the mask allows for shaping of the mask to conform to the contour of the nose. The facial seal is provided by the edge of the filter material only, except for along the nose, where a strip of closed-cell foam is fastened to the inside edge of the mask directly under the aluminum strip. A four-point suspension system is provided by two thin strips of synthetic elastic material 7.9-mm wide. The straps are of unequal lengths, and the lengths are nonadjustable.

Mask No. 2 is constructed from thin mechanical filter material, and can be folded almost flat along the nose-chin axis. It has no inhalation or exhalation valves. A thin aluminum strip across the nose area of the mask allows shaping to conform to the contour of the nose. The facial seal is provided by the edge of the filter material only. A four-point suspension system is provided by two thin bands of rubber 9.5

mm wide. The bands are of unequal lengths, and the lengths are nonadjustable.

Mask No. 3 is constructed of electrostatic felt filter material. A rectangular section of felt is attached to a soft plastic facepiece, which is molded to conform to the facial contours of the nose, cheeks, and chin. This mask has no inhalation or exhalation valves. A four-point suspension system is provided by two thin bands of rubber 6.4-mm wide. The lengths of the bands are adjustable.

Mask No. 4 is constructed of electrostatic felt filter material. A rectangular section of the filter material is attached to the outside of the soft plastic facepiece, which is molded in a "1/4-mask" configuration (i.e., it seals across the nose and on the chin directly under the lower lip). This mask has both an inhalation valve and an exhalation valve. A four-point suspension system is provided by four bands of elastic braid 12.7-mm wide with buckle fasteners. The lengths of the bands are adjustable.

Mask No. 5 is constructed of thin pleated mechanical filter material. The sealing edge is circular when the pleats are expanded and the mask can be folded flat. The facial seal is provided by a cloth edging sewn onto the edge of the filter material. A thin, soft wire sewn into the upper half of the sealing edge allows for shaping to conform to the contour of the nose. This mask has no inhalation valve and no exhalation valve. A four-point suspension system is provided by two bands of elastic braid 6.4-mm wide. The bands are of unequal length, and are nonadjustable.

Mask No. 6 is constructed of thick (~6.4 mm) mechanical filter material consisting of air-laid non-

woven coarse organic and ultrafine glass fibers. The mask has a hemispherical shape. A circular-shaped flat cushion of open-cell form is attached to the inside edge of the hemisphere to provide the facial seal, and this is supported on the outside edge by a circular strip of thin aluminum. This allows for shaping of the mask to conform to the contours of the nose and cheeks. The mask has an exhalation valve, but no inhalation valve. A four-point suspension system is provided by two bands of elastic braid 15.9 mm wide. The lengths of bands are adjustable.

APPENDIX B

NUMBERS OF MALE AND FEMALE SUBJECTS USED

APPENDIX C

PROBABILITY STATISTICS

1. Predicted probability of passing within a test panel box. After a series of respirator leak tests has been run, all of the test subjects are categorized as pass or fail according to their test penetration. For half-masks, test averages that exceed 10% mask leakage are considered to have failed. For full face-pieces, averages greater than 2% fail. Masks that have very few failures at these limits are examined at higher protection factors (lower leakages), also.

For a given test panel box, three numbers have been collected:

N = the number of subjects tested

F = the number of subjects who failed (at a certain protection factor)

M = the number of test subjects required (in a box or in the 25-person test panel).

The probability of any one subject failing is $\hat{p} = F/N$.

What is the probability of k failures occurring in the given test panel box number? This may also be written as the number of times that k objects may be selected from M objects, or the number of combinations of M objects taken k at a time. The formula for the combinations (C) is

$$C = M! / [k!(M-k)!].$$

The estimated probability of k failures ($P_{k,f}$) occurring in a box requiring M subjects where the probability of any one subject's failing is

$$P_{k,f} = C \cdot \hat{p}^k (1 - \hat{p})^{M-k}$$

To use an actual example from Mask 2, in box J the number tested was $N = 5$, the number who failed was $F = 2$, and the number required to be tested was $M = 2$. If we wish the probability of no failures then $k = 0$.

$$\begin{aligned} P_{k,f} &= (2!/0! \times 2!) (2/5)^0 (3/5)^2 \\ &= 1 \times 1 \times 0.36 = 36\% \end{aligned}$$

Similarly, the estimated probability of one failure is 48%. The same calculation done for two failures, $k = 2$, yields 16%.

2. Predicted Probability of the Entire Panel Passing with One Failure. In Sec. 5.b we stated that a mask is considered to have passed if only one of the 25 subjects fails. The predicted probability of this event occurring is the product of the probabilities of one failure in box A and no failures in boxes B through J, plus the product of the probabilities of no failures in box A, one failure in box B, and no failures in boxes C through J, and so on, until all boxes have been examined for one failure. In fact, when we report the estimated probability of the mask passing we state it as "one or fewer failures." This value is the sum of the probabilities of one failure and the probabilities of no failures. We believe that this single number, "the predicted probability of 95% of the panel passing," is a convenient way of summarizing the performance of all of the test subjects.