

## Powered-Air Purifying Respirator Study

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### Abstract

Three brands of powered air-purifying respirators were subjected to a simulated-work-place study. They were worn by six human subjects while working at 80% of their cardiac reserve on a treadmill. The air flow into the respirator was controlled to match that of a respirator with a newly charged battery and with various stages of battery discharge and filter plugging. The simulation took place in a large quantitative fit test chamber containing PEG 400 aerosol. The penetration of aerosol into the breathing zone of the respirator, the pressure in it, and the air flow were monitored while the subject was warming up as well as during the 80% tests. The exercises recommended in ANSI Z88.2 for helmets were also used after the 80% tests were completed. The subjects were tested clean shaven, with three days' growth of stubble, and with a two-month beard growth. A striking result was that the aerosol penetration into the two-helmet respirators increased dramatically as the subjects work rate increased. On the other hand, penetration into the half mask did not change with work rate. The penetration increased as the air flow was decreased in all cases for the helmets and for beard and stubble cases for the half mask. However, for the tight-fitting half mask on a clean-shaven face, the average penetration stayed below 0.001 for all flows.

### Introduction

Powered Air-Purifying Respirators (PAPRs) are used at LLNL and other DOE facilities as well as throughout industry. They are a relatively new form of respiratory protection, and their capabilities are not well understood. The protection that they provide has been questioned by field studies at National Institute for Occupational Safety and Health (NIOSH) and the Du Pont Company. It has also been suggested that workers with beards may get the same protection from these devices as do clean-shaven workers since the devices employ positive pressure and some have loose fitting facepieces.

The name, Powered Air-Purifying Respirator accurately describes the device. It consists of a power source for moving the air that is to be breathed and is carried by the wearer. It is usually a battery powered blower. The air is purified by

being blown through a filter and then into a respirator face covering. The face covering can be tight fitting like a full facepiece and a half mask, or it can be loose fitting like a helmet and hood. The NIOSH certification requires an air flow rate of at least 115 lpm for the tight-fitting facepieces and at least 170 lpm for the loose-fitting face coverings. The respiratory protection that the device can provide is accomplished mainly by the tightness of the seal to the wearer and by the air flow rate. The devices do not maintain a positive pressure inside the face coverings at all times.

The purpose of this study is to determine the effect of facial hair growth on the seal of the inlet covering, and the effect of air flow on the performance of PAPRs equipped with high-efficiency particulate filters.

## Equipment Used

### Half-Mask PAPR

**Mine Safety Appliances Company** catalog number 463354, PAPR with Medium Comfo Facepiece; complete with two HEPA filters, belt, and battery charger. A small and a large Comfo Facepiece were also available as needed.

### Helmet-Type PAPR

**3M Company** catalog number W-344 Airhat Brand High Efficiency System complete with Airhat Brand High Efficiency Helmet, high-efficiency filter, flow test plate, battery pack, waist belt, and battery charger. The standard rubber face seal part W-2934 and chin strap W-2913 were used.

**Racal Airstream, Inc.** Breathe-Easy 1 with type P3 high-efficiency filters, helmet assembly,

breathing tube, Turbo unit, battery pack, and battery charger. A chin strap and a new Tyvec face seal were used.

### Measuring Instruments

**Phoenix Precision Instruments** forward light scattering photometer, Model JM 7000.

**Validyne Engineering Corp.** differential pressure transducer, Model P24.

**Kurz Instruments Inc.** flow meter; probe for Model 505 in specially designed tube.

As a data collection system, **Digital Equipment Corp.** LSI-11/23 computer with the RSX-11M operating system.

**Quinton Instrument Co.** treadmill, Model Q55 with controller.

## Methodology

### Work Rate Control

The subject's work rate was controlled by use of the treadmill. Data were taken continuously as the subject warmed up by walking on the treadmill at 3.3 mph as it was stepped to increasingly steeper grades. It took about 10 min for the subject to reach 80% of his maximum work rate, i.e., for his heart rate to reach 80% of his cardiac reserve.

### Air Flow Rate Control

The air flow rate to the PAPR was controlled by replacing the battery pack with a dc power supply. During the warmup period, the flow was controlled at the level that could be produced by a slightly used battery. Once at the 80% work rate, the flow was varied from that of a freshly charged battery to below the minimum flow required by NIOSH. Table 1 shows the flows used and their order as well as the associated voltage for each of the units.

### ANSI Exercises

The exercises suggested in ANSI Z88.2-1980 section A6.1 for testing a respirator equipped with

a helmet, hood, or suit were used after the subject cooled down for from 4 to 6 min from the end of the 80% work rate tests described above. The order of the exercises was:

1. Bending knees and squatting.
2. Running in place.

**Table 1. Air flow rates used for each PAPR.**

| PAPR  | Flow (lpm)       | Flow (cfm)     | Voltage (V)      |
|-------|------------------|----------------|------------------|
| MSA   | 170              | 6              | 5.2              |
|       | 198              | 7              | 6.2              |
|       | 142              | 5              | 4.2              |
|       | 114              | 4              | 3.5              |
|       | 86               | 3              | 2.7              |
|       | 170              | 6              | 5.2              |
| 3M    | 255              | 9              | 4.3              |
|       | 283              | 10             | 4.7              |
|       | 198              | 7              | 3.6              |
|       | 170              | 6              | 3.2              |
|       | 114              | 4              | 2.5              |
|       | 255              | 9              | 4.3              |
| RACAL | 202              | 7.1            | 4.5              |
|       | 226              | 8              | 5.0              |
|       | 170              | 6              | 3.8              |
|       | 142              | 5              | 3.2              |
|       | 114 <sup>a</sup> | 4 <sup>a</sup> | 4.7 <sup>a</sup> |
|       | 202              | 7.1            | 4.5              |

<sup>a</sup> Two filters are also closed off to get this flow since the unit does not run well at lower voltages.

3. Bending forward and touching toes.
4. Raising arms above head and looking upward.
5. While holding a rod about 76 cm long, twist torso from side to side and slowly raise the arms till pointing upward 45°.
6. Normal breathing while standing.

This order is different from that in the standard since we wanted to do the most active exercises first while the subject's breathing and heart rates were still elevated.

### Facial Hair Conditions

Three conditions of facial hair were tested: clean shaven, 3 days growth of stubble, and a full beard of 2 to 3 months growth. All of the above described flows and exercises were used at each facial hair condition.

### Measurements

Measurements of aerosol penetration and pressure inside the face coverings were taken on each test. Inlet air flow rate was measured for the MSA half mask and the Racal helmet. Flows could not be measured on the 3M Airhat during exercise

without major modifications. The opening to the sampling tube inside the helmet faceshield was located about 1/2 in. from the subject's upper lip. On the half mask it was located flush with the rubber and just above the metal frame. This puts it near the upper lip of most subjects.

The length of each of the three exercise regimens was different. During the warmup period, the grade was increased every 2 min until the subject's heart rate was approaching 80%. Although the instruments sample continuously, their outputs were only sampled by the computer every 250 ms. The data taken at each grade were stored separately. After the subject was at 80%, the flow rate was changed every 2.5 min. The sampling for each 2.5-min period was divided into 30 s of waiting for the changed flow to have its effect, 1.5 min of sampling output every 250 ms, and 30 s of sampling every 16 ms, which is the fastest possible sampling cycle time for our computer and operating system. The 250-ms cycle time is good for obtaining the average value over the experimental period, and the 16-ms cycle is needed to get good definition of pressure and flow changes. Each ANSI exercise was performed for 2 min with a break of approximately 30 s between exercises. The data sampling rate was 250 ms. The faster rate was not needed since no pressure or flow data were taken during the ANSI exercises.

## Results

To analyze the test results we took various averages of the data. First the penetration was calculated for each data point and the average penetration calculated for each exercise interval. The flow was also averaged for the same intervals. These interval averages for each subject were then averaged over all of the subjects that had data in that interval. Since penetration follows a lognormal distribution, the geometric means and geometric standard deviations were calculated. A normal distribution was assumed for the flow data, which did not vary greatly. These results for the average subject are presented in Tables 2, 3 and 4. All further calculations and plots (except for the raw data plots) are derived from these tables.

### Effect of Varying the Work Rate

At greater work rates, the subject breathes deeper and faster, creating the possibility that he

may overbreathe the PAPR. To show this effect, we plotted the penetration, expressed as a fraction, against the grade of the treadmill. This is shown in Figs. 1, 2, and 3 for the three PAPRs. Subparts (a), (b), and (c) of each figure show the three different facial hair conditions. The geometric standard deviation,  $SD_g$ , is shown for each value by a vertical line terminated by hour glass characters. The  $SD_g$  varies considerably since the number of subjects included in the average varies from one to six depending on how many actually used that particular grade. Some subjects skipped grades, and not many went to 20%. A guide to the typical physiological response of a subject walking at 3.3 mph and the various grades is given in Table 5. Walking at the 10% grade would be considered "somewhat hard" by most people.

Table 2. MSA half-mask PAPR data summary for average subject.

|                                     | Clean shaven |      |            |      | Tree days of stubble |      |            |     | Full beard  |      |            |      |
|-------------------------------------|--------------|------|------------|------|----------------------|------|------------|-----|-------------|------|------------|------|
|                                     | Penetration  |      | Flow (lpm) |      | Penetration          |      | Flow (lpm) |     | Penetration |      | Flow (lpm) |      |
|                                     | Mean         | SD   | Mean       | SD   | Mean                 | SD   | Mean       | SD  | Mean        | SD   | Mean       | SD   |
| Warm up with increasing sh          |              |      |            |      |                      |      |            |     |             |      |            |      |
| Grace %                             | Mean         | SD   | Mean       | SD   | Mean                 | SD   | Mean       | SD  | Mean        | SD   | Mean       | SD   |
| 25                                  | 0.31E-3      | 4.34 | 167        | 16   | 0.11E-2              | 2.27 | 163        | 4.1 | 0.59E-4     | 4.52 | 153        | 4.4  |
| 5                                   | 0.12E-3      | 3.66 | 170        | 16.0 | 0.58E-3              | 1.50 | 165        | 1.4 | 0.83E-4     | 5.64 | 153        | 4.4  |
| 75                                  | 0.29E-3      | 4.61 | 168        | 12.4 | 0.79E-3              | 1.21 | 163        | 3.5 | 0.57E-4     | 6.03 | 153        | 4.3  |
| 10                                  | 0.27E-3      | 5.52 | 162        | 5.0  | 0.57E-3              | 1.16 | 163        | 3.5 | 0.20E-3     | 7.13 | 153        | 4.3  |
| 125                                 | 0.15E-3      | 3.25 | 170        | 12.5 | 0.57E-3              | 1.20 | 164        | 2.4 | 0.23E-3     | 1.5  | 153        | 4.9  |
| 15                                  | 0.10E-2      | 1.15 | 162        | 1.0  | 0.86E-3              | 1.82 | 162        | 1.5 | 0.40E-4     | 0    | 153        | 0    |
| 175                                 | 0.32E-3      | 7.18 | 174        | 17.0 | 0.16E-2              | 1.18 | 162        | 1.4 | 0.16E-4     | 0    | 153        | 0    |
| 20                                  | 0.35E-4      | 0    | 185        | 0    | 0.15E-2              | 0    | 161        | 0   | —           | —    | —          | —    |
| At 80% work rate with various flows |              |      |            |      |                      |      |            |     |             |      |            |      |
| Flow (cfm)                          | Mean         | SD   | Mean       | SD   | Mean                 | SD   | Mean       | SD  | Mean        | SD   | Mean       | SD   |
| 6                                   | 0.08E-3      | 4.63 | 166        | 2.9  | 0.10E-2              | 2.18 | 162        | 1.1 | 0.18E-3     | 4.82 | 156        | 1.6  |
| 7                                   | 0.06E-3      | 4.04 | 192        | 12.4 | 0.10E-2              | 1.88 | 190        | 1.1 | 0.18E-3     | 1.81 | 184        | 1.81 |
| 5                                   | 0.04E-3      | 4.18 | 132        | 4.1  | 0.10E-2              | 1.82 | 130        | 4.1 | 0.18E-3     | 2.10 | 126        | 1.81 |
| 14                                  | 0.07E-3      | 4.53 | 102        | 6.7  | 0.10E-2              | 5.55 | 107        | 1.1 | 0.18E-3     | 1.81 | 102        | 1.81 |
| 3                                   | 0.06E-3      | 0.87 | 82         | 2.6  | 0.10E-2              | 1.58 | 72         | 1.1 | 0.18E-3     | 2.10 | 78         | 1.81 |
| 6                                   | 0.10E-3      | 5.17 | 168        | 12.7 | 0.10E-2              | 2.11 | 160        | 1.1 | 0.18E-3     | 2.10 | 158        | 1.81 |
| ANS. exercises                      |              |      |            |      |                      |      |            |     |             |      |            |      |
| Exercise No                         | Mean         | SD   | Mean       | SD   | Mean                 | SD   | Mean       | SD  | Mean        | SD   | Mean       | SD   |
| 1                                   | 0.10E-3      | 3.84 | 165        | 4.1  | 0.10E-2              | 1.62 | 166        | 2.6 | 0.18E-3     | 1.81 | 158        | 1.81 |
| 2                                   | 0.04E-3      | 5.56 | 164        | 3.6  | 0.10E-2              | 1.62 | 165        | 2.4 | 0.18E-3     | 1.81 | 157        | 1.81 |
| 3                                   | 0.08E-3      | 4.88 | 166        | 3.8  | 0.10E-2              | 1.52 | 168        | 2.4 | 0.18E-3     | 1.81 | 159        | 1.81 |
| 4                                   | 0.04E-3      | 3.76 | 164        | 5.5  | 0.10E-2              | 1.54 | 166        | 2.7 | 0.18E-3     | 1.81 | 158        | 1.81 |
| 5                                   | 0.08E-3      | 3.83 | 163        | 6.0  | 0.10E-2              | 1.88 | 165        | 2.0 | 0.18E-3     | 1.81 | 157        | 1.81 |
| 6                                   | 0.08E-3      | 3.14 | 164        | 5.6  | 0.10E-2              | 2.02 | 166        | 2.2 | 0.18E-3     | 1.81 | 158        | 1.81 |

Table 3. Racial helmet PAPR data summary for average subject.

|                                    | Clean shaven      |                 |                   |   | Three days of stubble |                 |                   |      | Full beard        |                   |                   |   |
|------------------------------------|-------------------|-----------------|-------------------|---|-----------------------|-----------------|-------------------|------|-------------------|-------------------|-------------------|---|
|                                    | Penetration       |                 | Flow (lpm)        |   | Penetration           |                 | Flow (lpm)        |      | Penetration       |                   | Flow (lpm)        |   |
|                                    | Mean <sub>g</sub> | SD <sub>g</sub> | Mean <sub>o</sub> | N | Mean <sub>g</sub>     | SD <sub>g</sub> | Mean <sub>o</sub> | N    | Mean <sub>g</sub> | SD <sub>g</sub>   | Mean <sub>o</sub> | N |
| Warmup * 70% cret → g slope        |                   |                 |                   |   |                       |                 |                   |      |                   |                   |                   |   |
| Grade %                            |                   |                 |                   |   |                       |                 |                   |      |                   |                   |                   |   |
| 2.5                                | 0.611E-6          | 12.4            | 206               | 5 | 0.349E-4              | 1.76            | 200               | 13.1 | 0.322E-4          | 8.25              | 199               | 6 |
| 5.0                                | 0.857E-6          | 6.62            | 206               | 3 | —                     | —               | —                 | —    | 0.154E-4          | 10.0              | 198               | 6 |
| 7.5                                | 0.199E-5          | 8.78            | 202               | 4 | 0.599E-5              | 4.73            | 199               | 12.9 | 0.259E-5          | 85.8              | 200               | 5 |
| 10.0                               | 0.592E-5          | 320             | 206               | 2 | 0.249E-4              | ±85             | 196               | 18.8 | 0.278E-4          | 17.0              | 207               | 4 |
| 12.5                               | 0.977E-4          | 448             | 208               | 4 | 0.814E-4              | ±81             | 203               | 7.8  | 0.567E-3          | 10.1              | 203               | 6 |
| 15.0                               | 0.113E-2          | 23.9            | 209               | 3 | 0.155E-2              | ±96             | 198               | 16.9 | 0.143E-2          | 50.4              | 204               | 3 |
| 17.5                               | 0.109E-2          | 75.5            | 206               | 4 | 0.554E-2              | 21.0            | 198               | 17.2 | 0.563E-2          | 7.9               | 203               | 3 |
| 20.0                               | 0.778E-2          | 19.3            | 203               | 2 | 0.866E-2              | 4.4             | 208               | 14.9 | 0.171E-1          | 7.5               | 198               | 2 |
| At 80% → k → e with vari0 is f ows |                   |                 |                   |   |                       |                 |                   |      |                   |                   |                   |   |
| Flow (cfm)                         |                   |                 |                   |   |                       |                 |                   |      |                   |                   |                   |   |
| 7                                  | 0.113E-1          | 7.5             | 203               | 5 | 0.191E-1              | 2.64            | 185               | 30.1 | 0.111E-1          | 4.0               | 201               | 6 |
| 8                                  | 0.951E-2          | 8.2             | 226               | 5 | 0.211E-1              | 2.91            | 220               | 21.1 | 0.719E-2          | 4.2 <sup>3</sup>  | 224               | 6 |
| 6                                  | 0.528E-1          | 2.40            | 168               | 5 | 0.611E-1              | 1.85            | 167               | 13.4 | 0.318E-1          | 2.52 <sup>0</sup> | 169               | 6 |
| 15                                 | 0.820E-1          | 2.12            | 143               | 5 | 0.111E-0              | 1.45            | 141               | 12.4 | 0.616E-1          | 1.97              | 144               | 6 |
| 4                                  | 0.136E-0          | 1.52            | 110               | 5 | 0.151E-0              | 1.32            | 107               | 13.0 | 0.120E-0          | 1.60              | 107               | 6 |
| 7                                  | 0.412E-1          | 2.10            | 204               | 5 | 0.421E-1              | 1.96            | 195               | 19.0 | 0.212E-1          | 3.44              | 196               | 6 |
| ANS. ex → ses                      |                   |                 |                   |   |                       |                 |                   |      |                   |                   |                   |   |
| Exercise No                        |                   |                 |                   |   |                       |                 |                   |      |                   |                   |                   |   |
| 1                                  | 0.389E-3          | 7.09            | 203               | 5 | 0.389E-3              | 0.88            | 200               | 2.2  | 0.338E-3          | 17.3              | 200               | 8 |
| 2                                  | 0.129E-2          | 3.11            | 201               | 5 | 0.208E-2              | 0.28            | 190               | 5.8  | 0.437E-2          | ±9.1              | 194               | 8 |
| 3                                  | 0.248E-3          | 1.2             | 203               | 5 | 0.276E-3              | 0.21            | 195               | 14.3 | 0.384E-3          | 12.1              | 199               | 8 |
| 4                                  | 0.498E-4          | 5.0             | 201               | 5 | 0.153E-3              | ±3.2            | 194               | 3.2  | 0.162E-3          | 6.20              | 196               | 8 |
| 5                                  | 0.221E-5          | 2.0             | 203               | 5 | 0.336E-4              | 5.85            | 192               | 2.0  | 0.388E-4          | 4.83              | 196               | 8 |
| 8                                  | 0.223E-5          | ±0.8            | 206               | 5 | 0.307E-4              | 2.5             | 194               | 3.8  | 0.942E-5          | 3.80              | 199               | 8 |

**Table 4. 3M helmet PAPR data summary for average subject.**

|                                     | Clean shaven,<br>penetration |                 |   | Three days of stubble,<br>penetration |                 |   | Full beard,<br>penetration |                 |   |
|-------------------------------------|------------------------------|-----------------|---|---------------------------------------|-----------------|---|----------------------------|-----------------|---|
|                                     | Mean <sub>g</sub>            | SD <sub>g</sub> | N | Mean <sub>g</sub>                     | SD <sub>g</sub> | N | Mean <sub>g</sub>          | SD <sub>g</sub> | N |
| Warmup with increasing slope        |                              |                 |   |                                       |                 |   |                            |                 |   |
| Grade %                             |                              |                 |   |                                       |                 |   |                            |                 |   |
| 2.5                                 | 0.907E-4                     | 4.54            | 6 | 0.170E-3                              | 2.57            | 6 | 0.166E-3                   | 18.4            | 5 |
| 5.0                                 | 0.623E-4                     | 13.9            | 2 | 0.170E-3                              | 3.51            | 5 | 0.105E-3                   | 23.4            | 4 |
| 7.5                                 | 0.246E-3                     | 3.70            | 6 | 0.427E-3                              | 2.61            | 4 | 0.318E-3                   | 3.67            | 5 |
| 10.0                                | 0.659E-3                     | 2.51            | 4 | <b>0.647E-3</b>                       | 1.90            | 5 | 0.313E-3                   | 7.27            | 4 |
| 12.5                                | 0.495E-2                     | 1.49            | 4 | 0.885E-2                              | 3.56            | 5 | 0.135E-2                   | 11.9            | 4 |
| 15.0                                | 0.201E-1                     | 2.27            | 6 | <b>0.140E-1</b>                       | 1.90            | 6 | 0.218E-2                   | 13.2            | 5 |
| 17.5                                | 0.300E-1                     | 1.79            | 4 | 0.256E-1                              | 1.68            | 4 | 0.213E-1                   | 2.0             | 2 |
| 20.0                                | 0.400E-1                     | 2.79            | 2 | 0.359E-1                              | 1.06            | 2 | 0.600E-1                   | 0               | 1 |
| At 80% work rate with various flows |                              |                 |   |                                       |                 |   |                            |                 |   |
| Flow(cfm)                           |                              |                 |   |                                       |                 |   |                            |                 |   |
| 9                                   | 0.502E-1                     | 1.52            | 6 | 0.572E-1                              | 1.66            | 6 | 0.186E-1                   | 5.62            | 5 |
| 10                                  | 0.400E-1                     | 1.58            | 6 | 0.485E-1                              | 1.76            | 6 | 0.270E-1                   | 2.12            | 5 |
| 7                                   | 0.900E-1                     | 1.39            | 5 | 0.985E-1                              | 1.40            | 6 | 0.496E-1                   | 2.09            | 6 |
| 6                                   | 0.120E-0                     | 1.29            | 6 | 0.126E-0                              | 1.39            | 6 | 0.056E-0                   | 2.54            | 6 |
| 4                                   | 0.200E-0                     | 1.25            | 6 | 0.187E-0                              | 1.22            | 6 | 0.107E-0                   | 2.06            | 6 |
| 9                                   | 0.500E-1                     | 1.48            | 6 | 0.810E-1                              | 2.38            | 6 | 0.206E-1                   | 2.87            | 5 |
| ANSI Exercises                      |                              |                 |   |                                       |                 |   |                            |                 |   |
| Exercise No.                        |                              |                 |   |                                       |                 |   |                            |                 |   |
| 1                                   | 0.126E-2                     | 5.24            | 6 | 0.125E-2                              | 4.60            | 6 | 0.157E-2                   | 3.90            | 5 |
| 2                                   | 0.334E-2                     | 4.84            | 6 | 0.234E-2                              | 1.86            | 6 | 0.220E-2                   | 7.24            | 5 |
| 3                                   | 0.260E-2                     | 3.32            | 6 | 0.220E-2                              | 4.6             | 6 | 0.117E-2                   | 7.88            | 5 |
| 4                                   | 0.435E-3                     | 4.56            | 6 | 0.269E-2                              | 30.0            | 6 | 0.229E-3                   | 7.98            | 5 |
| 5                                   | 0.978E-4                     | 4.39            | 6 | 0.106E-3                              | 1.73            | 6 | 0.432E-4                   | 8.61            | 5 |
| 6                                   | 0.382E-4                     | 5.22            | 6 | 0.570E-4                              | 7.40            | 6 | 0.223E-4                   | 9.98            | 5 |

**Table 5. Physiological response at various grades.**

| Grade % | Heart rate per min | Breathing rate per min | Minute volume, l |
|---------|--------------------|------------------------|------------------|
| 2.5     | 116                | 23                     | 30               |
| 5.0     | 124                | 23                     | 36               |
| 10.0    | 155                | 30                     | 53               |
| 15.0    | 165                | 33                     | 72               |
| 20.0    | 177                | 41                     | 103              |

### Effect of Air Flow Rate

To study the importance of the amount of filtered air supplied to the PAPR, we varied the air

flow rate from below the NIOSH standard to as great as the PAPR could produce with a freshly charged battery and new filters. The results are shown in Figs. 4(a), (b), and (c); 5(a), (b), and (c); and 6(a), (b), and (c). After a short time of use, about 15 min, the battery voltage would drop so that about 1 cfm less air was moved, and then air flow would remain constant for many hours. Our flows varied some from test to test due mainly to variations in the voltage supplied to the PAPR. The standard deviation for the flow is shown as a horizontal line terminated by hour glass characters. The SD<sub>g</sub> for the penetration is shown as before. Since the flow into the 3M PAPR was not measured during the exercises, it was assumed to be the same as in the initial bench test.

## Effect of Facial Hair

The effect of facial hair on the penetration when the subject is working at 80% is summarized in Figs. 7, 8, and 9. Here, each facial hair condition is plotted with a different symbol on the graph of penetration vs flow for each make of PAPR. For clarity, no standard deviations are shown on these plots.

## The ANSI Exercises

The penetrations observed during the ANSI exercises are summarized in clustered bar graphs, Figs. 10, 11, and 12. The fractional penetration has been multiplied by 1000 for better plotting. The data for all three facial hair conditions have been grouped for each of the six exercises, with one plot for each PAPR.

## Pressure and Flow in the Facepiece

The pressure in the facepiece changes as the subject breathes in and out. When the subject is

working at 80% of his maximum, his peak inhalation flow rate can be greater than that supplied by the PAPR, causing a negative pressure inside the facepiece. The next series of plots show the pressure in the facepiece and the air flow into it vs time. These are shown for each subject both clean shaven and with a 2-month beard at the NIOSH-required flow rate of 4 cfm (114 lpm) for the half mask (Fig. 13), and both clean-shaven and with a 3-day stubble at 6 cfm (170 lpm) for the Racal helmet (Fig. 14). For one subject wearing the half mask, we also show these plots for each of the flow rates used at 80% work rate (Fig. 15). The mask pressure for this subject was about the average for all the subjects. For the Racal helmet, we show the plots at each flow rate used for two subjects. One set shows a typical light breather (Fig. 16), and the other shows a typical heavy breathing subject (Fig. 17). Only one plot is shown for the 3M helmet since the flow was not measured and the pressure trace looked the same for all of the tests (Fig. 18).

# Discussion

## The Importance of the Work Rate

As the subject's work rate increases and his breathing gets deeper, the penetration into the half mask PAPR remains constant at about 0.0002 (ratio of aerosol particles in the facepiece to those in the test chamber) [protection factor (PF) = 5000] for the average clean-shaven subject, Fig. 1(a). However, the penetration into the Racal helmet increases dramatically from  $10^{-6}$  to 0.01 (PF = 100), Fig. 2(a). Similarly the penetration into the 3M helmet increases from  $10^{-4}$  to 0.1 (PF = 10), Fig. 3(a). The trends with facial stubble or a beard were the same. The flow rates used for these plots were those obtained from a charged battery. The air flow to the helmets was not sufficient for work rates produced by a grade greater than about 10%.

## The Importance of the Air Flow Rate

Changing the flow to the half mask did not have any measurable effect on the penetration for a clean shaven subject, Fig. 4(a). It remained about  $4 \times 10^{-4}$  (PF = 2500) for all flows from 3 to 7 cfm.

For three days of stubble, we notice that the penetration increased at the lower flow rates, Fig. 4(b), and for a full beard, the penetration increased greatly at lower flows, Fig. 4(c). The PF drops to 67 at a flow of 3 cfm.

The penetration into the Racal helmet increases as the flow is decreased for all facial conditions, Figs. 5(a), (b), and (c). It increases from about 0.01 at a flow of 7 cfm to 0.1 at 4 cfm. The same is true for the 3M helmet, where the penetration increases from about 0.04 at 10 cfm to 0.15 at 4 cfm, Figs. 6(a), (b), and (c).

## The Role of Facial Hair

Stubble or a full beard has little effect on the penetration into the half mask as long as the flow rate is high enough, 6 or 7 cfm. However, with a full beard at lower yet approved flows, the penetration is 20 times greater than at 7 cfm. This lowers the PF at 4 cfm from 2667 to 132, Fig. 7. No effect of facial hair was seen on the penetration into the helmet-type PAPRs, Figs. 8 and 9. This is probably because the face to facepiece seal is so

poor that the effect of the addition of a beard cannot be detected.

### ANSI Exercises

The ANSI exercises performed while wearing the half mask all produced about the same results, Fig. 10. The data with the full beard is puzzling. There is a factor of 20 less penetration with a full beard for the average subject. A look at the individual subject's data reveals that two of the five subjects used for the average had very low penetrations when doing the ANSI exercises with full beards. The other three subjects had about the same penetration as when clean shaven. This skewed the average and caused the large  $SD_g$  shown in Table 2.

The helmet data show a general trend downward in penetration as the subjects progress through the exercises. This is partly due to the subject cooling off more and his breathing becoming normal. The Racal helmet data showed an increase in penetration during the running exercise. Again, this is due to increased breathing.

### The Myth of Positive Pressure

While it is advertized that PAPRs are positive-pressure respirators, we found that under our test conditions the helmet PAPRs could not maintain

a positive pressure inside the facepiece all of the time or even most of the time. The MSA half mask comes close to being a positive-pressure device. The set of plots for the MSA half mask, Fig. 15, show for a typical subject, BGH, how the facepiece pressure changes during the breathing cycle at an 80% work rate. Notice that as the flow increases from 3 cfm up to 7 cfm, the percent of time that the pressure is positive increases from less than 50% to almost 100%. At the NIOSH required flow of 4 cfm it is only positive 50% of the time. At 4 cfm, subject BGH has a facepiece pressure of about 0.8 in. water gauge (wg) when exhaling, but it drops to about negative 0.6 in. wg during inhalation. The average pressure during inhalation is a positive 0.2 in. wg when the flow is 6 cfm, which is the flow that the battery maintains for most of its charge. The pressure plots are shown for the rest of the subjects at 4 cfm in Fig. 13. The pressure goes negative during inhalation for all subjects when the flow is 4 cfm. It appears that the NIOSH-required flow rate is too low.

The pressure inside the Racal helmet facepiece did not change much with flow. It cycled between +0.2 and -0.2 in. wg depending on the subject, but depended very little on the flow rate. Figures 14, 16, and 17 show how the pressure and flow varied for the Racal helmet.

The pressure inside the 3M helmet facepiece stayed within  $\pm 0.05$  in. wg of zero and showed no discernible pattern associated with breathing. A typical plot is shown in Fig. 18.

## Summary

The difference in the performance between the tight fitting half mask and the loose fitting helmets is so great that they should be in separate categories when assigning respirator protection factors. The helmets should not be considered as positive-pressure devices. The half mask is a positive-pressure device at flows of 6 cfm, which

is its normal flow rate. At 4 cfm and an 80% work rate, the half mask does not maintain a positive pressure. Facial stubble or a full beard degrade the fit of the half mask. Facial stubble or a full beard do not affect the protection provided by the helmets since it is so poor even when the subject is clean shaven.

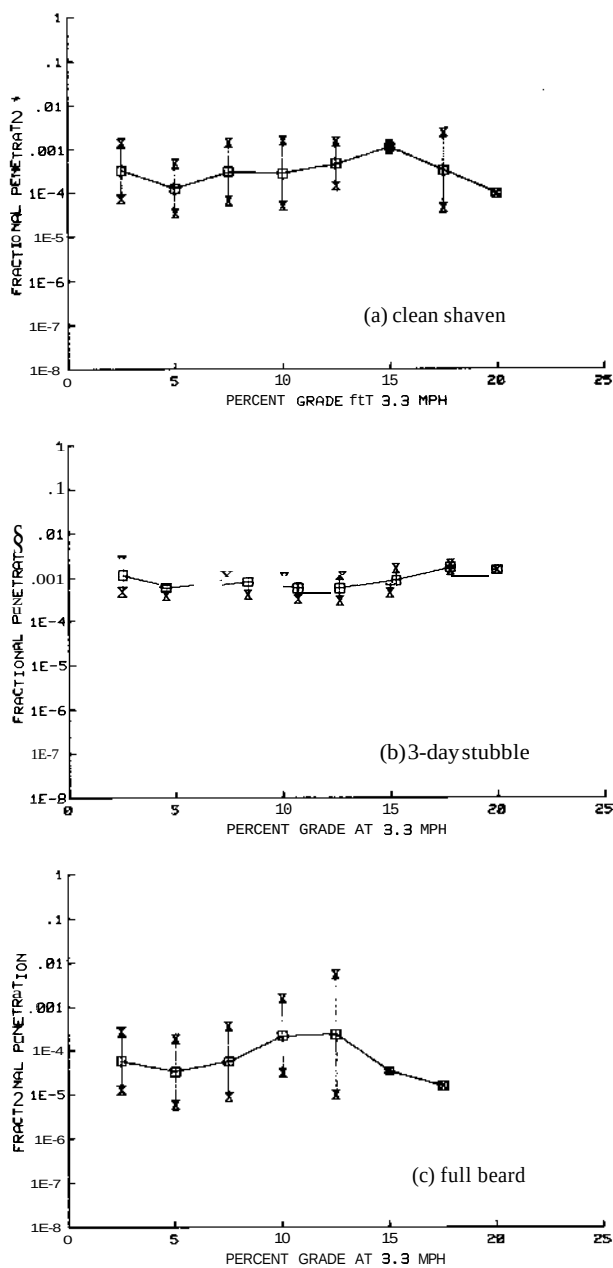


Figure 1. Effect of work rate, average subject, MSA half-mask **PAPR**.

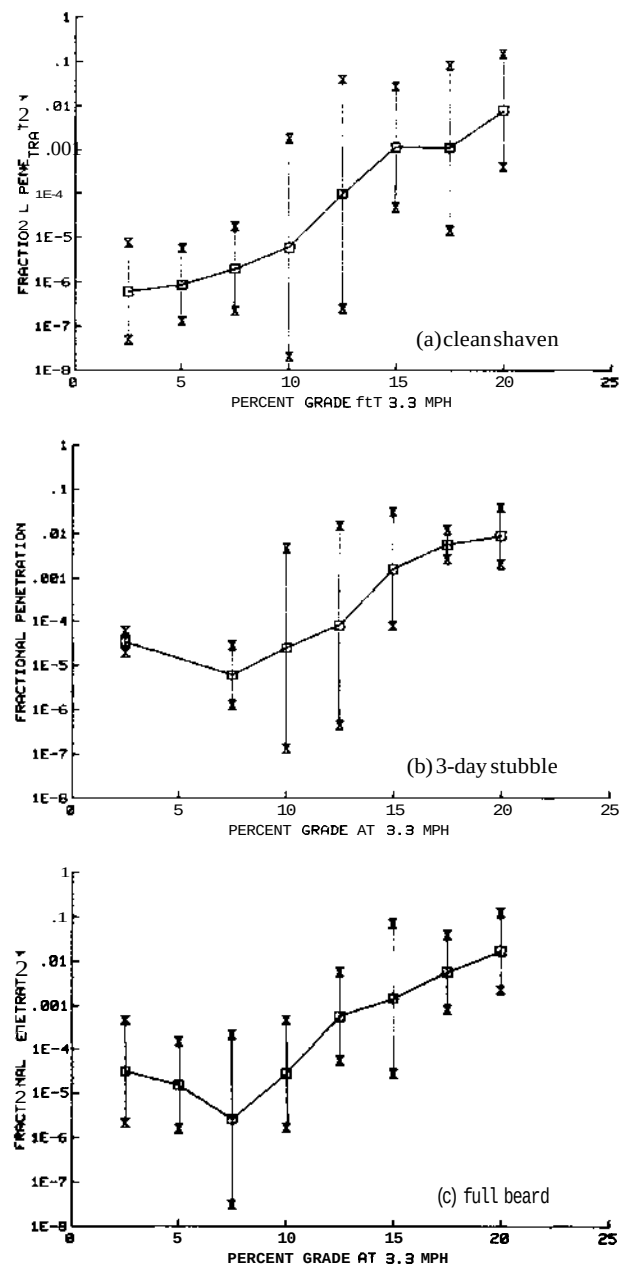


Figure 2. Effect of work rate, average subject, **Racal** helmet **PAPR**.

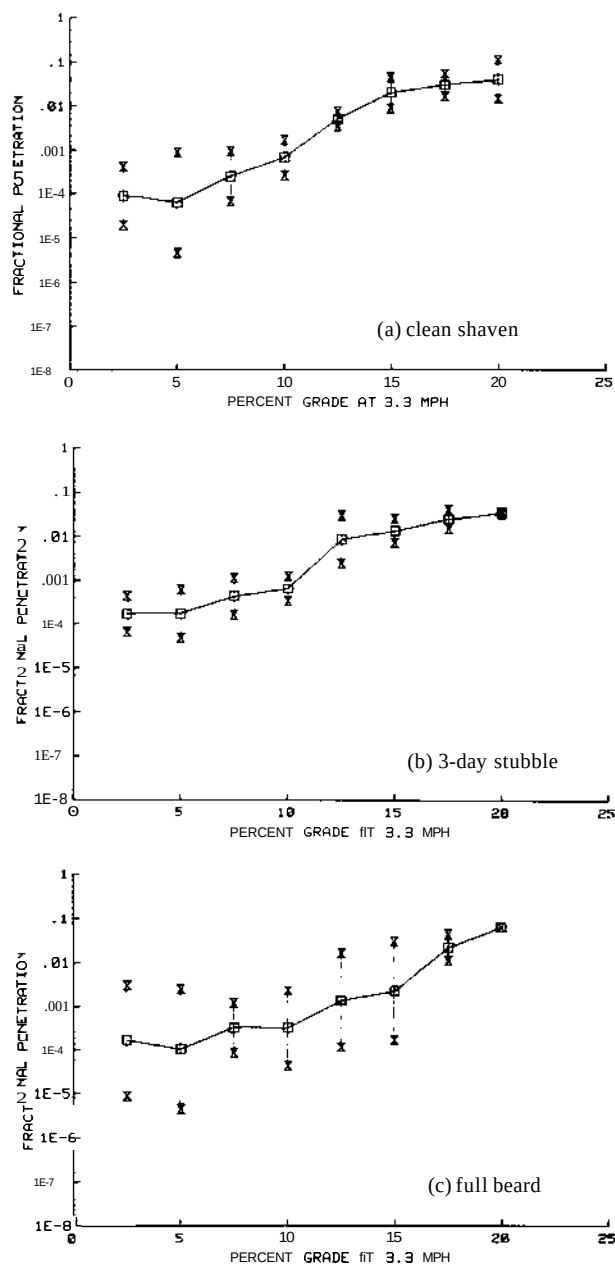


Figure 3. Effect of work rate, average subject, 3M helmet PAPR.

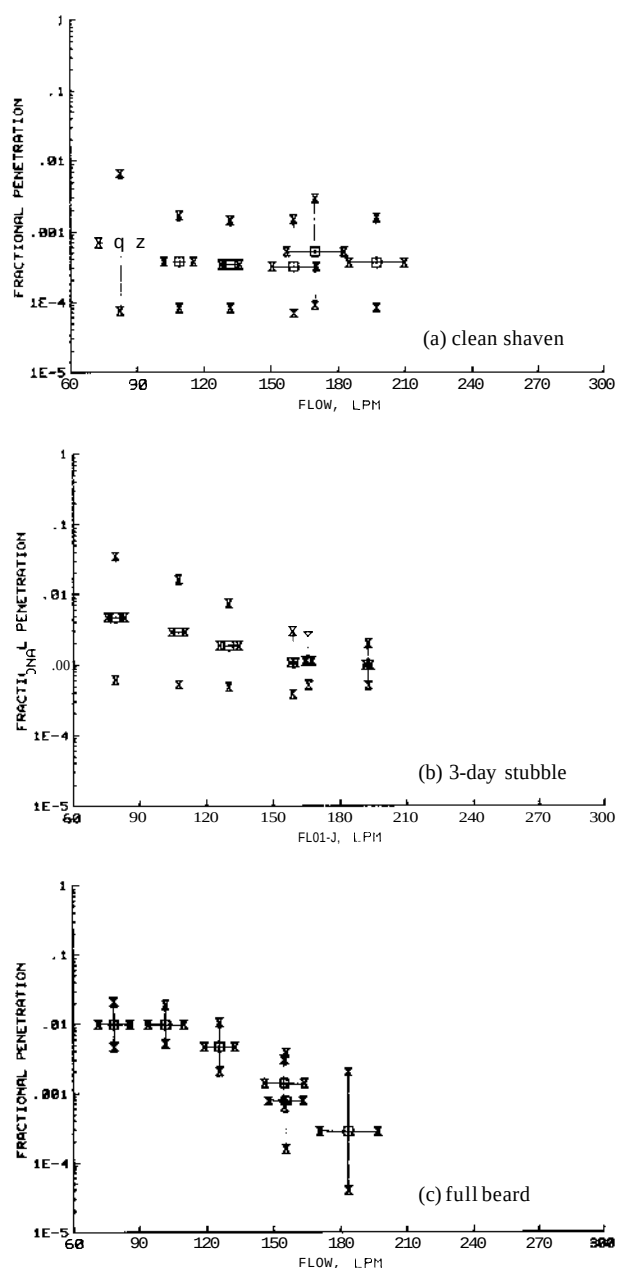


Figure 4. Effect of air flow, average subject, MSA half-mask PAPR.

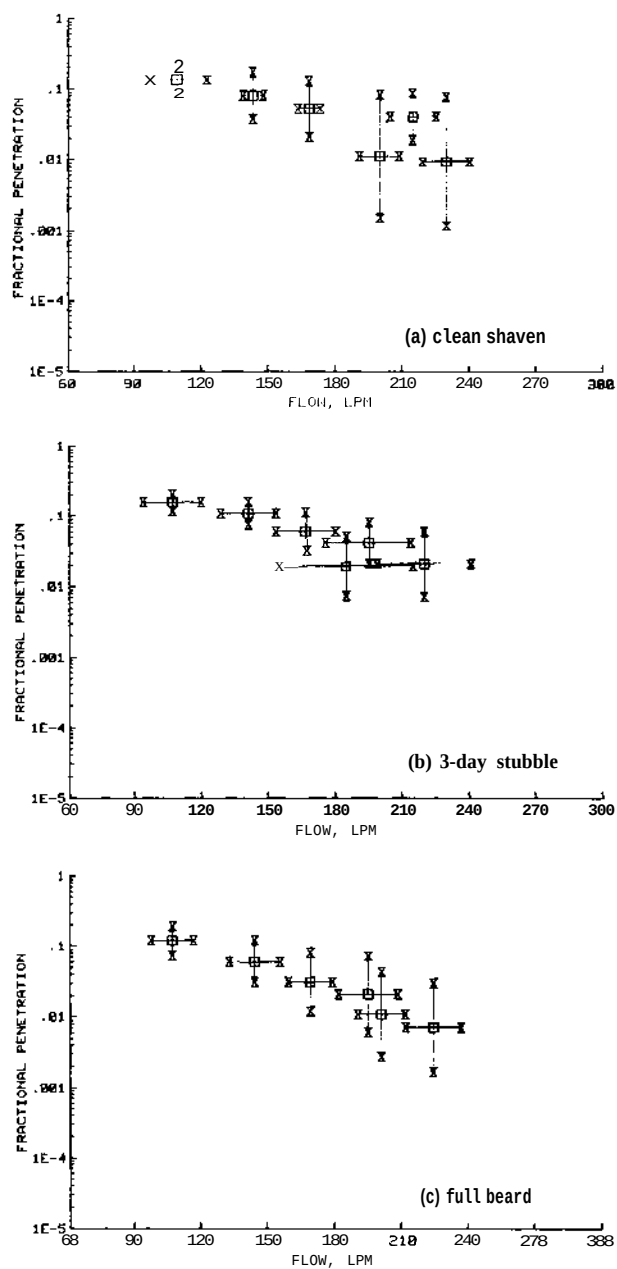


Figure 5. Effect of air flow, average subject, Racal helmet PAPR.

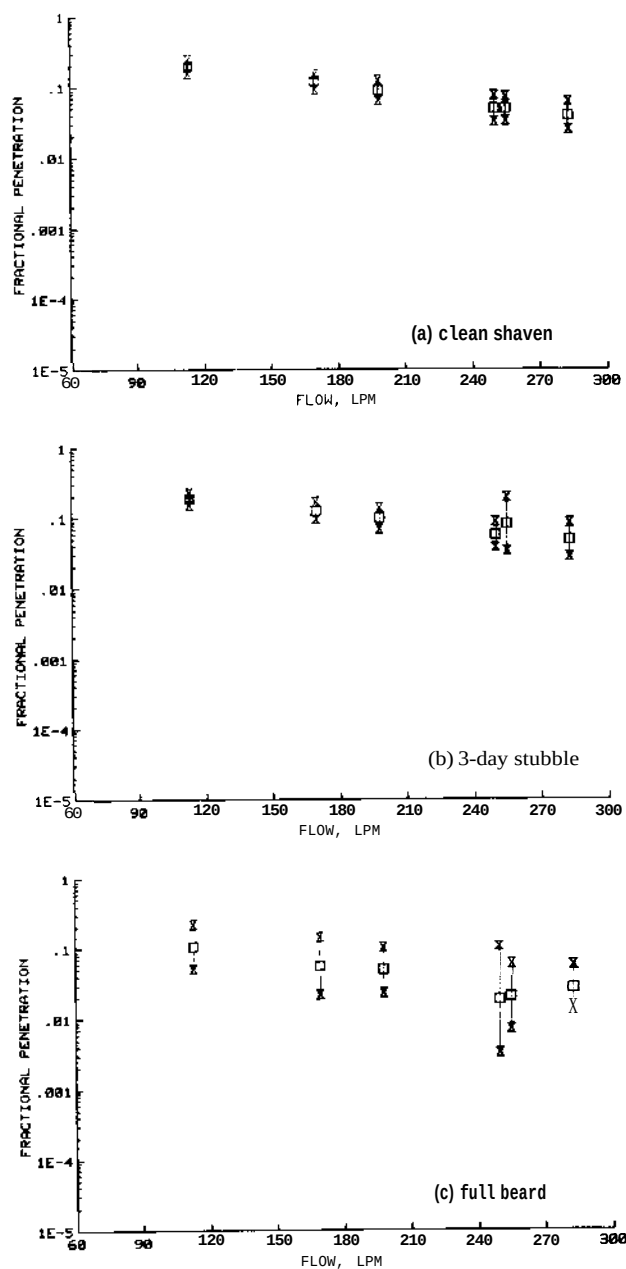


Figure 6. Effect of air flow, average subject, 3M helmet PAPR.

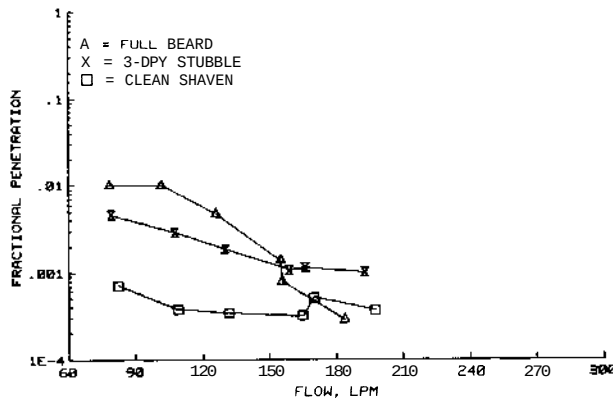


Figure 7. Effect of **facial** hair at 80% work rate, average subject, MSA half-mask PAPR.

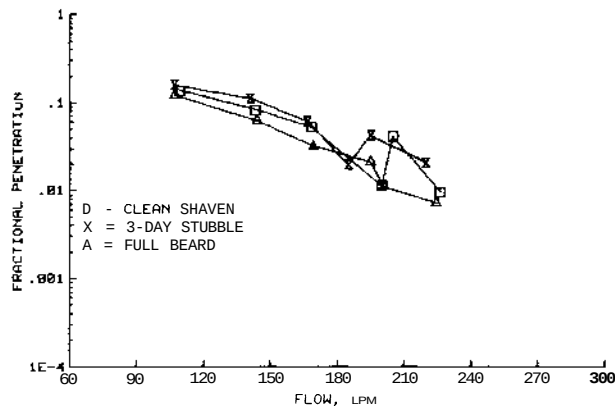


Figure 8. Effect of **facial** hair at 80% work rate, average subject, **Racal** helmet PAPR.

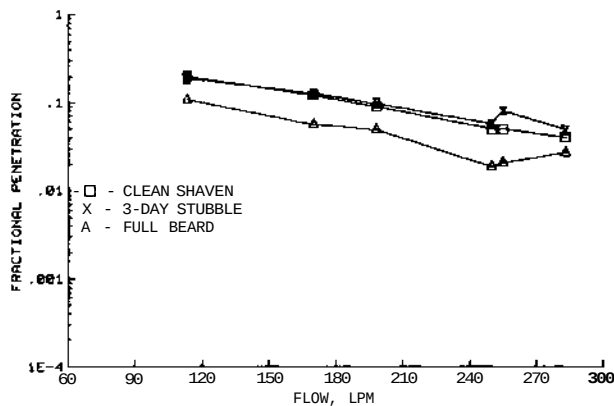


Figure 9. Effect of **facial** hair at 80% work rate, average subject, 3M helmet PAPR.

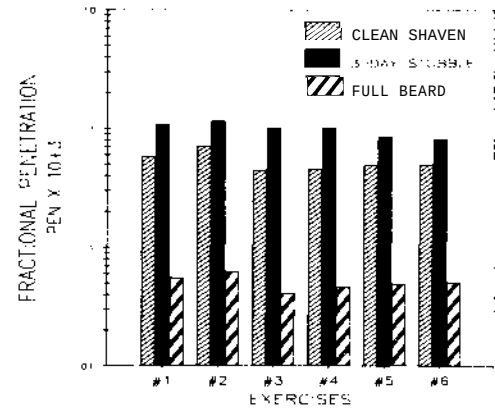


Figure 10. ANSI exercises, average subject, MSA half-mask PAPR.

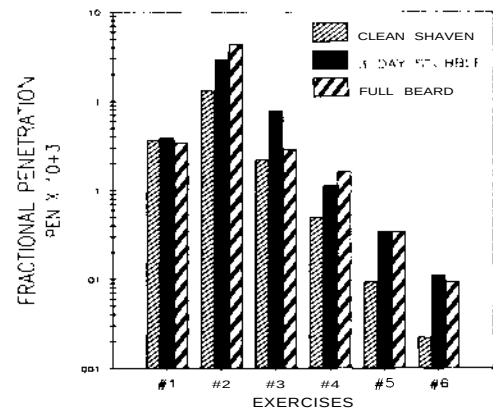


Figure 11. ANSI exercises, average subject, Racal helmet PAPR.

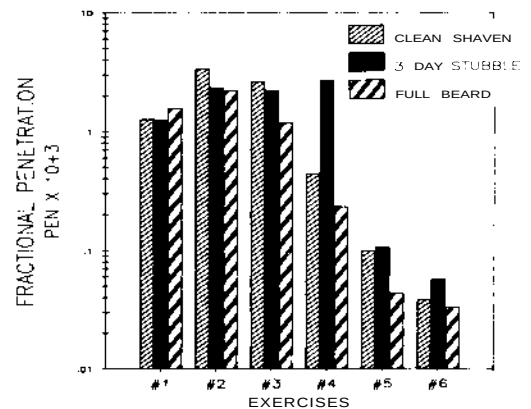
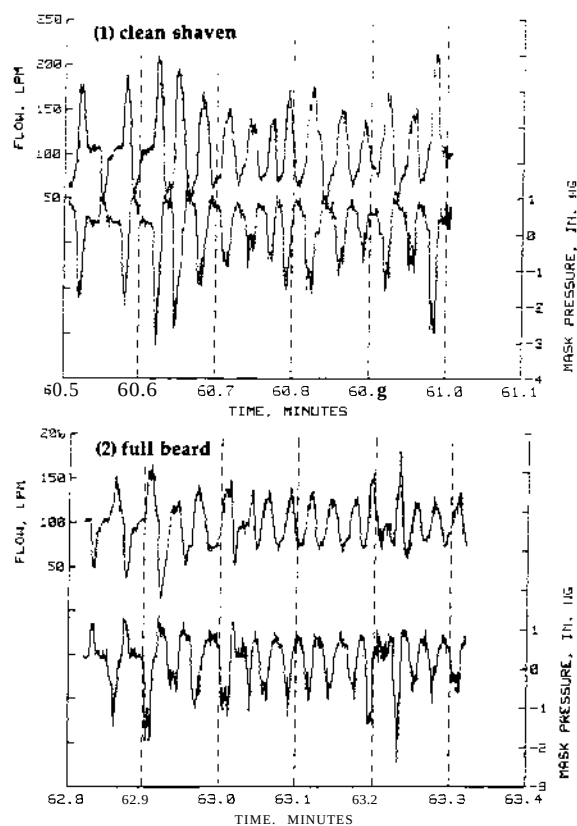
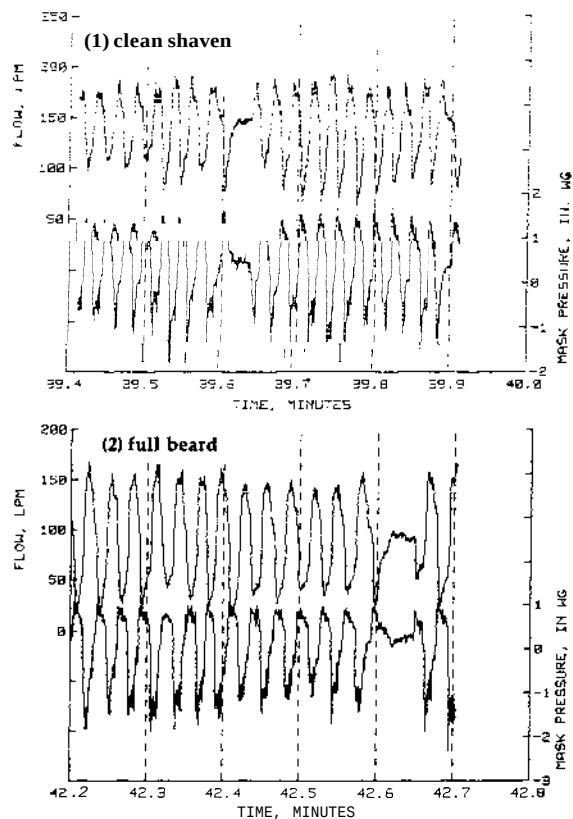


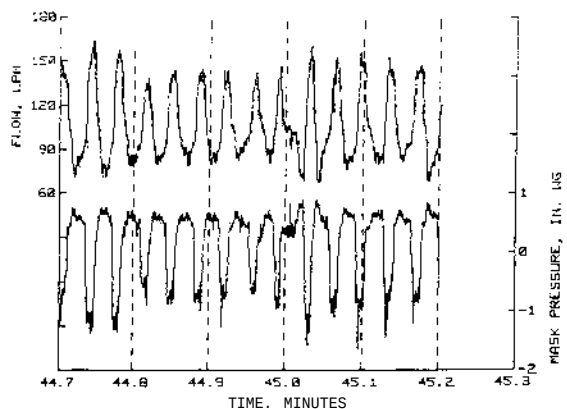
Figure 12. ANSI exercises, average subject, 3M helmet PAPR.



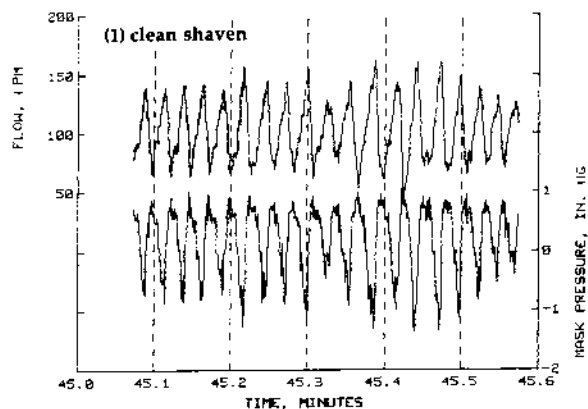
**Figure 13(a).** Pressure and flow vs time, MSA half-mask PAPR, flow of 4 cfs. Subject DAL.



**Figure 13(c).** Pressure and flow vs time, MSA half-mask PAPR, flow of 4 cfs. Subject SPS.



**Figure 13(b).** Pressure and flow vs time, MSA half-mask PAPR, flow of 4 cfs. Subject JML, full beard.



**Figure 13(d).** Pressure and flow vs time, MSA half-mask PAPR, flow of 4 cfs. Subject WGU.

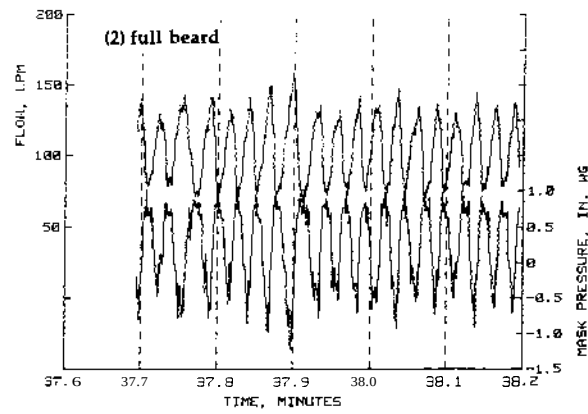


Figure 13(d). (Continued)

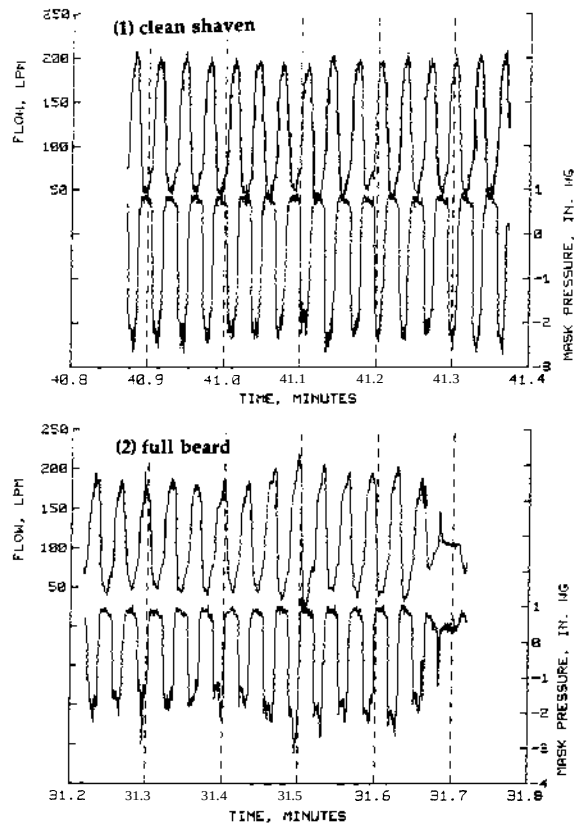


Figure 13(e). Pressure and flow vs time, MSA half-mask PAPR, flow of 4 cfs. Subject KCY.

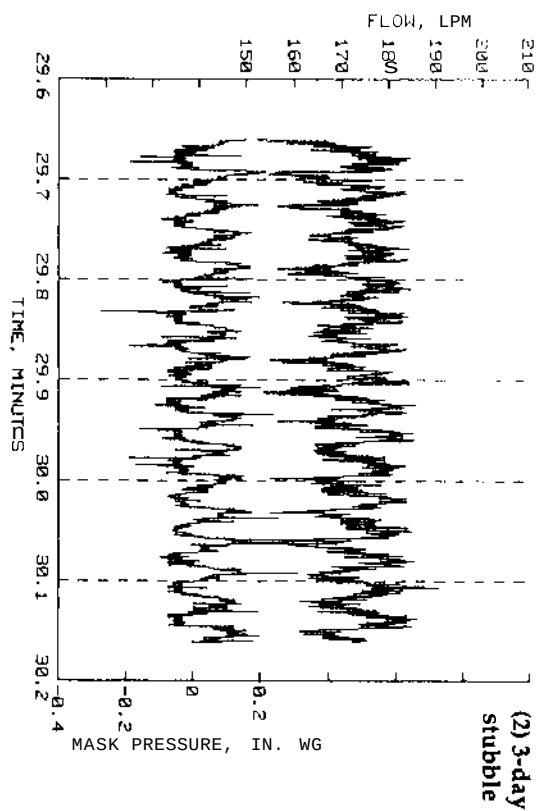
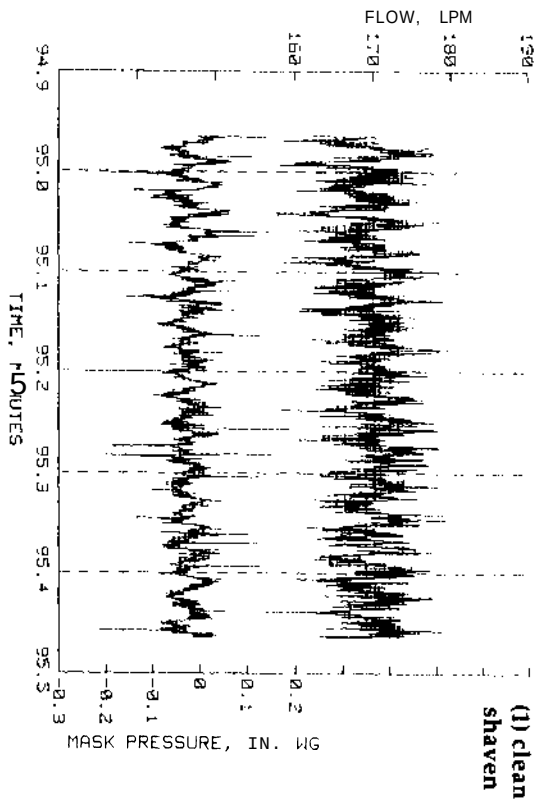


figure 14(a). Pressure and flow vs time, Racal helcoet PAPR, flow of 6 cfm; Subject NCB.

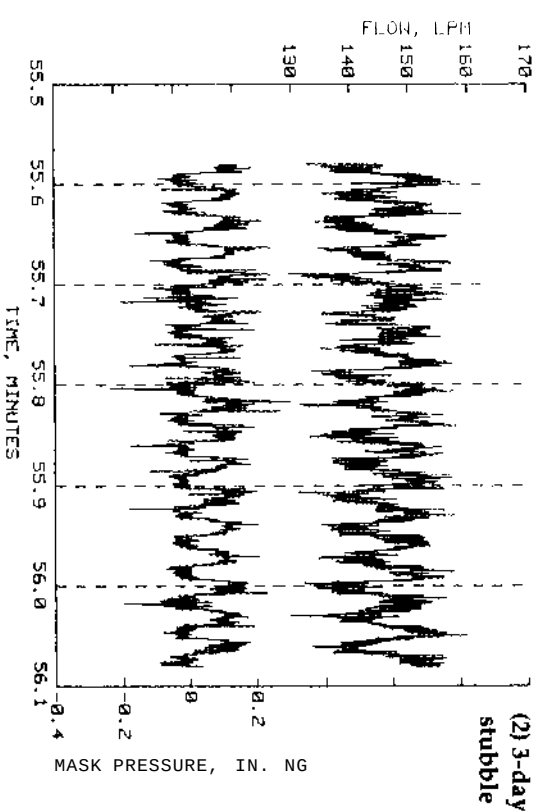
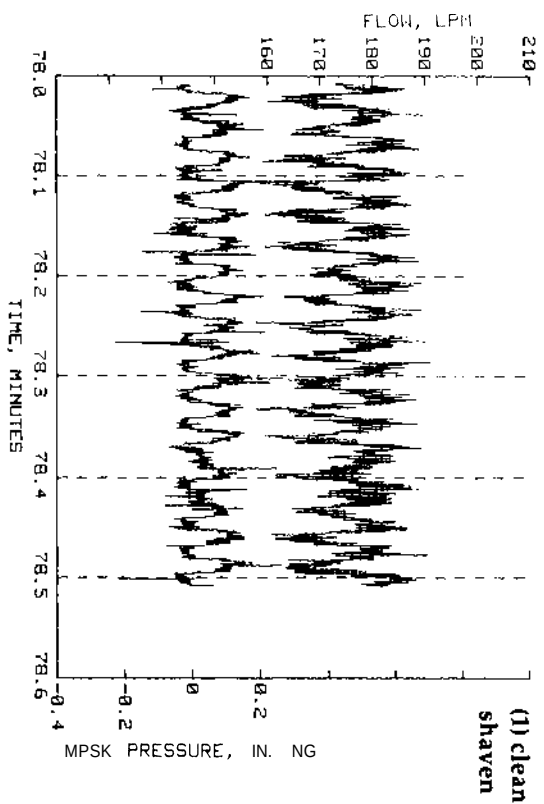


Figure 14(b). Pressure and flow vs time, Racal helmet PAPR, flow of 6 cfm; Subject JWD.

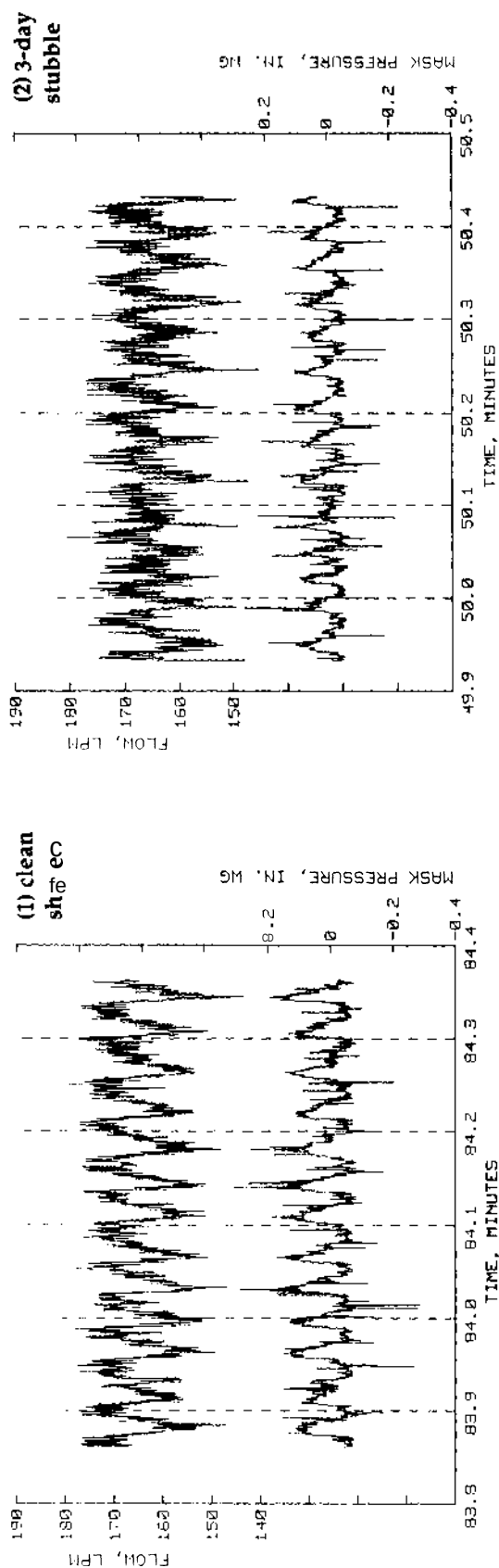


Figure 14(c). Pressure and flow vs time, Racal helmet PAPR, flow of 6 cfm; Subject GB.

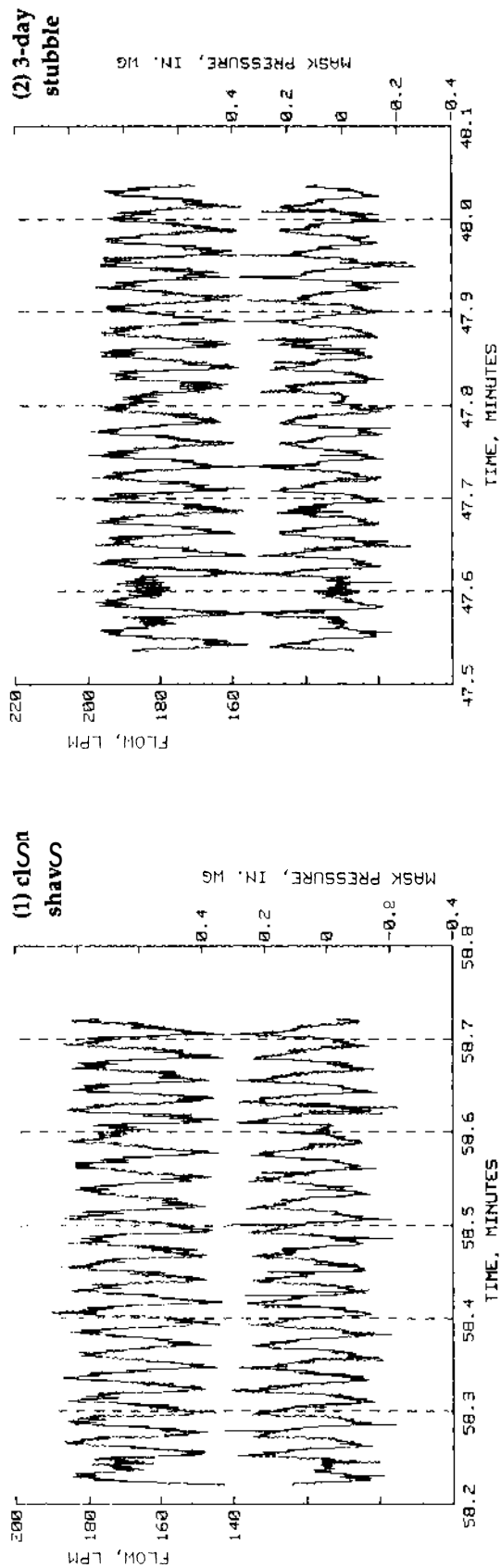


Figure 14(d). Pressure and flow vs time, Racal helmet PAPR, flow of 6 cfm; Subject RAK.

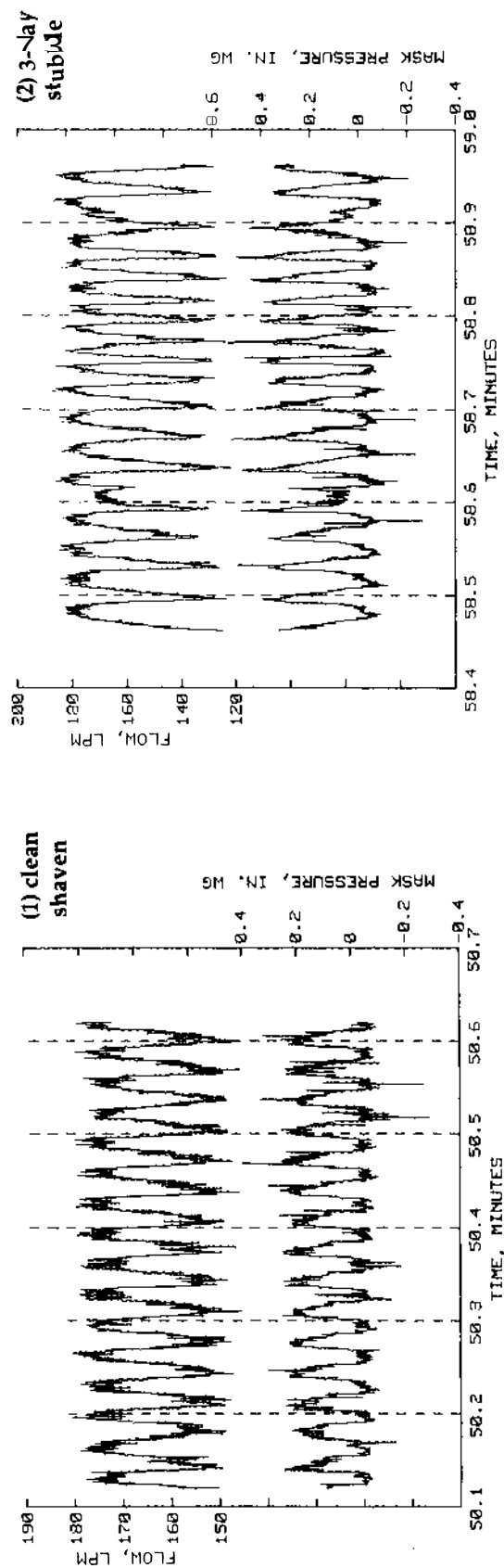


Figure 14(e). [redacted] sure and flow vs time, Rascal helmet PAPR, flow of 6 cfm; Subject KCY.

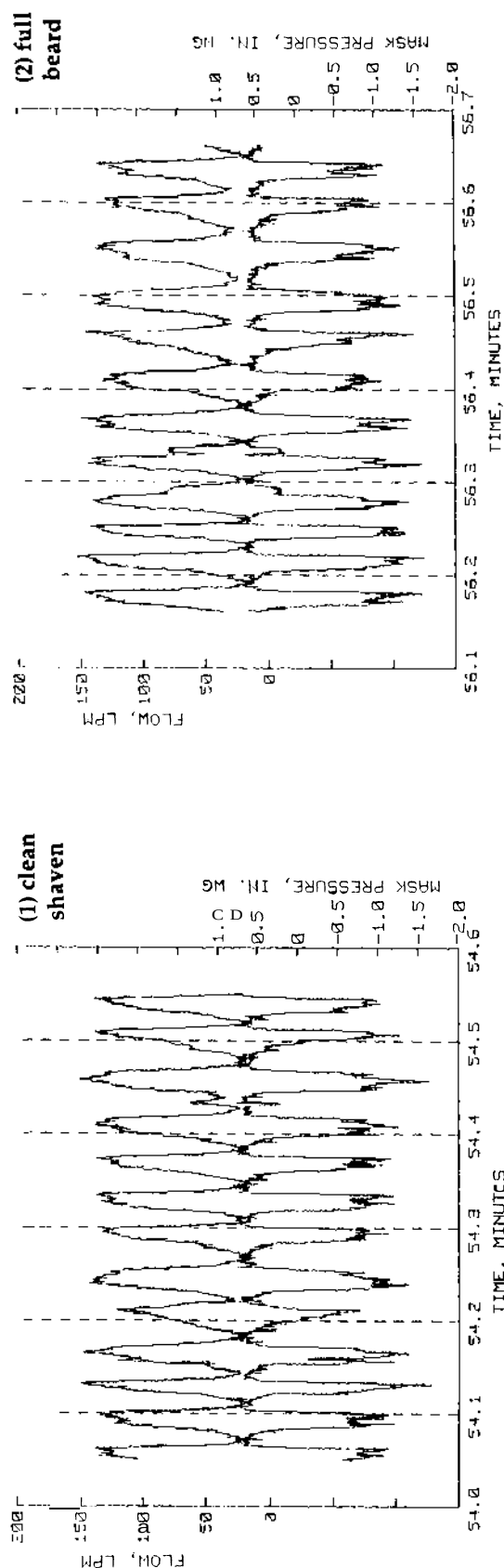


Figure 15(a). Pressure and flow vs time, MSA half-sk PAPR, flow of 3 cfm; Subject BGH.

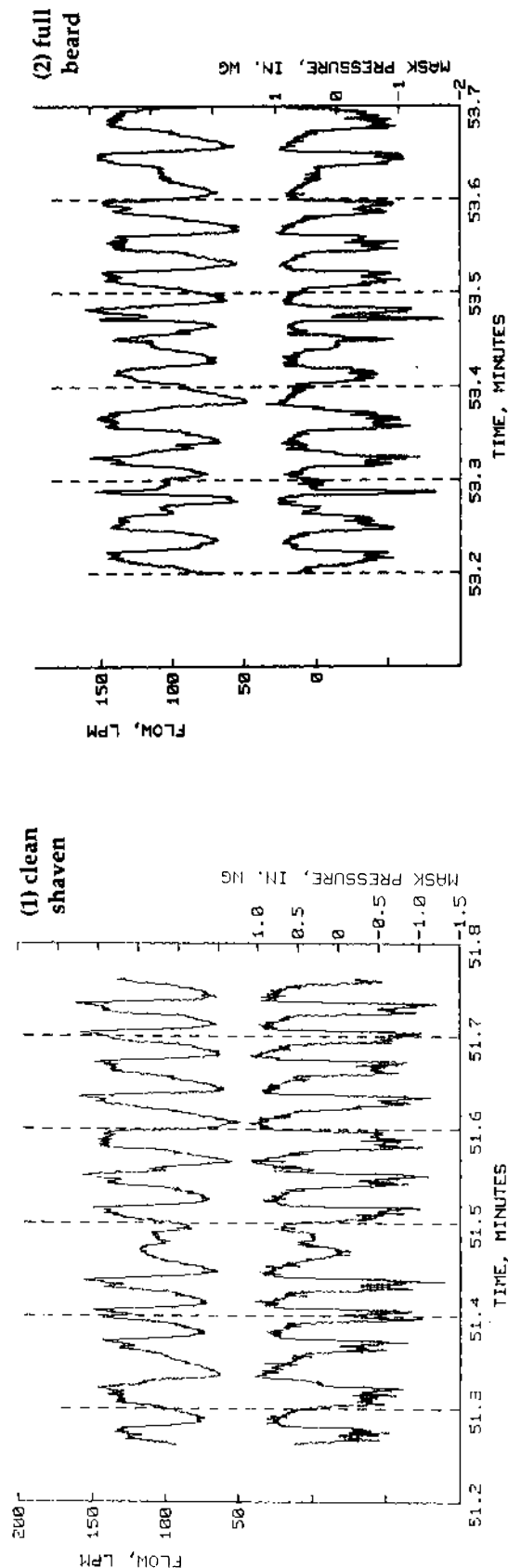


Figure 15(b). Pressure and flow vs time, MSA half-sk PAPR, flow of 4 cfm; Subject BGH.

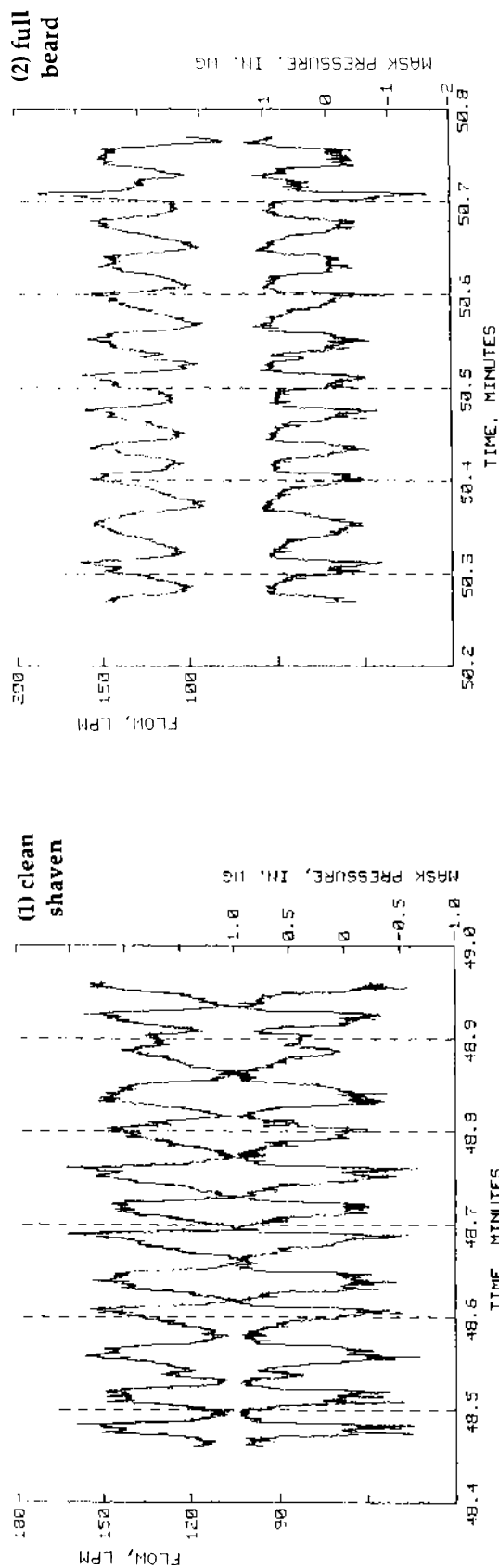


Figure 15(c). Pressure and flow vs time, MSA half-mask PAPR, flow of 5 cfm; Subject BGH.

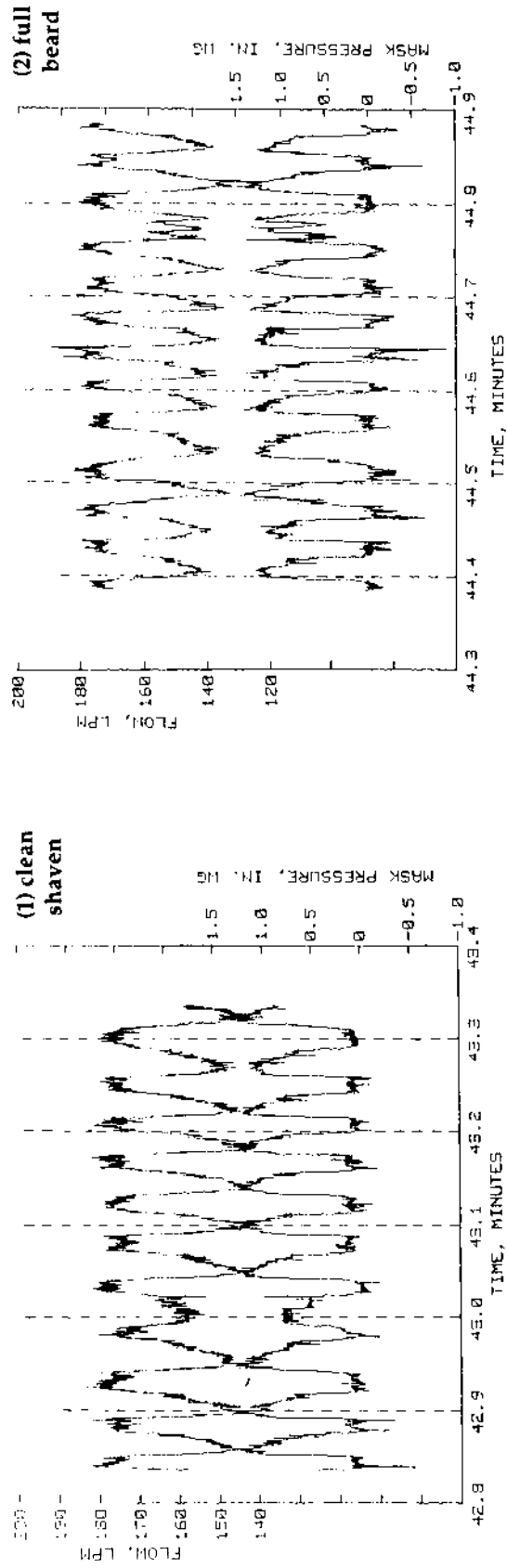


Figure 15(d). Pressure and flow vs time, MSA half-mask PAPR, flow of 6 cfm; Subject BGH.

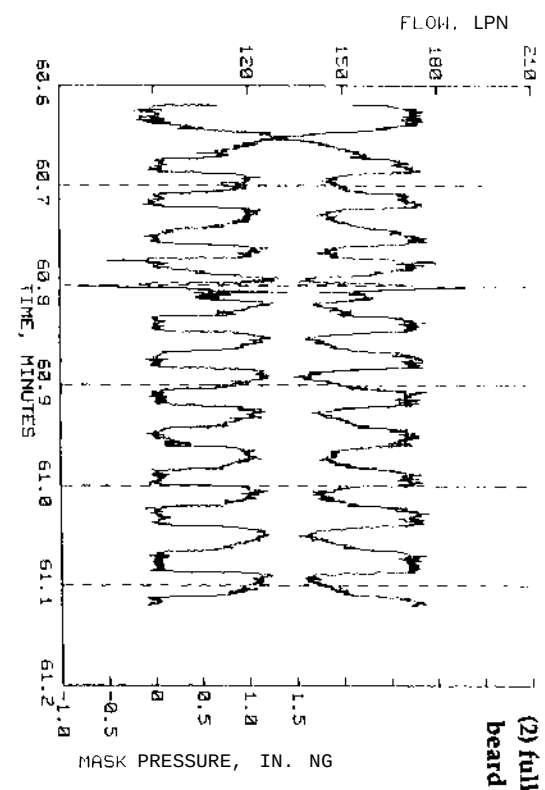
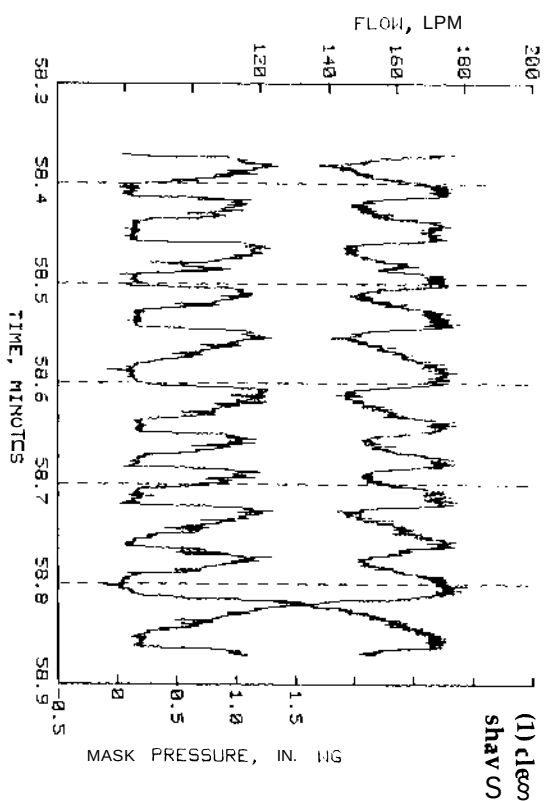


Figure 15(e). Pressure and flow vs time, MSA half-mask PAPR, flow of 6 cfm (repeat); Subject BOG.

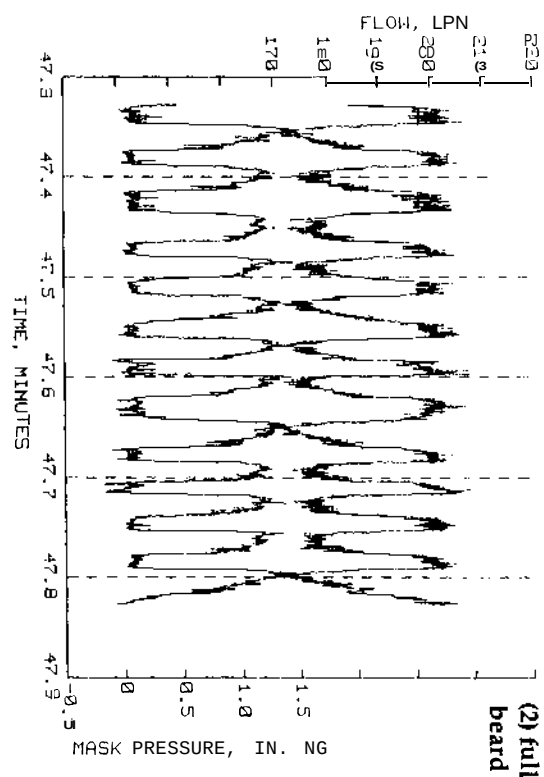
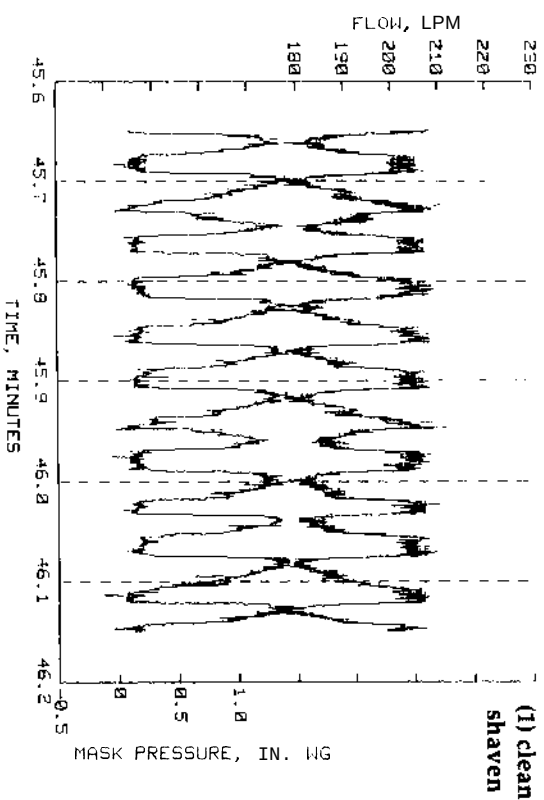


Figure 15(f). Pressure and flow vs time, MSA half-mask PAPR, flow of 7 cfm; Subject BOH.

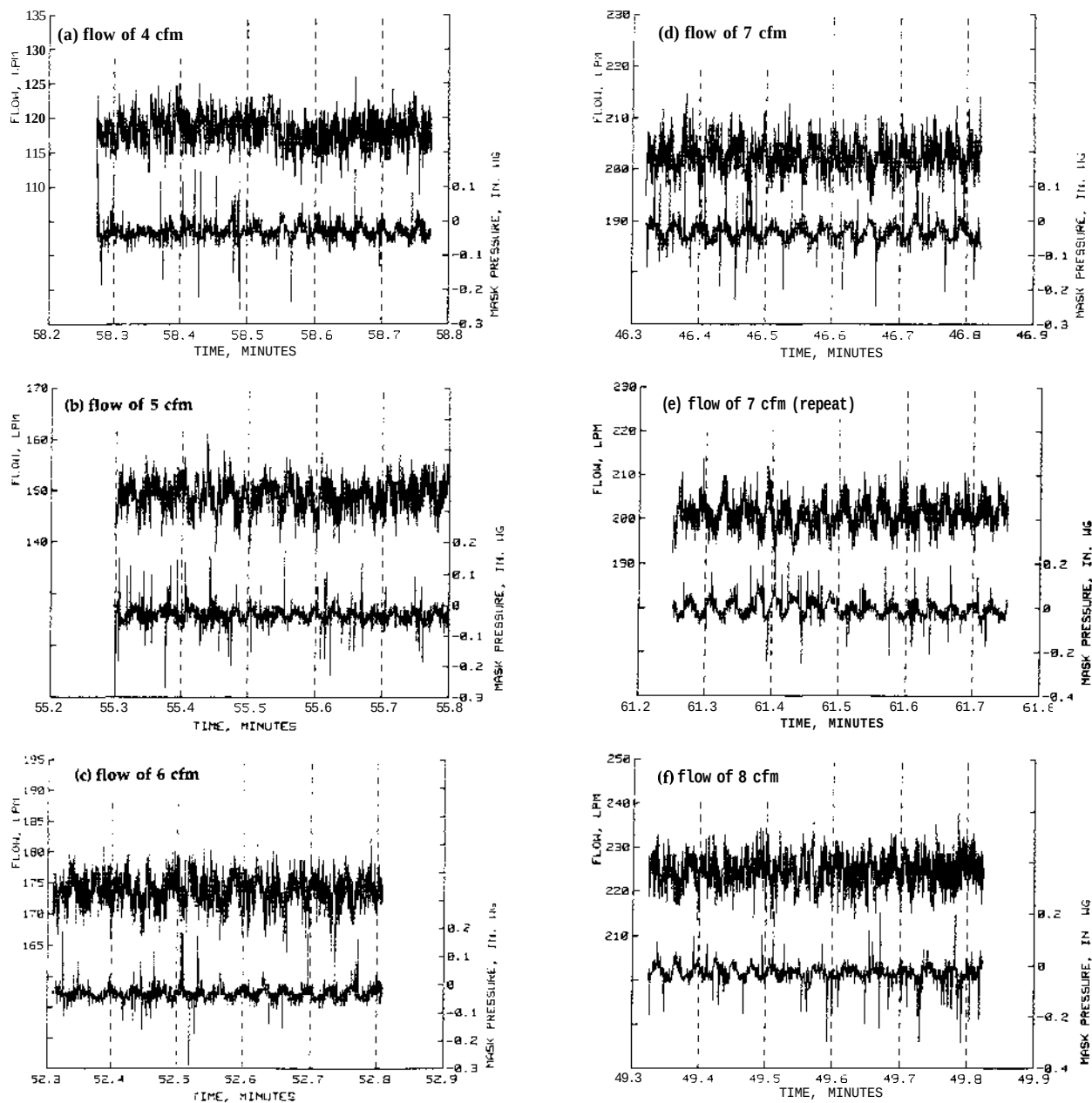


Figure 16. Pressure and flow vs time, Racal helmet PAPR, Subject NCB, full beard.

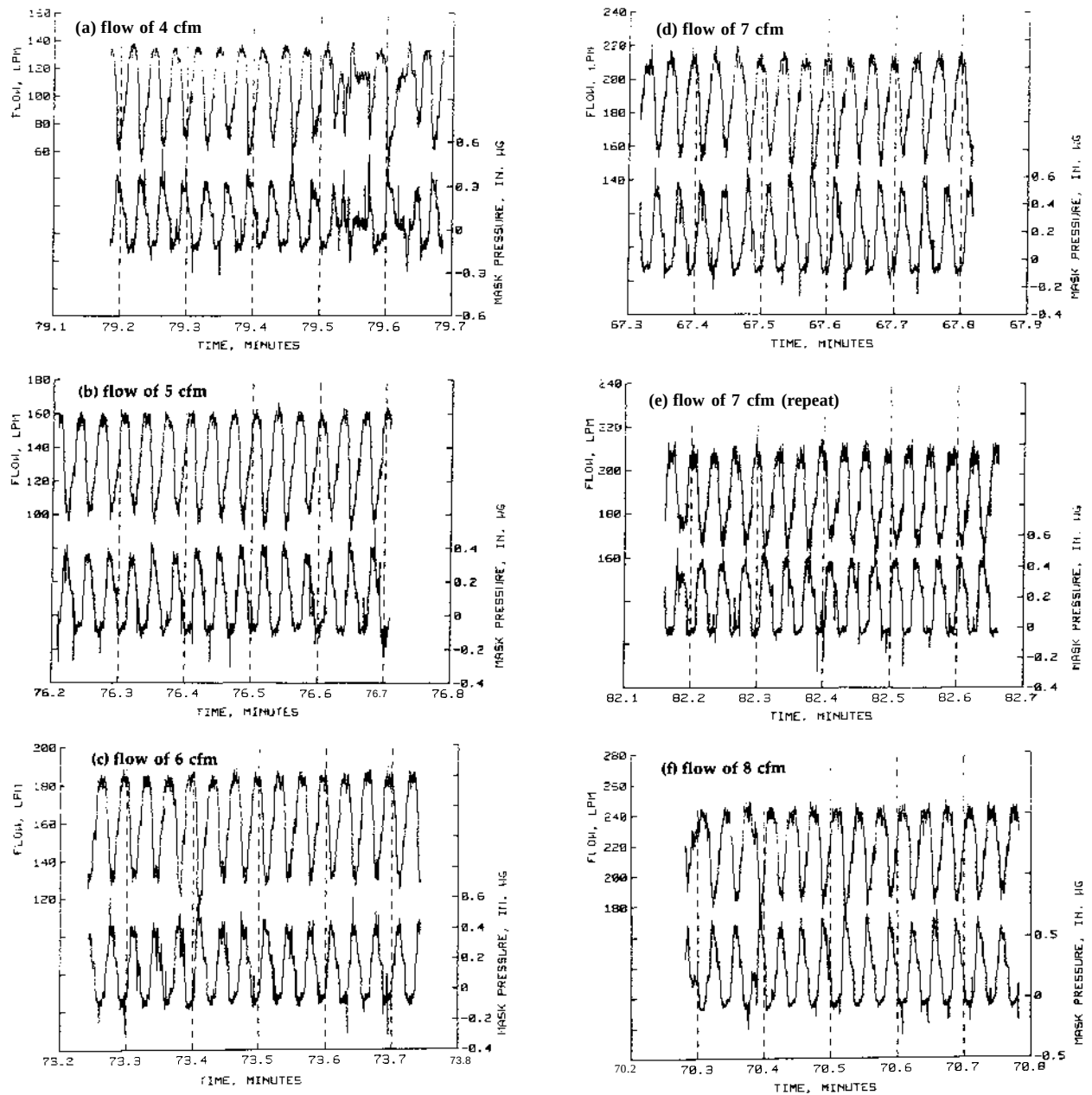


Figure 17. Pressure and flow vs time, Racial helmet PAPR, Subject KCY, full beard.

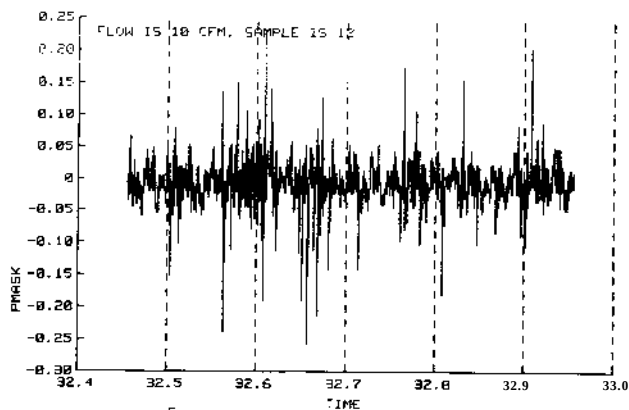


Figure 18. Typical plot of pressure vs time for 3M helmet PAPR.