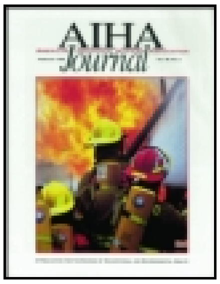

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# Measurement of protection factors of chemical cartridge, half-mask respirators under working conditions in a copper smelter

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*The performance of three commonly used chemical cartridge respirators for $SO_2$ was measured under working conditions in a copper smelter. An effective $SO_2$ protection factor for each man-respirator trial was calculated as the ratio between average $SO_2$ concentrations sampled outside the respirator mask and that simultaneously sampled from inside the mask. The in-use $SO_2$ protection afforded by the three respirators proved to be highly variable with mean protection factors of 22, 18, and 13. The distributions of the protection factors and the effects of mask type, facial size, and mask comfort are discussed.*

# Measurement of protection factors of chemical cartridge, half-mask respirators under working conditions in a copper smelter

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## Introduction

Chemical cartridge half-mask respirators are commonly used by workers for protection against noxious atmospheres in many industrial settings. The Mine Enforcement and Safety Administration (MESA) has established minimum requirements for safe respirator performance under specified hazardous conditions. To assess the efficiency of a number of "dust respirators" worn in various aerosol atmospheres, extensive testing has been conducted at Los Alamos Scientific Laboratory (LASL).[1-3] "Effective protection factors" provided by dust respirators have been measured in bituminous coal mining operations.[4] But, overall, very little field testing of respirator efficiency has been done, and none has been previously done in an $SO_2$ environment.

The present study was designed to measure the $SO_2$ protection factors of three chemical cartridge, half-mask respirators under actual working conditions in a copper smelter. For the purposes of this discussion, a "protection factor" has been defined as the average $SO_2$ concentration measured outside the respirator mask divided by the average $SO_2$ concentration measured inside the respirator mask. The respirators for this study were chosen from among the models used in the Los Alamos studies and include two currently used by workers at the smelter.

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## Test group

The test group was selected from workers in a high $SO_2$ environment: the reverberatory furnace "feeders". The six feeders in this test series were chosen, first, for their frequent and regular high exposure to $SO_2$ and, second, for their willingness to participate. Because only a small population of smelter workers was available (the smelter was, at the time, on a reduced working schedule with one of its three reverberatory furnaces shut down), no attempt was made to control the facial indices of the study group to conform to the LASL test panel.[1] The feeders' normal work involves charging copper concentrates into a reverberatory furnace (10 m wide x 5 m high x 33 m long) four times per 8-hour shift. Each feed lasts 0.5 to 1.5 hours, during which the feeder stands on top of the furnace and directs the ore con-

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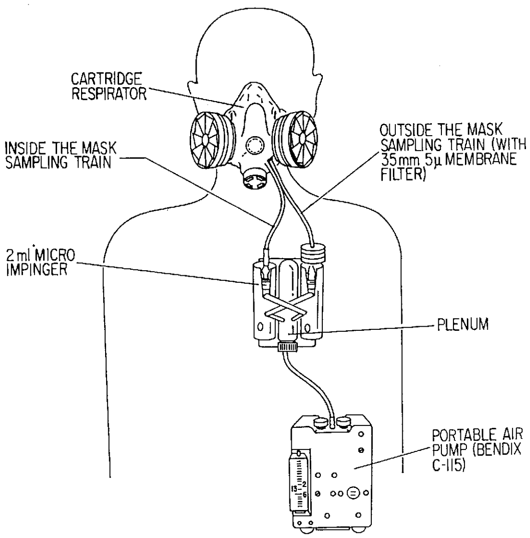


*Figure 1—Schematic of dual sampling train.*

centrate into a bank of chutes located along the furnace walls. The feeder watches the charging of the ore through a viewing port which communicates directly with the fired chamber. All respirator evaluations were made during furnace charging. Three supervisory personnel accompanied the feeders during respirator testing. These three observed the feeders during all sampling periods, acted as test participants themselves, and monitored the operation of the sampling equipment.

## Methods and materials

### *Sampling unit*

A personal sampling system was constructed to simultaneously measure $SO_2$ concentrations both inside and outside of a respirator while the respirator is being worn. A diagram of the system is shown in Figure 1. Dual trains were used to sample $SO_2$ from the two source atmospheres. Two impingers with a common plenum were used to achieve well matched flows. Limiting orifice tubes for the impingers were constructed by fusing 0.5 mm capillary tubes into the impinger tube tips. Flows through the tubes proved to be very stable, provided the vacuum source which produced those flows was itself stable. Impinger tubes were matched into pairs which maintained flows within 0.5 liter/minute of each other when evacuated by a common vacuum source. Commercially available sampling pumps were used as vacuum sources. These pumps were capable of maintaining a 2.0 liter/minute flow in excess of 8 hours. The demands of this study called for maintaining 1.0 liter/minute flow for 80-90 minutes. There was a slight tendency for the flow rate to decline during testing. Final flow measurements inside the mask averaged 90.8 ± 19.6% (mean ± S.D.) of their initial flows, while final flows of outside the mask measurements were found to average 95.1 ± 18.8% of their respective initial flows. The "inside the mask" sampling train was prefiltered for particulates by the respirator itself, while a 35 mm, 5 micron membrane filter was used to prefilter the "outside the mask" sampling train. Sampling rates were sufficiently low (0.25-0.5 liters/minute) to avoid significant interference with the participant's own breathing and to avoid significant pump induced negative pressures within the mask. The prefiltered gases were passed through the microimpingers and the $SO_2$ collected in acidified 0.5% (wt/wt) hydrogen peroxide. Analysis of total sulfates was accomplished by precipitation with barium chloride and measurement of barium from redissolved barium sulfate with an atomic absorption spectrophotometer.[5]

### *Data collection*

Three commercially available industrial respirator types were fitted on each of the nine subjects. Three sampling runs (approximately 80 minutes long) were made to measure the inside and outside the mask $SO_2$ concentrations for each subject/respirator combination. Lip length and menton-nasal root depression length were measured for each subject.[1] A total of 81 paired inside and outside the mask samples were collected. Sampling was conducted according to the protocol described in Appendix I.

### *Data analysis*

The data were analyzed using t-tests, Mantel-Haenszel chi square statistics, and regression techniques.[6] The Mantel-Haenszel chi square is a nonparametric statistic used to test for differences in categorical data. The technique considers the presence of ordering in the data, while allowing for control of other variables of interest.[7]

## Results

Table I shows the average inside and outside the mask $SO_2$ concentrations, and the average

**TABLE I**
**Average $SO_2$ Concentrations Inside and Outside Respirator Masks and Average Protection Factors**

| RESPIRATOR | n | $SO_2$ (mg/m³) OUTSIDE MASK MEAN | OUTSIDE MASK S.D. | INSIDE MASK MEAN | INSIDE MASK S.D. | PROTECTION FACTOR MEAN | PROTECTION FACTOR S.D. |
|---|---|---|---|---|---|---|---|
| A | 26 | 61.1 | 40.2 | 5.0 | 4.0 | 22.1 | 22.6 |
| B | 25 | 53.0 | 25.6 | 4.6 | 3.8 | 18.4 | 14.2 |
| C | 25 | 53.0 | 35.6 | 6.2 | 4.5 | 12.9 | 11.0 |

protection factors for each of the three masks tested. The outside the mask $SO_2$ levels averaged approximately 55 mg/m³ (21 ppm) and ranged from 16.1-196.1 mg/m³ (6.2-75.4 ppm). Statistical t-tests of the average outside the mask concentrations for each mask type reveal that no significant difference existed between the $SO_2$ atmospheres to which each mask type was exposed. Inside the mask concentrations averaged approximately 5 mg/m³ (1.9 ppm) and ranged from 0.9-18.1 mg/m³ (0.3-7.0 ppm). The protection factors showed a similar wide range, 2.6-83.1. Five tests of the eighty-one (1 Type A, 2 Type B, 2 Type C) were dropped from the data set because participants removed or lifted their respirators during sampling, thus causing inside the mask $SO_2$ accumulations to be unrepresentative of concentrations occurring with respirator protection.

Histograms showing the distribution of protection factors for the three masks are displayed in Figure 2. The protection factors were consistently grouped in the 2-20 range, with a few tests showing factors above 30. The Type A mask had 38.5% of its protection factors $< 10$, the Type B had 30.4% $< 10$, and the Type C had 56.0% $< 10$. Median protection factors were 15.29 for the Type A, 13.72 for the Type B and 9.59 for the Type C. The lowest three-test average for a subject was 5.5 for the Type A, 6.9 for the Type B, and 6.7 for the Type C. The lowest three-test average for the Type A and Type C occurred for the same subject.

The differences between masks were analyzed by forming three contingency tables contained in Table II. Mantel-Haenszel chi square tests were performed on these contingency tables to assess the difference between protection

**TABLE II**
**Mantel-Haenszel Chi Square Test**

| RESPIRATOR Type | PROTECTION FACTORS 0-10 | >10-20 | >20 | | |
|---|---|---|---|---|---|
| A | 10 | 6 | 10 | 26 | |
| B | 7 | 12 | 6 | 25 | $\chi^2_{MH}=0$ p*=1.00 |
| | 17 | 18 | 16 | 51 | |

| RESPIRATOR Type | PROTECTION FACTORS 0-10 | >10-20 | >20 | | |
|---|---|---|---|---|---|
| A | 10 | 6 | 10 | 26 | |
| C | 14 | 6 | 5 | 25 | $\chi^2_{MH}=1.75$ p*=.18 |
| | 24 | 12 | 15 | 51 | |

| RESPIRATOR Type | PROTECTION FACTORS 0-10 | >10-20 | >20 | | |
|---|---|---|---|---|---|
| B | 7 | 12 | 6 | 25 | |
| C | 14 | 6 | 5 | 25 | $\chi^2_{MH}=1.60$ p*=.20 |
| | 21 | 18 | 11 | 50 | |

*Assuming that no difference exists between the mask pairs, "p" is the probability that the value of $\chi^2_{MH}$ would be as large as it appears for each of the three tables.

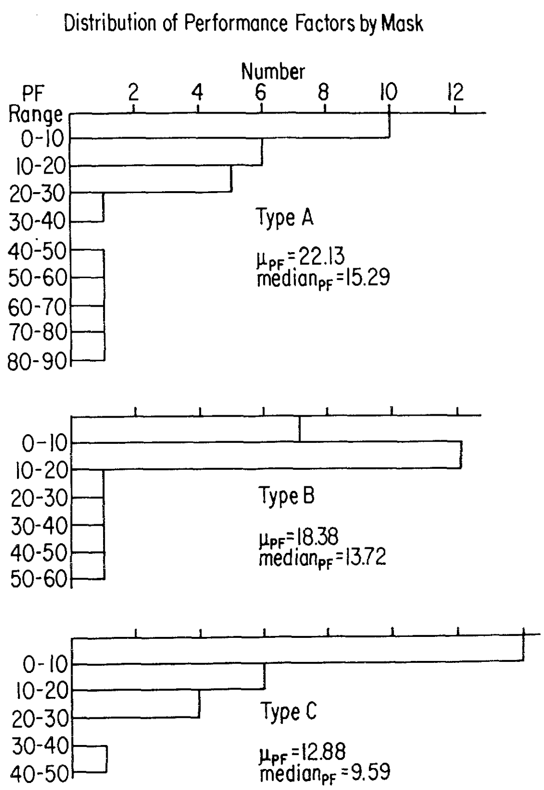


*Figure 2–Distribution of performance factors by mask.*

**TABLE III**
**Summary of Questionnaire Data**

| QUESTION | RESPIRATOR A | RESPIRATOR B | RESPIRATOR C |
|---|---|---|---|
| 1. Which respirator did you like best? | 3 | 6 | 0 |
| 2. Which respirator was worst? | 0 | 2 | 7 |
| 3. Rate each respirator according to the following criteria: 1=good, 2=fair, 3=bad | A | B | C |
| Ease | 2.2 | 1.8 | 1.7 |
| Seal | 1.9 | 1.3 | 2.8 |
| Comfort/Irritation | 2.0 | 1.6 | 2.8 |
| Draw | 2.1 | 1.4 | 1.8 |
| Ride down (tendency) | 2.2 | 1.2 | 1.8 |
| Visibility | 1.3 | 2.6 | 1.7 |

factors of each respirator pair. The Mantel-Haenszel procedure was used since the categories in the contingency tables were ordered and this procedure provides for a more powerful test to detect trends for this type of data. No significant difference was found between the protection factors of the Types A and B. However, as is shown in Table II, both the A and the B appear somewhat superior to the Type C mask. Additional data would be necessary to attain acceptable statistical confidence in such a conclusion. A mixed model analysis of variance was also performed with similar results.

An attempt was made to correlate the "somewhat superior" performance of the A and B masks relative to the C mask. This analysis is based on the hypothesis that, under working conditions, an uncomfortable mask will be adjusted less tightly than a comfortable one. The participants' subjective assessments of respirator function are summarized in Table III. Their evaluation of respirator seal was closely related to respirator comfort in seven of the nine men. Overall evaluations of respirator comfort by the participants suggested a positive correlation between comfort and respirator performance. Masks A and B were rated as more comfortable than mask C in 13 of 18 paired comparisons (A vs. C and B vs. C). However, on a man by man basis, subjective assessment of comfort was not a reliable predictor of the relative performance of the masks. In only 10 of 27 paired comparisons (A vs. B, B vs. C, C vs. A) did the "more comfortable" mask outperform the mask judged "less comfortable".

Three of the nine study participants had lip lengths which exceeded the criteria of the Los Alamos Scientific Laboratory (LASL) male panel for testing half-mask respirators, and all of the face lengths fell in the upper half of the panel. The lip lengths ranged 50-64 mm and the face lengths ranged 118-127 mm. A linear regression analysis was performed to test correlation of each participant's lip and face length with average respirator protection factor. No significant relationship was found ($r = 0.11$).

An apparent increase in protection factor with increasing ambient (outside the mask) $SO_2$ concentrations was noted in the data. The individual data points are shown in Figure 3. A linear regression was fitted to these data and found to be highly significant ($p < .001$) with $r = .56$. While the increasing trend is clear, it should be noted that the protection factor has an upper boundary because it is defined as a ratio of the inside and outside mask $SO_2$ concentrations and the inside mask concentration is limited by the analytical limit of detection (approximately 1 mg/m$^3$). As a result, the protection factor could not exceed a value approximately equal to the ambient $SO_2$ concentration. While a few of the lowest concentrations observed were near the limit of detection, the vast majority of samples contained detectable sulfate and were generally well above the limit. Hence, the increase in protection factor was not purely an artifact of the analytical method, but reflects an apparent improved $SO_2$ capture by the respirators.

## Discussion

The overall in-use $SO_2$ protection afforded by these three chemical cartridge respirators was poor. This is most clearly indicated by the percent of tests showing protection factors less than ten. The best mask had 30.4% of its tests with factors < 10, and the worst had 56.0% with factors < 10. Thus, if a worker were using one of these respirators with an $SO_2$ exposure near the 50 ppm (130 mg/m$^3$) ceiling allowed under the Occupational Safety and Health Administration's rules for half-mask respirator use, the inside the mask $SO_2$ concentration would exceed 5 ppm a substantial portion of the time. It should be noted that these conditions rarely occur in the smelter environment, even in the highest exposure category, the reverberatory furnace feeders.

The distribution of protection factors observed in this study was similar to those described in the coal mine studies.[4] In both studies protection factors were concentrated in the range of 2-15, with means exceeding medians and considerable variability. These findings are noteworthy, since the two studies were conducted in differing atmospheres, thus implying similar protection characteristics of half-mask respirators for both dust and gases. Mean protection factors of the $SO_2$ study were, however, higher than those observed for the coal dust study since the dust respirators were not worn continuously.

Many variables which are easily controlled in the laboratory are not well controlled under working conditions. Three such variables are discussed below. We believe that these "working condition variables" significantly contributed to both the increased variability and decreased protection factors observed in this study, as opposed to earlier laboratory studies.

1) **Respirator strap tension.** The performance of half-mask respirators has been shown to be directly related to the tension of the head band straps.[2] Under working conditions, strap tensions are seldom, if ever, regulated. Since increasing the tightness of mask straps adversely affects the comfort, mask comfort is likely to have an indirect effect on the performance of the respirators. Respirator strap tension was not controlled or monitored in this study.

2) **Facial hair.** Los Alamos researchers have shown that beards and wide sideburns detrimentally affect the performance of half-mask respirators.[3] They have also observed that a ten-fold decline in respirator performance can occur during the first day of facial hair growth following a shave. Participants in this study had neither beards nor wide sideburns. However, despite the fact that each was clean shaven, one could expect significant variation in facial hair as a function of daily shaving schedules.

3) **Normal work activities.** LASL researchers have also demonstrated that many activities associated with normal work can adversely affect a respirator's performance.[3] These activities include smiling, talking, moving one's head, and deep breathing associated with heavy work. Such activities were of course, observed in this study, but it was impractical to control or record them.

The observed increase in protection factor with ambient $SO_2$ concentration (Figure 3) may have been the result of workers being more aware of mask leakage because of the irritation produced by the $SO_2$. While this is a reasonable explanation of the test results, no changes in worker behavior were observed to substantiate a difference in respirator usage at higher ambient $SO_2$ levels.

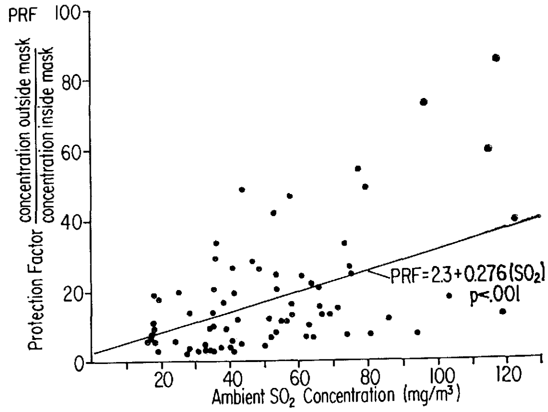


*Figure 3—Protection factors as a function of ambient $SO_2$ concentration.*

The sampling devices created for this study were found to be sturdy and reliable. The use of a common plenum with two matched orifices provided well-balanced and stable flow rates. The investigators feel, in retrospect, that had a larger impinger been used for data collection, some of the variability observed in the samples might have been reduced. The 2 ml spillproof microimpingers were chosen to collect $SO_2$ because of the compact size and spillproof feature. However, the very low capacity of these impingers limited the flow rate and the quantity of solution available for analysis.

**Acknowledgement**

We thank and acknowledge James Reading, Ph.D., for his considerable contribution in the data analysis of this study. We also wish to thank the United Steel Workers of America, Kennecott Copper Corporation and the various respirator equipment manufacturers for their aid and cooperation.

## Appendix 1

### Protocol for the use of dual sampling train (DST)

**A. Before shift**

1. Insert charged battery into pump.
2. Charge microimpingers with 2 ml

0.5% wt/wt hydrogen peroxide solution. Inject solution from a large syringe fitted with a Wintrobe cannula.

3. Connect tubing (Figure 1) and set flow for both sides, measuring at the microimpingers, and attach mask. (Note: Steps 1-3 are performed at the lab.)
4. Record before-shift blows on both sides, unit number, time on, and mask type.
5. Have subject adjust web belt to fit himself.
6. Attach pump and DST assembly onto belt and then to subject and instruct subject in its use. Stress that he must be wearing his mask at all times while the pump is operating.
7. Have subject put on mask; then switch on pump.

**B. During shift**

Observe all tubing connection for integrity. Also observe microimpinger flows through the case portholes.

**C. After shift**

1. Turn off pump before removing mask and sampling device from subject.
2. Note and record after-shift flows. Record time off.
3. After transporting sampling device to lab, break it down:
   a. Disconnect tubing
   b. Decant inside the mask sampling solution with clean syringe and cannula. Rinse out microimpinger and inside the mask sampling train with reagent grade distilled water.
   c. Place both sampling solution and rinse water into a clean, labelled polyethylene bottle and refrigerate it.
   d. Decant outside the mask sampling solution and rinse microimpinger. Bottle as before.
   e. Remove outside the mask membrane filter from its cartridge and place in a labelled polyethylene bag.
   g. Wash microimpingers and respirator mask.
4. Rebuild sampling device with clean microimpingers, new filter, and new chemical cartridge(s).

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