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# Powered Air Purifying Respirator (PAPR): An Efficient Personal Protective Device Against Respirable Dust in Underground Mining Operations

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## ABSTRACT

The health and safety of miners is critical in the industry. Prolonged exposure to dust-laden air results in irreversible ailments like pneumoconiosis that have a severe impact on their lives. Operations use various personal protective devices (PPEs) to alleviate their exposure to respirable dust. Powered Air Purifying Respirator (PAPR) is one such device that uses high- efficiency filters and positive pressure masks to shield miners from airborne contaminants. Used in the medical and other industries, these respirators efficiently protected healthcare workers during the COVID-19 pandemic. Recently, the mining industry has shown a growing interest in adopting this PPE to ensure safe working conditions for the miners. We present an introduction to the PAPRs and discuss their dust capture efficacy in this manuscript.

## INTRODUCTION

Dust exposure is a major concern in mining operations. These particles are generated in every unit operation. This includes extraction, material handling, crushing, and grinding [1–3]. In underground coal mining, exposure to respirable dust particles can lead to serious health hazards such as coal workers' pneumoconiosis (CWP), also known as 'Black Lung'. This disease in its most advanced stage leads to fatalities. Data shows an increasing trend in the cases of CWP during the last decade [4]. A survey conducted in 1968 showed that coal miners were exposed to high concentrations of dust during operations (Table 1) leading to detrimental health impacts. Later in 1969, the Coal Mine Health and Safety Act established a limit of 2.0 mg/m$^3$ for respirable coal dust. In 2014, the limit was lowered to 1.5 mg/m$^3$ [4]. In April 2024, the silica PEL was updated by MSHA, lowering it to 50 µg/m$^3$ time-weighted average (TWA) [5].

Lowering the workers' dust exposure is the key step in the alleviation of CWP. There are multiple mechanisms to prevent workers from breathing respirable dust. Figure 1 ranks mechanisms by effectiveness, with the most effective on the right and the least effective on the left-hand side. The best way to prevent exposure is to eliminate the source. If this is not possible, substitution with an alternate method can prevent the workers' exposure. The third mechanism is implementing engineering controls to lower emissions. Administrative control refers to implementing good practices and procedures that minimize exposure. Finally,

**Table 1. Operators' exposure to coal dust [6]**

| Occupation / Operator | Mean Exposure (mg/m$^3$) |
|---|---|
| Continuous miner operator | 4.08 |
| Continuous miner helper | 3.47 |
| Roof bolter operator | 2.46 |
| Cutting machine operator | 3.69 |
| Loading machine operator | 3.75 |

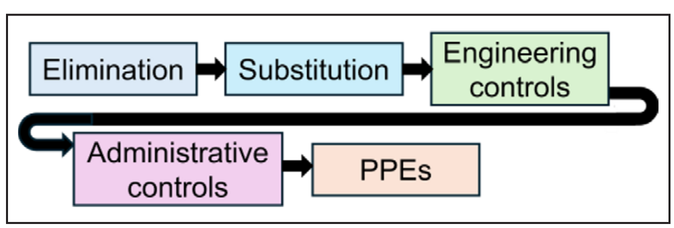


**Figure 1. Workers' protection mechanisms** [7]

using personal protected devices (PPE) is the last barrier to protection against hazards [7]. Ideally, all these measures should be implemented simultaneously.

Powered Air Purifying respirators (PAPRs) are a type of respirator that uses a battery and a blower to force air through a High-Efficiency Particulate Air (HEPA) filter and deliver clean breathable air to the user [8]. The principal advantage of these respirators is that they provide significantly better protection than the regular respirators commonly used in industry. HEPA filters are rated as 'P100', meaning they offer 99.97% filtration efficiency against airborne particles and are oil-resistant [9].

The basic components of a PAPR are the face mask, the blower, and the filters. PAPRs are classified into different categories based on the type of mask used. The two principal categories are tight-fitting and loose-fitting. Tight-fitting PAPRs provide a full seal between the wearer's face and the mask and provide better protection, as leakage is less likely to happen. However, these respirators need a fit test to ensure they fit well for each wearer. On the other hand, loose-fitting PAPRs do not need a fit test and provide protection using positive pressure to prevent leakage. These types of respirators can be used along with facial hair without affecting the fitting. Figure 2 shows both types of PAPRs. The mask design may vary depending on the model used, ranging from full to half-face masks in tight-fitting models, and from helmets to blouses, in loose-fitting ones.

## PROTECTION FACTORS

Respirator's efficiency of protection from particulates is the most important factor that determines their specific application. The most common way to understand and compare respirators is based on the protection factor (PF), which is the ratio of the concentration of a certain contaminant outside the respirator (Co) and the concentration inside of it (Ci). The mathematical definition of the PF is presented in Eq. 1.

**Figure 2. Loose-fitting helmet (left) and tight-fitting full-face mask (right)**

$$PF = \frac{C_o}{C_i} \tag{1}$$

Depending on the conditions under which the PAPR was tested, different PFs can be defined. However, all of them are calculated the same way. Definitions for the principal protection factors are given below:

a. **Assigned Protection Factor (APF):** This is the most general protection factor. It is defined by the Occupational Safety and Health Administration (OSHA) as the expected PF when the respirator is used correctly. This assumes that the respirator does not have any defects and that it is being used according to the provided instructions [10]. Tight-fitting PAPRs have a higher APF than the loose-fitting ones. However, these may not be suitable for workers who cannot pass a fitting test due to facial hair.
b. **Workplace Protection Factor (WPF):** When the factor is measured under the specific conditions in which the respirator is used, it is called the 'Workplace Protection Factor'. This allows companies to understand the expected protection under their unique operating conditions [11].
c. **Fit Factor (FF):** This protection factor is measured for a specific individual. It is used to obtain the APF, the minimum FF experienced by 95% of the users [11]. The protection factor of some commercially available PAPRs is shown in Table 2.

P100 filters, like the ones used in PAPRs, have also been compared to other filters. They show a higher filtration efficiency, as fewer particles can penetrate them. Table 3 compares P100 filters with N95, FFP2, and FFP3 filters.

The filters are named according to the respective standards and filtration efficiency. The N95 filter has 95%

**Table 2. Commercially available PAPRs and their protection factors [12]**

| PAPR | Filter | PF |
|---|---|---|
| 3M Airstream | 060-23-11PAUS (P2 rated*) | 50 |
| Drager X-plore 8000 | AR HE-F001 (P3 rated†) | 100 |
| CleanSpace 2 | PAF-0037 (P3 rated†) | 100 |

* Allows 1.0% particle penetration
† Allows 0.05% particle penetration

**Table 3. Filtration efficiency comparison [13]**

| Respirator Class | N95 | FFP2 | FFP3 | P100 |
|---|---|---|---|---|
| Mean particle Penetration [%] | 0.634 | 0.388 | 0.012 | 0.013 |
| Standard deviation | 0.363 | 0.186 | 0.008 | 0.019 |

efficiency when non-oil particles are present. The FFP2 and FFP3 are classified according to the European standard EN 149 and have efficacies of 94% and 99% respectively [14]. The P100 filter has an efficiency of 99.97% and is highly resistant to oil [9]. Protection factors may vary depending on the reporting agency and the methods used to measure them. The first reports were made between 1969 and 1972. Testing conducted at Los Alamos National Laboratory suggested a protection factor of 1,000 for PAPRs. However, the value was obtained by extrapolating data from a Self-contained Breathing Apparatus (SCBA) and not from PAPR testing [15]. Currently, the suggested APF for loose-fitting PAPRs is 25 [16].

## APPLICATIONS IN THE INDUSTRY

While still uncommon in mining operations, the PAPRs are used in other industries. In the healthcare industry, workers need protection against several microorganisms due to the risk of infection. PAPRs are used due to their high protection efficiency and were especially used during the SARS-CoV-2 2020 pandemic. Many workers have reported a preference for this type of PPE against regular respirators such as the N95 [17]. During the 1970s, PAPRs were implemented in the UK coke industry. This lowered the exposure of workers to polycyclic aromatic hydrocarbons. Their extended exposure can cause lung cancer [18]. The PAPRs used in the lead industry had a mean PF of 18.2. This result was lower than the suggested protection factor of 50, but still higher than other respirators [19]. During silica bagging operations in 1983, PAPRs also showed lower PFs. However, they were still higher than the ones for other types of respirators, ranging between 25 and 215 for tight-fitting masks, and 16-193 for loose-fitting masks [20].

### Mining Industry

During the late 1960s, PAPRs were evaluated for their efficiency in protecting uranium miners from daughter products of radon. These early models of PAPRs demonstrated protection factors up to 1,000; higher than the minimum required of 20 [21]. The most common type of respirators used are the negative pressure masks. However, a Ukrainian study demonstrated concentrations between 8.6–24.7 mg/$m^3$ inside the respirator, with protection factors ranging between 2.9 – 34.0 [22]. This is over the permissible exposure limit. The protection factor is lower than the PAPRs. Therefore, due to their high filtration efficiency, some mines have petitioned to implement PAPRs in their operations. The petitions refer to specific approved models that meet the standards and are intrinsically safe. These models are TR-800 by 3M, PAS- 0060, and EX by CleanSpace [23; 24].

## PERFORMANCE EVALUATION

PAPR performance can be evaluated depending on different parameters, including filtration efficiency, comfort, and ease of communication. Parameters that may affect the performance include the work rate, blower airflow, and leakages. Several scenarios in the underground mine environment have been studied. During testing, it is common to see higher protection factors than the ones reported by official agencies. It is difficult to set an appropriate range, as protection factors can vary across different orders of magnitude depending on the experiment conditions. This section will explain the correlation of these parameters. It also compiles some of the major results that researchers have obtained.

### Protection Factor Testing

Most studies focus on the performance of PAPRs in different conditions. Researchers have tested these respirators in real industrial conditions, failure conditions, and some other scenarios that may be common in some industries. The HALO CleanSpace was tested in the healthcare industry. It offered a PF between 3,576 and 4,290 during a chest compression simulation [25]. These results show that PAPRs can offer high levels of protection even during activities that may be considered as physically demanding. This is important as mining conditions can be demanding. The biggest limitation of this study was the low number of test subjects for reliable statistical inferences.

Another study using more subjects showed that the PF can exceed 250,000 [26]. During aircraft painting operations, the PF was observed to be greater than 1,000. For aircraft sanding operations, the concentration was even lower than the minimum required to obtain a PF certification. The PF was greater than 54,000 for strontium, and greater than 20,500 for magnesium when protection against unique particles was considered [27; 28]. In Japan, the PF was measured during dust-generating operations. The WPFs obtained ranged between 16 and 993, with an average of 117 [29]. Protection under unique abnormal conditions was also tested. This includes wearing the PAPR under non-recommended conditions and leakages and failures. The PF results are shown in Table 4. Leakage and its effects have also been studied. A group of researchers found a correlation between the airflow used by the PAPR and the leakage of contaminants into the mask (Figure 3). It also showed increased $CO_2$ concentration at a lower airflow [32]. Other researchers used holes to simulate leakages,

**Figure 4. PAPR airflow effect on the leakage Table 4. PFs under different conditions**

| Condition | PF | Source |
|---|---|---|
| Recommended fit (rest) | 787 | [30] |
| Recommended fit (exercise) | 445 | |
| Used with a knit (rest) | 762 | |
| Used with a knit (exercise) | 397 | |
| Used with a helmet (rest) | 737 | |
| Used with a helmet (exercise) | 469 | |
| Blower failure (low breathing flow) | 8 | [31] |
| Blower failure (high breathing flow) | 9 | |

finding that the efficiency of the masks lowered as the diameter of the hole increased [33].

### Other Parameters

Other parameters, such as comfort, temperature, carbon dioxide concentration, noise, and ease of communication, have also been tested. According to one study, PAPRs do not have a strong impact on the mobility of workers [17]. Tests were conducted in a confined space (ambulance) and participants took between 3–5 more seconds to complete four tasks when compared to performing the same tasks with traditional equipment. However, workers reported greater comfort while using the PAPRs [17]. Even though the workers may experience a slightly higher temperature, one study suggests that the temperature difference may not be felt, as it is less than the minimum difference that can be felt by the average person [34]. Noise has also been studied, as PAPRs use a blower that produces noise during operations. Noise levels can reach up to 56 dB, affecting communications. Word discrimination can be reduced to 48% even if the ear is left uncovered [35; 36]. Tests have been carried out to prove the feasibility of implementing a headset that facilitates

communication. Results are shown in Table 5. As can be seen, the implementation of a headset causes a great difference when it comes to identifying words with similar sounds (rhyme test). However, there is little to no improvement in understanding the ideas in a sentence.

**Table 5. Ratings [%] from communication tests for the HALO CleanSpace [25]**

| Test | Without Headset | With Headset |
|---|---|---|
| Rhyme Test | 70 | 84 |
| Word recognition | 98 | 97 |
| Meaning understanding | 95 | 95 |

## CONCLUSIONS

In the mining industry, workers could be exposed to dust and other particles that may cause irreversible diseases, such as CWP. PPE is the last barrier to safeguard a worker from undesirable elements. In underground mining operations, remedial measures such as ventilation airflow and dust scrubbers alleviate the exposure of the miners to respirable dust particles. However, the concentration of contaminants is still high in some places, and workers need this last barrier to ensure they are within a safe limit. The implementation of PAPRs in the mining industry could be a favorable step toward the improvement of the health of the miners. PAPRs are powerful tools for protecting workers against contaminants. They use high- efficiency filters and other additional mechanisms, such as positive pressure, to prevent hazards from reaching the worker. Several models (Figure 4) accommodate different needs and offer different protection levels. Therefore, they are a better option than most regular respirators currently used in various industries.

**Figure 4. Assembled PAPRs. 3M Versaflo loose-fitting helmet (left), CleanSpace EX tight-fitting (right)**

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