

Performance of Breath-Synchronized Powered Air-Purifying Respirator under Simulated Usage Conditions

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ABSTRACT

Certification tests for Powered Air-Purifying Respirators (PAPR) evaluate respirators according to a limited number of criteria, which may not include actual usage criteria such as comfort, cost and ease of wear. More extensive evaluations have been performed on two types of PAPRs under simulated workplace conditions: Breath-synchronized PAPRs (BS-PAPR) were compared to conventional constant-flow PAPRs (CF-PAPR) in a welding fume environment, where their airflow rates, total inward leakage, and maximum operating times were measured. The BS-PAPRs have an electronically controlled mechanism that synchronizes the fan's airflow rate with the wearer's breathing rate. These recently developed PAPRs mitigate several problems of conventional PAPRs that are due to the conventional PAPRs' high constant flow rate supply: high exhalation resistance, frequent filter replacement, and the need for a heavy battery. During the tests, a newly developed breathing machine simulated the inhalation and exhalation flows of individual welding workers whose breathing patterns were determined in a manufacturing facility for heavy machinery. While the total inward leakage of the BS-PAPRs was very low, similar to that of CF-PAPRs, the test data prove that BS-PAPRs use substantially less total airflow, thus extending the service life of the battery and filter by several times relative to the CF-PAPRs. This results in increased breathing comfort while providing high respiratory protection through use of a lightweight battery and a filter that is replaced infrequently.

Keywords: Powered air-purifying respirator, breathing simulator, peak inhalation air flow rate, respirator protection performance, total inward leakage, welding fume environment, filter

INTRODUCTION

Powered Air-Purifying Respirators (PAPR) move clean air through particulate filters or cartridges into the wearer's facepiece by means of a battery-operated blower. Since the pressure in the PAPR's facepiece is maintained above the surrounding atmospheric pressure, contaminated air is prevented from leaking into the facepiece while the wearer breathes. Therefore, PAPRs usually offer higher respiratory protection than negative-pressure air-purifying respirators (ANSI Z88.2, 1992; NIOSH, 2004), and are often used in hazardous workplaces, e.g., during asbestos removal. Conventional PAPRs supply a continuous high flow rate that is equal to or exceeds the peak breathing rate of the wearer (Burgess and Reist, 1969; Kimura, 2002). Continuously high clean-air supply may, however, increase breathing resistance, and may result in rapid clogging of the filter and in fast battery depletion. Currently used PAPRs employ large filters and a large battery whose weight may add to the strain on the wearer.

In order to increase the wearer's comfort, a PAPR has been developed with a Breath-Synchronized Air Flow System (BSFS) that supplies the optimal amount of air by monitoring the user's

breathing (Yuasa *et al.*, 2006). The BSFS comprises a small electronic circuit with a sensor that monitors the pressure inside the respirator in real-time. When the pressure drops during inhalation, the BSFS circuit increases the air supply rate, thus maintaining positive pressure in the facepiece. When the BSFS detects exhalation, it decreases the air flow-rate of the small variable-speed fan that is mounted on the facepiece, thus eliminating unnecessary air. In this study, the performance of the new breath-synchronized PAPRs is compared to that of conventional constant-flow PAPRs.

Most certification tests on respirators are carried out at constant airflow, but this does not simulate working conditions because breathing involves cyclic airflow. Linders *et al.* (2006), Nelson *et al.* (1972), Rowland (1970) and Brosseau *et al.* (1990) tested filters at sinusoidal airflow, but the breathing patterns of workers are more complex, and vary with work activity (Silverman *et al.*, 1951; Berndtsson, 2004; Coyne *et al.*, 2006). In workplace or laboratory evaluations (Lowry *et al.*, 1979; Cohen, 2001; Myers *et al.*, 1984; Lee and Lawrence, 1983), human subjects cannot easily repeat a breathing pattern, and large numbers of volunteers are needed to overcome this. This, and the problem of exposing volunteers to hazardous conditions, can be overcome by automated breathing and metabolic simulators (ABMS) (Nelson, 1972; Deno, 1984; Reimers, 1984; Kyriazi, 1986; Myojo, 1989), but these are not commonly available and no reports have been found on ABMSs that reproduce the breathing patterns of wearers in the workplace. Berndtson and Ekman (2003), and Groves (2006) recorded breathing patterns and obtained fit factors on human subjects, but their data have not been used in any breathing simulator.

In order to evaluate the new breath-synchronized PAPRs under simulated usage conditions and to compare them to conventional constant-flow PAPRs, a sampling device has been developed for recording the breathing patterns of individual workers, and a breathing simulator has been developed for reproducing their respiration.

MATERIALS AND METHODS

Respirators Tested

The respirators tested are tight-fitting half-face PAPRs: a breath-synchronized PAPR (BS-PAPR), and a conventional constant-flow PAPR (CF-PAPR). The latter is a BS-PAPR modified for constant airflow. The battery, filter resistance and maximum airflow of the blower are the same for both. The BS-PAPR has been designed to comply with the Japanese Industrial Standard for PAPRs (JIS T 8157, 1991). There is no national certification for PAPRs in Japan at this time. The airflow resistance of the particulate filter is 46 Pa at 40 LPM; the NaCl particle penetration, as required by the JIS T 8157 standard, is 1% or less at the maximum airflow rate of 150 LPM. With a new filter and a fully charged battery, the system maintains a positive pressure inside the facepiece for 5.5 hours or longer, when subjected to sinusoidal airflow of 40 LPM. The battery's rated voltage is 7.2 V. The fan and the BSFS circuit are installed in the facepiece. The response time of the BSFS circuit is short, a few milliseconds. The weight of this PAPR is 200 g, about the same as that of an air-purifying tight-fitting half-face particulate respirator.

Human Subjects for Respiration Measurements

In Japanese industry, about half of the operations with high aerosol concentrations involve welding (Ministry of Health, Labor and Welfare, 2001). Therefore, the breathing patterns were recorded of three experienced welders, trained to wear respirators (32 - 34 years old). Before their breathing patterns were recorded, each subject qualitatively checked that the respirator fit correctly, and then normal welding operations were performed. Their respirations were continuously recorded by a data-logger every 0.1 seconds for 800 seconds (13 min, 20 sec). The movements of the subjects were videotaped so that their breathing patterns could be related to the operations performed and to the working conditions.

System for Respiration Measurements

The system for recording the welders' respiration consisted of a half-face particulate respirator (1010, Koken, Japan) with a small pressure transducer implanted in it (GC-30, Nagano Keiki, Japan), and a battery-operated data-logger (GC-30, Nagano Keiki, Japan). The pressure transducer detects the changing pressure inside the facepiece and sends electrical voltage signals, to the small data-logger. The response time of the pressure transducer was 50 msec; the maximum recording frequency of the data-logger was 50 Hz. The total weight of the system, including the respirator, was less than 500 g. Since the pressure inside the facepiece does not linearly relate to the volumetric respiration rate, the recorded data were converted to breathing volume using calibration curves. This system can measure breathing in the range of 20 – 40 LPM, with an error margin of 5 % or less. Details on the system have previously been reported (Yuasa *et al.*, 2008).

Simulator of Individual Workers' Breathing Patterns

A breathing pattern simulator, consisting of a servo cylinder (CYA150D, Shinto, Japan) and two air cylinders (10A-6, Taiyo, Japan), has been developed for this study so that individual workers' breathing patterns can be repeatedly reproduced in performance tests with different types of respirators. The servo cylinder drives the air cylinders with a maximum stroke of 25 cm. The total capacity of the two air cylinders is 6 L. The maximum driving speed of the servo cylinder is 300 mm/s and its stroke frequency 300 cycles/min. The stroke distance can be adjusted to 0.1 mm, allowing the reproduction of very small changes in human breathing. The maximum frequency at full stroke is 0.5 Hz, equivalent to a respiratory minute volume of 180 LPM or a peak breathing rate of 600 LPM. Coyne *et al.* (2006) have reported that the peak inhalation airflow rate of a human working strenuously reached 600 LPM. Thus, the new breathing simulator can generate airflow rates that reflect human working conditions ranging from moderate to very strenuous workloads. The system can generate sinusoidal waves compatible with the breathing conditions used in the certification tests of many countries, as well as triangular and rectangular waves. Its most significant feature, however, is its ability to be controlled by varying external voltages, reflecting the airflow patterns of individual workers. In this study, the breathing patterns of the workers were entered as voltage waveforms from a function generator (2711A, Pragmatic Instruments, USA). The breathing patterns produced by the simulator were measured by a laminar flow meter and were compared with the applied waveforms, thus ensuring perfect reproductions of the workers' breathing patterns.

Performance Evaluations of PAPRs Using the Breathing Patterns of Individual Workers

Testing of airflow rates supplied by the PAPRs

The test setup shown in Figure 1 measured the airflow rate that the PAPR supplied during simulated human breathing. The test respirator was mounted onto a dummy head, which was connected to the breathing simulator. After starting the PAPR's fan, the breathing waveforms of each worker were successively reproduced by the breathing simulator. The airflow rate from the breathing simulator and the airflow rate supplied by the PAPR's fan were measured by a laminar flow meter (LFE-400, Sokken, Japan) and a pneumotachometer (Fleisch type, Metabo, Switzerland), respectively. The differential pressures for each flow meter were measured by micro differential pressure gauges (DP-320, Cosmo, Japan), and the pressure data were recorded by a personal computer using a data-logger (NR-250, Keyence, Japan). The measurement interval was 100 ms. Thus, this test system can monitor in real-time how the airflow rate supplied by the PAPR's fan changes with the breathing rate applied to the internal space of the respirator. The computer calculated the average minute volume of the subjects and the average airflow rate supplied by the PAPR's fan during the sampling period. The computer also calculated the amount of excess airflow supplied by the PAPR relative to the airflow needed for the pressure to remain positive inside the respirator.

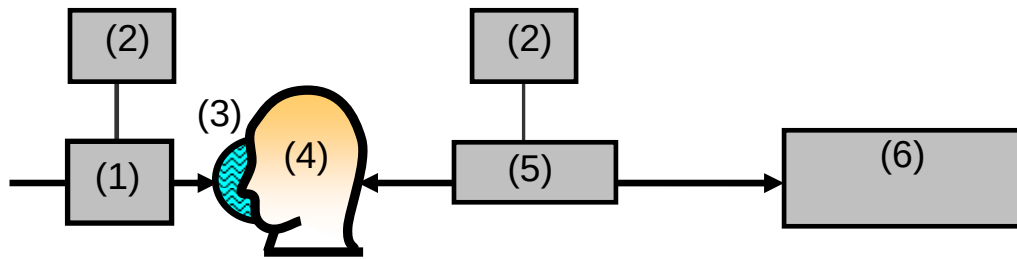


Figure 1. Test setup for supplied airflow test: (1) pneumotachometer for measuring supplied air, (2) pressure transducer, (3) test PAPR, (4) dummy head, (5) laminar flow meter for measuring breathing pattern, (6) breathing simulator.

Determination of the PAPRs' service life in a welding fume environment

Figure 2 shows the test setup for evaluating the PAPRs under simulated work conditions. The test respirator was attached to a dummy head, which was placed in a test chamber with a carbon dioxide gas arc welding machine (DynaAuto X3, Daihen, Japan). The faceseal between the test respirator and the dummy head was adjusted until the total inward leakage was 5 % without running the PAPR's fan. The total inward leakage was calculated from the fume concentrations in the chamber and inside the respirator, as measured by aerosol monitor 1 (AP-6320, Sibata, Japan):

$$\text{Total inward leakage (\%)} = 100 \cdot C_i / C_0$$

where C_i = fume concentration inside the facepiece (mg/m^3), and C_0 = fume concentration in the chamber (mg/m^3).

The fume concentration inside the respirator was sampled near the nose of the dummy head. The tests were terminated whenever the total inward leakage reached 2%, because the assigned protection factor (APF) of the tight-fitting half-face PAPR was 50 (ANSI Z88.2, 1992).

The mouth of the dummy head was connected to the breathing simulator which reproduced the breathing patterns of individual subjects. The mouth was located 30 cm horizontally and 60 cm vertically from the welding arc point, corresponding to the distance at which a worker is exposed to welding fumes. The total inward leakage is somewhat dependent on the level of the fume concentration in the test chamber, due to potential coagulation of the welding fumes. Therefore, the welding fume concentration was maintained at $30 \pm 3 \text{ mg}/\text{m}^3$ by adjustments of the arc interval, which was automatically controlled by aerosol monitor 2 (P-5H, Sibata, Japan).

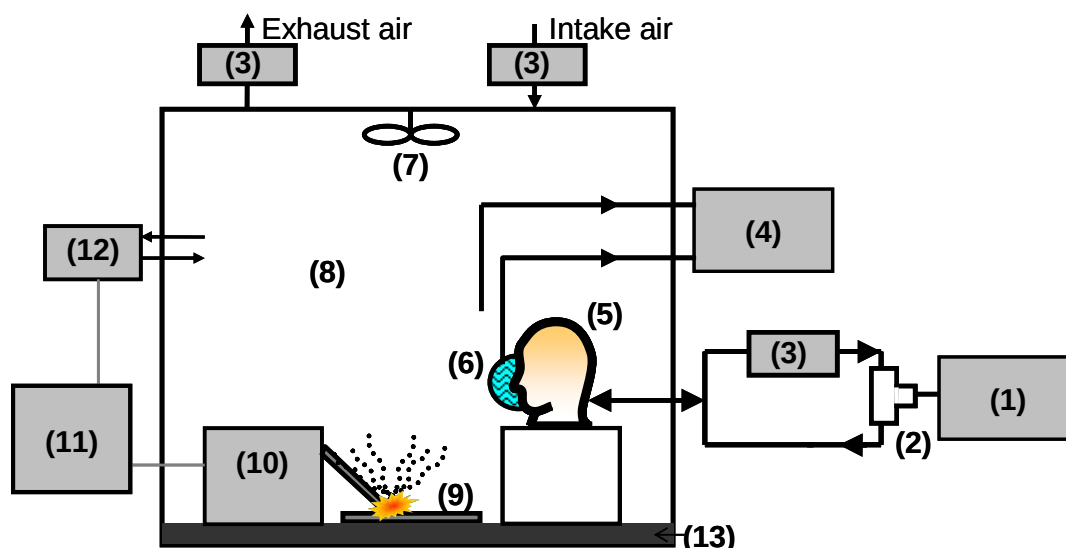


Figure 2. Test setup for determining the respirator service life in a welding fume environment: (1) breathing simulator, (2) three-way valve, (3) HEPA filter, (4) aerosol monitor 1 for measuring total inward leakage, (5) dummy head, (6) test PAPR, (7) fan, (8) fume chamber (2.7 m^3), (9) steel plate, (10) welding machine, (11) welding controller, (12) aerosol monitor 2 for measuring the fume concentration in the chamber, (13) isolation board.

RESULTS

Sampling and Reproduction of Workers' Respiration

The left side of Figure 3 shows the breathing patterns of three welders recorded in a factory manufacturing heavy machinery. The right side shows the breathing patterns reproduced by the breathing simulator. The breathing patterns of the three welders significantly differed from each other, due to differences in their work activities and differences in their lung capacities. Subject A was welding in sitting and in standing positions and was also polishing welded material. Examination of his breathing patterns indicates that his breathing volume decreased during welding and increased during polishing, and that his breathing changed significantly as his work progressed. Subject B worked standing, not welding much, but mainly polishing welded material. His breathing volume increased significantly with time, after he had been polishing for a prolonged period. Subject C worked in a well-ventilated area and his work was not strenuous. Therefore, his breathing was more constant. Table I shows the average respiratory minute volumes and the peak inhalation airflow rates calculated from the waveforms of Figure 3. The respiratory minute volume (i.e., the average volume of air moved per minute) ranged from 17 LPM for subject C to 31 LPM for subject B. The peak inhalation airflow rate was over four times that of the average minute volume for each subject. Any increase in filter resistance was found to be negligible, during the short sampling time of less than 14 minutes.

Table I. Respiration Data for Subjects A, B and C

	Original breathing pattern			Reproduced breathing pattern		
	A	B	C	A	B	C
Average minute volume (LPM)	24	31	17	23	29	16
Peak inhalation air flow rate (LPM)	128	145	85	128	140	91

Examination of the left side versus the right side of Figure 3 indicates that the waveforms reproduced by the breathing simulator match the sampled waveforms quite well. Table I proves that the respiratory minute volumes calculated from the reproduced waveforms match the workers' actual minute volumes within less than 10 %. A personal computer recorded the sampled breathing patterns of the welders, thus allowing the same waveforms to be repeatedly reproduced in respiratory evaluations. While only three subjects were studied at this time, breathing records from more workers in various types of working environments would allow for evaluating the practical performance of respirators in various types of simulated working environments.

Airflow Rates Supplied by PAPRs

Figure 4 shows the breathing patterns of the three subjects and the airflow rates supplied by the two types of powered air-purifying respirators, tested with the setup of Figure 1. The 30 seconds of data for the breathing patterns are taken 300 seconds after starting the tests, see also the right side of Figure 3. The area with light shading shows the supplied airflow rate of the breath-synchronized PAPR, BS-PAPR. The area with darker shading shows the supplied airflow rate of the constant-flow PAPR, CF-PAPR. From these results, the average minute volume and the average supplied airflow rate were calculated.

While Subject A's average respiratory minute volume was 23 LPM (see Table I), the CF-PAPR maintained a high average supplied airflow rate of 124 LPM, which is about five times the subject's needed air supply rate and approximately corresponds to its peak breathing flow rate. In contrast, the BS-PAPR supplied air according to the subject's breathing pattern. During inhalation, the air supply was slightly higher than the inhalation flow of the simulated subject. During exhalation, the air supply was very small. As a result, the average supplied airflow rate for the BS-PAPR was about twice the subject's demand, much less than for the CF-PAPR. Subject B had the most strenuous breathing pattern among the three subjects, but the supplied airflow rate of the BS-PAPR was still higher than its inhalation peak flow rate, thus proving the high responsiveness of the Breath-Synchronized Air Flow System. For subject B, the average supplied airflow rate of the BS-PAPR was 49 LPM, less than half of the 121 LPM supplied by the CF-PAPR. Subject C's average minute volume was 16 LPM and his average supplied airflow rate 32 LPM, the lowest among the subjects, but the CF-PAPR's average supplied airflow rate was 121 LPM, almost eight times the wearer's demand. Since the CF-PAPR supplies air continuously, regardless of the respirator wearer's volumetric breathing rate, the CF-PAPR supplies much excess air in work situations, where the breathing volume of the respirator wearer is low. In contrast, the BS-PAPR supplies much less air, when the breathing volume is small.

These data highlight the most significant difference between the BS-PAPR and the CF-PAPR: the average amount of air supplied to the powered air-purifying respirator is usually much less for the breath-synchronized PAPR than for the constant-flow PAPR. When the wearer inhales, the BS-PAPR supplies an airflow rate that is slightly higher than its inhalation flow rate, in order to maintain positive pressure in the facepiece. When the wearer exhales, the air supplied to the BS-PAPR is reduced to a low flow rate, thus avoiding the high flow rate of excess air supplied by the CF-PAPR. Thus, the BS-PAPR reduces the breathing resistance during exhalation, the accumulation of particulates on its filter, and the consumption of battery power.

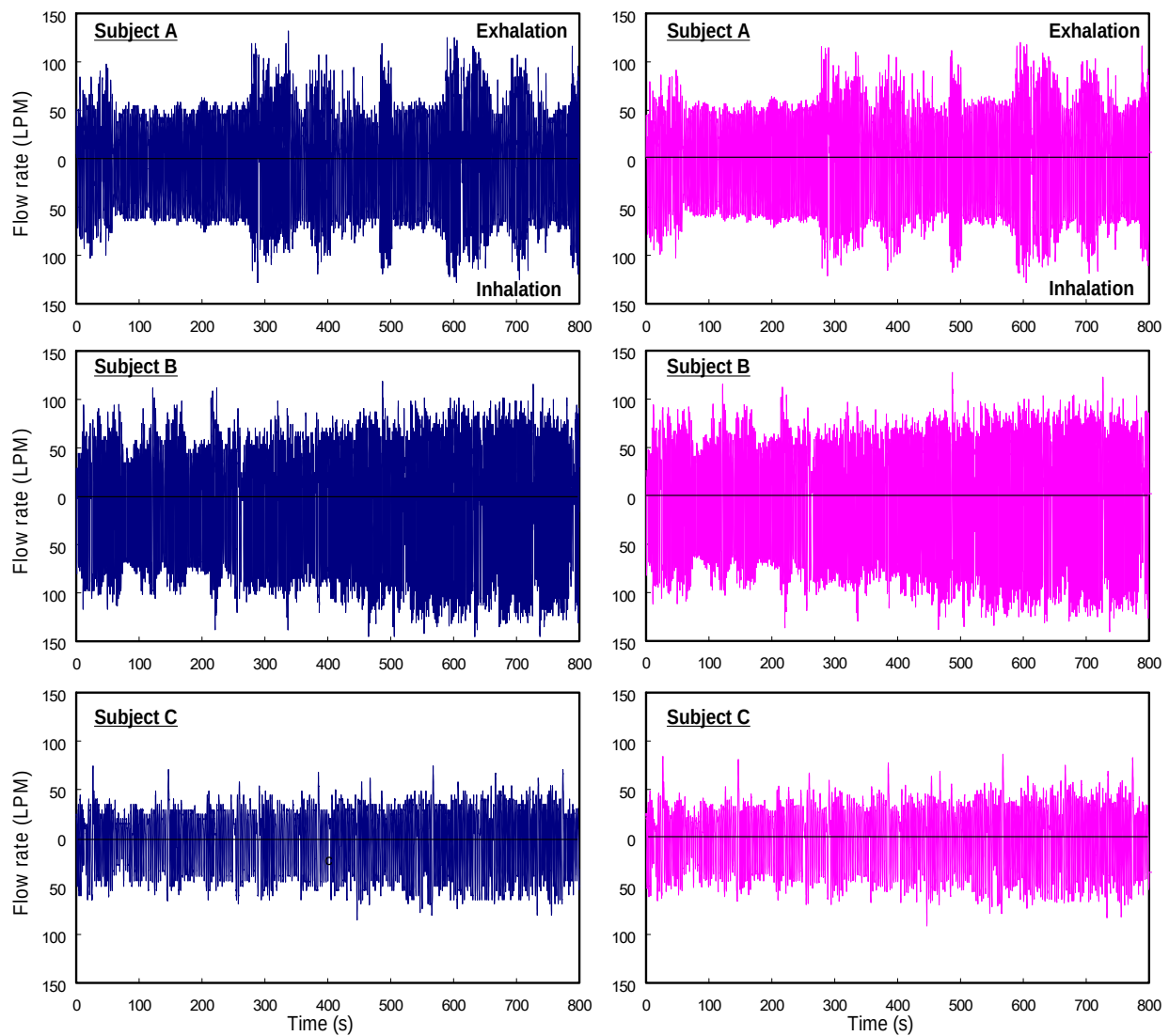


Figure 3. Breathing patterns of three welders during operation. Left: sampled in a factory manufacturing heavy machinery. Right: reproduced by the newly developed breathing simulator.

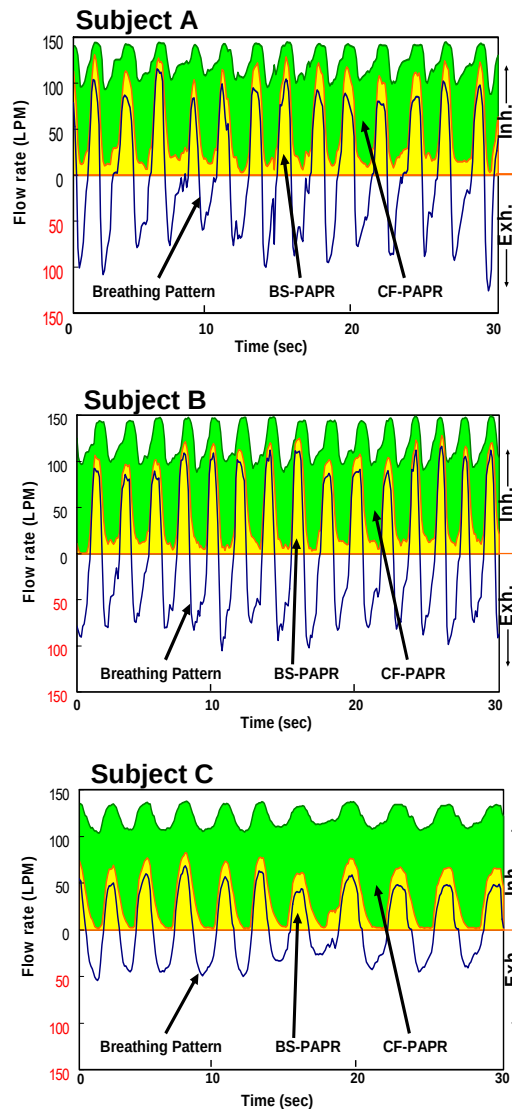


Figure 4. Airflow rates supplied to the breath-synchronized and constant-flow PAPRs.

Service Life in a Welding Fume Environment

Figure 5 shows the total inward leakage with time in the carbon dioxide gas arc welding fume environment. In this experiment, both types of PAPR were mounted on the dummy head so that 5% of intentional leakage was created before the blower was activated. Upon turning on the PAPR's blower, both types of PAPR showed almost no inward leakage, indicating the same initial protection. However, with time, inward aerosol leakage occurred after some time for both types of PAPR. Burgess and Reist (1969) and Kimura (2002) reported that inward leakage increases when the pressure in the PAPR became negative relative to atmospheric pressure. Therefore, it is concluded, that initially the airflow supply was higher than the peak inhalation flow rate, and positive air pressure was maintained in the facepiece, with no leakage through the face seal. However, with time, particulates accumulated on the

filter, lowering the supplied air flow rate, and the pressure in the PAPR became negative relative to atmospheric pressure, as the wearer breathed. The inward leakage of particles was significantly higher for high inhalation airflow rates; this suggests that inward leakage was affected by breathing intensity. Figure 5 shows the time span for which the PAPRs were most effective for the breathing of the subjects.

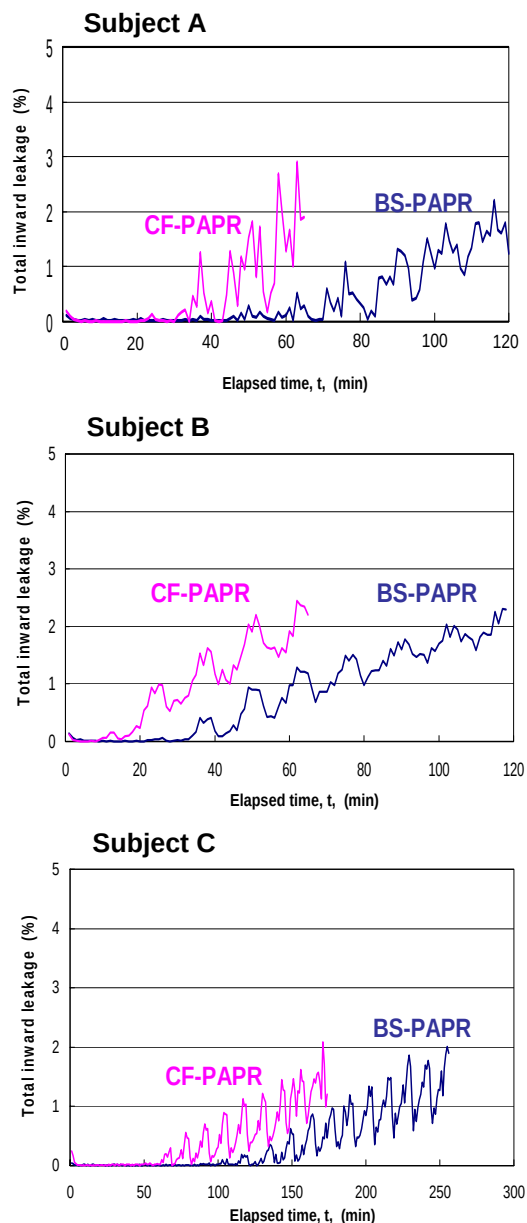


Figure 5. Total inward leakage after the PAPRs are activated. At $t < 0$, the blower is OFF, and the initial inward leakage is 5%.

In the case of subject A, the onset of inward aerosol leakage for the CF-PAPR occurred after about 30 minutes, for the BS-PAPR after about 50 minutes, i.e. the BS-PAPR maintained positive pressure in the facepiece about 50 % longer than the CF-PAPR. The breathing of subject B was the most vigorous among the subjects: the effective use time of PAPRs was short, about 10 minutes for the CF-PAPR and about 35 minutes for the BS-PAPR. The breathing for subject C was the lightest among the three subjects, and the onset time for inward aerosol leakage was the longest, 65 minutes for the CF-PAPR, and over 100 minutes for the BS-PAPR. Since the welding fume concentration was very high in this study, and the leak gap was rather large, the service life for the PAPRs was short. In actual work environments, the welding fumes are likely to disperse faster than in the small test chamber. Thus, in actual work environments, the usage times of PAPRs are expected to be significantly longer than in the extreme cases presented.

These data suggest that the BS-PAPR is very effective in practical applications, because it maintained positive pressure in the facepiece for a longer time than the CF-PAPR, thus providing respiratory protection for a longer time. This is likely due to less particulate loading on the BS-PAPR's filter, because the BS-PAPR pulls only a little more air through the filter than needed by the wearer. The filter and battery of the BS-PAPR may, therefore, be much smaller, weighing less than those of the CF-PAPR, thereby reducing the physical burden on the wearer. A negative pressure sensor may be desirable inside the facepiece to alert the wearer, when the PAPR's respiratory protection may have decreased due to the potential inflow of contaminants.

CONCLUSIONS

A method has been developed for measuring the breathing patterns of individual workers wearing powered air-purifying respirators. These breathing patterns were reproduced in a laboratory setup and used to evaluate newly developed breath-synchronized PAPRs against conventional constant-flow PAPRs. A breathing simulator was developed for reproducing these breathing patterns. The new device was found to be effective for comparing different types of respirators when subjected to various breathing patterns. In this study, the breathing patterns of only three welders were determined and used for the PAPR evaluations. However, the device is capable of investigating the breathing patterns of a great variety of industrial workers in various kinds of workplaces. The presented data show that the breathing patterns and the respiratory protection achieved differ among the subjects wearing PAPRs. The data also prove that the breath-synchronized PAPR is very effective in practical use, because it supplies the optimal airflow to the respirator according to the wearer's breathing. Thus, there is less excess airflow than with the conventional constant-airflow PAPR. This reduces filter clogging and battery power consumption, contributing to a reduction in operational costs and to a greater saving of resources. BS-PAPRs provide high protection and long service life in actual use, while reducing the physical burden on the wearer.

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