Peak Inhalation Air Flow during an Agility Test Performed by the US Marine Corps

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Introduction

This study was commissioned by the Chemical and Biological Incident Response Force (CBIRF). In conjunction with other testing, this survey forms part of CBIRF's quest to establish whether filter respirator devices can protect US Marine personnel in action, and to what extent.

Negative pressure respirators and Powered Air Purifying Respirators (PAPR), are used by the US Marine Corps to protect personnel when working in contaminated atmospheres.

The inhaled air passes through a filter or filters by the face mask and the fan unit to the lungs of the wearer. The level of protection provided to the wearer depends on the filter capacity and the seal offered by the face mask, as well as the integrity of connections, hoses, valves, etc.

One identified limitation is the capability of the equipment to function when the wearers are required to perform work at or near maximum physical capacity.

This study was designed to simulate the work intensity which could be required by US Marine Corps performing their assigned tasks. The decision to use the 'Agility Test' protocol, described below, was arrived at through a consensus between CBIRF, NIOSH, SBCCOM, NavAir, OSHA and CBRNC-TSWG.

*NOTE: To avoid misunderstandings, the term **liters/minute is used** when referring to PIAF (Peak Inhalation Air Flow) and **minute liters** when referring to volume of air.*

Material and methods

The equipment used was an FPBR (Fan-supplied Positive pressure Breath responsive Respirator) model SE400AT with a Domestic Preparedness Filter (ABEK3P4). This filter is designed to filter all known war-gases, TIGs (Toxic Industrial Gases) and particulates including biological and radioactive particulates. The respirator has a built-in flow meter that is based on the pressure-drop on a known restriction. The data is collected by a data logger at 50 Hz on two channels (pressure in the ori-nasal mask and flow, including the volume of air passing through the respirator).

The SE400AT used are identical to the NIOSH approved units, only calibrated according to Attachment 1.

For this report only the volume of air (minute liters) and the PIAF (liters/minute) are used.

The heart rate was measured with Polar Electro heart rate meter (S610).

All data was transferred to a computer for analysis.

Subjects

Forty-five marines (42 male and 3 female) participated in the study. Anthropometric details are given in table 1.

Table 1

	Average All Subjects	**Standard deviation**	**Min**	**Max**
Age	22	2	19	29
Weight kg	83	11	59	105
Height cm	181	9	152	191

Test Procedures

The test was carried out at US Marine Corps training facility (Indian Heads) on September 20, 2002. The weather was sunny, temperature +22 ±2 degrees Celsius, relative humidity 75%.

The subjects were dressed in military training uniforms including military boots. They were also wearing a 22.7 kg lead vest during the entire exercise, as well as the SE400AT respirator and data logger (3.62 kg).

A short introduction to the SE400AT was conducted before the test. The test subjects were then helped to get dressed, and to start the data logging.

The protocol was the same 'Agility Test' as that used as a requirement for a fire-fighter to join the brigade. Normally the subjects need to complete the test in a specific time (10 minutes 20 seconds). However, this time requirement did not apply to this test. The time spread was 12 to 20 minutes.

The Agility Test protocol includes the following elements:

#1 — Stair climb, wearing an extra 22.7 kg lead vest, 3 minutes

#2 — Hose drag, 1min

#3 — Carry equipment, 1min

#4 — Raise a ladder, 1min

#5 — Forced entry (hitting a wall with a certain force with a sledge hammer), 1 min

#6 — Search (crawling through a maze) 3 min

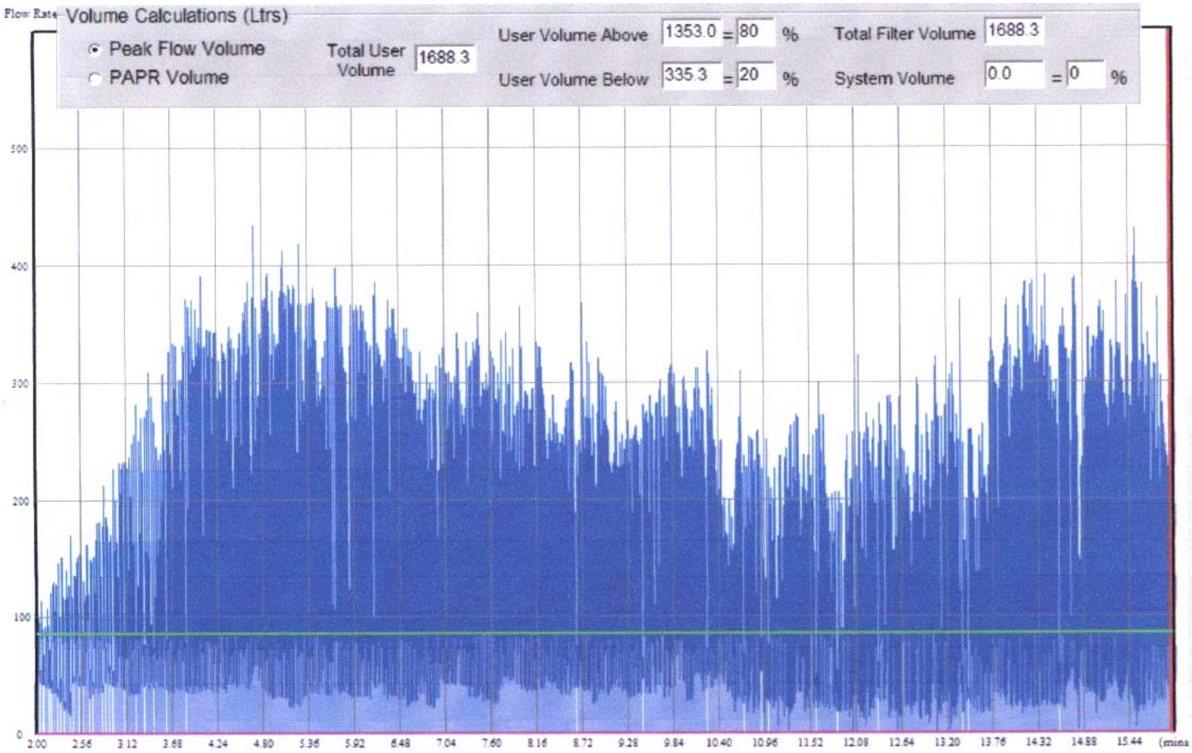
#7 — Rescue (pulling a stretcher with a mannequin [80 Kg] a certain distance), 1 min

#8 — Ceiling breach & pull down (opening and closing a smoke hatch a number of times), 1.5 min

Methods

The example of a recording of the flow rate for one subject is shown in figure 1.

Figure 1



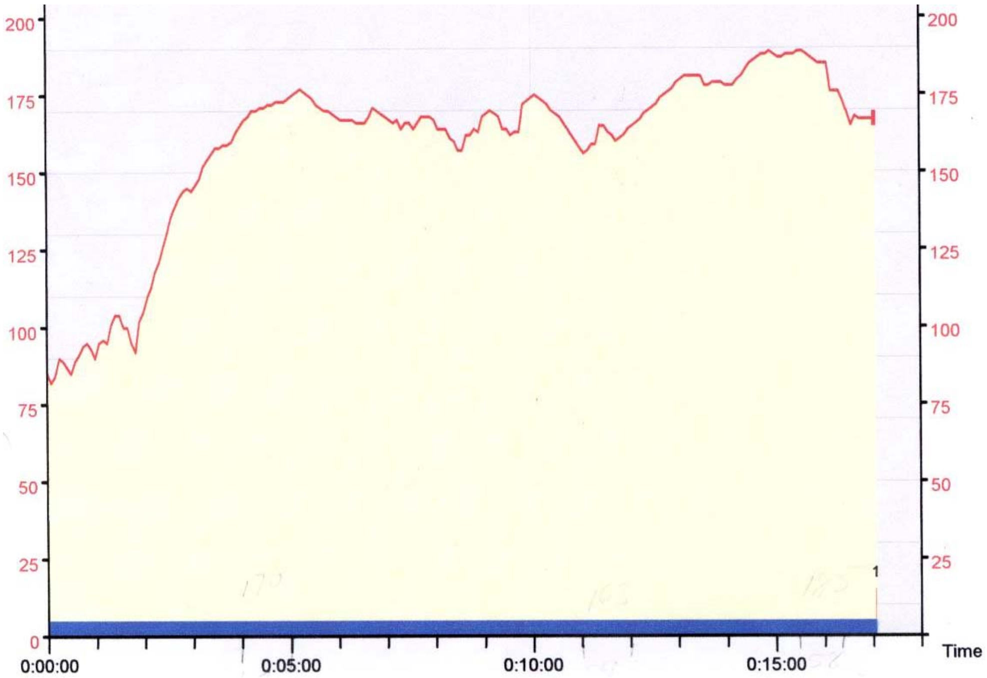
Vertical axis shows PIAF (liters/minutes) Horizontal axis shows time (min)

Each spike represents the inhalation phase of a breath. The high PIAF (Peak Inhalation Air Flow) in the first 3-6 minutes represents the stair climb. The high PIAF in the end represents the opening and closing of the smoke hatch. The period between shows the other exercises. As can be seen clearly, the first and the last exercises are the most demanding. They produce both the highest PIAF and the highest minute volume. During the stair climb, the subjects are carrying an extra 22.7 kg in the form of an additional lead vest.

From the first exercise and onward, the intensity and the air requirement constantly decrease until the Ceiling breach & pull down exercise (simulating opening and closing the smoke ventilation hatch). This is a very intense exercise and requires a lot of air.

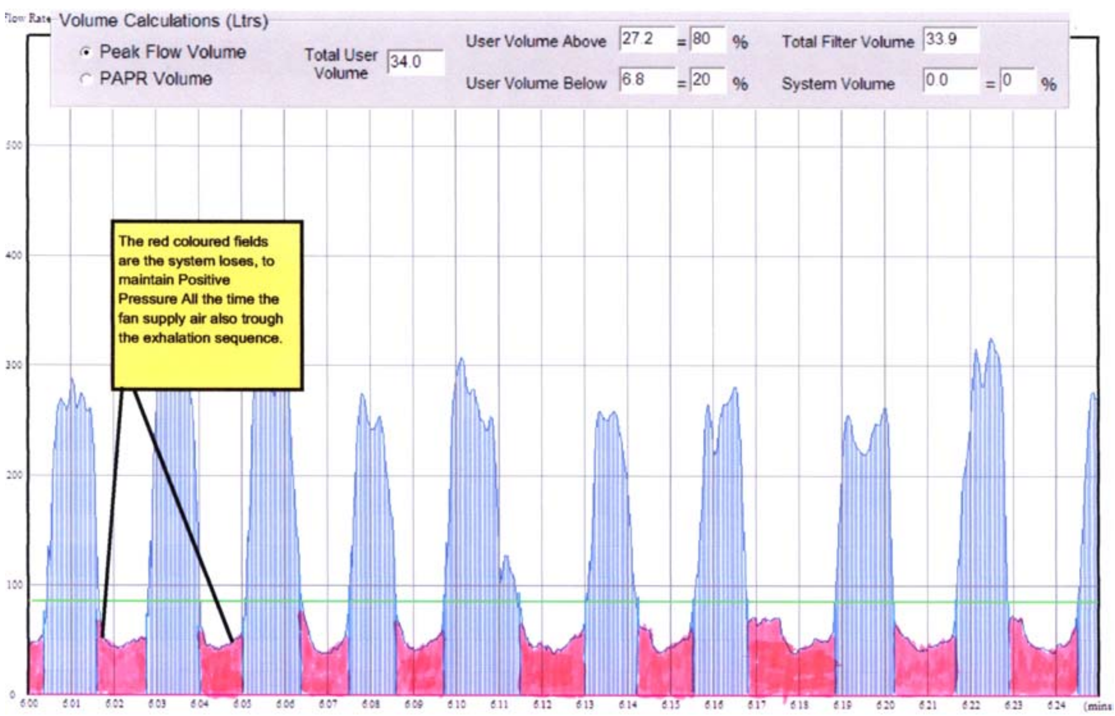
This is also verified by the heart rate (Figure 2).

Figure 2



Vertical axis shows heart rate Horizontal axis shows time

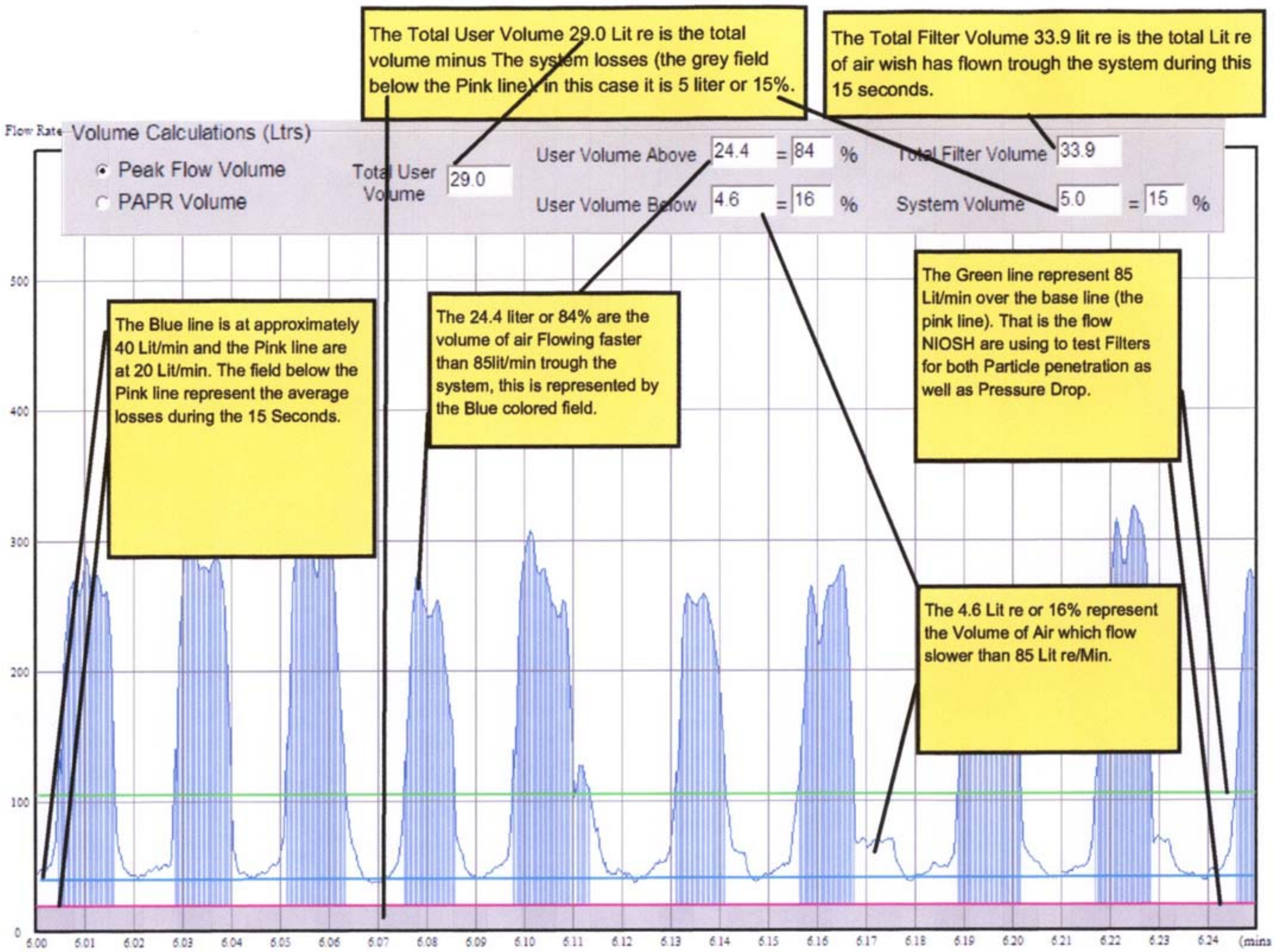
Figure 3



The function of an SE400AT is dependent not only on the flow requirement of the user but also on the pressure in the ori-nasal mask. The SE400AT adjusts its fan speed depending on the pressure in the ori-nasal mask to maintain Positive Pressure in the mask enclosure. Figure 3 shows a typical 15 second period of a subject. The blue fields are the inhalation phases of a breathing cycle. The red fields are the system losses in maintaining positive pressure All the time, the fan supplies air, also through the exhalation sequence. The volume of those losses varies from 10-30%. The higher percentage losses normally occur at low work rates. The average in this test was 17% (see sample Figure 5). In this report, the higher number is used, as it is the total volume flowing through the filters (as two filters are used, the volume through each filter is half of the total volume).

Figure 4 demonstrates how the different figures are calculated. As sampling is done at 50 Hz, the resolution is high. Data can be inspected down to 15 second periods. With this resolution it is easy to see how different each person's breathing is.

Figure 4

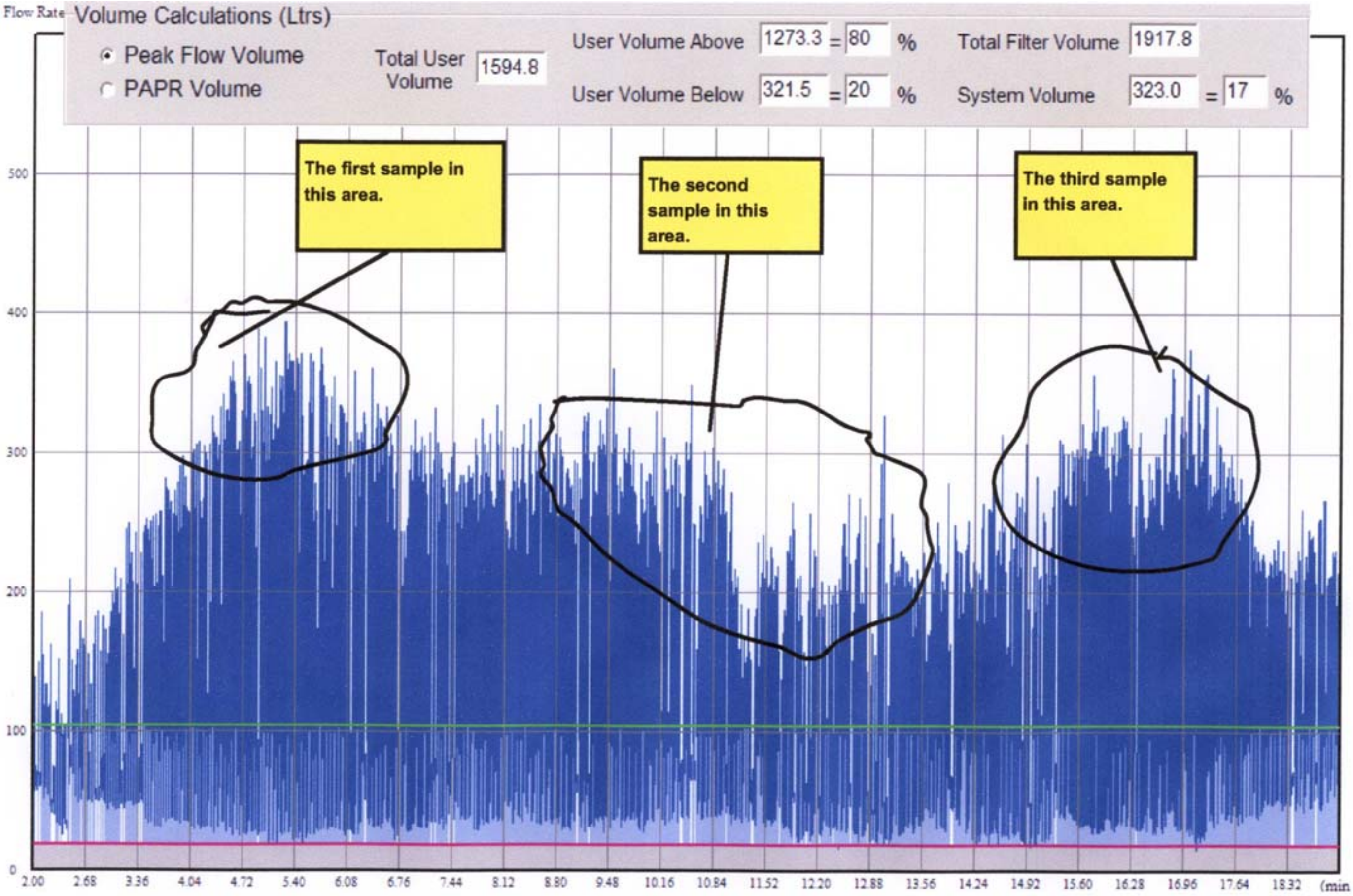


44 successful subjects were sampled for an average of 15 min at 50 Hz = 1,980,000 data points. It was decided to take three minutes from each of the subjects; one in the beginning of the exercise (as the first exercise was the longest in duration), one in the middle and one in the end. There is not a significant difference between the first and the last sample minute.

A number of minutes from a number of subjects was then randomly selected to verify the accuracy statistically.

Altogether, the final file contains data on 6,557 breaths.

Figure 5.



This person had a total system volume of 1,917.8 liter volume in the 16 minutes this graph represents. The total user volume is 1,594.8 liter minute volume (99.66 liters per minute). Of this total user volume, 1,273.3 liters or 80% flow faster than 85 lit/min (the rate used by NIOSH in testing filters for particle penetration and pressure drop).

Data

The first consideration is minute volume. The average minute volume for all data is 128 minute liters with a max of 211. The reason for this high volume is that there is next to no breathing resistance, which allows the subject to get the volume of air he/she needs to perform the required task. If it can be assumed that the system loss is 17%, the average volume of air used by the subject at the highest-use minute is 106.24 minute liters. This is 28% higher than Dr. J. Kaufman recorded as an average, which is a reasonable expectation without resistance.

Looking at how much of this volume was over 115 lit/min (the NIOSH requirement for PAPR with full face mask), an average 36% of the volume was above this requirement. More important, looking at how many breaths were over 115 lit/min, out of all the 6,557 breaths that were recorded for this report, 6,417 breaths or 97.9% were over 115 lit/min, and would out-breathe a PAPR into negative pressure.

In regard to the particulate filter performance and pressure drop, 78% of the volume was flowing faster than 85 lit/min. This is significant, as all filters are velocity-dependent in regard to filter penetration.

Again looking at how many of the breaths were flowing faster than 85 liters per minute, in 6,537 breaths or 99.69% of the breaths, the air flows faster than 85 lit/min.

The average breaths per minute (48) and average heart rate (169) indicate that the subjects worked very hard. Details can be found in Table 2.

Table 2

First minute	**Average**	**Standard Deviation**	**Max**	**Min**
Lit/min	148	24	211	106
% Volume Over 115 lit/min	45%	10	62%	24%
% Volume Flowing faster than 85 lit/min	83%	5	93%	71%
Breaths per minute	45	8	61	32
Heart rate	168	16	190	110
Second minute				
Lit/min	95	23	162	62
% Volume Over 115 lit/min	24%	13	52%	2%
% Volume Flowing faster than 85 lit/min	69%	11	89%	43%
Breaths per minute	46	7	60	31
Heart rate	164	15	195	125
Third minute				
Lit/min	140	25	201	76
% Volume Over 115 lit/min	39%	9	56%	20%
% Volume Flowing faster than 85 lit/min	82%	5	91%	71%
Breaths per minute	53	9	81	32
Heart rate	174	17	199	125
All Data				
Lit/min	128	33	211	62
% Volume Over 115 lit/min	36%	14	62%	2%
% Volume Flowing faster than 85 lit/min	78%	10	93%	43%
Breaths per minute	48	9	81	31
Heart rate	169	16	199	110

The importance of PIAF (Peak Inhalation Air Flow)

If the PIAF is higher than the supply capability of the PAPR, the performance protection of the PAPR is not higher than its face mask as a negative pressure respirator — in this case, a full face mask, and what is influencing the performance is the capability to seal against the face at all different pressure drops.

The performance of the filters also plays a role at this high PIAF. As mentioned above, the particulate part of the filter is influenced by the velocity of the air moving through it.

It is commonly accepted that a gas filters capacity against organic compounds is not significantly influenced by higher air flow (pulsating flow). The performance against acid and ammonia has yet to be verified at higher flow (pulsating flow).

As shown in Table 3, the average PIAF for all data is 290 lit/min with a max of 582 lit/min.

Table 3

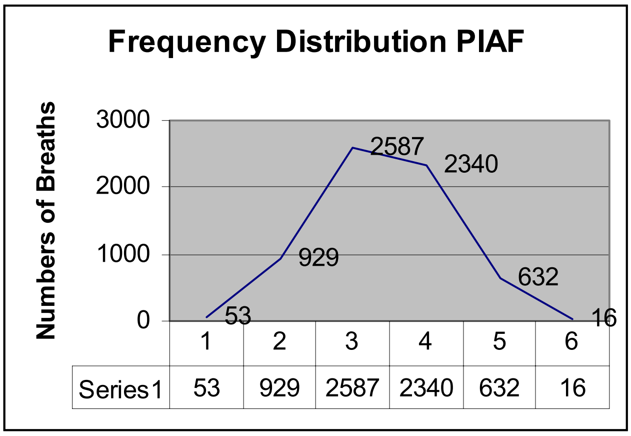
	Average PIAF	Standard deviation	Max	Min
First minute	340	67	520	407
Second minute	222	77	504	61
Third minute	301	67	532	103
All data (including additional sample for statistical verification)	290	85	582	61

The frequency distribution is shown in Table 4 and Graph 1.

Table 4

PIAF (lit/min)	Number of breaths	%
Less than 100	53	0.81
100—200	929	14.17
200—300	2,587	39.45
300—400	2,340	35.69
400—500	632	9.64
500—600	16	0.24
Total	6,557	100.00

Graph 1



This shows a typical distribution curve. 75% of the peak flows are between 200-400 lit/min.

The 95th percentile is 427 lit/min, which means that in order to maintain positive pressure all the time for 95% of the US Marines, the PAPR must have an airflow of 427 lit/min (see table 5).

Table 5

	Lit/min peak flow
95th Percentile	427
87th Percentile	390
80th Percentile	368
70th Percentile	338
60th Percentile	314
50th Percentile	290
40th Percentile	265
30th Percentile	243
20th Percentile	217
10th Percentile	175

Table 5 shows, for example, that a standard PAPR does not even provide sufficient airflow to the 10th percentile.

Conclusions:

1. Inspiratory air flow rates are high for all exercises. This concurs with earlier findings by the author as well as Dr. J. Kaufman, *Respiratory Airflow in Working Individuals Wearing Chemical Protection,* Mr. I. Holmér, *Respiratory flow patterns during physical work with respirators*, and Dr. P-O. Åstrand, *Textbook of Work Physiology.*
2. The high work activity required of the Marines generates high PIAF rates, often in excess of the typical test flows, raising the question, how well will the US Marines be protected?
3. Apart from the results seen here comes the question of speech. As talking was not part of the test program, it is know known whether the subjects did talk, and if they did, how loud or for how long. However, the test results indicate that no significant amount of speech took place during this test. As Mr. Ingvar Holmér concludes in his study, talking raises the PIAF by 50%.
4. A full 78% of the inhalation sequence is made up of air that flows faster than 85 lit/min.
5. The capabilities of a filter to filter out contaminants at that high PIAF is not known for some parts of the filter, as they are not tested at this high flow rate as part of standard testing.
6. In order to maintain positive pressure for 95% of all US Marines, an air flow of 427 lit/min is required.

Future work:

The test outlined here forms part of a wider spectrum of respirator research, and further work is in progress. The test subjects described here were young and fit. Future research will endeavor to establish the variations occurring in a larger and more diversified cohort. This should serve to give us a broader picture of the relationship between work rate, breathing resistance and PIAF in people of all ages and fitness levels.

Acknowledgements

Many thanks to Lt Col Scott A. Graham and Sam Pitts from CBIRF, to all volunteers, participants and observers, among them Terrence K. Cloonan of NIOSH, Dr Jonathan Kaufman of the Naval Air Systems Command and Walt Kaplan from the Special Operations Response Team (SORT).

References:

Åstrand, P.O., Rodahl, K., 1986 (1970), *Textbook of Work Physiology: Physiological Bases of Exercise*, 3rd ed., McGraw-Hill Book Co. International Series, New York

Berndtsson, G., Ekman, L., Jessup, S., Berndtsson, F., 2002, *Ventilation Volume and PIAF when Wearing Negative and Positive Pressure Respirators*, presented at International Society for Respiratory Protection Conference, Edinburgh, Scotland, 02 Oct

Holmér, I., Kuklane, K., 2002, *Respiratory Flow Patterns during Physical Work with Respirators*, Department of Ergonomics, National Institute for Working Life, Solna, Sweden

Kaufman, J., 2000, *Initial Findings: Respiratory Airflow in Working Individuals Wearing Chemical Protection*, presented at NIOSH/NIST/SBCCOM Public Meeting, Canonsburg, Pennsylvania, USA, 16 Oct

Wallaart, J., Winder, C., *The Determination of Peak Inspiratory Air Flows (PIAF) at Various Levels of Work and the Increased Air Flows that Result when Communicating in the Workplace*

Wallaart, J., *The Determination of Minute Air Flows and Heart Rates for a Typical Industrial Work Group at Various Levels of Work*

Attachment 1

January 21, 2003

Safety Equipment America

Attention: ***Mr Goran Berndtsson***

Re: Calibration History of the Data logging SE400 Kits

Dear Goran,

The Data Logging SE400 Kits that you currently have, are serial numbers:

Fan Serial Number	**Work Order**	**% Error at 50x2 litres**	**% Error at 25x2 litres**
F012295	2002-147-01-MF	+7%	+15%
F012283	2002-147-01-MF	+1%	+13%
F012288	2002-147-01-MF	+5%	+17%
F012287	2002-147-01-MF	+3%	+9%
F012293	2002-189-01-MF	+3%	+8%
F012296	2002-189-01-MF	+2%	+5%

Originally when Data Logging Kits were developed, the components were all standard, approved components, with the exception of the fan unit. The fan units were fitted with what were claimed to be improved transducers. It was hoped that these new transducers would give more precise results than the standard NIOSH approved transducers.

After evaluating the performance of the new transducers it was determined that the performance was no better than the standard NIOSH approved configuration.

A decision was made to rebuild all Data Logging Kits to NIOSH standard configuration.

The units listed above were rebuilt, to NIOSH standard configuration, and calibrated on the Work Orders shown above. The flow calibration results achieved for each unit are also shown above for your information. The calibration was done at between 20 and 25 degrees centigrade.

I hope that this letter addresses your requirements.

Sincerely,

Andrew Smith
Quality Assurance Manager
andrew.smith@seasafe.com.au

Attachment 2:

Observations made by Robin Howie

Data analysis

The data were analysed using EXCEL to identify the range of PIAF and Minute Volumes to establish equipment requirements.

Each test subject generated about 50,000 data points for about 600 breaths, i.e. a total of about 2 million data points were obtained for the 44 subjects. It was therefore necessary to restrict the number of data points analysed.

The initial restriction was to base analysis on three one minute periods: the periods of highest minute volumes during the first and last exercises and period of lowest minute volume over the whole test period. The validity of applying this restriction was tested by comparing 1) the results of these three periods with the results for the total results for one subject selected at random and 2) selecting at random a further three one minute periods for three test subjects selected at random.

The first comparison indicated that the randomly selected data point samples were representative of the results as a whole. The second comparison indicated that the mean PIAF of the two sets for each subject differed by less than about 5% of figure. It was therefore concluded that the initial set of three one minute periods for each subject was a valid basis for further analysis.

The current breathing resistance test condition of 85 l/min for negative pressure respirators is presumably based on the assumption of being the peak inhalation rate corresponding to a Minute Volume of 1 cubic foot, 28.3 litres.

The data were analysed to determine the actual numbers of PIAF and Minute Volumes for each subject which exceeded 85 litres/min or 115 litres/min or 28.3 litres respectively and the 75^{th} and 95^{th} percentile PIAF.

Distribution of PIAF

Individual PIAF ranged between 61 and 582 l/min. A total of 24 breaths for 9 subjects had PIAF < 85 l/min a total of 117 breaths for 22 subjects had PIAF < 115 l/min.

Of the total of 6,557 breaths analysed, 6,533, 99.6%, exceeded 85 l/min and 6440, 98.2%, exceeded 115 l/min.

The 75^{th} and 95^{th} percentile PIAF were 350 and 428 l/min respectively.

Distribution of Minute Volumes

Individual Minute Volumes ranged between 61.7 and 210.5 litres. All Minutes Volumes therefore exceeded the nominal figure of 28.3 litres by at least a factor of 2.

The 75th and 95th percentile Minute Volumes were 151 and 178 litres respectively.

Suggested Conclusions

The results of this study demonstrate conclusively that the current assumptions regarding the validity of respirator test results obtained at flow rates of 85 l/min for negative pressure respirators or 115 l/min for PAPR are inadequate in terms of predicting likely performance for high energy expenditure as observed during the Agility Test performed by the US Marine Corps on test subjects wearing SE 400 AT Positive pressure Demand Filter Respirators.

To provide relevant test data for such activities, it would be necessary to test all respirator components at flow rates of 350 l/min to cover 75% of likely wearer PIAF or 428 l/min to cover 95% of likely wearer PIAF.

It should be stressed that the above study results are corroborated by those of Holmér (2002) and Kaufman (2002).