

The Effect of Sampling Probes on Measured Protection Factors in Military Gas Masks

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ABSTRACT

In recent years it has become standard procedure to test large numbers of military personnel for adequate gas mask fit using a Portacount. Sampling is usually performed via the 3.6 mm wide drinking tube without the use of probes. A similar procedure is used for field tests. Theoretically particles up to 2 μm can be sampled without significant losses this way, based on their Stokes numbers and dimensionless settling velocity.

Experiments confirmed that the use of two standard probes, one a disk with 2 mm holes and one a sphere with 1.5 mm holes, had no beneficial effect on sampling from the gas mask. Mannequin tests with monodisperse oil particles and artificial leaks showed no influence of sampling through the drinking tube with or without two standard probes on the measured protection factors for particles up to 1 μm and a large range of protection factors. Tests with 2 μm particles showed some losses in the probe with the smallest holes.

Portacount tests on a human test panel of ten test subjects with a submicron NaCl aerosol showed fairly large standard deviations in three donnings. The differences between donnings tend to be larger than the differences between sampling probes. However, the protection factors measured using the disk probe were fairly consistently higher than protection factors measured using the other configurations. In some cases the difference was statistically significant despite the large deviation expected due to donning.

Keywords: aerosol sampling, in-mask sampling, aerosol fit testing

INTRODUCTION

One of the problems encountered when measuring inward leakage of a gas mask is how to take a sample from inside the mask that adequately represents the air inhaled by the wearer. Myers et al. (1986) investigated sampling bias extensively in both half-piece masks and full face-piece masks without nose cups. Depending on the exact location of the sampling probe, the sampling flow, and leak location deviations of more than 98% of true leakage were found. They identified imperfect mixing of leak flows with the breathing flow as the main cause for this problem.

Holton et al. (1987) obtained similar results with human test subjects when investigating the effect of leak and sampling location. They noted that the risk of oversampling is especially large when the leak is located close to the sampling position.

Military gas masks are generally full face-piece negative pressure respirators with an inner oronasal mask. Air enters the outer mask through a highly efficient filter on one side of the face, flushes the eye glasses (or visor), and enters the oronasal mask through inlet valves or a small hole near the top of the nose. The flow in the neighbourhood of the inlet to the oronasal mask is fairly turbulent as prior work with computational fluid dynamics has shown (Kievit and van Gulijk, 2003). Hence, unless a leak

occurs at the chin close to the sampling probe, a leak flow is well mixed with the inhaled air. Because of the double rim design of the masks used in this study a chin leak is not very likely.

In front of the mouth a drinking tube is placed. At the end of this tube is an adaptor which can be connected to special bottles for drinking. This adaptor can be removed temporarily and then the drinking tube can be used to draw air samples from the mask and perform a fit test on the wearer without damaging the mask. It is common practice to perform fit tests on large numbers of military personnel this way using a Portacount (model 8020, TSI Inc., St. Paul, MN), and no extra probes connected to the drinking tube inside the mask. The Portacount is a type of condensation particle counter especially designed for respirator fit testing. When measuring field protection factors with the equipment described by van der Gijp et al. (2004) sampling is also performed via the drinking tube without probes.

When using particles as tracers for leakage an additional problem is particle loss at the entrance of the sampling train. Theoretically sampling should be performed isoaxially and isokinetically but due to the rapid changes in the flow pattern inside a gas mask during a breathing cycle this is not possible.

To counter this problem EN 13274-1, the European standard for measuring inward leakage, strongly suggests the use of one of two probes. One is a disk 25 mm in diameter with 8 equally spaced holes 2 mm in diameter. The other is a 22 mm diameter sphere with 8 equally spaced holes 1.5 mm in diameter on the equator. NIOSH (CFR 42, Part 84, Subpart G, Procedure No. RCT-CBRN-STP-0001) also prescribes the use of a probe the shape of which is defined by Liu et al. (1984) for taking samples from powered air purifying respirators.

The aim of this work is to validate sampling through the drinking tube. To this end we first considered aerosol sampling theory and next performed two sets of protection factor measurements, one set on a mannequin head and one set on ten human test subjects with a Portacount.

METHODS AND PROCEDURES

Theoretical Considerations

Liu et al (1984) designed and tested two probes. The design of their probes was based on earlier work by Agarwal and Liu (1981) which has shown that sampling efficiency by a probe, excluding losses in the tubing, is more than 90% when the product of the Stokes number, St , and dimensionless settling velocity, v'_s , is less than 1. Davies (1968) suggested much more stringent criteria for close to 100% sampling efficiency:

$$St < 0.032 \quad \text{and} \quad v'_s < 0.04$$

$$St = \frac{d_p^2 \rho C_c U}{18\eta D_i/2} \quad \text{and} \quad v'_s = \frac{d_p^2 \rho g}{18\eta U} * \frac{1}{U}$$

Where d_p is particle size, ρ the particle density, C_c the Cunningham correction factor, U the gas velocity in the probe or tube, η the gas viscosity, D_i the inner diameter of the probe inlet or tube, and g the acceleration of gravity.

These criteria have been derived and proven experimentally for sampling from still air. As mentioned above the air flow within a mask is often quite turbulent and sampling will be for a large part sub-isokinetic, for a small part super-isokinetic, and rarely isoaxial. Under such circumstances imperfect sampling occurs at lower Stokes numbers than when sampling from stagnant air (Brockman, 1993 and references thereof). However, as long as the Stokes number remains below 0.1 and v'_s is much smaller than 1, inertial effects are unimportant and in practice the Liu probe with an inlet of 3.5 mm showed near perfect sampling for particles up to 5 μm .

Our experiments have been performed with particles up to 2 μm and the Portacount tests with human test subjects were performed with particles with an average diameter well below 1 μm . When we calculate the dimensionless settling velocity and Stokes numbers for the probes and drinking tube (Table

l) accurate sampling is expected in all cases. The flow rate is taken as 0.7 l/min, the nominal sampling flow of the Portacount. Losses due to Brownian motion, i.e. diffusion, are not taken into account here, although for the smallest particles the effect is not negligible.

Table I. Dimensionless Settling Velocity v'_s and Stokes Numbers St for Particles of 0.01 to 10 μm for Inlets of 3.6 mm, 2 mm, and 1.5 mm at a Sampling Flow of 0.7 l/min

dp (μm)	D _i 3.6 mm		D _i 2 mm		D _i 1.5 mm	
	v'_s	St	v'_s	St	v'_s	St
0.01	4.02×10^{-7}	3.45×10^{-5}	1.31×10^{-7}	1.85×10^{-4}	7.38×10^{-8}	4.38×10^{-4}
0.02	8.09×10^{-7}	6.93×10^{-5}	2.64×10^{-7}	3.72×10^{-4}	1.49×10^{-7}	8.81×10^{-4}
0.05	2.06×10^{-6}	1.77×10^{-4}	6.72×10^{-7}	9.46×10^{-4}	3.78×10^{-7}	2.24×10^{-3}
0.1	4.24×10^{-6}	3.64×10^{-4}	1.38×10^{-6}	1.95×10^{-3}	7.79×10^{-7}	4.62×10^{-3}
0.2	8.98×10^{-6}	7.70×10^{-4}	2.93×10^{-6}	4.13×10^{-3}	1.65×10^{-6}	9.78×10^{-3}
0.5	2.68×10^{-5}	2.30×10^{-3}	8.75×10^{-6}	1.23×10^{-2}	4.92×10^{-6}	2.92×10^{-2}
1.0	6.88×10^{-5}	5.90×10^{-3}	2.25×10^{-5}	3.16×10^{-2}	1.26×10^{-5}	7.50×10^{-2}
2.0	1.93×10^{-4}	1.66×10^{-2}	6.31×10^{-5}	8.88×10^{-2}	3.55×10^{-5}	2.11×10^{-1}
5.0	8.67×10^{-4}	7.43×10^{-2}	2.83×10^{-4}	3.98×10^{-1}	1.59×10^{-4}	9.44×10^{-1}
10	2.97×10^{-3}	2.55×10^{-1}	9.71×10^{-4}	1.37×10^0	5.46×10^{-4}	3.24×10^0

Experimental

The first set of protection factor measurements was performed on a mannequin head wearing the Dutch military version of an Avon FM12 mask. Tests were performed with monodisperse poly-alpha-olefin particles (Emery 3004) of 0.5, 1 and 2 μm generated with a condensation monodisperse aerosol generator or CMAG (TSI, type 3470). Standard deviations for these aerosols are ≤ 1.2 . The mannequin head was connected to a breathing machine (Figure 1) with a tube from the mouth through the back of the neck. The breathing pattern was sinusoidal and tests were performed at 15x1 l/min, 30x1 l/min and 25x2 l/min (frequency per minute x tidal volume). The inhaled air was filtered by a high efficiency filter (efficiency > 99.997% at 80 l/min) with a punctured cap to provide the same pressure drop as a standard military canister (± 92 Pa at 30 l/min).

A large range in protection factors was obtained by inserting injection needles of 0.2, 0.3 and 0.4 mm diameter in the mask near the left cheekbone. Aerosol concentrations were measured with an aerodynamic particle sizer (TSI, type 3321). The sampling flow rate from the mask was 1 l/min. The APS inlet was connected to the drinking tube with 2 m of 3.5 mm plastic tubing. Inside the mask the drinking tube is connected to a loose mouthpiece with a sharp curve of 90°. This mouthpiece was removed for the tests leaving the entrance of the drinking tube about 13 mm left of the center line.

Three series of tests were performed, two with the probes described in EN 13274-1 on the center line in front of the mouth connected to the drinking tube and one using the drinking tube without probes. As the reference sample for all probes a sample was drawn from an isoaxial sampling point in the plumbing between the mannequin head and the breathing machine. Myers et al. (1986, 1991) showed that such a sample is unbiased and therefore ideal as a reference sample.

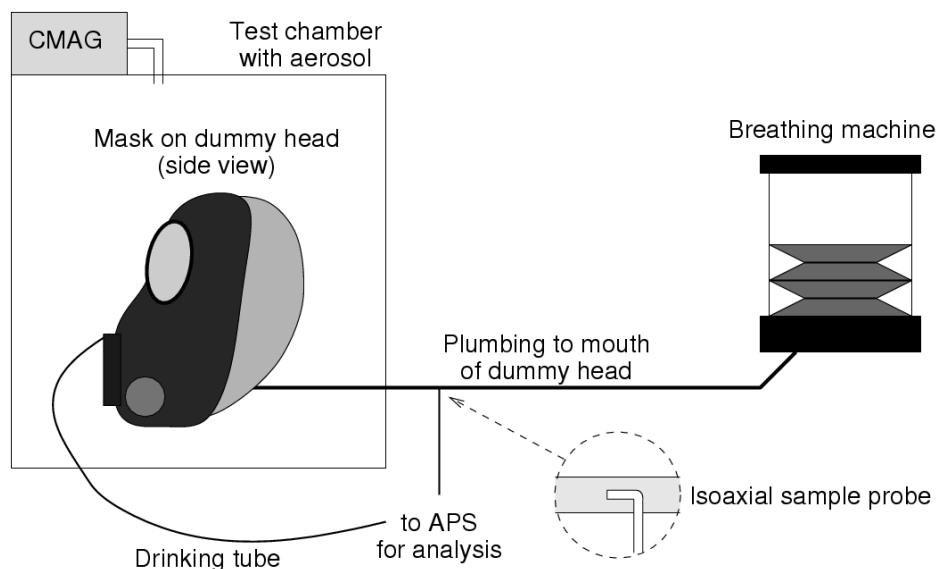


Figure 1. Experimental set-up for measuring the protection factor on a mannequin head.

The second set of experiments was performed with NaCl generated in accordance with EN 13274-1 as the challenge aerosol and a Portacount for measuring particle concentration inside and outside the mask. Tests were carried out in a test chamber 1x1.5x2 m, normally used for standard tests. The protection factors of ten test subjects, 9 males and one female, aged between 25 and 55, and all experienced wearers, wearing an Avon FM12 gas mask with high efficiency filters as described above, were measured using the probes described in EN 13274-1 connected to the drinking tube and using the drinking tube only. In the standard test it was customary at our institute to use the spherical probe and connect it to a flame photometer for analysis with a 10 cm long needle with an inner diameter of 1 mm. Preliminary tests without a filter showed losses of NaCl aerosol in the needle and probe of over 50%. Nevertheless, this sampling configuration was added to the procedure to see if significant losses also appeared in a series of tests measuring protection factors with a P3 filter. Figure 2 shows the particle size distribution and concentration of the NaCl aerosol measured with a scanning mobility particle sizer (system 3936, TSI Inc, St. Paul MN, consisting of a model 3080 electrostatic classifier with long differential mobility analyzer, combined with a model 3786 ultrafine water based condensation particle counter)

Before the beginning of the test series the straps of the harness were adjusted for each of the test subjects by the experiment leader and adequate fit was checked with the Portacount. For each test the test subjects were asked to don the mask themselves before entering the test chamber. After donning, entering the chamber, and connecting to the measurement configuration, two minutes waiting time were observed to flush the mask. Since the particle concentration inside the test chamber is orders of magnitude higher than outside this was considered sufficient. Protection factors, PF, at rest were measured for three donnings in each configuration. In addition one set of measurements was performed with a leaky speech membrane. The aerosol concentration in the chamber was monitored continuously by one Portacount. Because the aerosol concentration in the chamber exceeds the measurement range of the Portacount a calibrated diluter with a dilution ratio of 15 to 1 was inserted in the sampling line. The in-mask concentration was measured continuously for three minutes by a second Portacount and time averaged.

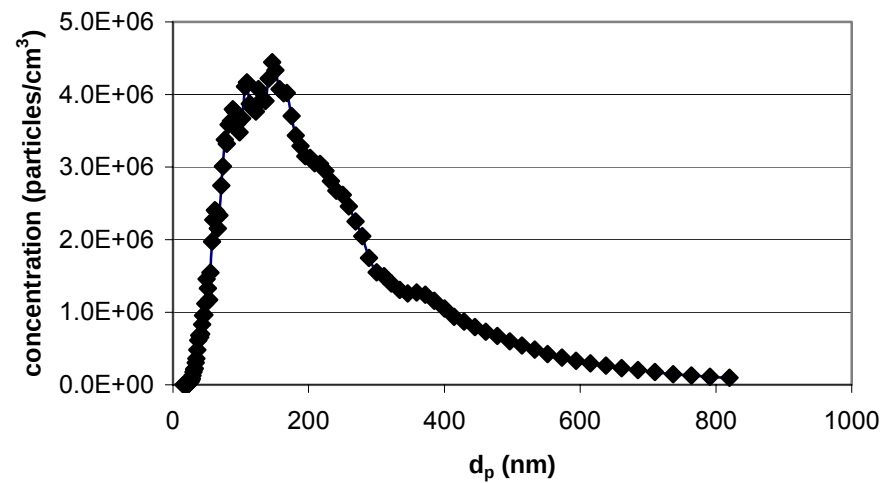


Figure 2. Particle size distribution of the NaCl aerosol measured with a scanning mobility particle sizer.

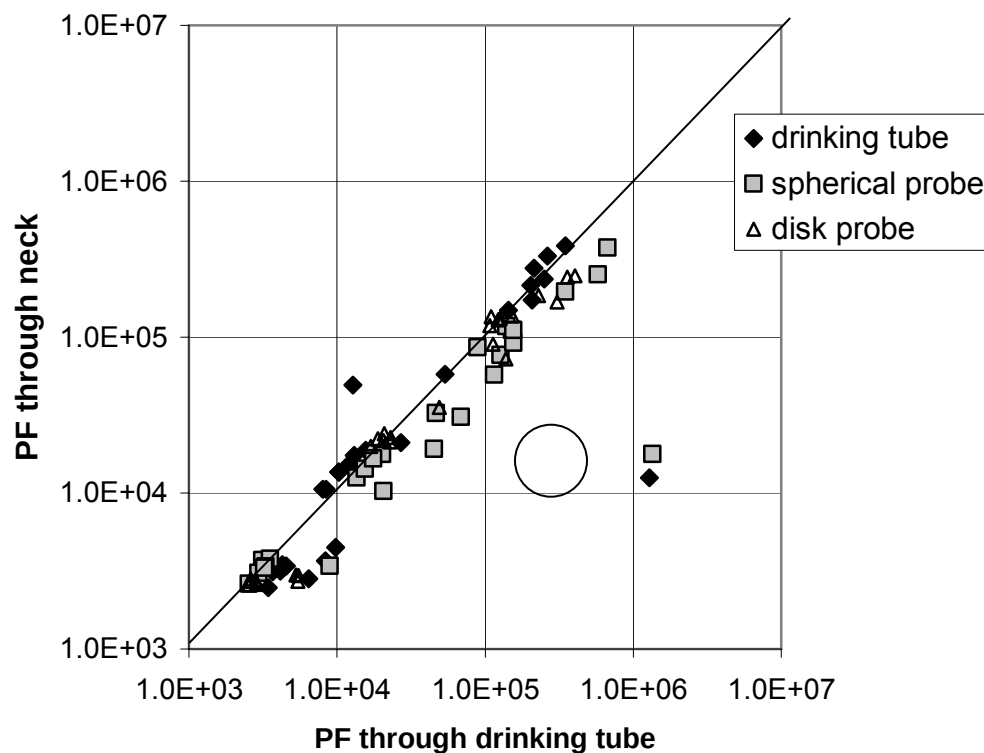


Figure 3. The protection factor, PF, measured sampling through the isoaxial tube at the back of the neck of the mannequin head is plotted against the protection factor measured sampling through the drinking tube with and without probes. Almost all points are located around the equality line. The two encircled points are probably the result of an obstruction in the drinking tube.

RESULTS

Figure 3 shows the results of the mannequin tests. The protection factor measured sampling through the isoaxial tube at the back of the neck of the mannequin head is plotted against the protection factor measured sampling through the drinking tube with and without probes. Almost all points are located around the equality line. The two encircled points are probably the result of an obstruction in the drinking tube. The ratio of the protection factor measured via drinking tube and the protection factor measured through the neck varies between 0.7 and 1.4 for the 0.5 and 1 μm particles. For the 2 μm particles the ratio is 0.9 to 2.6 indicating particle losses begin to occur at this size range in the probes. This is in accordance with the fact that for this particle size and the tested configurations the Stokes numbers begin to exceed the Davies criterion for perfect sampling. No effect of breathing rate between 15, 30 and 50 l/min on the ratio was observed. A t-test showed p-values of 0.46, 0.83, and 0.54 when comparing 15 vs. 30 l/min, 30 vs 50 l/min and 15 vs. 50 l/min, respectively.

Figure 4 shows the results of the measurements with human test subjects. The average challenge concentration was nearly a million particles per cm^3 of air, minimizing the effect of lung generated particles by the test subject (Zhuang et al., 2004, and Liang and Harrison, 2005). Each point gives the harmonic mean of the protection factors of three donnings. With fairly constant challenge levels that is equivalent to (time) averaging the leakage. The difference between the highest and lowest measurement was on average 51% of this mean:

average maximum value = harmonic mean +32%

average minimum value = harmonic mean -19%

This excludes the results of test subject 4 who showed extreme variations up to 300 % of the harmonic mean. This test subject has a rather long and narrow face which is difficult to fit.

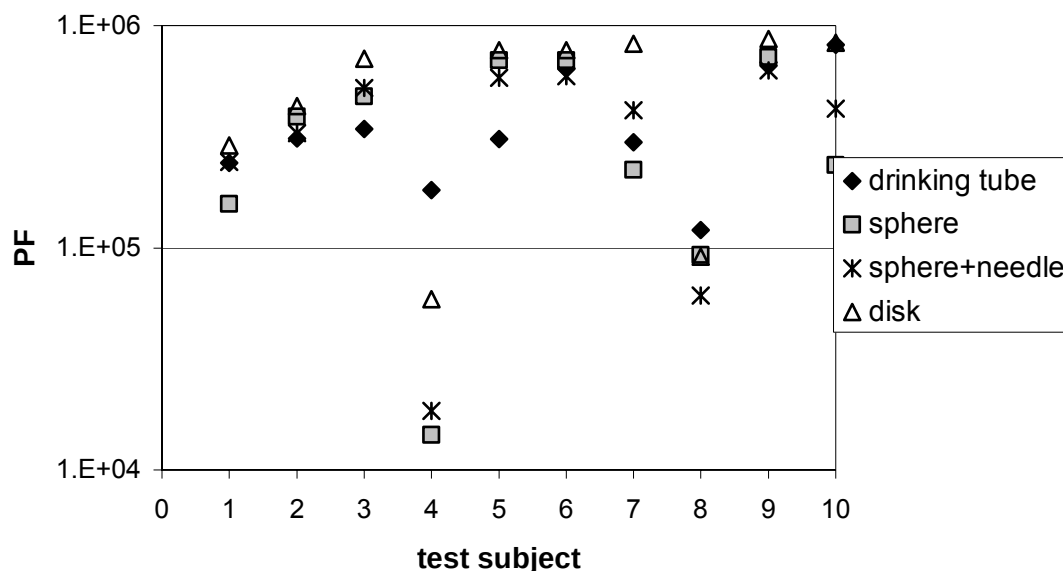


Figure 4. The protection factors, PF, of ten test subjects against a NaCl aerosol measured with Portacount using four different sampling lines for in-mask sampling.

To establish if the difference between probes is significant paired t-tests (Table II) on the log (PF) were performed. The reason for using log (PF) is that protection factors are generally log-normally distributed and t-tests require normal distributions. The t-tests show that sampling through drinking tube, ball or ball+needle gives the same results with p-values over 0.8. The disk probe gave the highest protection factor for eight of the ten test subjects. In six cases the mean protection factor measured with the disk exceeds the overall mean by more than 30%, which is the standard deviation observed for three donnings. With p-values between 0.2 and 0.3 for the two-tail tests and 0.1-0.15 for the one-tail tests there is an indication that the protection factors measured with the disk probe are indeed higher than for the other probes. However, it is common to demand lower p-values (below 0.1 or even 0.01) in order to reject the hypothesis that the measurements are equal.

Table II. P-values for Two-Tailed Paired t-tests of the Log(PF) Measured with Different Probes

	tube	ball	ball+needle	disk
tube	1	0.82	0.99	0.26
ball		1	0.84	0.22
ball+needle			1	0.29
disk				1

DISCUSSION

Based on the results obtained from the mannequin test no effect of the probes was observed for particles up to 1 μm . The results with the 2 μm aerosol indicate particle losses in all three sampling configurations, but the spherical probe caused higher losses than the disk probe and the sampling tube without probes, with $p < 0.05$. This is probably due to the fact that the spherical probe has the smallest entrance holes thus the highest Stokes number and hence the lowest inlet efficiency. Additionally, this means impaction losses are most probable for this set of parameters.

The results of the human test subjects showed a higher PF for the disk probe than for the other configurations with 85% certainty, i.e. $p < 0.15$. However, standard deviation between donnings even for one probe and one test subject was so high, on average nearly 30% of the mean, that a larger set of experiments is necessary to obtain more certainty that the disk probe gives consistently significantly higher protection factors than the other probes. The tests with oil aerosol on the mannequin did not show this trend at all, so, if it is significant, it may be a specific NaCl problem. Notably, EN 13274-1 has added the use of a flush flow in the probe for NaCl testing to prevent condensation problems. We intend to include this flush probe in a future, extended set of experiments.

Our results are in general agreement with the findings of Liu et al (1984). One of the two probes they tested takes samples through a 3.5 mm tube protruding only approximately a centimeter into the mask just like the entrance of the drinking tube.

CONCLUSIONS

Based on the results and calculations we can conclude that the use of a probe has no beneficial influence on the sampling from gas masks for protection factor measurements. The observed differences between probes are so small that they will generally be lost in the effect of other parameters and, if anything, favoured the results of the drinking tube without probe.

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