

Quantitative Fit Testing of Military Gas Masks with the TSI Portacount: Part II - Quantifying the Limitations and Recommendations for Use

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ABSTRACT

In this report we detail how the Canadian quantitative fit test (QNFT) for the C4 gas mask using TSI Portacount Plus Model 8020 Respirator Fit Tester was developed. Instead of using ambient particle, sodium chloride aerosol was generated inside a test chamber where the required fit factor of two test subjects could be measured at the same time. In addition, we conducted a series of experiments measuring subject-exhaled particles while wearing the C4 gas mask. To ensure that the particles were indigenous, test subject's face was surrounded with clean air to eliminate normal leakage from face seal and outlet valve etc. We found that there were significant amounts of ambient particles exhaled during normal and deep breathing and also during talking (Rainbow passage) and coughing. Taking these exhaled particles into account, we demonstrated that the measured fit factor ("apparent FF") obtained with the TSI Portacount was always much lower than the modeled fit factor of the gas mask, if only ambient particle was used. We found that measured fit factor (FF) increased as the ambient particle concentration increased, but the optimum ambient particle concentration occurred at about 40000-60000 particles/mL. This was derived from a theoretical calculation that in order to obtain an apparent FF of 50000 for a gas mask with a modeled FF of 50000, an ambient particle concentration of at least 50000 particles/mL is required.

Keywords: quantitative fit test, required fit factor, particle concentration, exhaled particles, exercise routine, talking, breathing, apparent fit factor

INTRODUCTION

In a previous report (Liang & Harrison 2005) we described the limitations in conducting quantitative fit testing (QNFT) on the Canadian C4 military gas masks using the TSI Portacount Model 8020. The use of TSI Portacount manufactured by TSI, MN, USA is becoming commonplace in industry in the measurement of QNFT. However, we found that QNFT of military gas masks cannot be conducted simply using the OSHA procedure (OSHA 29CFR1910.134) with the TSI Portacount when the required pass level is well above that used in industry. After discussion with military gas mask specialists at Defence Science and Technology Laboratory, Porton Down, UK (Richardson, 2003), and at TNO Prince Maurits Laboratory, in the Netherlands (van der Gijp, 2003), it was determined there are several limitations that are encountered with the TSI Portacount. These include:

- a) Naturally occurring ambient particle concentration in our laboratory may not be high enough to measure high fit factors accurately;

- b) Fit factors measured during the "talking" exercise (Rainbow Passage) seem artificially low compared to other exercises; and
- c) It may not be necessary to perform more than 3 exercises during a fit test.

Furthermore, smokers retain particles in their lungs that are gradually released when they breathe. These particles also interfere with the QNFT measurements. The same occurred when the test subject coughed during the fit testing. Another problem with the TSI Portacount that we found out (Liang & Harrison 2005) is that the sampling tubes may "kink" during the exercises, producing abnormally low fit factors. This is very puzzling. It is common sense that blocking the flow through the sampling tube (as in a "kink") of a properly functioning Portacount will always produce a particle count of zero. This will result in a very high fit factor since the Portacount thinks the fit is perfect. On the other hand, if the ambient sampling tube is blocked, a low particle warning will result. If the particle count rises when a sampling tube is blocked, it may indicate a leak within the instrument, and therefore not functioning properly. The implication of this observation is unclear at this point.

Thus, if the Portacount is to be used by the Canadian Forces to fit test the C4 mask it is clear that additional information is required to better define the test conditions and test protocol that should be used. The primary objective of the experiments described here is to assess factors that could cause errors in the QNFT measurements and to try to determine the optimum ambient particle concentration and the correct procedure to be used for the fit test. Part of this includes a better knowledge of how ambient particles from the air or smoking are trapped in the lungs and are subsequently released during normal breathing, deep breathing, talking, and coughing. The initial trial objectives were therefore to:

- a) Measure the particles that are exhaled from the lung during normal breathing.
- b) Measure the particles that are exhaled from the lung during deep breathing.
- c) Measure the particles that are exhaled from the lung during talking.
- d) Measure the particles exhaled when the subject coughs.
- e) See if the particle count is affected when the sampling tube is 'kinked'.

After the first part of these experiments, it was recognized that the particles that are exhaled during normal breathing may decrease with time and that the effect of time also needed to be quantified. A second set of experiments was therefore arranged to resolve this question. In the OSHA procedure (29CFR1910.134), a 5-minute wait is suggested before the QNFT. It is intuitive to consider that when the mask is first donned, it is full of ambient particles. It takes some time for the person's breathing to purge these particles. Most people would consider that a few minutes would be adequate for a full mask like the Canadian C4 military gas mask. We would like to find out if this time waiting has been optimized, or if more time may be required. We have also mentioned that smoking may affect the Portacount measurements. However, in this investigation, we could only find two test subjects who smoked. Whilst the result is interesting, we felt that we should report it at a later date after we obtained sufficient data.

MATERIALS AND METHODS

Test Subjects

A total of 11 test subjects were recruited in this trial ranging in age from 19 to 59 years. This included 3 females and 8 males. Whilst the number of the test subjects was relatively small, it was considered sufficient to provide a preliminary evaluation of the background particle concentrations that are likely to be encountered during QNFT that could interfere with the measurement. The experimental protocols employed in this set of experiments were submitted to the Royal Military College of Canada Research Ethics Review Board, and approval to proceed was obtained before the experiments took place, as human subjects were involved.

Equipment

A TSI Portacount Plus Model 8020 was used to measure the number of particles (particle concentration) exhaled by the subjects. The air from inside the mask was sampled through the drink tube connector. The Portacount was mounted on the subject using Canadian Forces Load Carriage Webbing and data transmitted to a base station through a telemetry link (Figure 1).



Figure 1. Portacount and blower mounted on CF webbing (left) and base station to record data from the Portacount (right).

We wanted to measure particles that were exhaled from the lungs during a number of activities while the test subject dons the mask. To do this, we connected the TSI Portacount to the drink tube adapter on the C4 gas mask in sampling the particles inside the gas mask. To avoid sampling ambient particles that may have leaked into the mask, we put a 3M "Breathe Easy 10" system on top of the C4 gas mask (Figure 2). This way, the hood was supplied with a continuous source of relatively clean air using HEPA filters, and only filtered air that is ultra-clean with no particulate matters will go around the C4 gas mask. This way, no ambient particle could leak into the mask and all particles measured by the Portacount must have been originated from the lung. The Portacount was used in the direct sampling mode where the particle count per second was recorded (see test data).

One of the reviewers suggested that a "hard zero" count inside the 3M hood with such an arrangement is difficult to believe. Furthermore, there may be particulate matters generated by the fan on the blower that may end up inside the hood. We had not measured the particle count inside the hood because we did not consider that a "hard zero" could be achieved with this arrangement. However, since the C4 military gas mask was designed at a required fit factor of 6667, any significant reduction of ambient particle concentration outside the mask by the HEPA filters on the 3M "Breathe Easy 10" system will lead to a very tiny amount of particles that may leak into the mask. Thus, most of particles detected inside the mask should come from exhaled particles from the lungs.



Figure 2. 3M Breathe Easy hood surrounding the gas mask (left) and 3M hood and the blower system (right).

Test Protocols

Three separate test protocols were used:

TEST PROTOCOL 1

- A. The subject was asked to do normal breathing (through the nose) for 120 seconds.
- B. Following a short pause the subject was then asked to do deep breathing (through the nose) for 120 seconds.
- C. Following another short pause the subject was asked to read the Rainbow Passage for 120 seconds.
- D. The subject was then asked to cough continuously for 10-20 seconds.

TEST PROTOCOL 2

- A. Record particle count as sampling tube is kinked several times.

TEST PROTOCOL 3

- A. Particle count measured continuously during normal breathing for 20 minutes

RESULTS

Test Protocol 1

The actual particle count/mL from the Portacount was recorded every second. The average particle count/mL (over the two minute period) and the maximum individual reading are presented in Tables I to III for normal breathing, deep breathing and "talking" (reading the Rainbow Passage) respectively. It can be seen that a significant amount of particles are exhaled from the lungs during normal breathing and deep

breathing. However, the highest particle count/mL were recorded when the subjects read the "Rainbow Passage" (Table III) or coughed (to be discussed later).

Table I. Particle Count Results for Normal Breathing

Subject	Highest Particle Count/mL	Average Particle Count/mL
1	2.4	0.56
2	1.2	0.18
3	1.8	0.16
4	1.2	0.07
5	0.6	0.05
6	1.2	0.1
7	1.4	0.20
8	1.2	0.14
9	1.2	0.24
10	5.4	0.66

Table II. Particle Count Results from Deep Breathing

Subject	Highest Particle Count/mL	Average Particle Count/mL
1	1.2	0.26
2	0.6	0.04
3	1.2	0.07
4	0.6	0.02
5	1.8	0.07
6	2.4	0.12
7	1.3	0.10
8	10.8	0.38
9	3.6	0.35
10	1.2	0.18

Table III. Particle Count Results from Talking (Rainbow Passage)

Subject	Highest Particle Count/mL	Average Particle Count/mL
1	14.4	4.62
2	6	2.53
3	15.6	4.83
4	4.8	1.29
5	6.6	1.88
6	17.4	8.5
7	5.1	2.2
8	10.2	3.54
9	12.6	5.07
10	14.4	6.49

It may be observed that whilst the particle count/mL for normal breathing and deep breathing are small they are measurable, and the particle count/mL for talking is about an order of magnitude higher than those for the normal and deep breathing. A graph of the particle count/mL with time for talking for all ten subjects is represented in Figure 3. Although Figure 3 may appear to be busy, it illustrates the general trend of the periodic increase in exhaled particle counts (related to breathing), and the highest particle count.

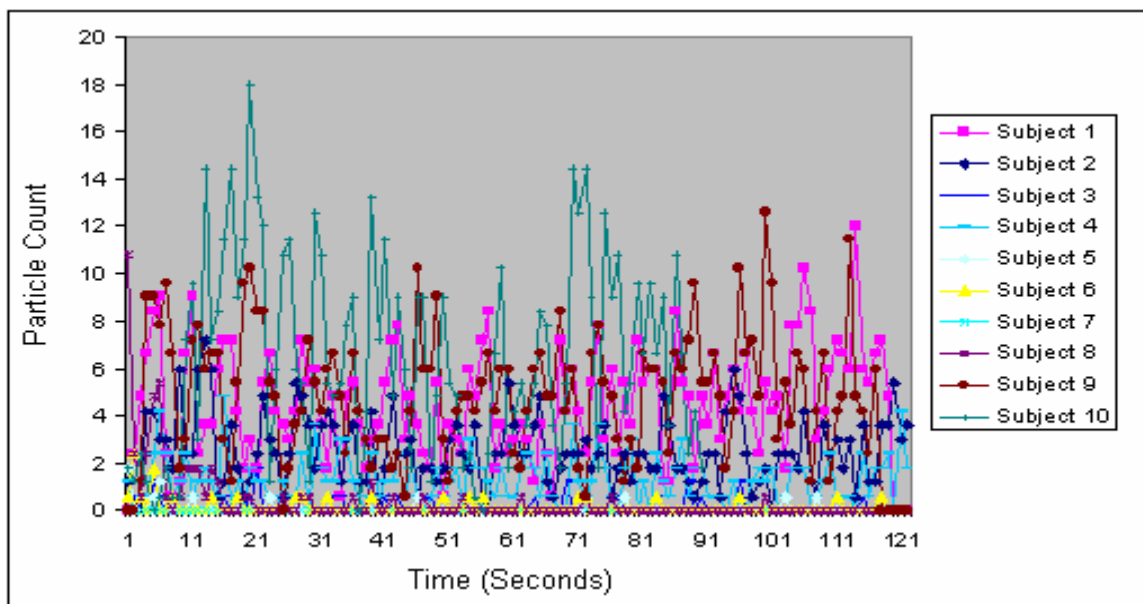


Figure 3. Graphical representation of particle counts/mL exhaled over time (in seconds) during talking.

It is interesting to note that the particle count/mL for deep breathing are smaller than for normal breathing, which may indicate that it takes several minutes to purge the particles that are normally found in the air out of the lungs, as suggested by the OSHA protocol. It was also noted that the particle count in the first 60 seconds of the experiment was usually much higher than in the remaining 60 seconds. This will be explored later.

From the data shown in Tables I to III, we could estimate the worst-case particle count for each activity as summarized in Table IV. We could then use these worst-case numbers to assess the error that this background count causes in the QNFT measurements.

Table IV. Worst Case Particle Count from Each Activity

Activity	Worst Case: Particle Count/mL
Normal Breathing	0.6
Deep Breathing	0.3
Talking	8

For the error in the QNFT measurement we have assumed that we are looking at a particular mask that has a required fit factor of exactly 10000 (the new Canadian requirement). A mask with a modeled fit factor of 10000 is equivalent of having an overall leakage of 0.01% (i.e., leakage from the face-seal, outlet valve, and canister mount etc.). We have then looked at the various ambient particle concentrations that could be used around (outside) the mask when the QNFT measurement is conducted.

For each ambient particle concentration it is possible to calculate the particles/mL that would leak into the mask with a modeled fit factor of 10000 (see particle count based on modeled FF - Column #3 in Tables V - VII). We have then added the contribution of particles exhaled from the lung and calculated the apparent fit factor and the error this causes. The results of this assessment can be found in Tables V–VII using the worst case counts from Table IV.

Table V. Worst Case Error Assessment for Normal Breathing

Outside Particle Count*	Modeled Fit Factor**	Particle Count in Respirator Based on Modeled FF*	Particle Count in Respirator from Lungs (normal breathing)*	Total Particle Count Inside Respirator*†	Apparent FF***	Error**** (%)
1,000	10,000	0.1	0.6	0.7	1,430	-86
5,000	10,000	0.5	0.6	1.1	4,545	-55
10,000	10,000	1.0	0.6	1.6	6,250	-37
20,000	10,000	2.0	0.6	2.6	7,690	-23
40,000	10,000	4.0	0.6	4.6	8,695	-13

* Particle Count (particles/mL)

** Modeled Fit Factor of Respirator

† Sum of Columns 3 and 4

*** Apparent Fit Factor Includes Particles Generated in Lungs
= Column 1/Column 5

**** Error = (Modeled FF – Apparent FF)/(Modeled FF) x 100%

Table VI. Worst Case Error Assessment for Deep Breathing

Outside Particle Count*	Modeled Fit Factor**	Particle Count in Respirator Based on Modeled FF*	Particle Count in Respirator from Lungs (deep breathing)*	Total Particle Count Inside Respirator*†	Apparent FF***	Error**** (%)
1,000	10,000	0.1	0.3	0.4	2,500	-75
5,000	10,000	0.5	0.3	0.8	6,250	-37
10,000	10,000	1.0	0.3	1.3	7,690	-23
20,000	10,000	2.0	0.3	2.3	8,695	-13
40,000	10,000	4.0	0.3	4.3	9,300	-7

Notations same as in Table V.

It can be observed immediately that in Table V that, when an ambient particle concentration of 1000 particles/mL is used outside the mask the actual number of particles that leak into a mask that has a modeled fit factor of 10000 is 0.1 particles/mL and this is significantly smaller than the background particle count generated from the lungs during normal breathing (i.e. up to 0.6 particles/mL). This could

cause an error of up to 90% in the measurement. Only when the ambient particle concentration is around 40000 does the error become acceptable.

Table VII. Worst Case Error Assessment for Talking (Rainbow Passage)

Outside Particle Count*	Modeled Fit Factor **	Particle Count in Respirator Based on Modeled FF*	Particle Count in Respirator from Lungs (talking)*	Total Particle Count Inside Respirator*†	Apparent FF***	Error**** (%)
1,000	10,000	0.1	8.0	8.1	123	-99
5,000	10,000	0.5	8.0	8.5	588	-94
10,000	10,000	1.0	8.0	9.0	1111	-89
20,000	10,000	2.0	8.0	10.0	2000	-80
40,000	10,000	4.0	8.0	12.0	3333	-67

Notations same as in Table V.

When the worst case particle count/mL for deep breathing was used (See Table VI), it could be seen that an ambient particle concentrations of 20000 to 40000 particles/mL were required to reduce the error to acceptable levels. However, when talking was considered, as shown in Table VII, an ambient particle challenge concentration of 40000 particles/mL produced an error that was unacceptable. This unequivocally shows that talking cannot be used as an activity in the protocols when QNFT is conducted using a TSI Portacount and when required fit factors in excess of 10000 is required to be measured. In fact, any speech during a test (e.g. test subjects talking to each other or to the operator) could significantly affect the result. This explains the unusually low numbers that were observed in our first trial with TSI Portacount in 2003. Particle counts in the laboratory were about 1000 - 2000 particles/mL and it can be easily seen that even if the mask had a modeled fit factor of 10000 or more the actual fit factor that would have been obtained would have been very low (less than 200).

A corollary from Table VII is that even for commercial respirators designed with a fit factor at 100-1000, the talking exercise during QNFT would seriously affect the measured FF under this worst-case scenario. Quick calculations similar to that shown in Table VII revealed that for a mask designed at a "modeled FF" of 100, the apparent FF would have an error less than 10% only when the outside particle count is more than 10000 particles/mL. Theoretical results for apparent FF obtained for masks with modeled FF designed at 100, 200, 1000 and 2000 (assuming that these FF exist) at different ambient particle concentration are shown in Table VIII. It seems that the talking exercise may cause some problems for these respirators designed with required fit factor of 100-1000 using the TSI Portacount for QNFT. However, this is outside the scope of this study on military gas mask designed with much higher required fit factor.

Table VIII. Worst Case Apparent FF Obtained for Masks with Different Modeled Fit Factors at Different Ambient Particle Concentrations if Test Subjects Talked During the Exercise Routine

Ambient Particle Concentration	Calculate "Apparent FF"			
	Modeled FF =100	Modeled FF =200	Modeled FF =1000	Modeled FF =2000
1000	55	77	111	118
5000	86	152	385	476
10000	93	172	556	769
20000	96	185	714	1111
40000	98	192	833	1428

In addition to normal breathing, deep breathing and talking, the test subjects were also asked to cough for 10 – 20 seconds. The results of these measurements can be found in Table IX and Figure 4. Similar to Figure 3, this figure is very busy, but we only want to illustrate the trend for different test subjects, and some high particle count measured.

Table IX. Results for Coughing

Subject	Highest Particle Count/mL	Average Particle Count/mL
1	9	2.53
2	6	1.77
3	127.8	52.13
4	32.4	7.97
5	15.6	6.49
6	238.8	47.26
7	7	1.90
8	12	5.13
9	335.4	80.13
10	354.6	47.27

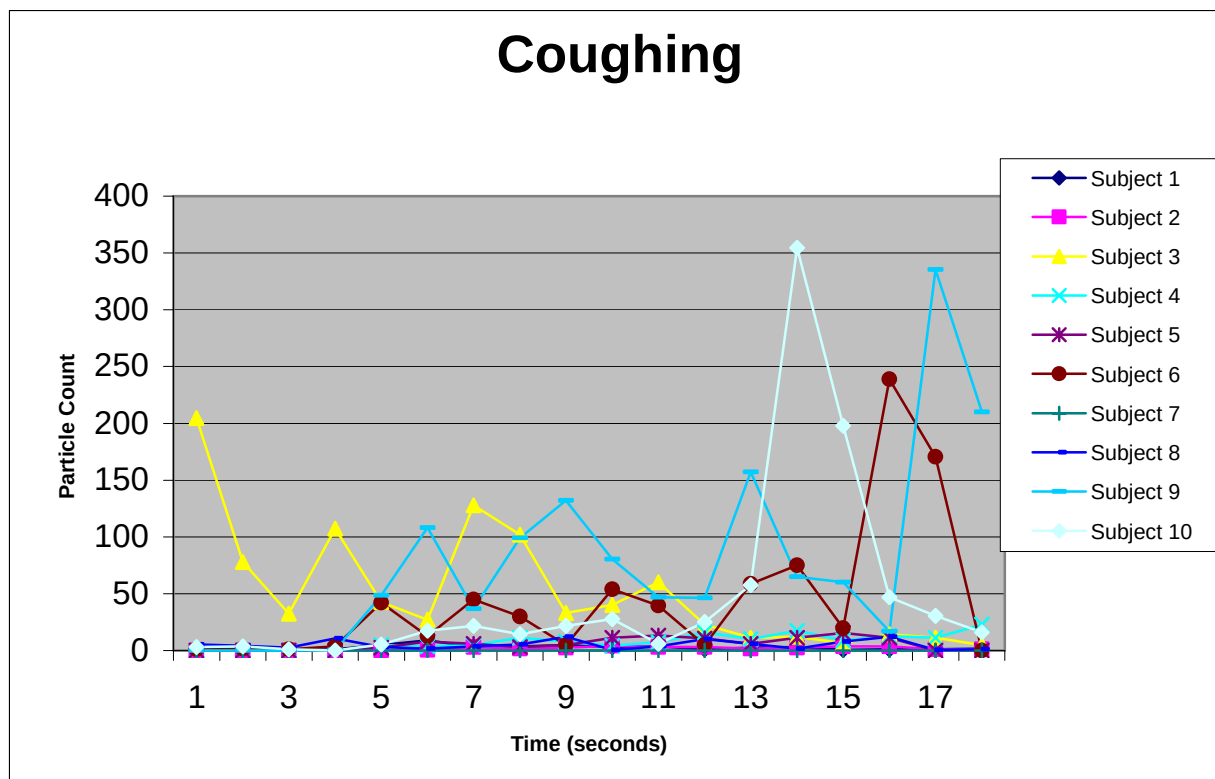


Figure 4. Graphical representation of particles exhaled during coughing.

It could be seen from Table IX that extremely high particle counts were reached when the test subject coughed. As this would have a significant impact on the measurement in any fit factor measurements, data should be rejected if the subject coughed during the measurement. The authors consider this as a serious issue. If a test subject coughed and obtained a failed fit factor (i.e., a required fit factor < 6667 - the old requirement) during the fit testing and chose not to inform the operator, the normal recourse for us is that a different gas mask be issued to the test subject, and the QNFT repeated with the newly-issued mask. The impact is simple for industrial operations where a few hundred to a few thousand personnel are being fit tested. For military operation and deployment, this can be a tremendous waste of resources and time, and logistics nightmare when the problem could have been identified at the earliest sign of trouble.

The calculations on errors in Tables V - VII were based on the new Canadian requirement of a required fit factor of 10000. However when QNFT is used one would like to be able to measure fit factors up to at least 50000. Table X has therefore been generated to look at the errors involved in measurements this high with a TSI Portacount.

Table X. Worst Case Error Assessment When Measuring Fit Factors of 50,000

Ambient Particle Count	Modeled Fit Factor **	Particle Count in Respirator Based on Modeled FF	Particle Count in Respirator from Lungs*	Total Particle Count Inside Respirator*†	Apparent FF***	Error**** (%)
20,000	50,000	0.4	0.3	0.7	28,570	-43
40,000	50,000	0.8	0.3	1.1	36,360	-27
20,000	50,000	0.4	0.1	0.5	40,000	-20
40,000	50,000	0.8	0.1	0.9	44,440	-14
50,000	50,000	1.0	0.1	1.1	45,450	-9

Notations same as in Table V

Table X showed that with the worst case particle count exhaled from the lungs of 0.3 particle/mL, significant errors were involved even with an ambient particle counts of 40000 particles/mL when a modeled fit factor of 50000 needs to be measured. Table X showed that the best way to get meaningful results at this level is to use an ambient particle counts of at least 50000 particles/mL and try to keep the contribution from the lung to below 0.1 particle/mL. The question therefore arises whether particle counts from the lung below 0.1/mL during a test are achievable? Certainly over half of the test subjects had counts this low during the deep breathing test. Whether the remaining test subjects would have counts this low given additional time needs to be determined. This will be explored later in the report.

Test Protocol 2 (Kinked Tube)

Three tests were conducted in which the sampling tube was constricted by bending it (kinking it). The results were shown graphically in Figure 5. The results showed that the particle count rose sharply when the tube was kinked and that this could significantly affect the result. If this occurred or was suspected of occurring, the measurement should be repeated. As discussed in the Introduction, intuition dictates a "kinked" tube would cause a blockage of sampling, and "excellent" fit factor should result. This is obviously not the case here. We are still quite puzzled with this observation, and the lack of explanation for this occurrence.

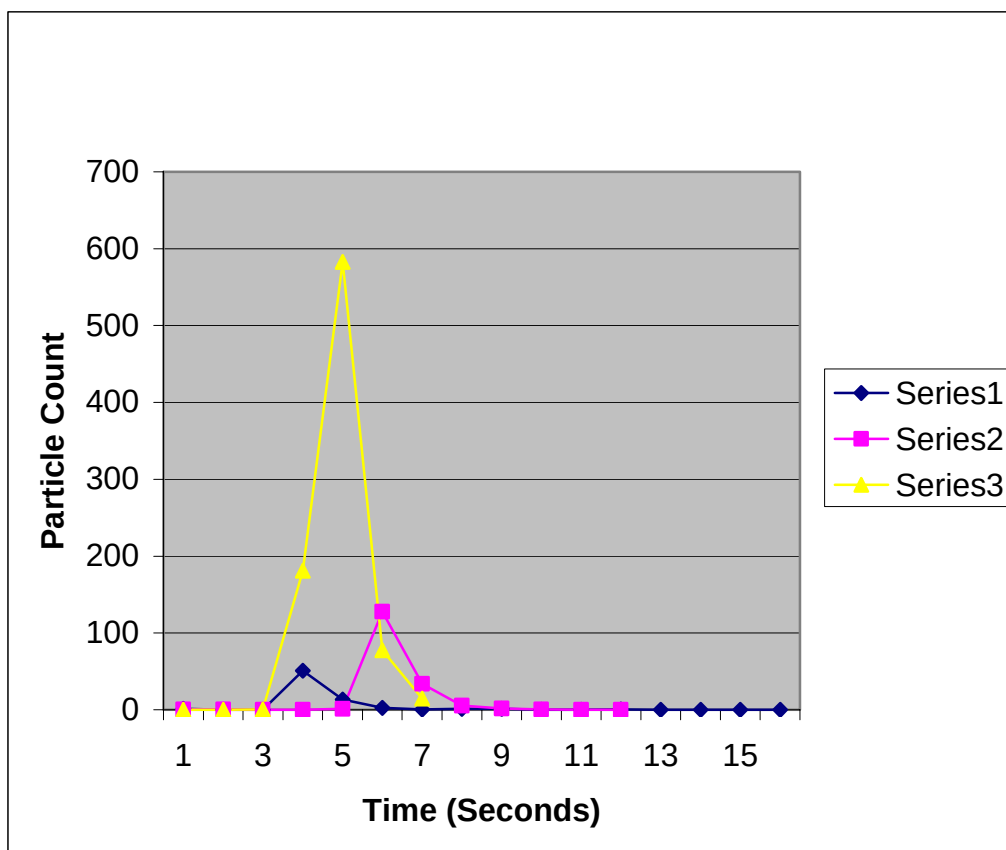


Figure 5. Effect of kinking the sampling tube.

Test Protocol 3 (Normal Breathing)

The conclusion from Test Protocol 1 was that it would be highly desirable to establish test conditions where the background particle count from the lungs was below 0.1 particle/mL. It was therefore decided to add Test Protocol 3 and to do a second trial to determine whether simply wearing the mask for a predetermined time (e.g., 5 - 10 minutes) before the test would accomplish this. The data collected from this trial is shown in Table XI. The data showed the average particle count measured over two minute periods for ten minutes after the mask was donned. The data indicated that it takes at least 5 minutes, and preferably 10 minutes, to clear the lungs of particulates.

Current OSHA procedure suggests that the QNFT test be delayed by at least 5 minutes whilst the test subjects sits and does nothing while wearing the mask. This will allow the exhaled particle counts from the lungs to be brought down to the lowest threshold. In this case, 70% of the test subjects would have a particle count around 0.1/mL whilst the remaining 30% had a count at about 0.3/mL. This would still impact on the measurement compared to starting the QNFT test immediately. However, this particle concentration did not improve even after 10 minutes of "delay".

Table XI. Normal Breathing for Ten Minutes

Time in minute	Average Particle Count (particles/mL)												
	Subject Numbers												
	12	13	14	15	16	17	18	19	20	21	22	23	24
0 to 2	0.44	0.19	0.29	0.16	0.56	0.25	1.67	0.26	0.16	2.4	0.38	0.38	1.02
2 to 4	0.28	0	0.42	0.22	0.4	0.2	0.19	0.22	0.32	0.12	0.04	0.04	0.1
4 to 6	0.36	0.03	0.24	0.15	0.33	0.14	0.06	0.09	0.14	0.1	0.05	0.05	0.24
6 to 8	0.39	0.03	0.27	0.22	0.34	0.13	0.07	0.09	0.14	0.12	0.12	0.12	0.18
8 to 10	0.27	0	0.27	0.16	0.34	0.14	0.07	0.08	0.13	0.05	0.11	0.11	0.1

Other Factors

Whilst the above-mentioned factors are critical in establishing a reproducible, reliable QNFT methodology there are a number of other factors that are worthy of mention. The first is the sampling location. In the tests that have been conducted so far, the particle concentration has been sampled via the drink tube connector that samples the air inside the nose cup. Alternatively the sampling location could have been in the eye-space. This would have simply measured face-seal leakage but would not have captured any leakage from the outlet valve. It has the advantage that it eliminates the effects arising from lung retention. If the performance of the outlet valve is well known this is another option but does suffer from the disadvantage that the mask has to be modified to conduct this measurement (through the incorporation of a sampling port in the mask). One reviewer suggested that the US Army samples from the eye region during fit tests. This is achieved by extending a tube from the inside end of the drink tube up under the nose cup seal into the eye region. TSI Portacount has set up a limit on how long the sampling tube should be, and we felt that any arbitrary lengthening of the sampling tube may cause other errors in the fit factor measurement. Currently, we are investigating the use of TSI Model 8025-40mm (8025-CEN) mask sampling adapter that may allow us to sample at locations outside the nose cup of the C4 gas mask.

Particulate matters from the carbon in the gas mask canister can also be released and affect the measurement. In these experiments, we have used special canisters prepared by 3M (Canada) at Brockville, ON that have the same weight and breathing resistance as the C7A canister but only contain a particulate filter (no carbon). In addition one must ensure that the performance of the particulate filter in the canister is sufficient that particles do not directly penetrate the canister and interfere with the measurement. The performance of the particulate filter in the canisters supplied by 3M for the trial was sufficient to eliminate interference from this effect.

It is well known that the particles retained in the lungs from smoking affect the Portacount and that smokers should refrain from smoking prior to the QNFT measurement. For the purpose of the trials that have been conducted by RMC we have requested that the test subjects refrained from smoking for at least 12 hours before the test. Whether this time can be reduced should be explored. We have had difficulty obtaining sufficient test subjects who smoke to conduct such a test.

CONCLUSIONS

If reproducible and reliable results are required for QNFT with the TSI Portacount on respirators such as the C4 mask which was designed at a required fit factor (RFF) of 10,000-50,000, it is essential that:

1. A particle count of 40000-60000 particles/mL is used to conduct the measurement;
2. The test subject wears the mask for at least five minutes before the test to clear out their lungs;
3. The test protocol not includes talking (such as the Rainbow Passage);
4. The test is repeated if the test subject speaks at any time during the measurement;
5. The test is repeated if the test subject coughs during the measurement;
6. The test is repeated if the sampling tube is kinked during the measurement; and
7. The test subject refrains from smoking for at least 12 hours prior to the test.

This study reported some of the proper ways to conduct QNFT with TSI Portacount on a military gas mask designed with a required fit factor of at least 6667. We tried to correlate this result to industrial respirators designed with assigned fit factor of 100-1000 that may not apply.

We have also found that it is important for the test subject to sit around for at least 5-10 minutes before the QNFT with equipment employing the condensation nuclei counter type technology and the OSHA 8-exercise protocol. This will bring a low threshold particle concentration inside the gas mask, and eliminate as much of the lung-exhaled particles as possible. This will apply to respirators with different levels of assigned protection factor.

ACKNOWLEDGEMENT

We would like to thank 3M(Canada) at Brockville, ON in supplying us with the special carbon-less C7 canisters and the "Breathe Easy 10" Hood for this trial.

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