

Effect of Particle Size on Assessment of Faceseal Leakage

Warren R. Myers, Ph.D., Hyunwook Kim, Ph.D., and Nani Kadrichu

Department of Industrial Engineering, West Virginia University

Abstract

Aerosol and vapor penetrations through fixed-diameter capillaries have been measured on a dynamic laboratory test system as a function of challenge aerosol size and breathing tidal volume. Four sizes of polystyrene latex (PSL) spheres were used to generate the challenge aerosols. In addition to the PSL aerosols, an acetone vapor was also used as a challenge agent. Significant effects on measurement of penetration were found for tidal volume and particle size range. Penetration measurements made with the vapor challenge agent were, in all cases, higher than penetration measurements made from the aerosols. The measured vapor penetration was also found to be a function of tidal volume. Higher capillary penetration occurred with the 1.5 L tidal volume as compared to the 0.6 L tidal volume. All PSL aerosols provided the same order of ranking of the leak sizes. However, for measuring fit factors of greater than 1000 a gas or vapor fit test appears to represent a more critical test than a fit test assessment using aerosols (Dp 0.36 to 2.56 μm) and a data reduction technique based upon particle number counts.

Introduction and Literature Review

The US Occupational Safety and Health Administration (OSHA) regulation covering occupational use of respirators (1910.134) requires employers to provide, when necessary, respiratory protective equipment (RPE) for protection against a wide variety of airborne contaminants. These contaminants can be in the physical form of a solid or liquid aerosol or a gas/vapor. These different physical forms of airborne contaminants may be present at the same time.

A very important part of the selection and evaluation process required by OSHA is to determine how well the respirator fits individual workers. The importance of respirator fit for achieving proper respiratory protection is obvious. However, not as readily obvious is how the reliability and validity of the results of the fit test may be influenced by the

test methodology. Aspects of the test methodology, particularly those associated with the use of aerosols, are of interest.

Many different test agents, both gases and particulates, have been employed over the years in QNFT methods. Gases that have been used include helium,¹ freon,² argon,³ and radon.⁴ Aerosols that have been used in various QNFT procedures include bacteria,⁵ uranine,⁶ sodium chloride,⁷⁻⁹ and oil mists of di-2-ethylhexyl phthalate,^{10,11} di-2-ethylhexyl sebacate, and corn oil.¹³ These aerosols are generated by a number of different techniques and are usually considered to represent a polydispersed aerosol. The reported mass median diameter of these aerosols typically range from roughly 0.14 μm to 2.5 μm with geometric standard deviations generally between 1.9 to 2.3.

* This paper has been peer reviewed.

Recent research studies, first reported in the United States¹⁴⁻¹⁶ and later in the United Kingdom¹⁷ have shown that current in-facepiece sampling methods do not provide representative samples of face seal leakage. These studies demonstrated that face seal leakage doesn't mix rapidly or uniformly within the respirator. Based upon these results, it is now hypothesized that face seal leakage can form localized flow patterns of contaminated air within the facepiece cavity. Because of these flow patterns, in-facepiece sampling can produce biased and highly variable concentration measurements. Variations in several parameters of the person-respirator system have been identified as significant sources of sampling bias.¹⁴⁻¹⁶ These findings have been corroborated by other investigators.^{18,19}

Another issue with QNFT is the use and interpretation of the fit test results. This issue is currently under considerable debate within the respirator community. Research studies have been unable to demonstrate that a correlation exists between the level of fit ascribed to a respirator-person combination by QNFT and the level of protection achieved in use.²²⁻²⁴ Therefore it does not appear that QNFT results are adequate predictors of "in-use" protection even when the respirator is conscientiously used and worn. As a result of this realization, results of QNFT are now referred to as fit factor and not protection factor.²⁵ This change is noteworthy and is based on the understanding that fit test results may not indicate protection as use of the term protection factor implies.

A number of studies have been conducted to evaluate the effect of gas and aerosol test agents on measuring face seal penetration. Hounam et al. evaluated face seal leakage using a particulate test agent, sodium chloride and a gaseous test agent, difluorodichloromethane.⁸ For face seal penetrations equivalent to fit factors up to 500, he noted similar estimates of face seal leakage with both agents.¹⁶ Griffin and Webb, cited by Schwabe,²⁴ obtained similar results using sodium chloride and argon.

In 1980, Schwabe investigated the differences between gases and aerosols in the measurement of face seal leakage using three different types of military respirators.²⁴ Test agents were gases of methane, penthrane, and amyl acetate and aerosols of sodium chloride and oil aerosols. He concluded that no exceptional differences exist between gases and aerosols in the measurement of face seal leakage over the concentration range 0.1 to 5000 mg/m³ and for leakages in the range 0.05% to 10% (FF from 10 to

2000). He also observed in face seal leakage tests using different aerosols that the dimension of the leak path had an influence on the deposition mechanism of the oil mist.

The quantitative assessment of respirator fit using a gas as a test agent appears to be rather straightforward since the amount of gas entering through the face seal leak is equal to the product of the leak flow and the concentration of the gas outside the respirator. In the case of aerosol exposure, however, the assessment appears to be more complicated. There are a limited number of studies dealing with the effects of particle size on assessment of respirator face seal leaks.

Tuomi found that the effects of particle size on face seal leakage performance were significant.²² He evaluated the performance of half-mask respirator as a function of particle size using a corn oil aerosol over the size range of 0.35 to 9 µm. He reported that the measured aerosol penetration was approximately constant for particle sizes below 2 µm but decreased for larger particles.

Hinds and Kraske investigated the face seal leakage performance of half-mask and single-use respirators that were mounted on a mannequin in a chamber.²⁶ The test aerosols were mono- and poly-dispersed oleic acid aerosol in the size range of 0.1 to 11.34 µm. Three configurations of face seal leak were used. Aerosol in the size range of 0.1 to 1 µm was found to have approximately 100% penetration, regardless of the size of the leak or pressure drop across the respirator. In the size range from 1 to 12 µm, however, penetration first increased as pressure drop increased and then decreased with further increase in pressure drop. They suggested that the initial increase in penetration is due to decreased sedimentation losses in the leaks. The noted decrease in penetration with further increase in pressure drop was attributed to increased inlet losses and impaction losses against the face at the leak inlet.

Similar results were obtained by the Holton, et al., who investigated leakage into the half-mask negative-pressure respirator with particle sizes ranging from 0.07 to 4.4 µm using a human subject.¹⁸ Test aerosols were generated from a mixture of smoke, nebulized corn oil aerosol, and limestone dust. Leakage into the respirator was through three holes punched into the body of the respirators. Aerosol penetrations were measured using various optical particle size or count instruments. Their results showed that as the particle size increased

from 1 to 4.4 μm the percent aerosol inside the mask decreased for all three hole sizes. Furthermore, as particle size decreased from 0.22 to 0.07 μm the percent aerosol inside the mask once again decreased. However, for particles between 0.2 to 1.0 μm there was little difference in the penetration of aerosol into the respirator. The higher penetration of certain particle sizes appeared to be independent of the leak sizes used in the study.

The geometry of the face seal leak has also been observed to influence the measurement of face seal leakage when aerosols are used to assess penetration. Holton et al. observed that a slit or narrow gap in the face seal, as compared to a circular hole, decreases the total aerosol leakage and reduces the entry of larger particles through the leaks.¹⁸ This is

in contrast to studies by Myers et al.,^{7,15} which found no effect of face seal leak geometry on penetration of a vapor test agent into the respirator.

Based upon the reported studies in the literature, aerosol penetration into a respirator through face seal leaks appears to be dependent on particle size and leak geometry and less so on leak size or pressure drop.

The objective of this research was to study the effect that the particle size of the fit-test aerosol has on estimates of face seal leakage. This investigation evaluated quantitative assessments of face seal leakage as a function of leak size, particle size, physical state of the test material (vapor vs particulate), and tidal volume.

Methods and Materials

Test System

The configuration of the test system used in the study is presented in Figure 1. The test chamber is approximately 2' x 2' x 2' and constructed of 1/2 inch plexiglas. The aerosol or vapor enters the test

chamber through four inlets uniformly positioned on top of the chamber. The top and bottom diffusing plates are constructed from 1/4 inch plexiglas with 3/8 inch holes on 1 inch centers. The top plate distributes the aerosol or vapor evenly over the entire

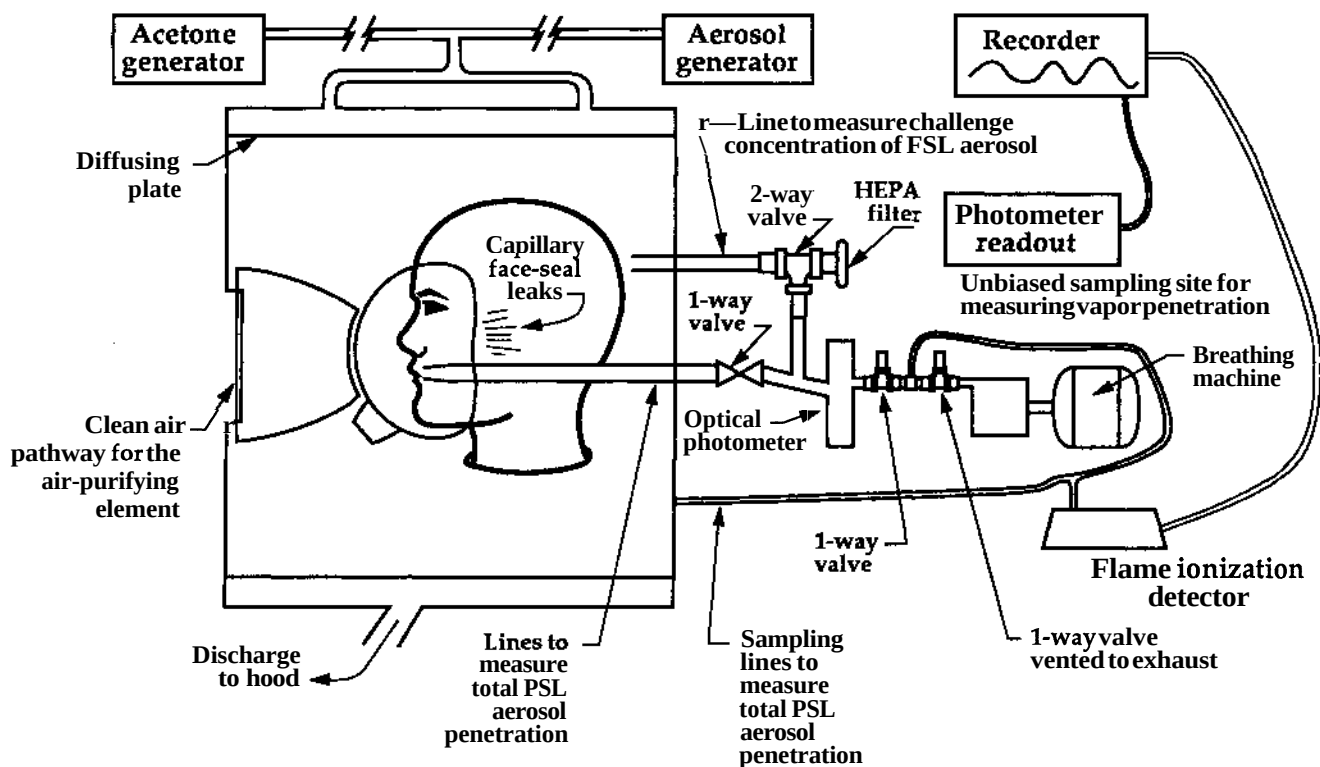


Figure 1. Aerosol and vapor test system.

cross-section of the chamber after it has been discharged from the four inlets. The bottom plate supports the headform and helps facilitate a more uniform discharge of the air from the chamber. One wall of the chamber is equipped with two 8" diameter circular openings which are located opposite the headform during testing. The shoulder-end of heavy-walled, rubber, glove-box sleeves are attached to these openings. During testing the wrist-end of the sleeve(s) can be attached to the air-purifying element on the facepiece. This allows acetone-free or polystyrene latex (PSL) sphere-free air to be drawn through the air-purifying elements during operation of the breathing machine. This provides enhanced test reliability. Concerns about vapor or PSL sphere penetration through the air-purifying element of the respirator are greatly reduced. Ports are provided in the walls of the chamber for the test operator to manually open and close the capillary leaks. Ports are also provided for determining the chamber concentrations of vapor and PSL aerosol.

The plumbing between the chamber and the breathing simulator was designed so that the entire inspired tidal volume could be drawn through the aerosol detector. To complement this design an aerosol detector was required that could handle sampling rates of at least 32 lpm. This design feature was critical to the assurance of obtaining aerosol measurements that would have a minimum of bias associated with sample collection, since all the inspired air volume was drawn through the detector. This test system design helped minimize sampling errors associated with the uniformity of the aerosol within the tidal volume.

Aerosol Generation and Measurement

Polystyrene latex spheres having diameters of 0.36, 0.62, 1.0 and 2.56 μm were chosen for use in the study. The dilution ratio used for generating the PSL aerosol was approximated from the following relationship proposed by Raabe.

$$y = \frac{F(\text{vmd}^3) \cdot \exp(4.5 \ln^2 T_g)}{(1-R)D^3} \cdot [1 - ((\exp \ln^2 T_g)/2)]$$

where y = approximate dilution ratio

R = singlet ratio, chosen to be 0.95

D = diameter of PSL particle

vmd = volume median diameter of the output of the atomizer

T_g = geometric standard deviation of the output particle distribution

F = fraction by volume of the particles in the original PSL stock solution.

A singlet ratio of 0.95 was chosen to estimate the dilution ratio. This ratio indicates that 95% of generated PSL particles will be singlets and 5% will be doublets, triplets, etc. The dilution ratio is a function of the volume median diameter (vmd) of the generator's output. The output of the TSI generator is stated by the manufacturer to have a geometric mean (GM) of 2 μm and a geometric standard deviation of <2 . For purposes of calculations it was assumed to be 1.9.

Measurement of PSL aerosol was made using a PPM Incorporated Aerosol Scanner® Model S-0.2/2. The detection size range of the instrument is from $<0.2 \mu\text{m}$ to $>5.0 \mu\text{m}$. It is divided into eight different channels, <0.2 ; $0.2-0.3$; $0.3-0.5$; $0.5-0.7$; $0.7-1.0$; $1.0-2.0$; $2.0-5.0$; $>5.0 \mu\text{m}$. The Scanner could handle flowrates from 0.2 to 2.1 ACFM. The operating temperature for the instrument is between $0-40^\circ\text{C}$. The maximum particle count rate is 12,000 particles/min.

Calibration of the Scanner® was performed by the manufacturer using monodispersed PSL spheres. Before beginning experimentation, the Scanner® was checked using aerosols of 0.6 and 1 μm PSL. Figure 2 illustrates particle count assignments made for 0.6 μm PSL under both constant and cyclic flowrates of 10.8 lpm. With this size particle there appears to be little effect of flow condition on particle range assignment. Approximately 70% of the particles counted were correctly assigned to the $0.5-0.7 \mu\text{m}$ size range. Figure 3 illustrates particle count assignments made for 1 μm PSL. Under constant flow conditions, approximately 60% of the particles counted by the instrument were assigned to the $1-2 \mu\text{m}$ range and 20% to the $0.7-1 \mu\text{m}$ range. Under cyclic flow conditions it appears that a higher number of the 1 μm particles are misassigned. However, the count distribution was stable during the period of the experiment. As a result, count data from a given size range was still suitable for the proportional data reduction needed to calculate a fit factor.

Vapor Generation and Measurement

Acetone vapor generation was accomplished using a syringe pump, a calibrated dilution air source, and an evaporation column. The generated vapor was routed into the chamber from the evaporation column. Syringe flowrates and dilution air volumes were selected to produce roughly 15,000 ppm of acetone in the chamber. Samples to determine the chamber concentration of acetone and the concentration of acetone vapor leaking into the respirator were collected from a sampling site located in the plumbing between the test chamber and

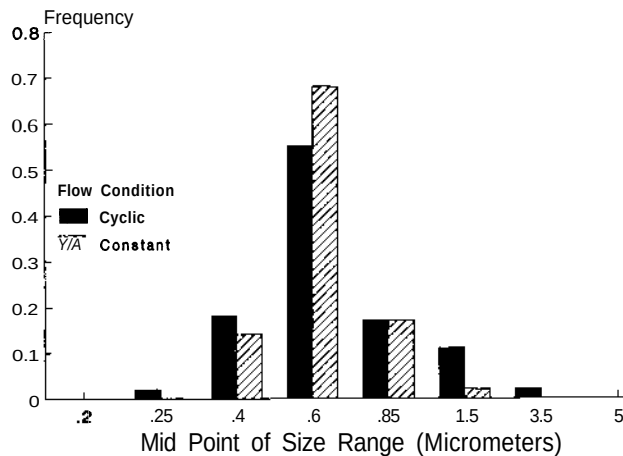


Figure 2. Frequency of particle counts in all Scanner® size ranges for a 0.6 µm PSL Aerosol with a cyclic and constant flow of 10.8 LPM.

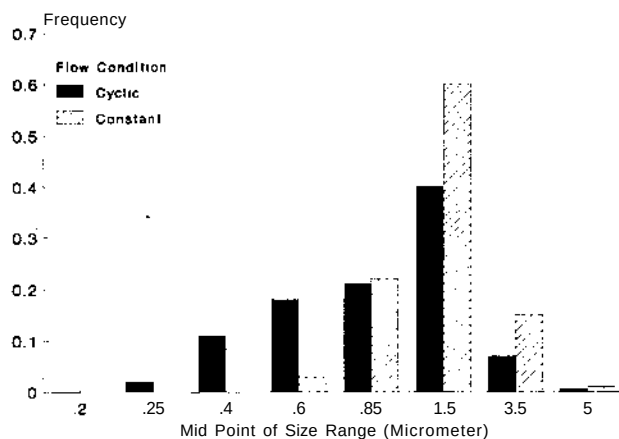


Figure 3. Frequency of particle counts in all Scanner® size ranges for a 1.0 µm PSL aerosol with a cyclic and constant flow of 10.8 LPM.

breathing machine (Figure 1). A similar sampling location has been evaluated and reported on in the literature (Myers, et al., 1986).

A Beckman Industrial Model 400A Hydrocarbon Analyzer was used for acetone vapor measurement. It has a lower-limit of detection of approximately 0.5 ppm of acetone. Flame ionization is used as the method of detection. The analyzer was calibrated with certified mixtures of acetone in ultra-pure air (hydrocarbon content < 0.5 ppm).

Breathing simulation was produced with a TSI Model 8091 breathing simulator. The breathing curve used in the experiment was representative of a

622 kg-m/min(watt) work rate. The breathing rate was held constant at 18 per minute. The tidal volume was set at 0.6 or 1.5 liters to simulate rest and moderate workload tidal volumes. The 0.6 L tidal volume produced a maximum pressure drop inside the respirator of 0.6" of water and the 1.5 L tidal volume 2.1" of water.

In preparation for testing, the test facepiece was mounted on a mannequin headform. Five capillary tubes of various diameters were inserted between the facial surface of the mannequin and the sealing lip of the respirator. The leak capillary diameters and length-to-width ratios are given in Table 1. Faceseal leaks are generally believed to have a circular or slit geometry. Oestenstad (1988) reported from some fit test experiments that approximately 27% of the faceseal leaks could be represented by a circular geometry.

After the capillary tubes were positioned, an airtight seal was made around the entire perimeter of the sealing-lip surface using silicone adhesive.

The integrity of the airtightness of the respirator was very important to assure that no leakage occurred, other than through one of the open capillary tubes. To evaluate the airtight integrity of the respirator, a slight negative pressure was created in the cavity of the facepiece. Evidence of air-tightness was demonstrated by maintaining two inches of water negative or positive pressure over a period of approximately 1 hour.

After the airtight integrity of the mounted respirator was assured, it was placed in the test chamber and attached to plumbing connecting the headform to the breathing machine.

Table 1. Capillary diameters and length-to-diameter ratios.

Internal diameter (mm)	L/D ratio
0.25	76.0
0.275	69.1
0.3	63.3
0.33	57.6
0.51	37.

Length = 19 mm for all capillaries.
0.275 mm rounded to 0.28

Experimental Design and Data Analysis

The experiment considered three main parameters—leak size (LS), particle size (PS), and tidal volume (VOL) as independent variables and penetration of a particular particle size (PRPEN) as the dependent variable. Five levels of leak size, five levels of particle size, and two levels of tidal volume were evaluated. For the experiment, acetone vapor was considered as a level of particle size. Three replications were run on each of the 50 (5 x 5 x 2) test cells.

The experimental design adopted for the study was a split-plot design. This design was necessary because the 150 treatment cells (50 test configuration x 3 replications) could not be randomly evaluated. The plots in the split-plot design were the replications. The main treatment within plot was particle size and the sub-treatments (sub-plots) were leak size and tidal volume. The error mean squares (EMS) used for hypothesis testing are discussed and shown in the Addendum.

The null hypotheses to be tested are:

1. The mean penetration estimates made for a given leak size are not different for different size PSL and the vapor.
2. The mean penetration estimates made for different tidal volumes are not different.
3. The mean penetration estimates made for different leak sizes are not different. NOTE: This null hypothesis should be rejected given the physical principles involved.

The linear model for the split-plot design is:

$$Y_{ijkl} = U + P_i + R_j + e_{ij} + V_k + (PV)_{ik} + L_l + (PL)_{il} + (VL)_{kl} + (PVL)_{ikl} + e_{ijkl}$$

Where:

U = the true mean,
 Ti = the effect of the i^{th} replication,
 Bj = the effect of the j^{th} particle size,
 Vk = the effect of the k^{th} tidal volume,
 Gl = the effect of the l^{th} tidal leak size, and
 (XX), etc. represent various interactions.

The penetration data in each treatment combination were checked for normality using the Shapiro-Wilks test. Of the 50 test cells in the test matrix, 45 of

the penetration data sets could be considered normally distributed and five were not. Based upon these test results the complete data was considered to be normally distributed. Tests on means were done with a Duncan's Multiple Range Test with an $\alpha = 0.05$. Apparent fit factor (AFF) values were not used as a dependent variable in the analysis of variance but were subsequently calculated from the penetration values for inclusion into the report.

Test Procedure

The test procedure used to collect experimental data was as follows. The procedure was repeated for each treatment setup for each different particle size and the acetone vapor.

1. The in-facepiece line valve was opened in order to measure the in-facepiece background concentration. The chamber line valve and all the leaks were closed and sealed. The breathing apparatus was turned on. Three 2-minute in-facepiece background values were recorded. The first sample was discarded and the last two were used for further data analysis.
2. The chamber line valve and the in-facepiece line valve were opened and closed respectively to obtain four 2-minute samples of the chamber concentration. The first of the four 2-minute samples was discarded. The last three samples were used for further data analysis.
3. The in-facepiece line valve and the chamber line was opened and closed again. The system was given one minute to equilibrate, then the aerosol measurement was started. The value obtained should verify the initial background reading.
4. A specific leak was opened and four 2-minute samples were recorded. The first one was discarded and the last three were used for data analysis.
5. The chamber line valve and the in-facepiece line were opened and closed respectively, to obtain a second set of four 2-minute samples of the chamber concentration. These samples were treated as identified in Step 2 above.

The data collected by the aerosol scanner was expressed as particle counts per unit volume. These count data are subsequently referred to as particle range counts (PRC). The PRC data was used directly to calculate the particle range penetration (PRPEN).

All scanner count data were corrected for background. When the in-facepiece concentration (C_i) was zero or when C_i minus background was zero, the apparent fit factor (AFF) could not be estimated. In those cases the following rules were observed for handling the data. When C_i was zero, AFF was estimated by using the background observations averaged over the 30 test cells involving that specific particle size range. No further background correction was made. If a background particle concentration was equal to or greater than a C_i value, then it was replaced with the average background calcu-

lated from all the background observations made for the 30 test cells involving that particle size.

The acetone concentration data collected inside and outside the respirator were expressed as PPM. Vapor penetration was calculated using a ratio of the PPM data.

The inverse of the penetration was expressed as the AFF achieved under the contrived conditions of our test equipment, experimental setup, and test procedure.

Results and Discussion

The results of the analysis of variance are given in Table 2. Leak size, particle size, and tidal volume were all found to be significant effects on facepiece penetration as well as a leak size x tidal volume interaction. The effect of leak size on PSL and acetone penetration was entirely expected and the explanation is simple: the bigger the leak diameter the greater the flow through the leak and therefore the greater the measured penetration.

The effect of tidal volume on PSL and acetone penetration was also significant. The mean penetration and apparent fit factor data are summarized in Tables 3-7. The higher pressure drop in the facepiece associated with the 1.5 L tidal volume caused increased flow through the leaks. The relationship between leak flow Q and pressure drop P is given by

$$Q = aP^b$$

Table 2. Analysis of variance.

Source	DF	ANOVA SS	F Value	PR > F
REP	2	2.66E-09		
PS	4	3.52E-07	4.7	0.0303*
REP*PS	8	1.49E-07		
VOL	1	8.59E-08	69.39	0.0141*
REP*VOL	2	2.47E-09		
PS*VOL	4	6.37E-08	1.48	0.2951
REP*PS*VOL	8	8.61E-08		
LS	4	3.87E-06	244.29	0.0001*
REP*LS	8	3.17E-08		
PS*LS	16	2.45E-07	1.15	0.3581
REP*PS*LS	32	4.27E-07		
VOL*LS	4	1.20E-07	14.58	0.0010*
REP*VOL*LS	8	1.65E-08		
PS*VOL*LS	16	1.98E-07	1.03	0.4580
REP*PS*VOL*LS	32	3.86E-07		

* significant at alpha = 0.05

REP = replication

PS = particle size generated

VOL = minute volume

LS = leak size

Table 3. Gas penetration data and apparent fit factors as a function of leak size and tidal volume.

Leak size (mm)	Tidal volume (L)	Mean penetration	Standard deviation	Minimum penetration	Maximum penetration factor	Apparent fit factor*
0.51	.6	4.43E-04	4.57E-04	1.78E-04	9.70E-04	2256
0.51	1.5	9.38E-04	2.79E-04	6.17E-04	1.12E-03	1067
0.33	.6	1.92E-04	1.42E-05	1.80E-04	2.08E-04	5200
0.33	1.5	2.25E-04	2.33E-05	2.04E-04	2.50E-04	4441
0.3	.6	1.20E-04	7.45E-06	1.13E-04	1.28E-04	8321
0.3	1.5	1.38E-04	5.49E-06	1.33E-04	1.44E-04	7258
0.28	1.5	7.75E-05	4.21E-06	7.46E-05	8.24E-05	12897
0.28	.6	6.30E-05	3.53E-06	5.94E-05	6.65E-05	15873
0.25	.6	4.54E-05	5.50E-07	4.49E-05	4.60E-05	22046
0.25	1.5	7.19E-05	3.01E-06	6.98E-05	7.53E-05	13910

* FF = (mean penetration)⁻¹**Table 4. Mean penetration fraction and apparent fit factor for a 0.36 µm diameter PSL aerosol as a function of leak size and tidal volume.**

Leak size (mm)	Tidal volume (L)	Mean penetration	Standard deviation	Minimum penetration	Maximum penetration factor	Apparent fit factor*
0.51	1.5	3.07E-04	9.11E-05	2.41E-04	4.11E-04	3260
0.51	.6	3.52E-04	1.51E-04	2.13E-04	5.12E-04	2843
0.33	1.5	8.58E-05	3.58E-05	4.63E-05	1.16E-04	11652
0.33	.6	8.18E-05	2.12E-05	5.76E-05	9.72E-05	12228
0.3	.6	3.88E-05	1.90E-05	1.69E-05	5.02E-05	25747
0.3	1.5	5.83E-05	1.58E-05	4.01E-05	6.81E-05	17144
0.28	.6	3.09E-05	1.86E-05	1.03E-05	4.64E-05	32404
0.28	1.5	2.43E-05	1.95E-05	9.71E-06	4.65E-05	41118
0.25	1.5	2.42E-05	1.02E-05	1.78E-05	3.60E-05	41254
0.25	.6	1.62E-05	7.53E-06	1.09E-05	2.48E-05	61843

* FF = (mean penetration)⁻¹

where a and b are constants for a given leak.²⁷ The exponent b is a function of the length-to-diameter ratio. For ratios greater than 18, b approaches unity, indicating laminar flow through the capillaries.²⁸ The L/D ratios used on this experiment were all greater than 18 suggesting laminar flow conditions existed within the capillaries. The leak size x tidal volume interaction is thought to be due to the unique linear flow vs pressure drop relationship which existed for each different L/D ratio.

As a result of these volume effects, for any leak size-particle size combination, a lower AFF was measured for the 1.5 L tidal volume than for the 0.6 L tidal volume. This observation is similar to other pressure-drop effects on aerosol flow into a respirator reported by Hinds and Bellin²⁸ and Campbell.²⁹ It suggests that use of an "at rest condition" that translates into smaller tidal volumes in a fit test will tend to produce inflated estimates of fit as compared to estimates of fit made with larger tidal volumes, i.e.

Table 5. Mean penetration fraction and apparent fit factor for a 0.62 µm diameter PSL aerosol as a function of leak size and tidal volume.

Leak size (mm)	Tidal volume (L)	Mean penetration	Standard deviation	Minimum penetration	Maximum penetration factor	Apparent fit factor*
0.51	1.5	4.78E-04	6.92E-05	4.04E-04	5.41E-04	2091
0.51	.6	3.63E-04	9.11E-05	2.95E-04	4.67E-04	2753
0.33	1.5	9.94E-05	1.60E-05	8.79E-05	1.18E-04	10065
0.33	.6	6.02E-05	1.69E-05	4.08E-05	7.18E-05	16606
0.3	.6	3.46E-05	4.55E-06	3.20E-05	3.99E-05	28868
0.3	1.5	7.80E-05	2.27E-05	6.04E-05	1.04E-04	12827
0.28	.6	2.82E-05	4.69E-06	2.37E-05	3.30E-05	35398
0.28	1.5	1.93E-05	4.04E-06	1.56E-05	2.36E-05	51894
0.25	1.5	2.62E-05	9.28E-06	1.94E-05	3.68E-05	38183
0.25	.6	1.95E-05	5.70E-06	1.60E-05	2.61E-05	51282

* FF = (mean penetration)⁻¹**Table 6. Mean penetration fraction and apparent fit factor for a 1 µm diameter PSL aerosol as a function of leak size and tidal volume.**

Leak size (mm)	Tidal volume (L)	Mean penetration	Standard deviation	Minimum penetration	Maximum penetration factor	Apparent fit factor*
0.51	1.5	4.99E-04	2.26E-04	3.32E-04	7.56E-04	2002
0.51	.6	3.17E-04	1.07E-04	2.20E-04	4.31E-04	3152
0.33	1.5	1.09E-04	4.61E-05	5.61E-05	1.40E-04	9163
0.33	.6	7.11E-05	5.26E-05	4.05E-05	1.32E-04	14055
0.3	.6	1.24E-05	1.18E-05	1.07E-06	2.46E-05	80972
0.3	1.5	9.09E-05	1.83E-05	7.11E-05	1.07E-04	11004
0.28	.6	1.51E-05	6.79E-06	7.87E-06	2.13E-05	66050
0.28	1.5	4.24E-05	3.70E-05	2.74E-06	7.59E-05	23602
0.25	1.5	1.16E-05	7.81E-06	2.58E-06	1.66E-05	86430
0.25	.6	1.49E-05	1.27E-05	2.06E-06	2.74E-05	67340

* FF = (mean penetration)⁻¹

under conditions of exercise which increase pulmonary tidal volumes.

In a fit test scenario where the goal of the testing is to select a better fitting respirator (brand and/or size) and the in-facepiece sampling biases are similar (between brands and/or sizes) the importance of the measured fifts dependence on tidal volume is small because a relative comparison

is being made. While the difference in AFF determined by this study was significantly different ($P < 0.05$) for the 0.6 L vs the 1.5 L tidal volume. The data in Tables 3–7 show that the same relative order of size ranking of the leak is obtained with either tidal volume.

The degree to which tidal volume will remain somewhat consistent for a given individual or group

Table 7. Mean penetration fraction and apparent fit factor for a 2.5 μ m diameter PSL aerosol as a function of leak size and tidal volume.

Leak size (mm)	Tidal volume (L)	Mean penetration	Standard deviation	Minimum penetration	Maximum penetration factor	Apparent fit factor*
0.51	1.5	4.31E-04	2.40E-04	2.90E-04	7.08E-04	2318
0.51	.6	3.87E-04	2.91E-04	2.01E-04	7.22E-04	2583
0.33	1.5	7.46E-05	1.44E-05	6.05E-05	8.92E-05	13412
0.33	.6	4.89E-05	1.95E-05	2.69E-05	6.39E-05	20471
0.3	.6	3.04E-05	3.34E-05	4.00E-07	6.65E-05	32884
0.3	1.5	7.30E-05	5.50E-05	3.52E-05	1.36E-04	13704
0.28	.6	7.10E-07	2.60E-07	4.30E-07	9.30E-07	1408451
0.28	1.5	3.81E-06	3.55E-06	6.80E-07	7.66E-06	262467
0.25	.6	1.14E-06	7.80E-07	4.60E-07	1.99E-06	877193
0.25	1.5	4.03E-06	6.43E-06	3.00E-07	1.15E-05	248139

* FF = (mean penetration)⁻¹

of individuals undergoing fit testing is unknown. What is more certain **however**, is that the tidal volume exhibited by an individual who is basically "at rest" in a fit test will be substantially higher during actual use of the respirator. Even if the respirator "fits" him identically as when he was fit tested, he will experience greater facesal penetration (i.e., lower protection) than what he experienced during fit testing. This will be true given the increased pressure differential does not change the leak size. While it is often stated that naturally occurring facesal leaks will seal better at higher pressures, the literature searched by these authors revealed no published data upon which such conclusions can be substantiated.

Another significant determinant on penetration was particle size. The mean value of the apparent fit factor, AFF, calculated as $1/(\text{mean PRPEN})$, for different size aerosol, different leak sizes, and different tidal volumes are also given in Tables 3-7.

It should be noted that very high AFF values were measured for the largest particle size-smallest leak diameter treatment combinations (Tables 5 and 7). All of the AFF values determined with the four PSL aerosols, for both tidal volumes on the 0.25 mm capillary, were greater than 38,000; five of eight AFF values determined on the 0.28 mm capillary were greater than 38,000; and one of eight AFF values on the 0.3 mm capillary was greater than 38,000. With the test system and test procedures used, the reliability of measured AFF values above 38,000 must be

cautioned. Only small numbers of particles were counted with these high AFF values even with test times of 20 minutes. However, the data do suggest that very high AFF values were being measured even if it is not believed that they could be reliability quantified with the test equipment and methodology used. The mean penetration values measured with the 2.5 μ m PSL on the 0.25 and 0.28 mm capillaries were significantly different ($P < 0.05$) from the mean penetration data obtained with the other PSL aerosols and the acetone vapor.

Another observation arising from the data is that regardless of particle size or tidal volume, the order of the leak size rankings based upon the AFF rankings were all the same $0.51 > 0.33 > 0.3 > 0.28 > 0.25$ (if AFF values equal to or greater than 38,000 were excluded from the rankings). Relatively speaking, the correct order of capillary size (or degree of fit by analogy) could be determined with gas or particles at either 0.6 or 1.5 L tidal volumes.

Perhaps the most interesting observation is the finding that the mean penetration values measured with a vapor, for all leak sizes, were larger than those mean penetration values measured with any of the different size PSL aerosols. Duncan's Multiple Range Test indicated that acetone vapor penetration was significantly higher than the penetration measured with any of the aerosol sizes tested. Tables 8 and 9 contain mean penetration data for a vapor challenge agent and each PSL particle size as a function of leak size for tidal volumes of 0.6 and 1.5 L, respectively.

Table 8. Mean fit factors as a function of leak size and particle size for a tidal volume of 0.6 ml.

Challenge Agent	Leak Size				
	1	2	3	4	5
Gas	8,300 ^A	5,200 ^A	15,900 ^A	2,300 ^A	22,000 ^A
0.36 mm PSL	25,700 ^B	12,200 ^B	32,400 ^B	2,800 ^A	61,800 ^C
0.62 mm PSL	28,900 ^B	16,600 ^B	35,400 ^B	2,800 ^A	51,300 ^{BC}
1.01 mm PSL	81,000 ^B	14,100 ^B	66,100 ^{BC}	3,200 ^A	67,300 ^C
2.52 mm PSL	32,000 ^B	20,500 ^B	1.408 × 10 ⁶ ^C	2,600 ^A	2.481 × 10 ⁵ ^C

n=3

Values rounded to hundreds.

Values within a leak size with different superscripts are significantly different.

Table 9. Mean fit factors as a function of leak size and particle size for a tidal volume of 1500 ml.

Challenge Agent	Leak Size				
	1	2	3	4	5
Gas	7,300 ^A	4,400 ^A	12,900 ^A	1,100 ^A	13,900 ^A
0.36 mm PSL	17,100 ^B	11,700 ^B	41,100 ^B	3,300 ^B	41,300 ^C
0.62 mm PSL	12,800 ^B	10,100 ^B	52,900 ^B	2,100 ^B	38,200 ^{BC}
1.01 mm PSL	11,000 ^{AB}	9,200 ^B	23,600 ^{AB}	2,000 ^B	86,400 ^{CD}
2.52 mm PSL	13,700 ^B	13,400 ^B	2.625 × 10 ⁵ ^B	2,300 ^B	8.772 × 10 ⁵ ^D

n=3

Values rounded to hundreds.

Values within a leak size with different superscripts are significantly different.

These mean penetration data expressed as AFF are plotted in Figures 4 and 5 for tidal volumes of 0.6 and 1.5 L, respectively, and in Figure 6 for the pooled tidal volume data. With the largest leak size (0.51 mm), the AFF determined with the vapor challenge was significantly less ($P < 0.05$) than the AFF determined with the 0.36 μm particle range penetration data. None of the AFFs determined by the particle range penetration data on the 0.51 mm capillary leak were significantly different from one another. For the larger leak sizes (0.3 mm, 0.33 mm, and 0.51 mm), the penetration for acetone vapor was 1.6 to 3.4 times higher than the penetration calculated by particle size range data.

With the two small diameter leaks (0.25 mm and 0.28 mm) the AFF measured with the 2.5 μm aerosol was also significantly higher than those obtained with the other size aerosol. For these leak

sizes, the acetone vapor penetration was approximately two times higher than that determined with PSL aerosol up to 1 μm and 22 to 30 times higher for PSL aerosol above 1 μm . Figure 6 illustrates the marked increase in AFF that occurs with the 1 and 2.5 μm particle range data for the 0.25 mm and 0.28 mm diameter leaks. The 0.36 and 0.62 particle range data seem to parallel each other (as well as the vapor data) very nicely over the range of leak diameters studied.

Significantly lower penetration of particles over 1 μm vs vapor penetration may be attributed to the particles' inability to penetrate the smaller leaks. This may be due either to insufficient capture velocity of the leak inlets or possibly inlet losses of the larger particles. In comparison with earlier results, the ratio of vapor to aerosol penetration observed in the study penetration ratios are much higher than reported by Schwabe,²⁴ who compared the penetration by

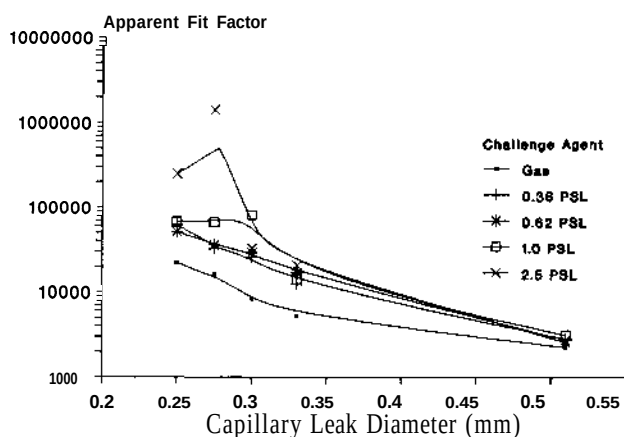


Figure 4. Apparent fit factor measured with 0.6 L tidal volume plotted for various PSL aerosols and a vapor as a function of leak diameter.

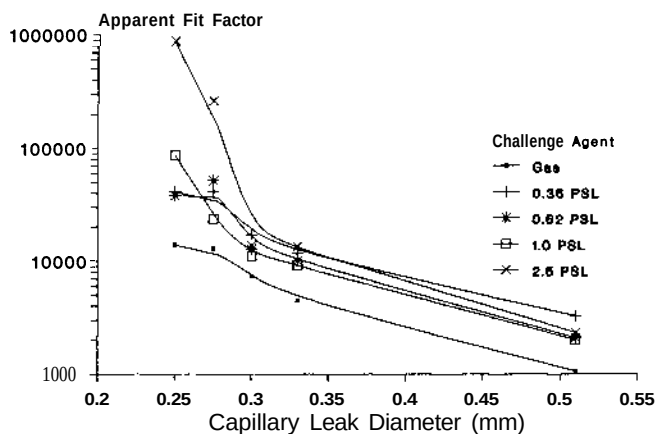


Figure 5. Apparent fit factors measured with a 1.5 L tidal volume plotted for various PSL aerosols and a vapor as a function of leak diameter.

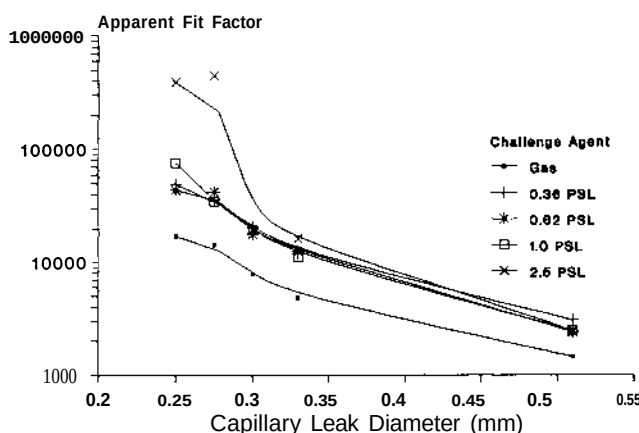


Figure 6. Apparent fit factors averaged for 0.6 and 1.5 L tidal volumes plotted for various PSL aerosols and a vapor as a function of leak diameter.

methane with that of salt aerosol. He reported that the average leakage measured by methane was 50% greater than the same leakage measured by salt aerosol. Considering the differences in that study and this study between the number of leaks (9 vs 5), sizes of leaks (0.1 mm vs 0.25 to 0.51 mm), and the sizes of particle used ($0.2\mu\text{m}$ MMAD vs 0.27 to $2.5\mu\text{m}$) the ratios obtained by this study appear to be comparable to Schwabe's results for the smaller particle sizes. In contrast, Hounam, who compared the penetration by sodium chloride with difluorodichloromethane,⁸ and Griffin, who used sodium chloride and argon,³ reported no difference between face seal penetration measurement made with gas or aerosols. These data clearly do not support such an observation.

Findings from this present study suggest that the aerosol sizes used in the study did not provide the same measurement of penetration obtained with the acetone vapor. Given the test system setup, this result is not likely caused by sampling errors. It is concluded that the difference is real and one that must be recognized when developing fit-test techniques and comparing measurements of penetration made with different challenge agents (size and physical state) and different methods of quantifying penetration (count data vs scatter data vs mass data). Based upon this experimental data, it is felt that for fit determinations above 1000, a vapor or gas fit-test agent provides a more realistic assessment of the true face seal penetration than aerosols having AMMD greater than $0.2\mu\text{m}$. The difference between penetra-

tion measurements made by vapor and particle size range penetration data implies that fit test assessments made with aerosols and subsequently used in considerations that involve a gas or vapor may underestimate the penetration of the gas or vapor. Correlations appear to be evident in the data. Further research to clarify and further define this correlation is needed.

In Figures 7 and 8 the mean penetration is plotted as a function of particle size for three of the five leak sizes. For the 1.5 L tidal volume measurements the features of the penetration curves appear to similar to those reported by Holton et al.¹⁸ That is, a maximum penetration appears to occur in the particle size range of roughly 1 μm . This is evident with both the 0.3 mm and 0.51 mm diameter leaks.

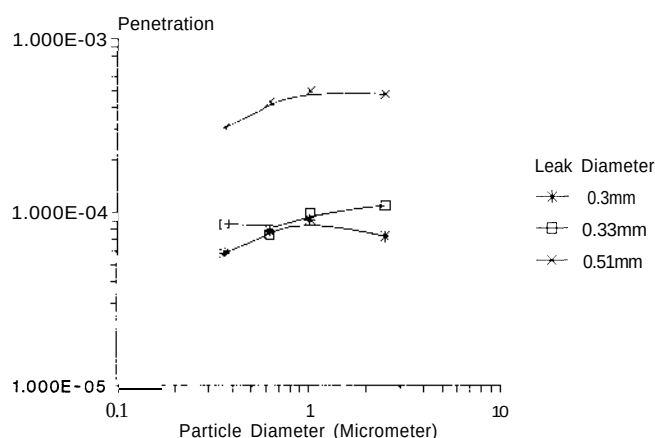


Figure 7. Penetration measured with a 1.5 L tidal volume plotted as a function of particle size and leak diameter.

Our range of particle sizes was insufficient to confirm Holton's observation that penetration begins to decrease again with increasing particle sizes. For the 0.6 L tidal volume the features of the penetration curves are quite different from those obtained with the 1.5 L tidal volume and those reported by Holton et al.. With the 0.51 mm diameter leak no variation appears to be present in the mean penetration values measured over the range of particle sizes used in this study. With both the 0.3 mm and 0.33 mm diameter leaks a minimum in penetration occurs at roughly the 1 μm particle size range, rather than a maximum in penetration. The reason for this observation is not known. The 0.25 mm and 0.28 mm leak diameters were not plotted with these data because of the small particle counts measured with these leak sizes.

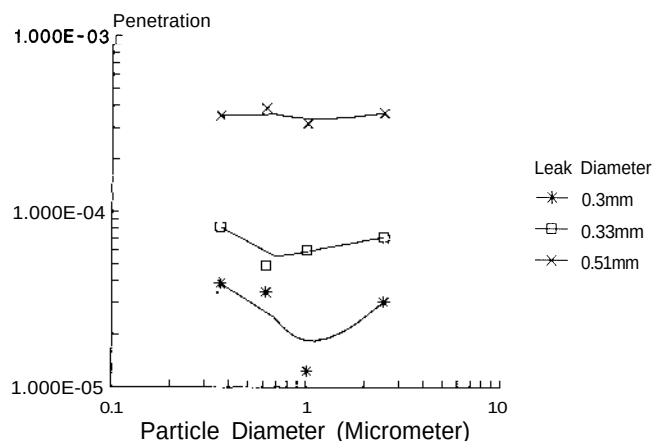


Figure 8. Penetration measured with a 0.6 L tidal volume plotted as a function of particle size and leak diameter.

Conclusion and Recommendations

Findings that measurement of faceseal leakage is affected by particle size and tidal volume are in agreement with the few studies that have evaluated such relationships. The difference in the calculated fit factors arising from using aerosol count concentration data vs vapor mass concentration is a significant new observation. The test results suggest that a fit test utilizing a vapor or gas challenge agent may be a more critical test in terms of penetration than fit tests utilizing an aerosol. Efforts need to be undertaken to evaluate the feasibility of such test systems.

Such systems should also consider means for increasing the tidal volume of test subjects. This recommendation is based on the significant difference in measured faceseal penetration that was observed when a low or high tidal volume was used.

Differences in penetration as a function of particle size, noted particularly with the smaller leak sizes, is an important observation to consider when attempting to compare fit factors measured with a sodium chloride aerosol of 0.28 μm and an oil mist aerosol of 0.5 μm MMAD.

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Addendum

The whole plot error is the PS*replication (REP) interaction and the subplot errors are the 3-factor interactions REP*PS*LS and REP*PS*VOL. The main factor, particle size, in the whole plot is tested against the REP*PS interaction, i.e., the whole plot error. The effect of leak size and tidal volume are tested against the interaction terms REP*LS and REP*VOL, respectively. The PS*LS and PS*VOL interactions are tested against the subplot errors terms REP*PS*LS and REP*PS*VOL, respectively. The LS*VOL and PS*VOL interactions are tested against the R*LS*TV and REP*PS*VOL interaction terms, respectively.

Estimated Mean Squares and Tests for Hypotheses

FACTOR	abc d 1 3 5 2 5 1 R F F F R i j k l m	Estimated Mean Squares (EMS)	F-Test
WHOLEPLOT			
$T_i=(A)$	1 3 2 5 1	$\tau^2+50\tau^2_T$	
$\beta_j=(B)$	3 0 2 5 1	$\tau^2+30\Sigma\beta_j^2/4+10\tau^2_{T\beta}$	B/AB
$(T\beta)_{ij}=(AB)$	1 0 2 5 1	$\tau^2+10\tau^2_{T\beta}$	
SUBPLOT			
$\zeta_k=(C)$	3 5 0 5 1	$\tau^2+75\Sigma\zeta_k^2+25\tau^2_{T\zeta}$	C/AC
$(T\zeta)_{ik}=(AC)$	1 5 0 5 1	$\tau^2+25\tau^2_{T\zeta}$	
$(\beta\zeta)_{jk}=(BC)$	3 0 0 5 1	$\tau^2+15\Sigma\Sigma\beta\zeta^2/4+5\tau^2_{T\beta\zeta}$	BC/ABC
$(T\beta\zeta)_{ijk}=(ABC)$	1 0 0 5 1	$\tau^2+5\tau^2_{T\beta\zeta}$	
$\delta_l=(D)$	3 5 2 0 1	$\tau^2+30\Sigma\delta_l^2/4+10\tau^2_{T\delta}$	D/AD
$(T\delta)_{il}=(AD)$	1 5 2 0 1	$\tau^2+10\tau^2_{T\delta}$	
$(\beta\delta)_{jl}=(BD)$	3 0 2 0 1	$\tau^2+6\Sigma\Sigma\beta\delta^2/16+2\tau^2_{T\beta\delta}$	BD/ABD
$(T\beta\delta)_{jil}=(ABD)$	1 0 2 0 1	$\tau^2+2\tau^2_{T\beta\delta}$	
$(\zeta\delta)_{kl}=(CD)$	3 5 0 0 1	$\tau^2+15\Sigma\Sigma\zeta\delta^2/4+5\tau^2_{T\zeta\delta}$	CD/ACD
$(T\zeta\delta)_{ikl}=(ACD)$	1 5 0 0 1	$\tau^2+5\tau^2_{T\zeta\delta}$	
$(\beta\zeta\delta)_{jkl}=(BCD)$	3 0 0 0 1	$\tau^2+3\Sigma\Sigma\Sigma\beta\zeta\delta^2/16+\tau^2_{T\beta\zeta\delta}$	BCD/ABCD
$(T\beta\zeta\delta)_{ijkl}=(ABCD)$	1 0 0 0 1	$\tau^2+\tau^2_{T\beta\zeta\delta}$	
$E(ijkl)m$	1 1 1 1 1	τ^2	