

An Experimental Study for Measuring the Degree of Vapor/Aerosol Correlation For Respirators

Christopher J. Karwacki and Gregg W. Adams

Individual Protection Division • Physical Protection Directorate

Chemical Research and Development Center, Aberdeen Proving Ground, Maryland 21010

ABSTRACT

Leakage into respirators is measured by sampling the mask interior and reporting the value as a percent of the challenge concentration or the inverse as a protection factor (PF). Polydispersed (liquid or solid) aerosols are used as a surrogate for vapors and are assumed to be representative of the vapor leak. Therefore, the test is a measure of the degree of protection from a vapor. It is not intended to be a test against an aerosol threat. Even though the majority of the chemical hazards in the field exist as vapors, limited data have been collected on the performance of the respirator with vapors.

A program for studying the degree of correlation between a vapor and an aerosol leak is being pursued. The objective is to obtain a more thorough understanding of the relative response factors of various vapor and aerosol challenges through a given leak source. The approach in addressing their transport properties is to conduct three stages of investigation, (1) theoretical predictions, (2) controlled leak chamber measurements, and (3) controlled leak respirator measurements. In each stage the same leak source is evaluated theoretically and experimentally for each challenge. Vapors were selected on a number of factors such as material interactiveness (solubility) and detectability. Freons and dimethyl methylphosphonate (DMMP) are candidates at this time. Aerosols were selected based on their present usage for respirator leakage tests.

The theoretical maximum leaks were calculated for the known leak dimensions using Poiseuille flow equations. For aerosol challenges, the predicted penetration value was determined for Poiseuille flow using the diffusion-sedimentation formulae of Davies (1973), Appendix A.

To date, the relative leakage and penetration values through standard capillaries have been measured under steady flow conditions using NaCl aerosol and Freon 11, DMMP, and air for vapors. Predicted values were also obtained on each of the leak sources. Aerosol measurements were obtained utilizing a LASER spectrometer (PMS Model ASASP-X) which provides sizing and number concentration data. Vapor leak data were obtained by flame photometric and halide detection (for DMMP and F-11, respectively). Air leakage data were measured by a soap bubble film test which resulted in a direct measurement of the leak through the capillary.

Preliminary data suggest several trends. For the NaCl aerosol with diameters between 0.107 to 0.406 microns the fractional penetration (leak rate) appears to be a function of particle size. In one case, data suggest changes in penetration range from 23.1 to 53.0 cc/min for the largest capillary (0.35 mm bore by 32.4 mm length) at a pressure drop of 6.0 inches of water. Additionally, penetrations for the smallest capillary (0.16 mm bore by 19.7 mm length) ranged between 1.8 and 3.1 cc/min for a pressure drop of 6.0 inches of water. In contrast, the predicted values for the corresponding leak size and aerosol distribution indicate greater than 95 percent

penetration, resulting in a predicted value of 54.5 (23 G) cc/min.

The vapor leak studies utilizing Freon-11, DMMP, and air, for the same capillaries used in the aerosol tests, indicate good agreement with the predicted values. Agreement improved with smaller capillaries, with the predicted values being greater than or equal to those measured in most cases. The effects of the manufacturers fixed tolerances (plus or minus 0.05 mm) between the predicted and measured values for the various sized capillaries has been observed. Measured values are variable for the different size capillaries and are indicative of the instrument's response. Overall, the soap bubble test data (air) provided the best fit in accuracy to the predicted values.

For comparison purposes, the air leakage average value for the largest capillary was 52.5 cc/min (-6.0 dP), whereas for NaCl under equivalent conditions the leakage ranged from 23.0 (0.406 microns) to 54.0 (0.107 microns) cc/min.

The results of the preliminary findings are significant to the current test technology utilizing polydispersed aerosols. The findings indicate that even for conditions that approach ideal environments (i.e. leak source and controlled chamber), the utilization of aerosols for assessing the degree of vapor leak are variable and may potentially yield widely differing results for a respirator on man. In particular, for non-laboratory conditions, the actual respirator leak path may not be of a simple geometry, such as a capillary. More complex geometries could decrease the aerosol penetration, thus indicating a smaller total leak

I. INTRODUCTION

Most protective respirators used for respiratory protection are certified for use by obtaining a leakage value based on the level of aerosol entering the mask. The aerosol distribution of the challenge and leak are assumed to be equal, thus providing information representing a vapor leak.

The origin of this technology and its applications to respirators dates back to the nuclear industry's need for respirators to be worn within radioactive particulate environments. In conjunction, industry adopted the use of hot smoke generated aerosols (i.e. dioctyl phthalate, DEHP) for certifying High Efficiency Particulate Air (HEPA) filters. Both applications utilizing the same technology provided the impetus for respirator assessment.

Although experts have recognized the problems associated with using test aerosols for evaluation purposes, little has been reported addressing the low leakage requirements (i.e. < 0.01%). Numerous data have been reported for leakage in the 0.1 to 10.0% range where reasonable accuracy between a vapor and aerosol leak has been demonstrated. The concern with leaks less than 0.01%, when using aerosols, is that the chances for loss may be greatly enhanced. Without appropriate detection capable of

accounting for these losses, information regarding the true concentration will be diminished. Davies, et al. have provided equations capable of predicting these losses through pipes. In addition, they have provided insight with respect to the effects of particle loss due to entrance effects and bends in the leak source. Although it is realized that ideal slits and capillaries probably do not exist in respirators, the magnitude of these losses may be greatly increased due to the non-uniformity of the leak source.

n. THEORETICAL METHODS

One of the major difficulties in providing predictive equations for aerosol leakage is the degree of complexity of the leak geometry. In respirator testing the use of aerosols to trace the vapor leak assumes that the leak flow rate, $Q(l)$, is the product of the total flow rate, $Q(t)$, and the fractional penetration, $F(p)$, of the challenge, $Q(l)=Q(t) \times F(p)$ (for ideal mixing) (1) This follows from the assumption that no particle loss occurs while trans- itioning the leak path, or once inside the mask.

A convenient model that has been historically used to demonstrate the apparent validity of these assumptions

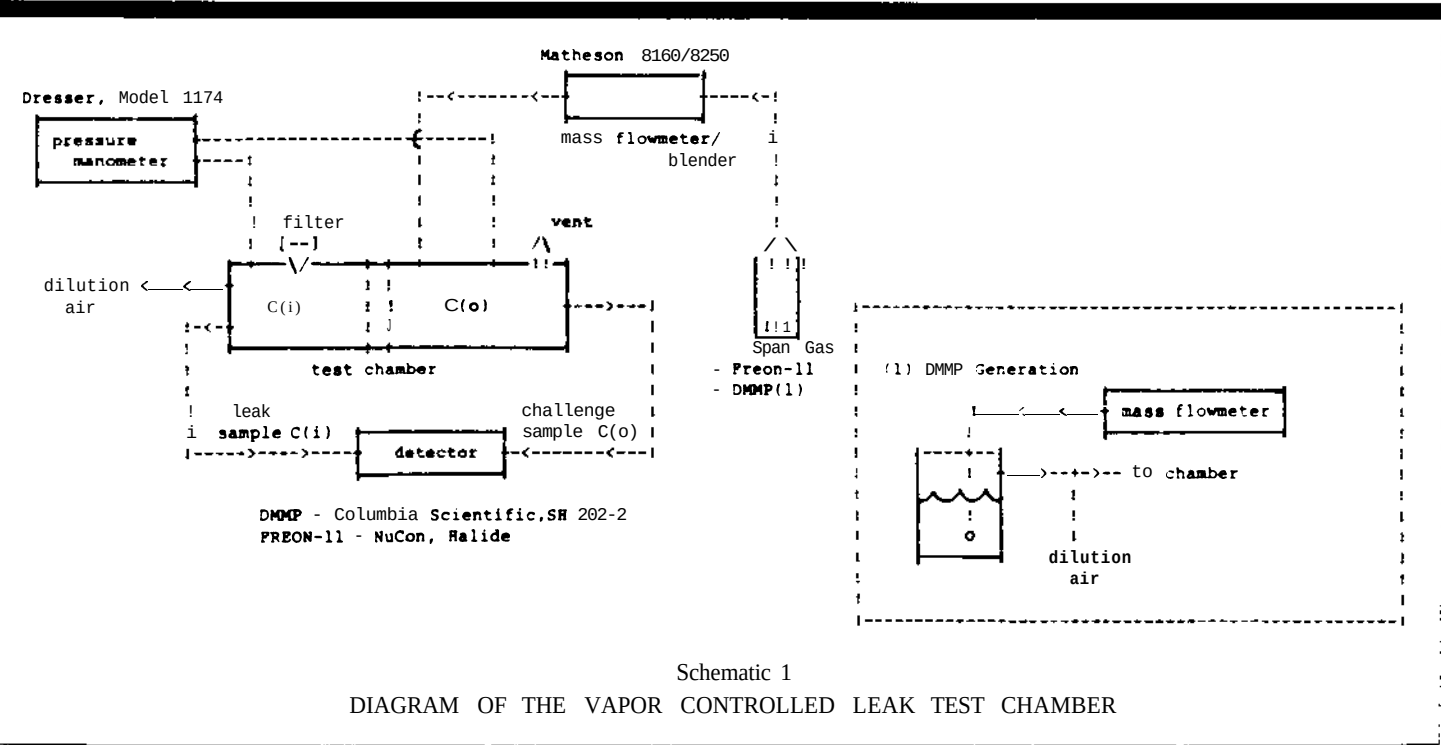
is to further assume that the leak geometry is a perfect capillary or slit. This model provides the best case in showing a correlation between a vapor and an aerosol. Additionally, they are reproducible experimentally and are easy to theoretically predict.

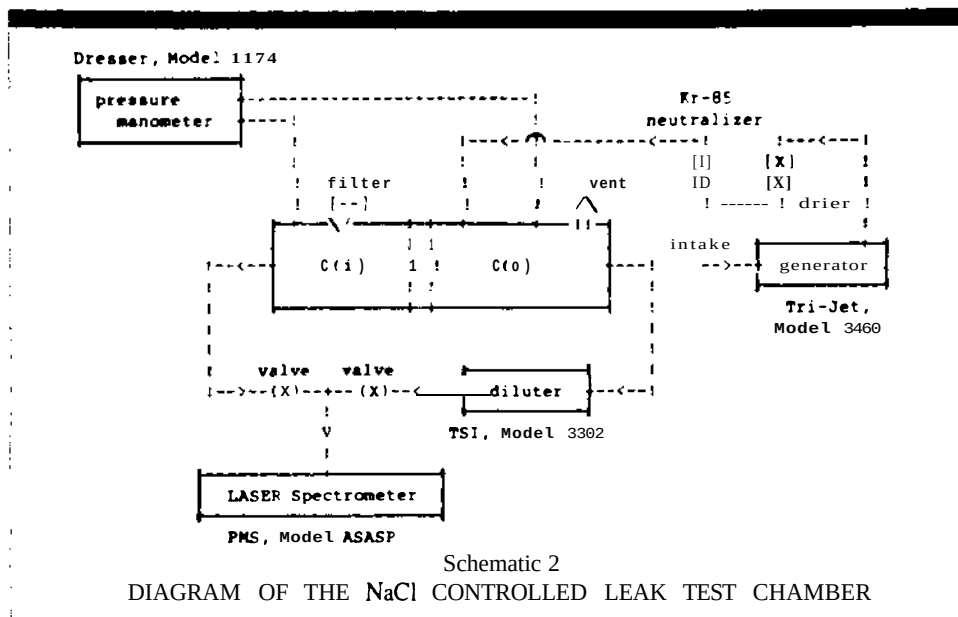
Utilizing the equations expressed in appendix A, it has been determined that the transport efficiencies for the capillaries used in this study approach 100%. In other words, losses due to diffusion and sedimentation are negligible and therefore a vapor/aerosol correlation may be valid. However, as mentioned earlier, it is highly unlikely that a respirator would contain a perfect capillary for leakage.

The capillaries used in this study provide variable results from the predicted values for vapors and aerosols, as shown in Tables 4 - 7. The results of these effects may be attributed to non-ideal fluid flow at the capillary entrance. Graphically, these values are shown in Figures 1-8.

III. EXPERIMENTAL

Similar arrangements were used for evaluating the vapor and aerosol leaks and differed only in methods of generation and detection. The vapor and NaCl test systems are shown in schematics 1 and 2, respectively.





The controlled leak test chamber is designed to provide leakage measurements of vapors and aerosols under steady and breather flows. Data in this report addresses leaks created under steady flow by varying the pressure drop across the chamber. The chamber is cylindrical in shape and is partitioned between the challenge, C(o), and leak side, C(i). The partition is a flange design and is sealed air tight to allow only transport of the vapor or aerosol through the leak source. The challenge medium enters near the leak site and exits at the far right end. On the leak side, various ports are placed to provide for clean air (filter), outlet valve (breather flow), pressure monitoring (dP), and sampling. Accurate control of the dP is performed by measuring the C(o)/C(i)

chambers. This is required in order to correct for elevations in pressure due to purging of the mediums through the challenge side.

Four capillaries were evaluated and range in length from 19.7-32.4 mm and a bore diameter of 0.14-0.37 mm. Selection criteria and detailed dimensions are discussed in Section III.C.

III. A. VAPOR EVALUATION

Freon-11 and DMMP vapors were generated under controlled conditions by using a mass flow meter/blender system (Matheson 8160/8250). The vapor challenge, C(o), entered the chamber upstream of the leak source partition and exited through a vent. The challenge concentration for DMMP was mon-

itored by taking bubblers and analyzing for total phosphorous. Freon-11 vapors were not directly measured during a test, but were predetermined by knowing the span gas concentration delivered from a compressed gas cylinder. Table 1 lists the challenge concentration and instrument performance characteristics for each vapor utilized.

Leakages through the capillaries were created by varying the resistance through the dilution air filter at a fixed flow rate. Pressure drops were set at -10, -6, -4, -2, and -1 inches of water. An electrical manometer measured up and downstream absolute pressure and provided a real-time recording of the pressure drop during the test. The vapor leak was allowed to reach equilibrium, then sampled and measured at a controlled sample rate of 0.250 and 2.0 1pm for the DMMP and Freon-11, respectively. This method maximized the precision of the test trials since changes in the ambient temperature appeared to effect the rate of equilibrium.

Calibration of the instrument for F-11/DMMP was conducted by blending the span gas, C(o), with clean air, down to approximately 10% of the lowest measured value obtained during an actual test. A power fit of the calibration data, shown in the following equation,

$$\ln Y = \ln A + B \ln X \quad (2)$$

provided a fit for the unknown values.

Air leakage data was obtained by a standard soap bubble film test where the capillaries leak could be measured directly.

III. B.

AEROSOL EVALUATIONS

NaCl aerosol was generated by using an aspirator under fixed pressures and flowrates (20 psig/approx. 5 1pm). The wet aerosol was conditioned with a diffusion dryer, then charged to a Boltzman equilibrium distribution with a Kr-85 bipolar charger (TSI, Model 3012). The aerosol was introduced in a manner similar to that described for the vapors.

Aerosol measurements were performed with a LASER aerosol spectrometer (PMS, Model ASASP-X), which provided 64 channels of size and number concentration.

CHALLENGE	CHALLENGE RANGE	DETECTOR	SENSITIVITY (A)	DETECTOR THRESHOLD LOWER/UPPER (B)
FREON-11	500 PPM	HALIDE SOURCE	0.005 PPM	0.005/0.5 PPM
DMMP	50-70 PPM	FLAME IONIZATION PHOTOMETRIC MODE (LOW CONC'N)	0.002 PPM	0.002/0.2 PPM
DMMP	50-70 PPM	COLORIMETRIC (HIGH CONC') BUBBLER METHOD)	1000 PPM	1.0-1000 PPM

(A) Determined by actual calibration (B) Boundaries set by experimental design values are not representative of manufacturer's claims

Table 1
INSTRUMENT PERFORMANCE CHARACTERISTICS

CHALLENGE	PARTICLE SIZE	CHALLENGE RANGE	DETECTOR	SENSITIVITY (A)	DETECTOR THRESHOLD LOWER/UPPER (B)
NaCl	.1-.5 microns	1.0B05-1.0B06 PARTICLES PER CC	HELIOK/HEOH LASER (SIZE DISCRIMINATION)	1 PART/CC (.09-3.0 microns) PARTICLE SIZE RANGE	1/3B04 PART/CC

(A) DETERMINED BY ACTUAL CALIBRATION

(B) BOUNDRIES SET BY EXPERIMENTAL DESIGN;

VALUES ARE NOT REPRESENTATIVE OF MANUFACTURER'S CLAIMS

Table 2
INSTRUMENT PERFORMANCE CHARACTERISTICS

Table 2 lists several of the ASASP-X's operating characteristics.

Manufacturer's calibration data indicated a particle diameter range from 0.090 to 3.000 microns. Sizing data was obtained with latex polystyrene particles (PSL-monodispersed). Tests with PSL prior to these experiments showed satisfactory agreement with the calibration in the size range of 0.1 and 1.0 microns.

Prior to the sampling of the challenge from the test chamber, the aerosol was diluted 100:1 with a TSI 3302 diluter. This was required to maintain the number concentration below 10K particles per 10 second sampling period with the ASASP-X. After recording the C(o), the leak side of the test chamber was evaluated for background, followed by the leaks occurring at pressure drops of -10, -6, -4, -2, and -1 inches of water.

Data was printed out by a CIT-101E monitor and TEC impact printer. Reported values were obtained by determining the average of 4 channels. Up to seven 4-channel intervals were reported (See Section IV, Findings) since the distribution of the aerosol challenge was greatest in this region (0.107-0.406 microns). Concentrations above 0.406 microns were so low that they were not statistically meaningful to include in the data set. Values below 0.107 microns approached the detectable

limits of the ASASP-X. However, it was likely that particles existed below the 0.107 micron size.

III. C.

LEAK SOURCE SELECTIONS

The capillaries selected for this study are shown in Table 3. These dimensions were selected based on the expected (for Poiseuille flow) leak rate for the given pressure drop range (-1 to -10 inches of water). This range also is significant for respirator leakage in the 0.001 to 1.0% range, depending upon the mask's minute volume and air resistance. Future studies will be conducted on a respirator using the same capillaries as in this study. Therefore, it was important to select the proper range.

IV. FINDINGS

Tables 4 - 7 and Figures 1-8 show the results of the measured and predicted values for the four capillary sizes. For

each capillary approximately 10 trials per dP were obtained for the DMMP and F-11 vapors, while for air, three trials per dP were measured. The NaCl data is the average of five per dP for each capillary.

Data show, overall, that penetration (NaCl) is a function of particle size for the 0.107-0.406 micron range. For the smaller leaks (I.E. 27 and 30 G, Tables 6 and 7) the change in penetration is more noticeable. This may be significant in actual respirator leakage when considering that this particle size range has been defined as the most penetrating. Furthermore, for small leaks that fall below the 0.01% leakage limit, more than one leak source may occur, yielding an additional effect to the total measured leak.

V. CONCLUSIONS

The evaluation completed to date indicates that NaCl penetrations through small capillaries are size dependent. This data suggests that for more complex geometries of the leak source the transport efficiencies may decrease, thus providing a lower apparent vapor leak.

Vapor test data show good agreement with predicted values. Variations appear to be due to the type of vapor selected (i.e. material/non-material interactive) and method of evaluation.

Additional evaluation is planned to account for possible losses due to entrance effects through capillaries. Further testing will be conducted with light scattering on NaCl and oil aerosols under steady and breather flows.

LEAK TYPE	STANDARD GAUGE	SPECIFICATION SIZE	
		BORE RANGE (MM)	LENGTH (MM)
CAPILLARY RIGID	23	0.32-0.37	32.4
CAPILLARY RIGID	25	0.24-0.29	22.9
CAPILLARY RIGID	27	0.19-0.24	19.7
CAPILLARY RIGID	30	0.14-0.18	19.7

Table 3
LEAK SOURCE DIMENSIONS

Table 4

MEASURED AND PREDICTED LEAK RATES OF VARIOUS CHALLENGE MEDIUMS FOR A 23 GAUGE CAPILLARY (0.345 mm bore by 32.4 mm length)												
Vapor Leak Rate (cc/min)					Aerosol Leak Rate (1) (cc/min)							
dp in H ₂ O	DMMP	P-11	Air	Theory (2)	Sodium Chloride Particle Diameter (microns)							
					0.107	0.134	0.167	0.208	0.260	0.325	0.406	
10	68.9	104.9	87.4	90.5	76.4	69.2	61.7	52.3	63.6	53.0	44.1	
6	45.9	73.4	52.5	54.5	53.0	43.9	36.4	31.5	31.4	23.7	23.1	
4	34.0	57.3	34.9	36.3	35.7	28.7	23.9	19.7	16.2	14.2	15.2	
2	18.6	34.1	17.4	18.1	13.2	8.3	6.7	5.4	6.3	5.7	6.1	
1	9.1	19.1	8.3	9.1	6.1	5.4	4.7	3.9	5.6	4.4	5.5	

(1) Instruments utilized: PMS, Model ASAP-X

(2) Applicable value for vapors and NaCl

MEASURED AND PREDICTED LEAK RATES OF VARIOUS CHALLENGE MEDIUMS
FOR A 25 GAUGE CAPILLARY (0.265 mm bore by 22.9 mm length)

Vapor Leak Rate (cc/min)					Aerosol Leak Rate (1) (cc/min)							
dp in H ₂ O	DMMP	P-11	Air	Theory (2)	Sodium Chloride Particle Diameter (microns)							
					0.107	0.134	0.167	0.208	0.260	0.325	0.406	
10	25.5	42.4	41.0	45.6	44.9	37.1	30.5	25.2	22.0	19.3	22.4	
6	17.5	26.3	24.8	27.4	28.6	24.5	20.8	17.0	14.3	12.7	16.0	
4	12.3	16.9	16.7	18.2	20.1	13.4	10.8	8.1	7.1	6.2	4.6	
2	6.3	9.5	8.5	9.1	6.7	4.6	3.6	2.8	2.9	2.8	2.3	
1	2.8	5.5	4.2	4.6	2.7	2.2	1.7	1.2	1.3	1.4	1.1	

Table 5

(1) Instruments utilized: PMS, Model ASAP-X

(2) Applicable value for vapors and NaCl

Table 6

MEASURED AND PREDICTED LEAK RATES OF VARIOUS CHALLENGE MEDIUMS FOR A 27 GAUGE CAPILLARY (0.215 mm bore by 19.7 mm length)												
Vapor Leak Rate (cc/min)					Aerosol Leak Rate (1) (cc/min)							
dp in H ₂ O	DMMP	F-II	Air	Theory (2)	Sodium Chloride Particle Diameter (microns)							
					0.107	0.134	0.167	0.208	0.260	0.325	0.406	
10	--	23.3	20.8	23.6	21.1	17.3	15.5	13.4	9.4	9.6	8.6	
6	--	14.5	12.8	14.1	12.4	9.3	8.7	5.6	5.6	6.3	5.5	
4	--	10.2	8.7	9.4	5.8	4.2	3.6	3.0	3.4	3.7	3.4	
2	--	5.5	4.6	4.7	2.2	1.8	1.6	1.4	1.6	2.1	1.9	
1	--	3.1	2.3	2.4	1.1	0.9	0.8	0.6	0.7	0.7	0.7	

(1) Instruments utilized: PMS, Model ASAP-X

(2) Applicable value for vapors and NaCl

- Testing not complete for inclusion

MEASURED AND PREDICTED LEAK RATES OF VARIOUS CHALLENGE MEDIUMS
FOR A 30 GAUGE CAPILLARY (0.16 mm bore by 19.7 mm length)

Vapor Leak Rate (cc/min)					Aerosol Leak Rate (1) (cc/min)							
dp in H ₂ O	DMMP	F-II	Air	Theory (2)	Sodium Chloride Particle Diameter (microns)							
					0.107	0.134	0.167	0.208	0.260	0.325	0.406	
10	5.9	5.8	7.1	7.3	7.9	5.7	3.9	3.3	4.1	4.9	5.1	
6	4.4	3.9	4.3	4.4	3.1	2.6	2.2	1.8	2.5	2.8	3.3	
4	3.3	--	3.0	2.9	2.1	1.8	1.5	1.3	1.6	2.2	2.2	
2	2.2	1.5	1.4	1.5	1.1	0.9	0.8	0.6	0.4	0.8	0.8	
1	1.7	--	0.7	0.7	0.4	0.4	0.3	0.3	0.3	0.4	0.5	

Table 7

(1) Instruments utilized: PMS, Model ASAP-X

(2) Applicable value for vapors and NaCl

-- Testing not complete for inclusion

FIGURE 1
Leak Rate vs. Pressure Drop For Vapor Challenges Through A
23 Gauge Capillary (0.345 mm bore by 32.4 mm length)

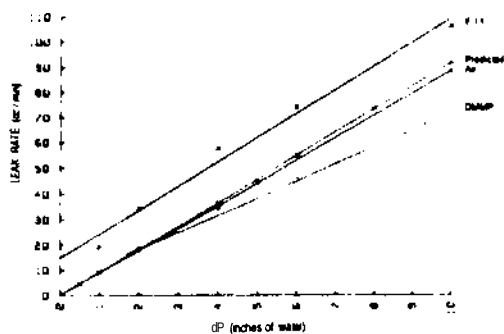


FIGURE 2
Leak Rate vs. Pressure Drop For Vapor Challenges Through A
25 Gauge Capillary (0.265 mm bore by 22.9 mm length)

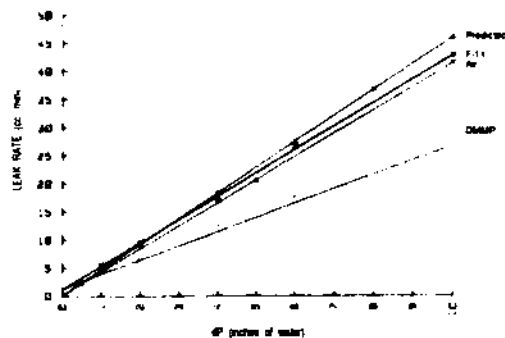


FIGURE 3
Leak Rate vs. Pressure Drop For Vapor Challenges Through A
27 Gauge Capillary (0.215 mm bore by 19.7 mm length)

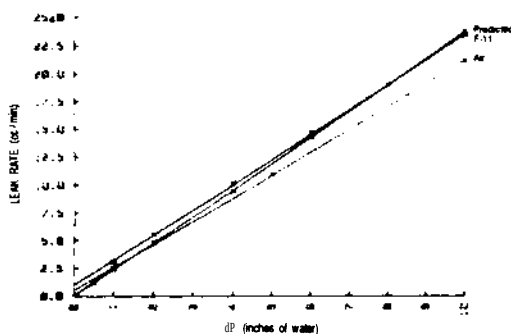


FIGURE 4
Leak Rate vs. Pressure Drop For Vapor Challenges Through A
30 Gauge Capillary (0.16 mm bore by 19.7 mm length)

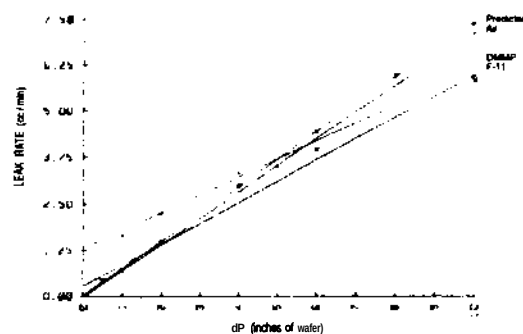


FIGURE 5
Leak Rate vs. NaCl Particle Diameter At Various Pressure Drops
For A 23 Gauge Capillary (0.345 mm bore by 32.4 mm length)

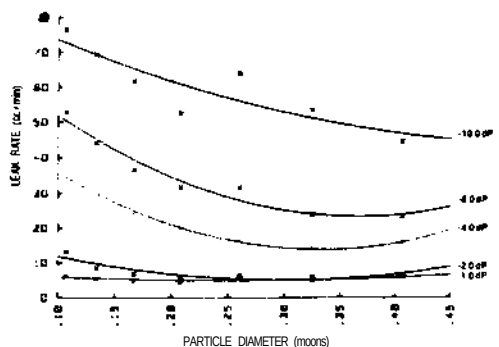


FIGURE 6
Leak Rate vs. NaCl Particle Diameter At Various Pressure Drops
For A 25 Gauge Capillary (0.265 mm bore by 22.9 mm length)

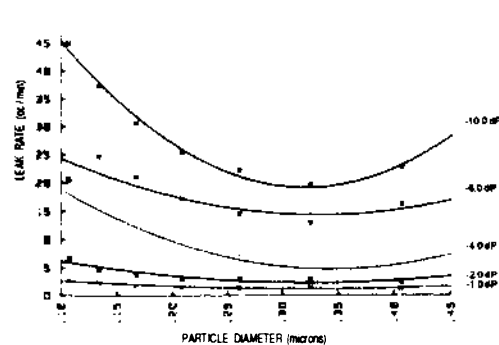


FIGURE 7
Leak Rate vs. NaCl Particle Diameter At Various Pressure Drops
For A 27 Gauge Capillary (0.215 mm bore by 19.7 mm length)

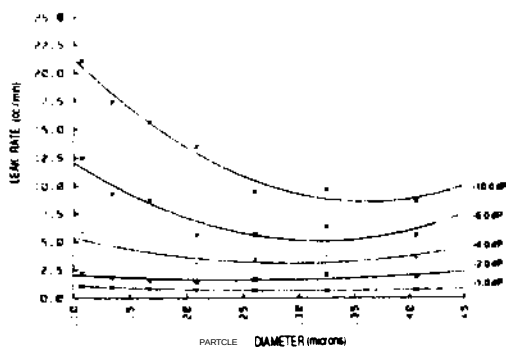
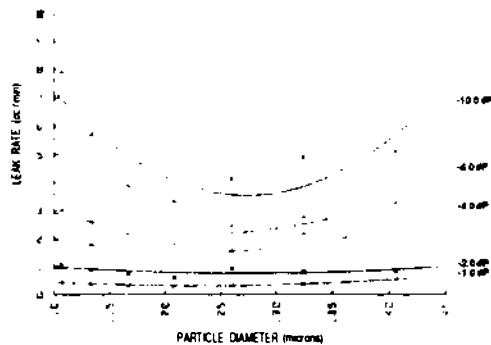


FIGURE 8
Leak Rate vs. NaCl Particle Diameter At Various Pressure Drops
For A 30 Gauge Capillary (0.16 mm bore by 19.7 mm length)



APPENDIX A

In 1973, Davies, 1, 2, Fuchs, 3, Schmidt, 4, Thomas, 5, et al. considered various particle loss mechanisms such as diffusion and sedimentation through perfect capillaries and slits. Particle losses were determined using equations 5-7 in this phase of work. Losses due to impaction and interception will be considered for more complex geometries with several of these equations (8-13) reported.

For conditions in a capillary where there is Laminar flow, the Poiseuille flow field, velocity, is,

$$V = \frac{(R^{**2} - r^{**2}) dP}{4 n L} \quad (3)$$

where,

R = radius of capillary bore

r = capillary wall thickness

dP = pressure drop

n = viscosity of the fluid

L = capillary length

note that (X**2) means that the variable X is square

Furthermore, the mean velocity, V, where Q is the volumetric flow rate is,

$$V = \frac{Q}{\pi R^{**2} L} = \frac{R^{**2} dP}{8 n L} \quad (4)$$

The capillaries in this study ranged in velocity from 0.42 (30 G at 1.0" H₂O) to 135 (23 G at 10.0" H₂O) meters per second.

Rearrangement of equation 4 to solve for the volumetric flow rate, Q, was done for the four reported capillaries. Predicted gas flow rates for these capillaries are shown in Tables 1-4 (Theory), Section IV.

DIFFUSION

Davies found that diffusional losses through a capillary can be expressed as, (1)

$$\frac{N}{N(o)} = 0.819 \exp(14.63 A) + 0.097 \exp(-89.2 A) + 0.032 \exp(-228 A) + 0.027 \exp(-492 A) + 0.025 \exp(-3000 A) \quad (5)$$

where,

N(o) = number challenge

N = number penetration

A = D L / [4 V (R**2)]

D = diffusional coefficient of the particle

The diffusional coefficient, D, is expressed as,

$$D = \frac{k T}{6 K n R} C$$

where,

C = Cunningham Slip Factor

$$= 1 + [2.514 + 0.8 \exp(-55 dP/y)] y/dP \quad (6)$$

These equations result in a penetration value that is size dependent and various fractions, N/N(o), can be applied to any number concentration.

SEDIMENTATION

Natanson, Fuchs (1964), and Thomas (1958), calculated sedimentation losses for a horizontal circular tube as,

$$\frac{C}{C(0)} = 1 - \frac{2}{\pi} [2 \phi \sqrt{1 - \phi^{2/3}} + \arcsin(\phi^{1/3}) - \phi^{1/3} \sqrt{1 - \phi^{2/3}}] \quad (7)$$

where,

$$0 = 3 V(g) (L/8) R V \ll (3/4) (1/R(e)) (V(g) L/V)$$

INTERCEPTION

Spurny reported in 1969 for velocities and concentrations uniform at the inlet, (8)

$$N(r) \gg 2 R - R^{**2}$$

where,

$$R = D(p) / dP$$

For parabolic fields Smith reported in 1976,

$$N(r) = 1 - [(1 - R)^{**2} \times (2 - (1 - R)^{**2})] \quad (9)$$

and for non-uniform fields John et al. (1978) reported,

$$N(r) = (2 R - R^{**2})^{**3/2} \quad (10)$$

IMPACTION

The impaction theory by Pich (1964) is initially considered due to its popularity, yet may present some problems with the flow fields,

$$N(i) = \frac{2 E(i)}{1 + B} - \frac{E(i)^{**2}}{(1 + B)^{**2}} \quad (11)$$

where,

$$E(i) = 2Stk(\sqrt{B}) + 2 Stk^{**2} B \exp[-1/(Stk \sqrt{B})] - 2Stk^{**2} P(p)$$

and

$$B = \frac{\sqrt{P}}{1 - \sqrt{P}} \quad (12)$$

$$Stk = \frac{C Dp^{**2} P(p) V(o)}{9 \mu d P} \quad (13)$$

where,

Dp = particle diameter
 $P(p)$ = particle density

REFERENCES

1. Davies, C. N. (1949) *Proc. Roy. Soc. A.* 200, 100-115.
2. Davies, C. N. (1973) *J. Aerosol Science*, 4, 317-328.
3. Fuchs, N. A. (1964) *The Mechanics of Aerosols*, p. 112 The Pergamon Press, Oxford,
4. Schmidt, E. W., Liu, C. Y., Luttinger, M., Sverdrup, G.M., and Gieseke, J. A. (1978) Face Mask Periphery Leakage Evaluation: Analytical Assessment, Contract No. CSL 611.51-1.
5. Thomas, J. W. (1958) *J. Air Pollut. Contr. Assess.* 8 (1), 32-34.