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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

APPLICATION OF SMOKE DETECTOR TECHNOLOGY TO QUANTITATIVE RESPIRATOR FIT TEST METHODOLOGY

G.W. Mulholland, R. Bukowski, B.Y.H. Liu* and W. Szymanski*

Abstract

A quantitative respirator fit test apparatus was developed based on using a light-scattering type smoke detector for the sensing element and a clinical nebulizer for the aerosol source. The performance of three smoke detectors and nine clinical nebulizers considered for use in the final system are reported. Key design features of the apparatus include the generation of a corn oil aerosol concentration of 500 mg/m^3 at a flow rate of 50 ℓ/min and LED display for protection factors of 25, 50, 125, and 450. The total cost of the component parts for the apparatus is less than $300. This apparatus is designed to meet the need for a low cost, easy to use instrument for quantitatively monitoring a respirator's fit to a worker's face.

Keywords: corn oil aerosol, face seal, LED, nebulizer, protection factor, quantitative fit test, respirator, smoke detector.

1. INTRODUCTION

The use of respiratory protection devices to protect workers from harmful air contaminants is a standard industrial hygiene practice. The effectiveness of such devices in the actual work place is critically dependent upon the amount of air leakage between the subject's face and the sealing surface of the respirator. To insure that a given respirator will fit properly on a

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worker's face, it is necessary to perform face piece fit tests. The fit test can either be qualitative, which depends on the worker's subjective sensation of the presence of some substance, such as isoamylacetate (banana oil), that has penetrated through the face seal, or quantitative, which uses instrumental methods to detect the penetration of an aerosol through the face seal. It is quantitative fit tests that are the subject of this study.

In the usual quantitative fit test, a corn oil aerosol is generated with a nebulizer. A light-scattering photometer is used to measure the relative aerosol concentration inside and outside the face mask. The test is usually conducted with the worker wearing the respirator in a chamber or hood. The commercially available quantitative fit test equipment, which includes an aerosol generator, a chamber, and photometer, typically costs approximately $10,000. In addition to the relatively high cost, the operation of the equipment requires a skilled operator for performing such operations as zeroing the photometer, interpreting the strip chart readings, and maintaining the system. After all, the system is comparable in complexity to a variety of state of the art aerosol measuring devices.

The high cost of the commercial quantitative fit test system and the attendant operator skill needed to use such systems have limited their application to relatively large industrial firms, where the financial and human resources needed are adequate and can be justified. For small firms, namely, those with affected workers numbering less than 50, the cost of running such a quantitative fit test program often becomes too expensive. The availability of a simple and relatively low cost system would greatly enhance the appeal for a quantitative fit test system for such industries. The increased use of

such systems would greatly improve the effectiveness of respiratory protection programs in general.

In a joint research study by Mulholland and Liu [1], the responses of several commonly used smoke detectors to monodisperse aerosols were studied. Based on this study it appears that a smoke detector might be suitable as the basic detector element in a quantitative fit test apparatus. The fact that smoke detectors are inexpensive as a result of mass production is another reason for utilizing this technology. The other major component of a quantitative fit test apparatus is the aerosol generator. From our experience with a variety of nebulizers, it appears that an inexpensive clinical nebulizer would be adequate for producing sufficient aerosol in the appropriate size range.

This report describes our investigation of the feasibility of developing a low cost quantitative fit test apparatus based on smoke detector technology and clinical nebulizer technology. The operational characteristics of light scattering type smoke detectors are presented in section 2 together with results on the performance of three candidate smoke detectors. The performance characteristics of nine commercially available nebulizers including generation rate, droplet size distribution, and maximum operation time are reported in section 3. The overall design of a prototype quantitative fit test apparatus based on using a smoke detector and clinical nebulizer is described in section 4. Performance characteristics of the prototype apparatus are also discussed. The operation of the prototype fit test apparatus is described in section 5.

2. LIGHT-SCATTERING TYPE SMOKE DETECTOR

There are two principal types of smoke detectors in common use, the so-called photoelectric or light-scattering detector and the ionization detector. Mulholland and Liu [1] have shown that ionization type smoke detectors are more sensitive to small particles with diameters less than about 0.3 μm, while the light scattering type smoke detectors are generally more sensitive to particles larger than 0.3 μm. For our study the light scattering detector is the detector of choice, since the mass median diameter of the test aerosol is expected to be about 1 μm and the light scattering type detectors have a wider dynamic range for aerosol concentration.

2.1 Principle of Operation

As the name suggests, the scattering of light by smoke particles is the basic physical phenomenon for the light-scattering type smoke detectors. A schematic of such a smoke detector is shown in figure 1. Smoke detectors in the mid-seventies utilized a variety of light sources including tungsten filament lamps and light emitting diodes (LED's) in both the visible and the near infra-red wavelengths. By 1985 most of the commercially available smoke detectors utilized LED's operating in the near infra-red. Both GaAs with a spectral peak at 940 nm and GaAlAs with a peak at 880 nm and a spectral width of about 50 nm are used. The LED's are operated in a pulsed mode with a pulse length on the order of 100 μs and a current on the order of 0.3 amps. The time between pulses ranges from about a second to several seconds. The short, intense pulse produces a good signal to noise ratio without overheating the unit, as would a continuous, intense current to the LED.

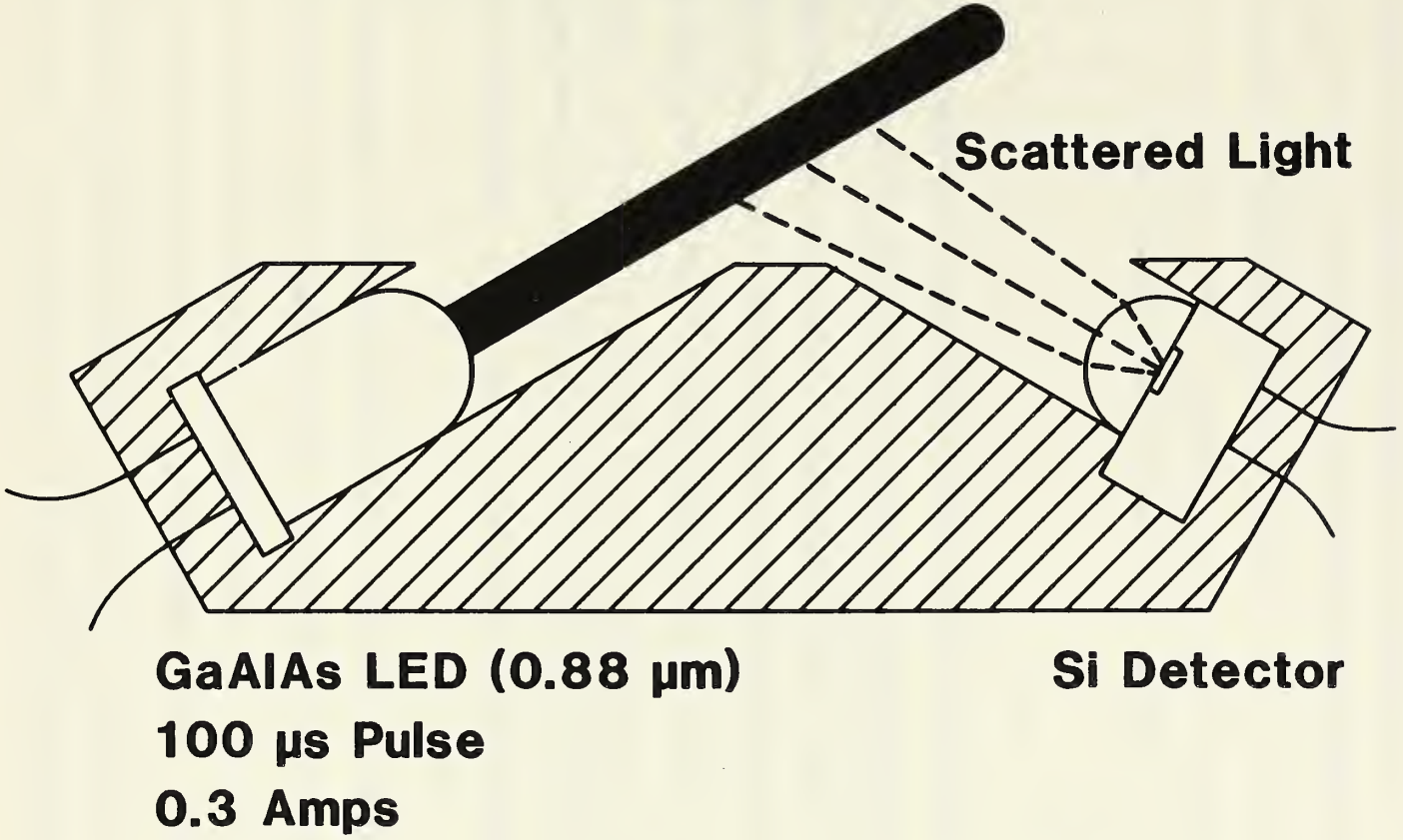


Figure 1. Schematic of light-scattering type smoke detector.

The smoke detector housing is designed to minimize reflections so that only scattered light reaches the detector element. The detectors are generally silicon type with a lens preceding the detector to focus the scattered light onto the active surface of the detector. The light scattered by the smoke particles over a certain angular range reaches the photo-detector causing an electrical signal to be generated. This signal is amplified and is used to trigger an audible alarm when a certain threshold level, typically 1 volt, is reached.

In our study we have used special purpose smoke detectors which produce an analog output proportional to the intensity of the scattered light rather than simply an audible alarm. The detector circuitry includes a sample and hold feature to keep the signal at its peak value until the next pulse arrives. Other features of the smoke detector circuitry include a power supply, a pulser for the LED, and noise filtering components. Many of the functions are performed by integrated circuits, which are now inexpensive since the units are mass produced at a level of many thousands.

The design constraints for a smoke detector are to some extent at cross purposes with the optimal design of a high sensitivity detector for leak test apparatus. In fact, if the sensitivity of the smoke detector is too high, it may have a problem with a high incidence of false alarms. By contrast, the ideal leak test apparatus would have a sensitivity limited only by the Rayleigh scattering from air.

In this study, we have analyzed the performance of three presently available analog output smoke detectors. In addition, we have measured the dependence of detector sensitivity on scattering angle for a particular detector configuration. Other design modifications that could improve the detector sensitivity are also considered.

2.2 Detector Sensitivity Measurements

Two sets of detector sensitivity measurements were made. One set was based on the generation of a monodisperse aerosol and measuring detector output versus mass concentration of the aerosol. The second set of measurements consisted of the analog output of the detector, as configured in the prototype fit test apparatus, versus mass concentration of corn oil aerosol generated by the nebulizer in the prototype apparatus.

A detailed description of the monodisperse aerosol generation system is given by Mulholland and Liu [1]. Here we briefly describe a minor variant of this configuration, which is illustrated in figure 2. A pneumatic nebulizer produces a polydisperse aerosol by spraying a solution of dioctylphthalate (DOP) in isopropanol. The alcohol rapidly evaporates from the generated droplets leaving pure DOP droplets. The aerosol then passes through an evaporation-condensation column, in which the droplets first evaporate in the upper half of the tube and then condense in the lower half to form a monodisperse aerosol. The droplet size is determined by the concentration of

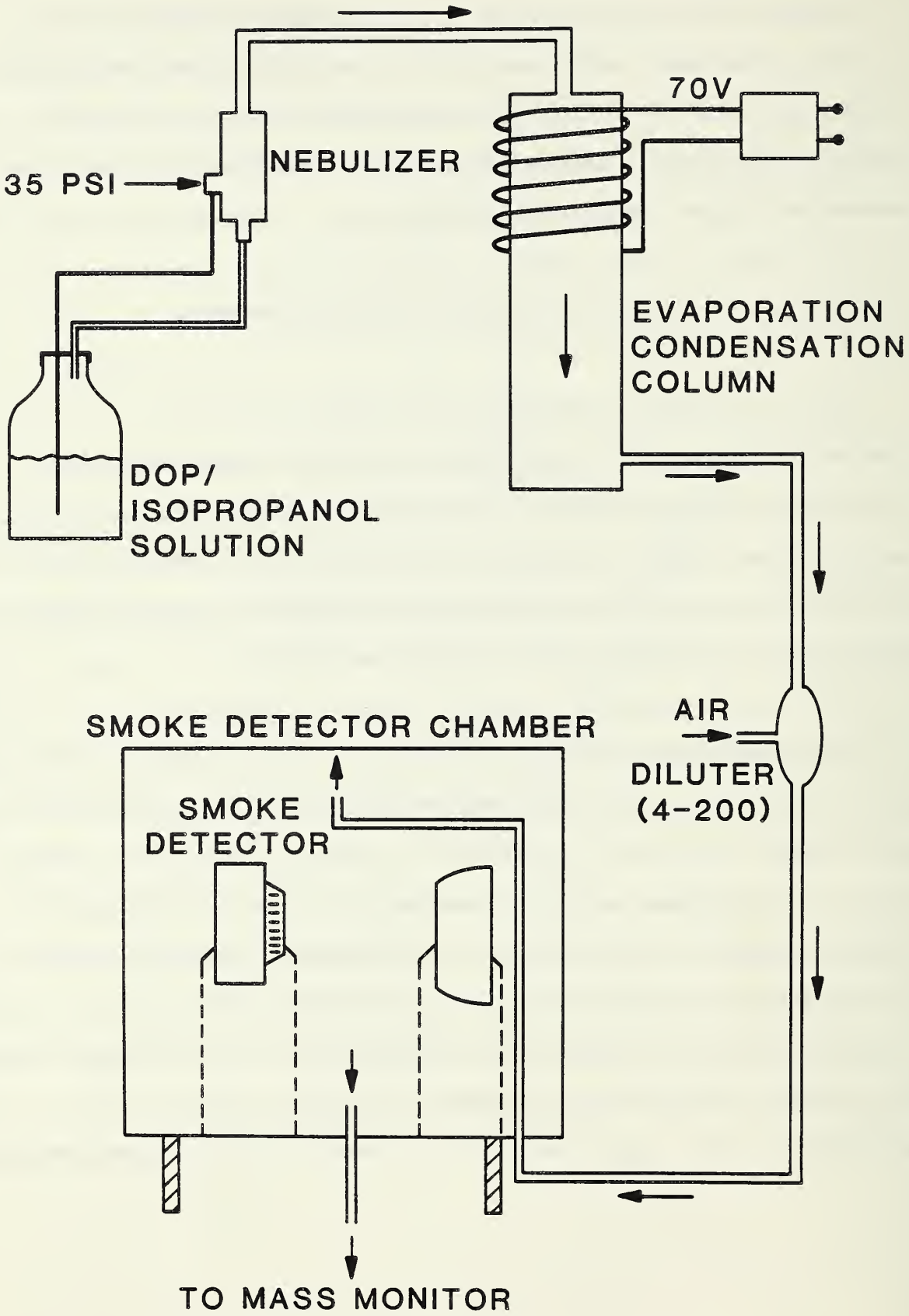


Figure 2. Monodisperse aerosol generation system.

DOP in isopropanol (2.1 volume % produces 0.3 μm droplets; 20 volume %, 0.7 μm droplets; 100 volume %, 1.3 μm droplets). Next the aerosol is diluted and then finally enters the smoke detector chamber. The mass concentration of the aerosol leaving the chamber is monitored by a quartz-crystal mass monitor.

The results for light scattering detector L-1 are given in figure 3. It is seen that the detector output minus background voltage is a linear function of mass concentration from about 1 mg/m^3 to about 25 mg/m^3 independent of droplet size. The light source is a GaAs light emitting diode with a spectral peak at 940 nm. The nominal scattering angle is 60° as measured with respect to the transmitted beam. The noise level of the detector was found to be ± 0.025 volts, which is approximately ± 1 σ. As a measure of the relative threshold sensitivity of the smoke detectors, we use the mass concentration of 0.7 μm DOP aerosol that produces a detector output signal equal to twice the noise level (2σ). For L-1 this corresponds to a mass concentration of 0.25 mg/m^3.

The second smoke detector tested, L-2, used the same basic components for the source and detector as L-1 but was operated in a continuous mode at 100 mA rather than in a pulsed mode. The detector contained a feedback circuit that increased the current to the LED if smoke were detected. This design was intended for transient smoke detection, since continuous operation of the LED at the high current would cause over-heating. We deactivated the feedback circuit since we were interested in the detector response to a constant aerosol concentration. We found the threshold sensitivity for L-2 to be 0.3 mg/m^3.

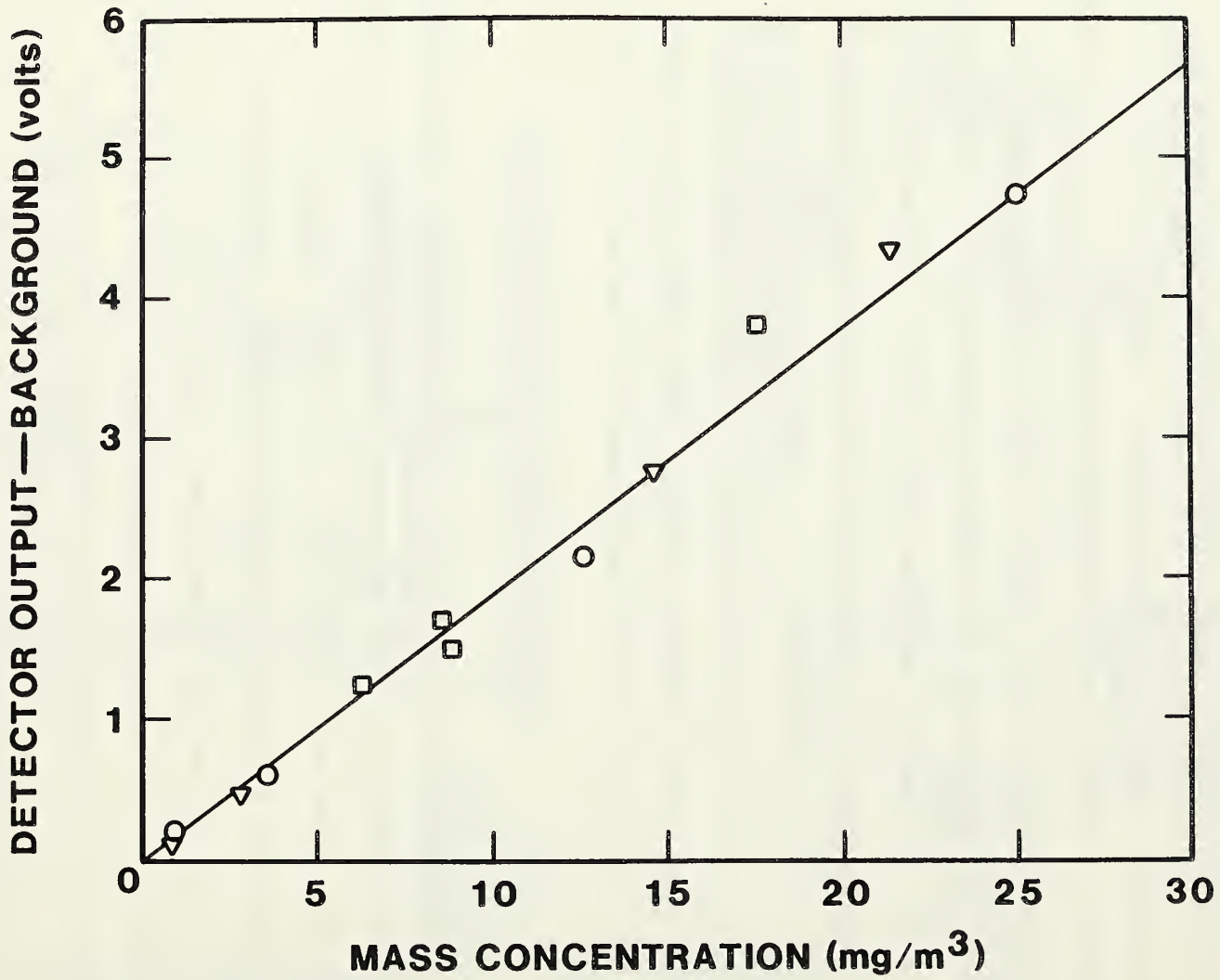


Figure 3. Response of smoke detector L-1 to monodisperse DOP (∇ - 0.3 μm, □ - 0.7 μm, O - 1.3 μm).

The third smoke detector, L-3, contained a special lens/light trap geometry such that the light was focussed in a conical ring with the detector on line with the source. The nominal range in scattering angle was 35-45°. The threshold sensitivity for L-3 was found to be 0.05 mg/m^3. Because of its much higher sensitivity compared to the other two smoke detectors, L-3 was chosen for use in the prototype fit test apparatus.

The response of smoke detector L-3 was measured as a function of the mass concentration of corn oil aerosol generated by a Hudson[1] nebulizer used in the prototype fit test apparatus. The aerosol mass concentration was monitored by a high sensitivity light scattering instrument, the GCA RAM-1, with five orders of magnitude dynamic response. As seen in figure 4, the detector output is linear with respect to aerosol concentration over more than two decades. The apparent sensitivity of detector L-3 to corn oil aerosol is about 0.3 mg/m^3. The apparent mass concentration indicated by the GCA RAM-1 is approximately twice the true mass concentration so that the actual threshold sensitivity of L-3 to corn oil aerosol is about 0.15 mg/m^3, which is a factor of three greater than the threshold sensitivity of L-3 to 0.7 μm monodisperse DOP.

2.3 Optimization of Smoke Detector Performance

Up to this point we have considered only commercially available smoke detectors. Now we address the question: What improvements in sensitivity

[1]Certain commercial equipment and instruments are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation by the National Bureau of Standards, nor does it imply that the equipment identified is necessarily the best available for the purpose.

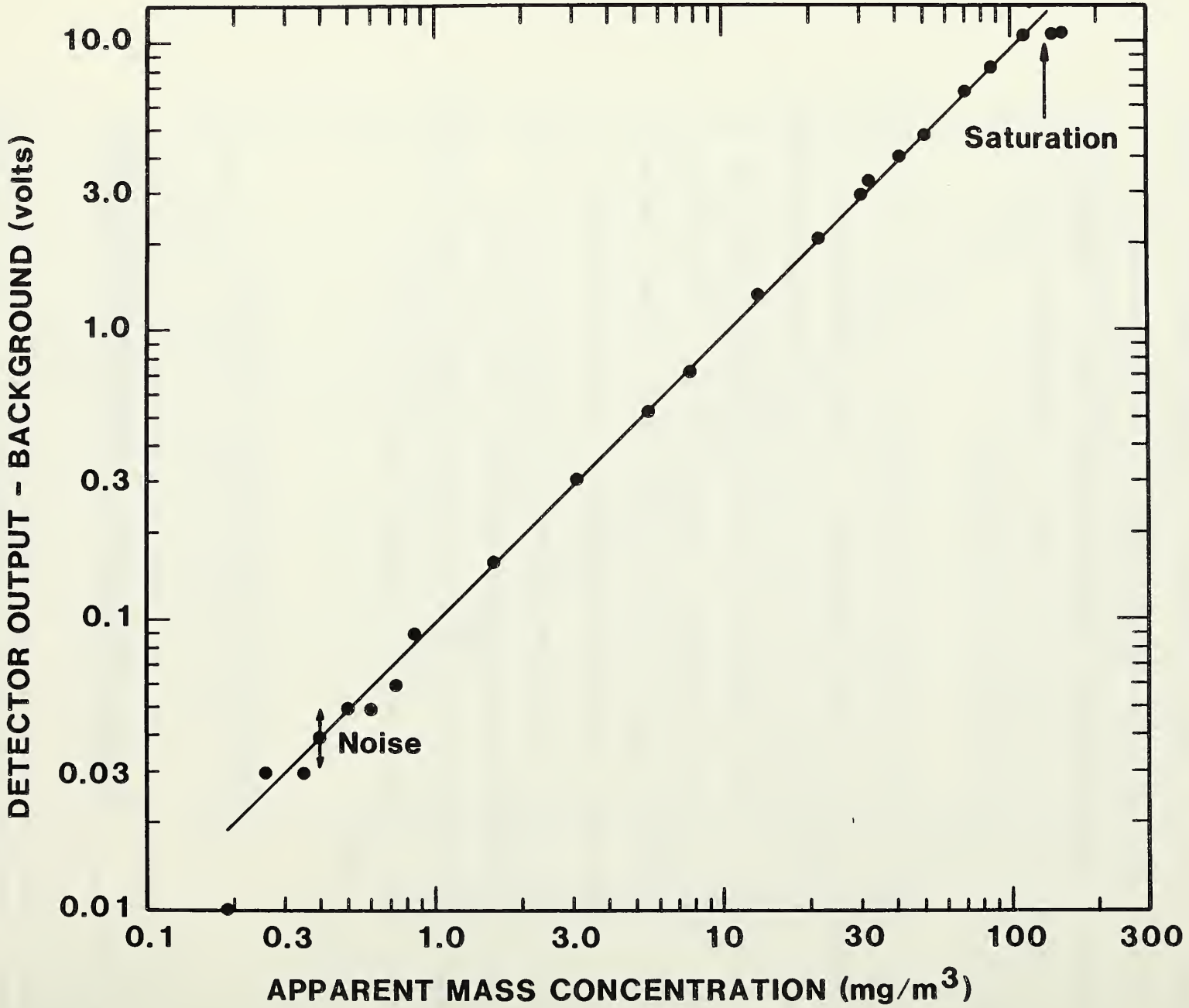


Figure 4. Response of smoke detector L-3 to corn oil aerosol generated by the prototype fit test apparatus.

might be possible with minor design changes in the smoke detector? One of the smoke detectors studied by Mulholland and Liu [1], S-2, had a sensitivity of about 0.03 mg/m^3 for DOP aerosol. This is several times more sensitive than L-3. The major difference in design between S-2 and L-3 is in the scattering angle. The scattering angle for S-2 is about 20° while for L-3 is about 40°. Unfortunately, smoke detector S-2 is no longer manufactured.

In order to determine the optimum scattering angle for the corn oil aerosol produced by the Hudson nebulizer, measurements were performed at Electro Signal Lab, Inc. to determine the smoke detector output as a function of scattering angle from 20° to 60° (Fig. 5). An angle of 60° corresponds to the nominal angle used in the commercial smoke detector. As the scattering angle is decreased, the detector output increased for the corn oil aerosol, which has a mass median diameter of about 1 μm. This result is consistent with Mie theory prediction for enhanced forward scattering for particle size comparable to the wavelength of light. The relative enhancement to the scattering intensity at 60° was a factor of 3 at 40°, a factor of 6.5 at 30°, and a factor of 9.5 at 20°. As the scattering angle is made smaller and smaller it becomes increasingly more difficult to shield the silicon detector from the LED beam.

The sensitivity of smoke detectors could also be improved by modifying the electronic design. Two of the most promising changes are detection synchronous with the pulsing of the LED and the use of shorter, more intense pulses of light. There is a commercially available aerosol instrument, GCA RAS-1, based on the same generic technology as smoke detectors but is advertised to have a threshold sensitivity of 0.01 mg/m^3, which is a factor of 15 more sensitive than L-3.

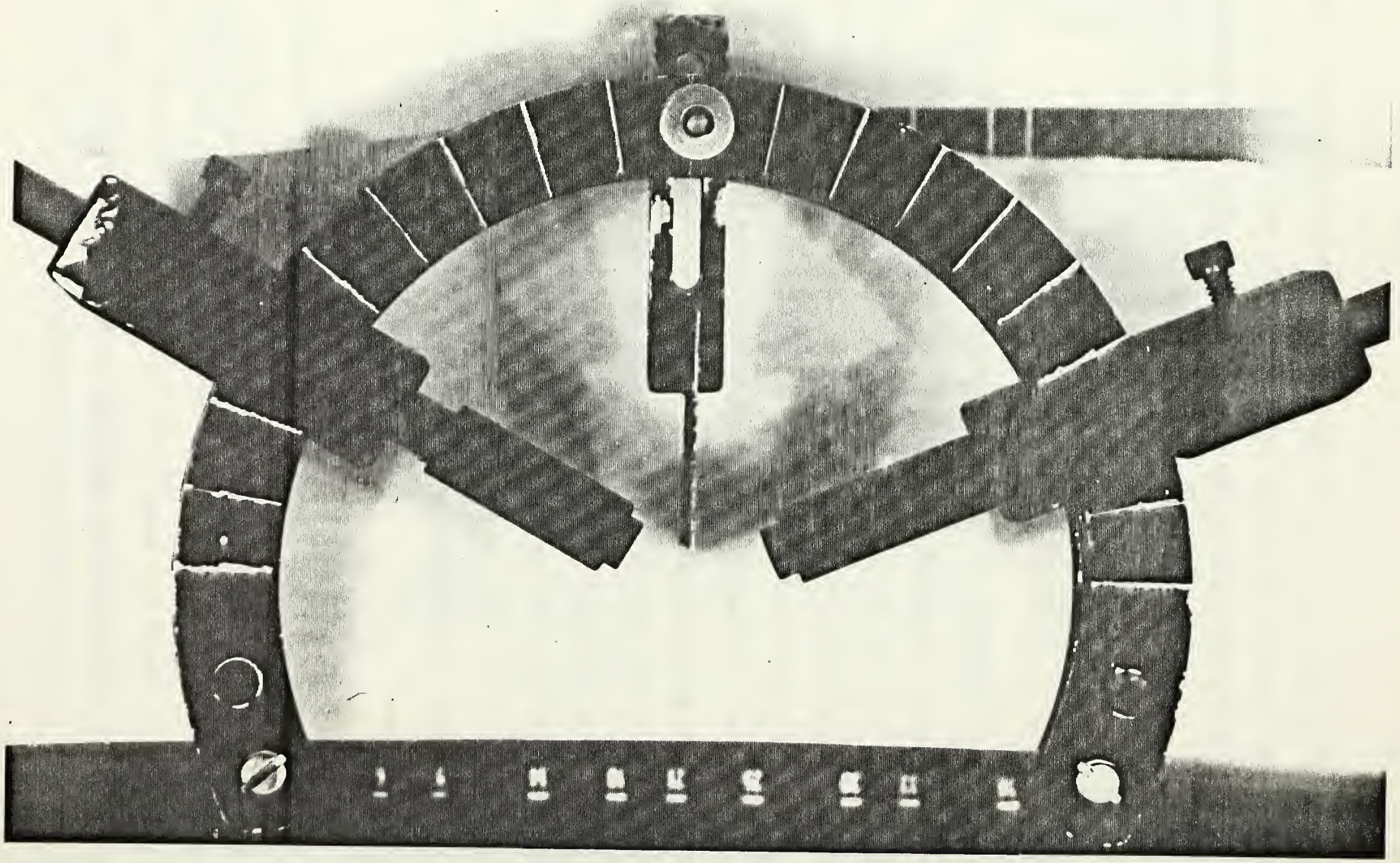


Figure 5. Electro Signal Lab, Inc. variable angle smoke detector. The shield at the center of the picture prevents the light beam from directly reaching the detector.

As our last point in regard to smoke detectors, the optical assemblies of smoke detectors lend themselves to miniaturization. The electronic industry has taken advantage of this fact in the design of a miniature, end of tape reader (Fig. 6). The advantage of such a design for fit testing would be to position the detector inside the face mask so that an in situ measurement of leakage could be made.

3. CLINICAL NEBULIZERS

This section presents results of a screening test of several commercial medical nebulizers. The purpose of the test is to identify a low-cost nebulizer that is suitable for use as a generator for producing test aerosols of a stable, high concentration in quantitative fit tests of respirators.

A nebulizer is a device for producing aerosols of fine particles by the pneumatic atomization of liquids. Either soluble or insoluble materials may be aerosolized by nebulizing a solution or a suspension of the aerosol material. The nebulizer is capable of producing high concentration of aerosols with good stability. Important performance parameters of the nebulizer include:

(a) liquid output rate, in ml/min,

(b) aerosol concentration, in particles/cm^3,

(c) droplet size distribution,

(d) aerosol volumetric output, in l/min,

(e) maximum and minimum volumes of liquid required for operation, in ml,

(f) maximum operating time for stable operation.

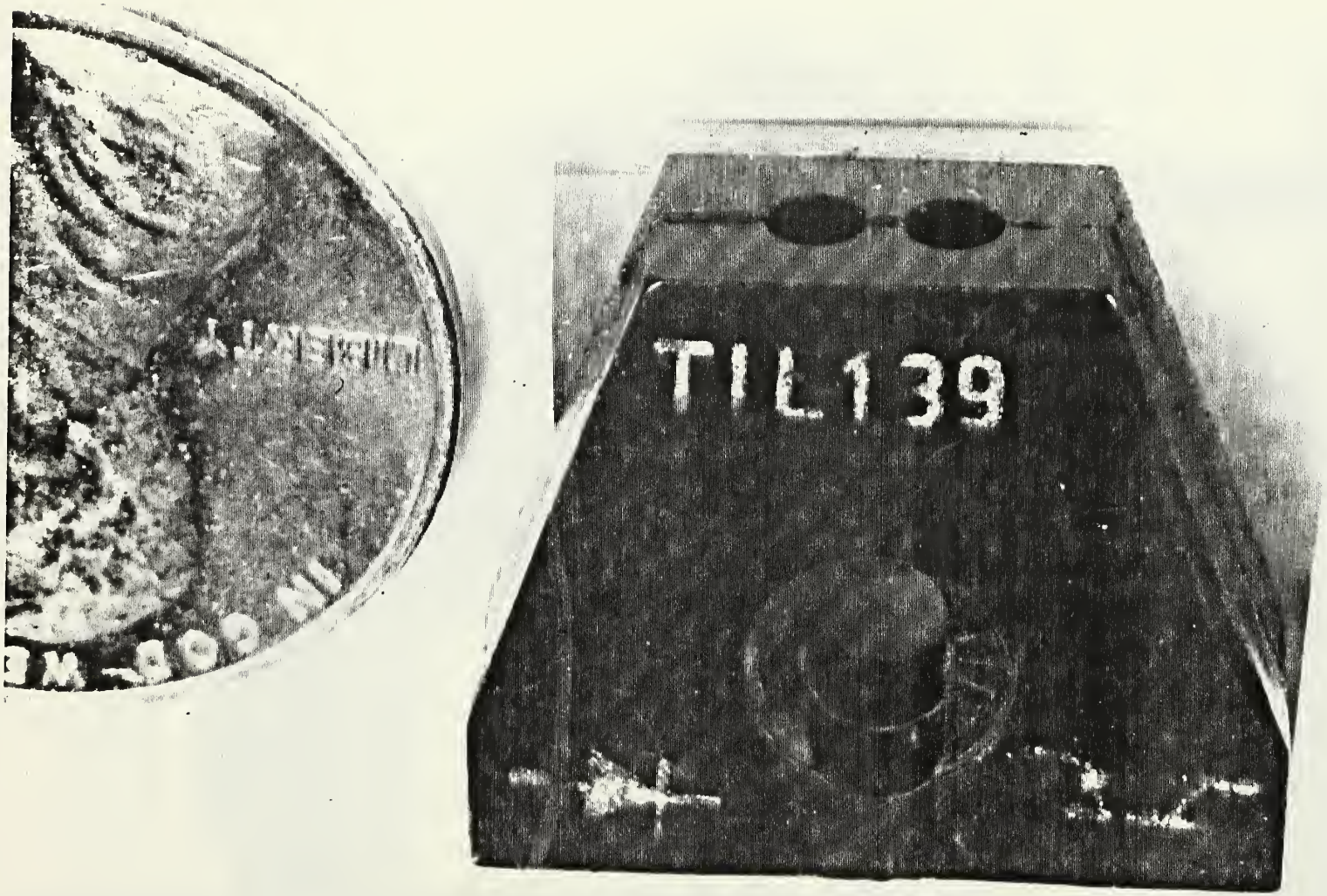


Figure 6. End of tape reader. The LED and the Silicon detector are located in line with the two holes at the top of the picture.

All these parameters are important in the selection of a suitable nebulizer for face mask fit tests.

All the above mentioned parameters have been determined in the tests reported here and are summarized in this report. Two methods were used to determine the droplet size distribution. In one method, a pure, undiluted oleic acid was nebulized and the aerosol produced was measured by a laser optical particle counter (OPC, PMS-ASAS-300X). In the second method, an aqueous solution containing 0.1% by weight of NaCl was nebulized and the aerosol produced was measured by the TSI Model 3932 Differential Mobility Particle Sizer (DMPS). The first method was used because the pure oleic acid aerosol gave the desired particle size for actual face mask testing. However, because of the non-ideal behavior of the laser OPC in the measured size range, the OPC measurement gave inaccurate results for the determination of the geometric standard deviation. Consequently, the second method was used to measure the particle size of the dry NaCl aerosol. The droplet size distribution was then calculated from the measured size distribution of the NaCl particles and the volumetric concentration of the NaCl in the nebulizing solution. The actual measurement was made with a DMPS system which is capable of giving high resolution and accurate particle size information in this size range. Since all the droplets contained the same concentration of non-volatile solute, the geometric standard deviation of the dry particles should be the same as that of the droplets. In addition, the mean droplet size can be calculated from the known concentration of solute in the solution.

3.1 Operating Parameters and Output Rate of Nebulizers

Most nebulizers required an operating pressure of the compressed air supply of about 0.7 - 3.5 x 10^5 Pa (10-50 psig). The corresponding volumetric air flow rate was found to be between 4 and 23 L/min. Figure 7 shows this relationship for seven of the nebulizers tested. Depending on the design of the liquid reservoirs, the maximum amount of liquid that the nebulizers could hold for stable operation varied between 5 and 25 ml. These three quantities are shown in the first three columns in Table 1.

The liquid output rate, in ml/min, of the nebulizer was measured by nebulizing a pure oleic acid liquid and monitoring the weight loss with time of the nebulizer due to aerosolization of the liquid. Together with the known maximum reservoir volume, the maximum operating time without refill could be calculated for each operating condition of the nebulizers. The output rate and the corresponding maximum operating time are shown in the fourth and fifth columns of Table 1.

The design and the material of construction of the nebulizers varied greatly. Most nebulizers made use of different types of plastic materials for the reservoirs, the nebulizing nozzles-impaction spheres, and the caps. Care should be taken to insure that the specific plastic used in the nebulizer construction is compatible with the aerosolizing liquid. For example, the Cadema nebulizer was softened and partially dissolved by dioctyl sebacate. Leaks were detected on several nebulizers between the interface of the reservoirs and the caps. In general, these leaks were found on devices which made use of hard plastic materials for both the caps and reservoirs. The

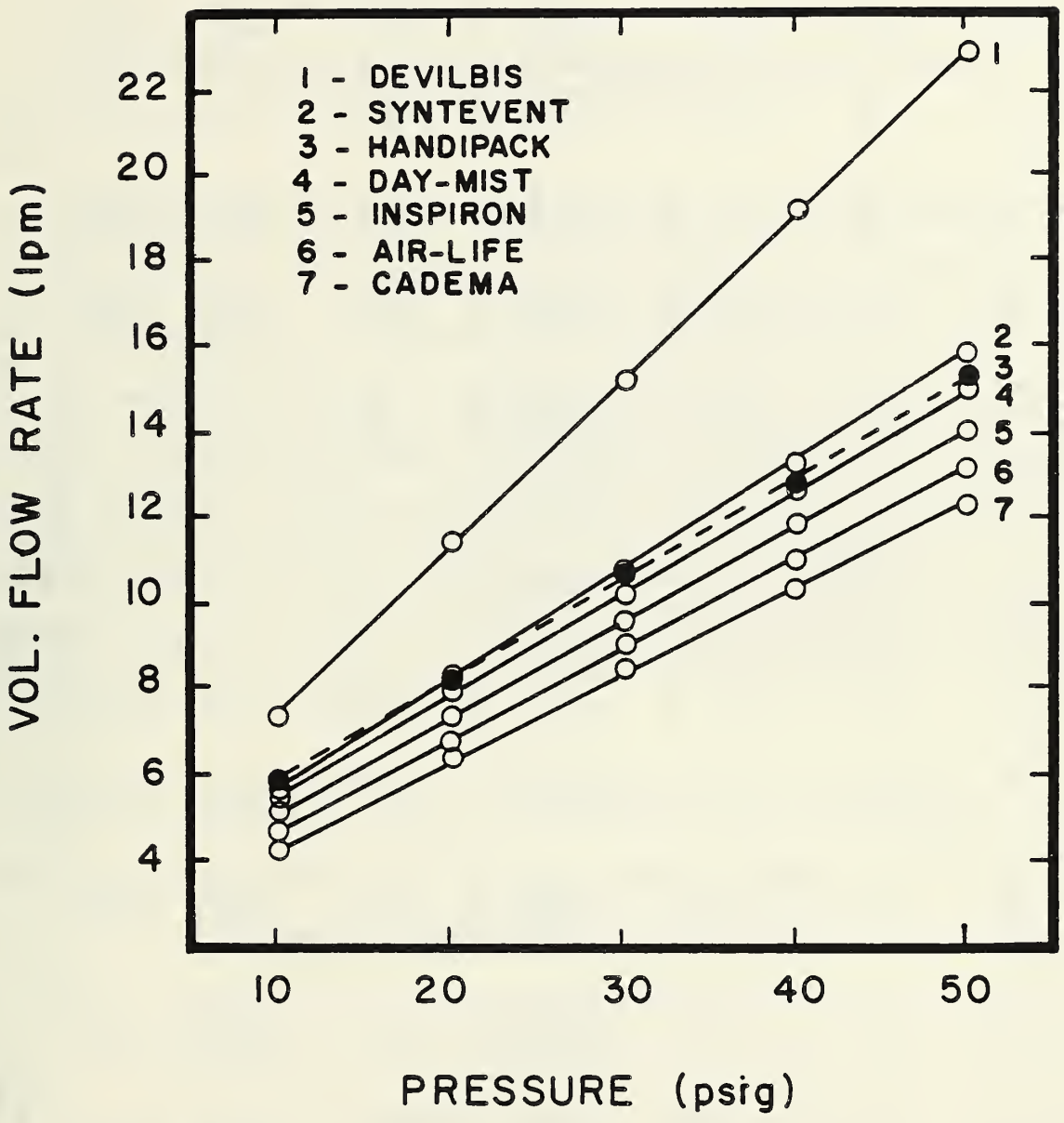


Figure 7. Volumetric flow rate as a function of nebulizer operating pressure.

Table 1. Characteristics and Performance of Various Commercial Medical Nebulizers

Nebulizer	ΔP (psig)	Q (lpm)	V (ml)	A (ml/min)	t (min)	PMS - OPC[a] MMD (μm)	PMS - OPC[a] σ_g	PMS - OPC[a] N (#/cc)	TSI - DMPS[b] MMD (μm)	TSI - DMPS[b] σ_g	TSI - DMPS[b] N (#/cc)	Remarks
Airlife #002010	30	9.0	9.5	0.58	16	1.27	1.4	2×10^8	2.62	1.97	5.1×10^6	small leaks; sometimes bursts of aerosol
Cadema #929-2	20	6.3	15.0	0.13	115	1.45	1.35	9.5×10^7	2.79	1.95	3.2×10^6	no leaks very stable easy handling
Day-Mist #9005	30	10.3	9.5	0.49	19	1.35	1.30	2.2×10^8	2.52	1.91	5.1×10^6	leaks between cap interface
Devilbiss Mod. 645	30	15.2	5.0	0.18	27	1.40	1.30	5.8×10^7	2.73	1.95	7.7×10^6	very stable aerosol bursts
Handipak #602-01	20	8.1	25.0	0.17	150	1.40	1.30	6.5×10^7	3.11	1.98	6.2×10^6	no leaks
	30	10.2	25.0	0.24	104	1.33	1.35	1.1×10^8	2.76	1.95	4.9×10^6	very stable
	40	12.8	25.0	0.32	78	1.40	1.35	1.1×10^8	2.95	1.98	5.9×10^6	
Inspiron #002220	30	9.4	20.0	0.31	64	1.40	1.30	1.3×10^8	1.86	1.81	1.4×10^7	some leaks around inlet
Syntevent	20	7.1	5.5	0.14	39				2.23	1.89	5.6×10^6	no leaks
	30	10.6	5.5	0.11	50	1.40	1.25	4.7×10^7	2.38	1.89	6.1×10^6	stable difficult refill
Retec	20	3.7	10.0	0.41	24				3.21	2.03	4.1×10^6	
	30	5.2	10.0	0.39	26				2.62	1.93	1.2×10^7	
	40	6.4	10.0	0.38	26				2.37	1.90	1.4×10^7	
Hudson	20	6.3	16.0	0.27	59				2.72	1.99	5.2×10^6	small leak at cap interface
	30	8.4	16.0	0.28	57				2.04	1.87	7.8×10^6	
	40	10.2	16.0	0.35	46				2.02	1.86	1.1×10^7	

ΔP: Operating pressure
Q: Volumetric flow rate
V_{max}: Maximum liquid volume
A: Aerosol output
t_{max}: Maximum operating time withou refill

[a]oleic acid aerosol
[b]NaCl aerosol

leak-free nebulizers all had a soft and hard plastic combination at the interface. The last column, "remarks", in Table 1 contains information on the aerosol leak and other operating difficulties encountered in some of the nebuliziers.

3.2 Droplet Size Distribution Measurement Using Oleic Acid and Laser Optical Particle Counter

In the first series of tests, aerosols consisting of pure undiluted oleic acid were generated by the nebulizers listed in Table 1 and the aerosols produced were measured by the PMS-ASAS-300X laser optical particle counter. Oleic acid has been considered as a candidate material for producing the test aerosol for face mask fit testing. Oleic acid (9-octadecenoic acid, $CH_3(CH_2)_7CH{:}CH(CH_2)_7CO_2H$) is a non-toxic substance with a density of 0.8935 g/cm^3 at 20°C and refractive index of 1.4582 at λ = 589 nm. Since the oleic acid was undiluted, the measured size distribution should give the size distribution of the nebulized droplets directly.

Figure 8 is a schematic diagram of the system used to determine the droplet size distribution of the oleic acid aerosol by means of the laser optical counter. The optical counter had a limited capability of counting high particle concentration. A two stage dilution system was therefore set up to dilute the aerosol before introducing it into the counter. The high dilution ratio, typically on the order of 10,000:1, also minimized the coagulation of the original aerosol which had a high particle concentration of over 10^7 particles/cm^3.

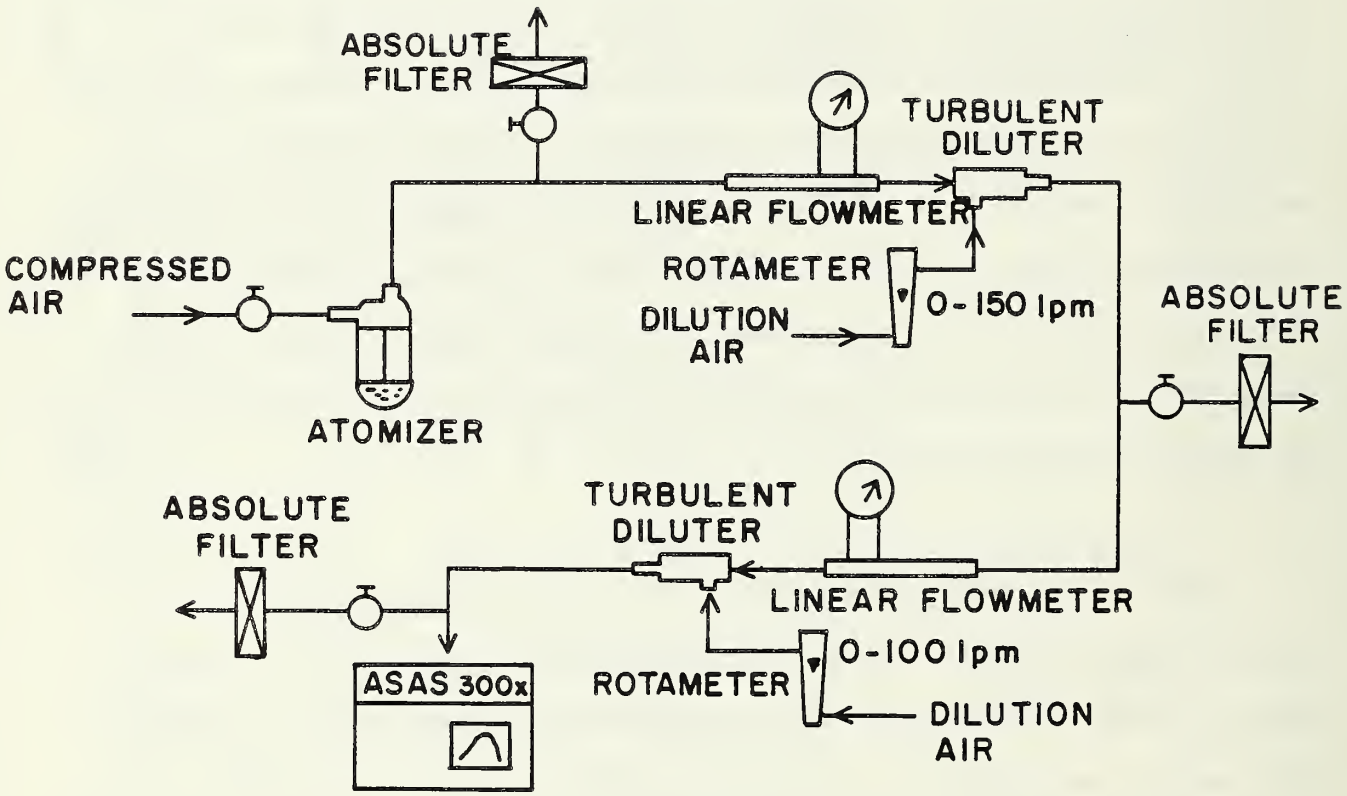


Figure 8. System used to determine the droplet size distribution of the oleic acid aerosol by means of the laser optical particle counter.

The measurement results are summarized in Table 1. The number median diameter (NMD), mass median diameter (MMD) and geometric standard deviation (σ_g) values were obtained by fitting a log-normal distribution to experimental data using the "chi square" procedure [3]. As shown in Table 1, most of the nebulizers gave a mass median diameter of between 1.27 and 1.4 um with a geometrical standard deviation of 1.25 to 1.4. The number concentration varied between about 1.6×10^7 to 4.4×10^8 particles/cm^3.

A typical particle size distribution shown in Figure 9 suggests the existence of two modes which may be formed by two different aerosol generation mechanisms. The first mode, NMD between 1.3-1.5 um, was formed by the process of atomization, and droplets were generated by the shattering of a liquid stream in the fast-moving airstream. The liquid was drawn into the airflow by the reduction in pressure in the exit region of the tube caused by Bernoulli effect. The second mode, NMD between 0.1-0.15 um, was perhaps formed by the agitation of air jet which created a dense foam of microscopic bubbles in the liquid. These bubbles burst at the liquid surface and create additional fine aerosol particles.

The geometric standard deviation from the OPC measurement was lower than expected. This may be caused by the non-ideal characteristics of the laser counter in the measured size range. Figure 10 shows the theoretical response of the laser counter. It is seen that the instrument response is not a single valued function of particle size in the size range between 0.8 and 2 um. This non-ideal behavior causes the measured particles to be grouped into only one or two channels of the instrument instead of the expected six to seven channels. This would reduce the measured geometric standard deviation of the aerosol in question.

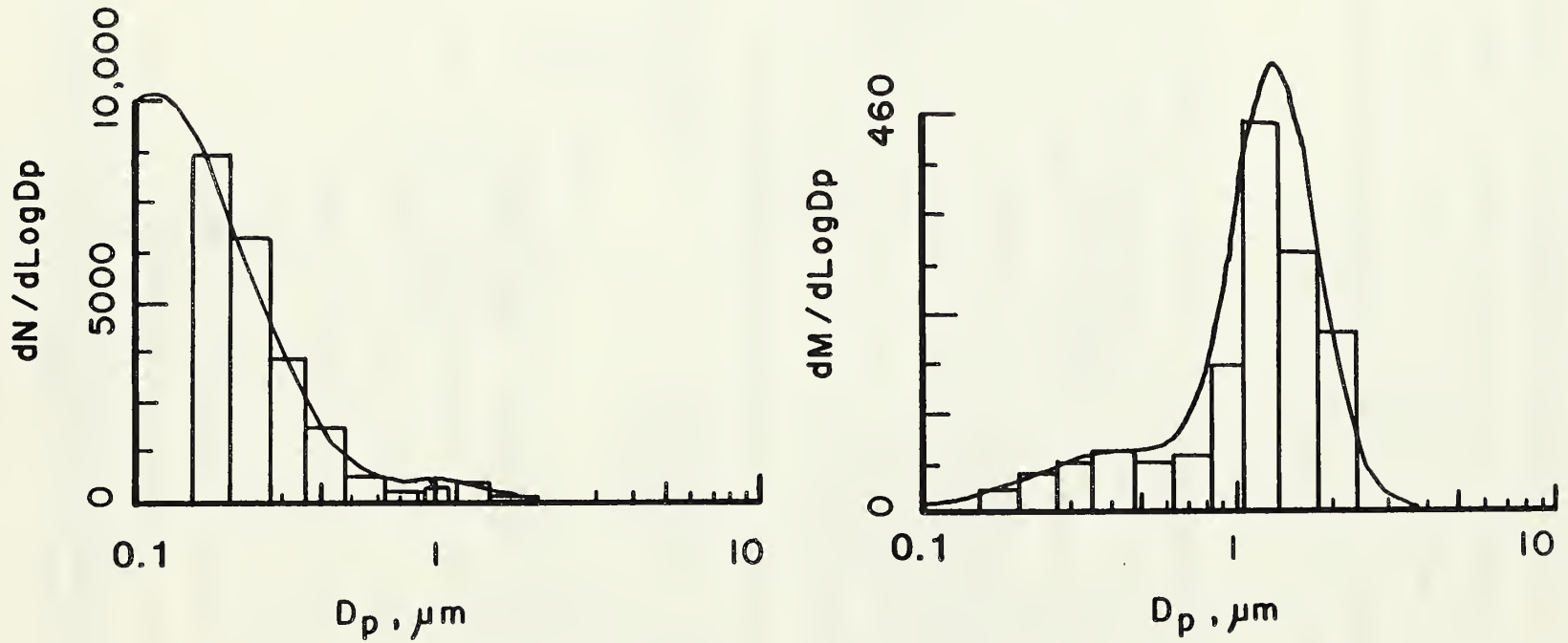


Figure 9. Number and mass size distribution of oleic acid aerosol generated by Handipak nebulizer at 2 x 10^5 Pa (30 psig) operating pressure.

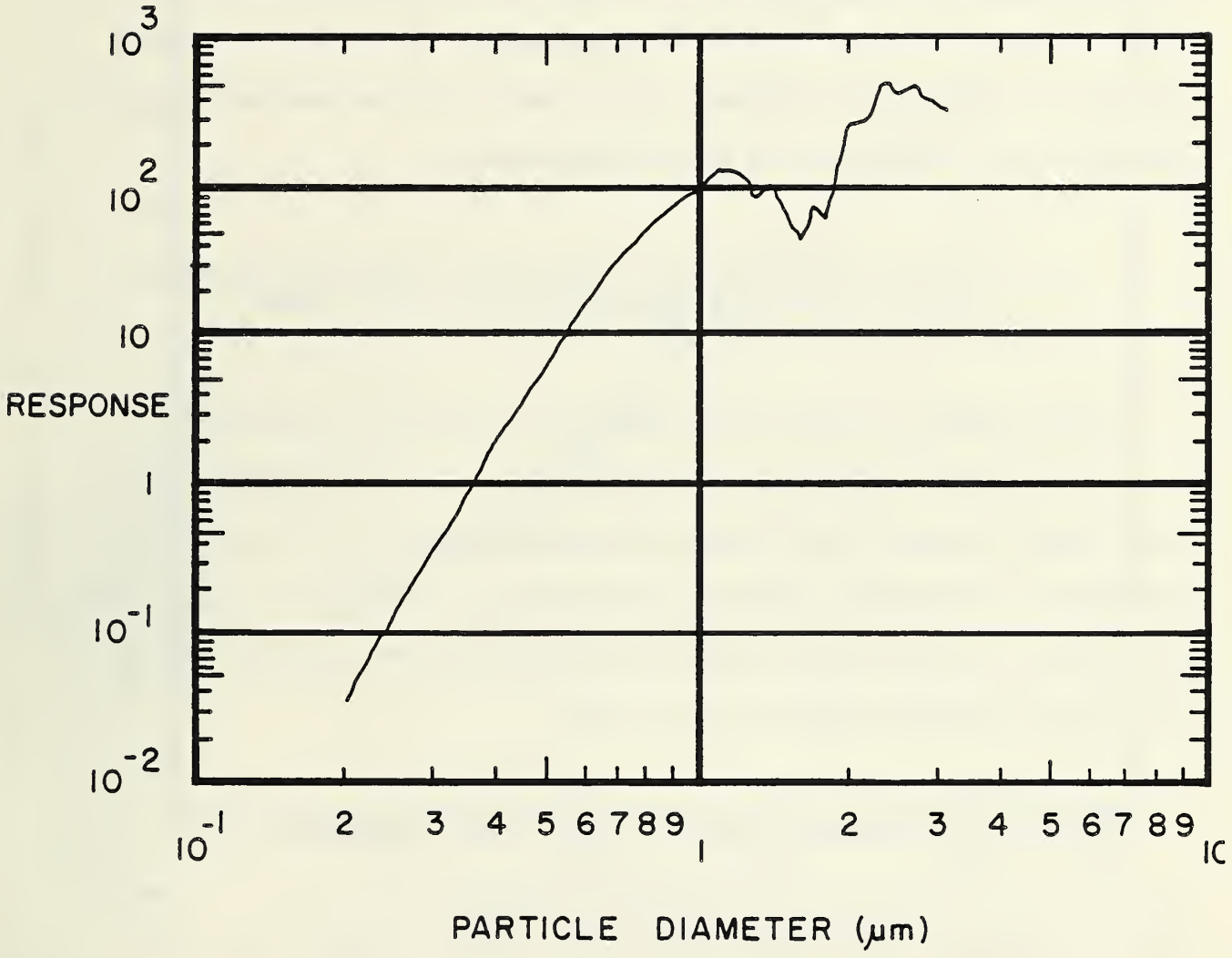


Figure 10. Theoretical response of the PMS optical particle counter for droplets with a refractive index of 1.45.

In addition to the above non-ideal behavior of the laser OPC, another potential source of measurement error is that the laser OPC was calibrated with polystyrene latex (PSL) particles, whose refractive index is different from that of the oleic acid. However, this small difference in refractive index is not expected to give rise to significant errors in the measurement. Nevertheless, an impactor measurement for one nebulizer (Cadema) aerosol was made in order to confirm the optical measurement. The result is shown in Figure 11. Both methods are seen to give nearly the same mean particle size, indicating the validity of the optical measurement.

3.3 Droplet Size Distribution Measurement Using NaCl Aerosol and the Differential Mobility Particle Sizer (DMPS)

In an attempt to improve the measurement accuracy of the aerosol geometric standard deviation, a second technique was used which involved nebulizing an aqueous NaCl solution and measuring the resulting dry NaCl particles. The dry NaCl particle size was about a factor of ten smaller than the droplet size and could be measured accurately by the high-resolution, Differential Mobility Particle Sizer (DMPS).

Figure 12 is a schematic diagram of the second measurement system. The nebulizer was filled with 0.1% by weight of aqueous NaCl solution to about half the maximum liquid volume and was set to the appropriate operating pressure. Most of the output aerosol was discarded through a filter and only a small amount of aerosol was sampled through a capillary tube flowmeter. A dilutor was used to reduce the aerosol concentration by mixing the aerosol with a much higher volume of particle-free air. The aerosol is diluted by a factor of between 40 and 90 from the original concentration. The diluted

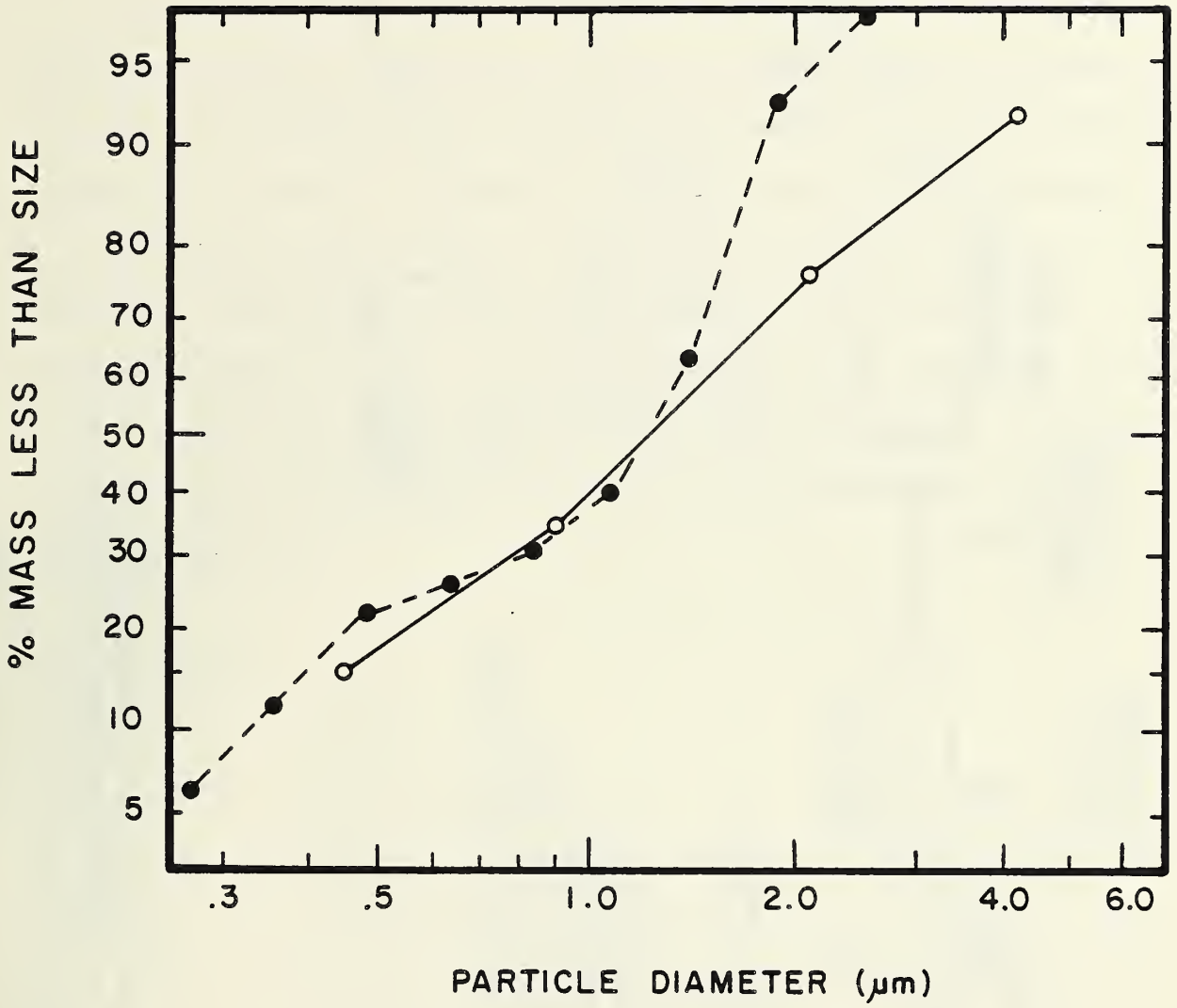


Figure 11. Comparison of the impactor measurement (o) and ASAS-300X measurement (•) for oleic acid aerosol produced by a Cadema nebulizer operated at 2 x 10^5 Pa (30 psig).

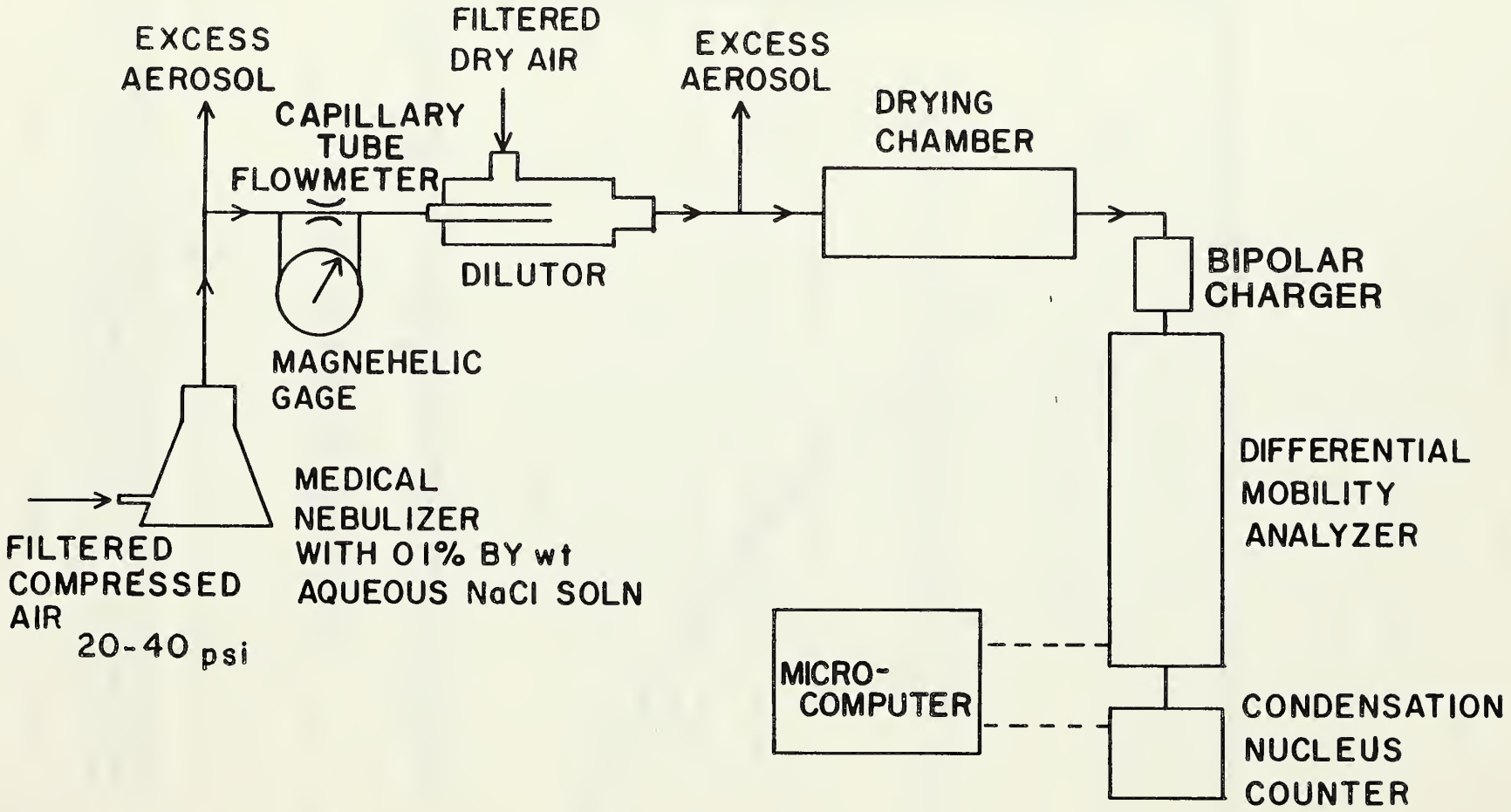


Figure 12. System used to determine aerosol size distribution from the nebulizer by means of the DMPS system.

aerosol was allowed to pass through a drying chamber before being introduced into the differential mobility particle sizer (DMPS). The DMPS is based on a bipolar charging-mobility analysis technique for size distribution measurement. The size range covered by the DMPS is from about 0.01 to 0.5 um.

Figure 13 shows the measured number size distribution of the dry NaCl particles produced by the handipak nebulizer. Both the number size distribution and the cumulative number distribution are shown. The values of NMD and σ_g for the dry particles are found to be 0.056 μm and 1.95, respectively. From these parameters, the droplet size distribution parameters can be calculated. Since every droplet had the same solution concentration, the geometric standard deviation of the droplets distribution should be the same as that of the dry particles distribution. The droplet NMD was calculated from the known dry particle NMD and known solution concentration using the following equation

$$D_d^3 C = D_p^3 \rho$$

where C is the NaCl concentration by weight in the aqueous solution, D_p is the dry NaCl particle size, D_d is the droplet size, and ρ is the density of the NaCl particle which was assumed to be the same as the bulk density of NaCl, 2.165 g/cm^3. Knowing the droplet NMD, the MMD of the droplet size distribution can also be calculated from the measured geometric standard deviation, σ_g:

$$\ln(MMD) = \ln(NMD) + 3(\ln\sigma_g)^2$$

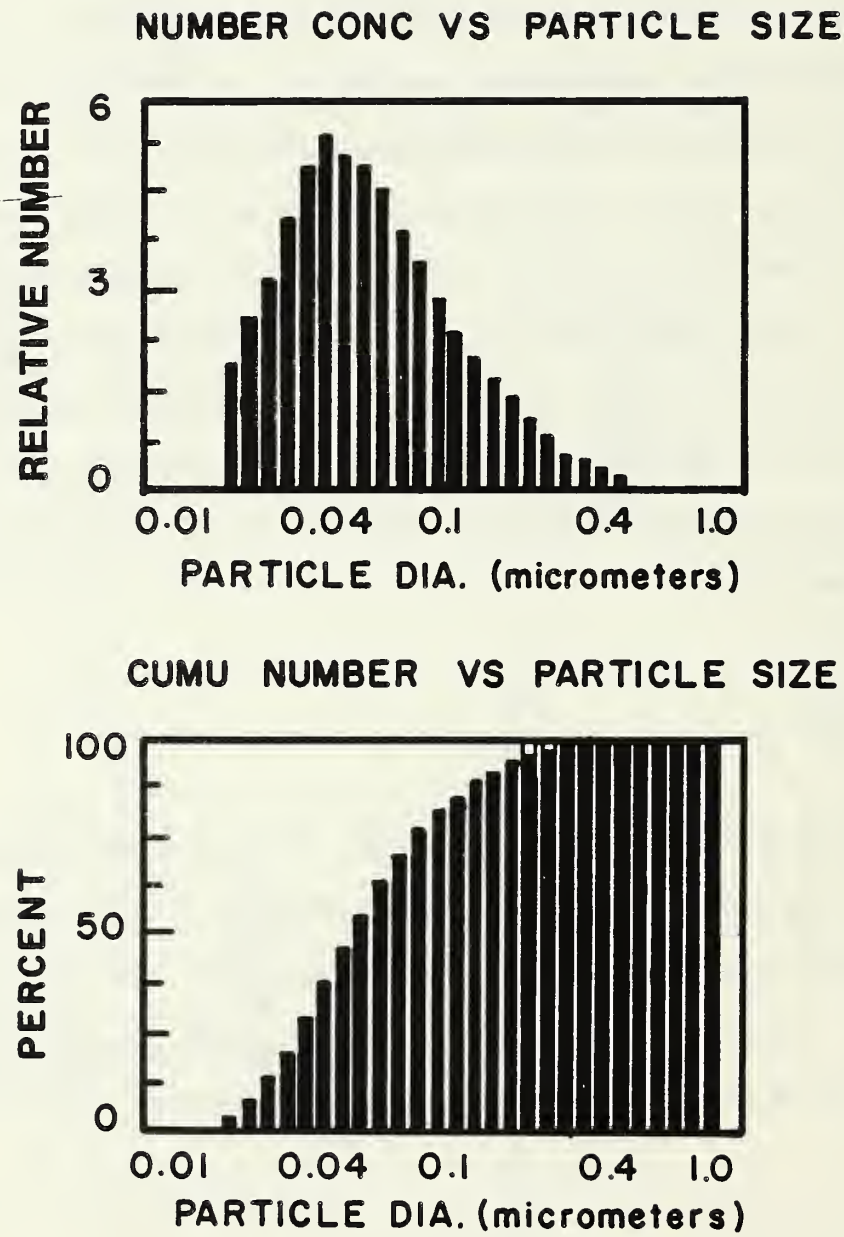
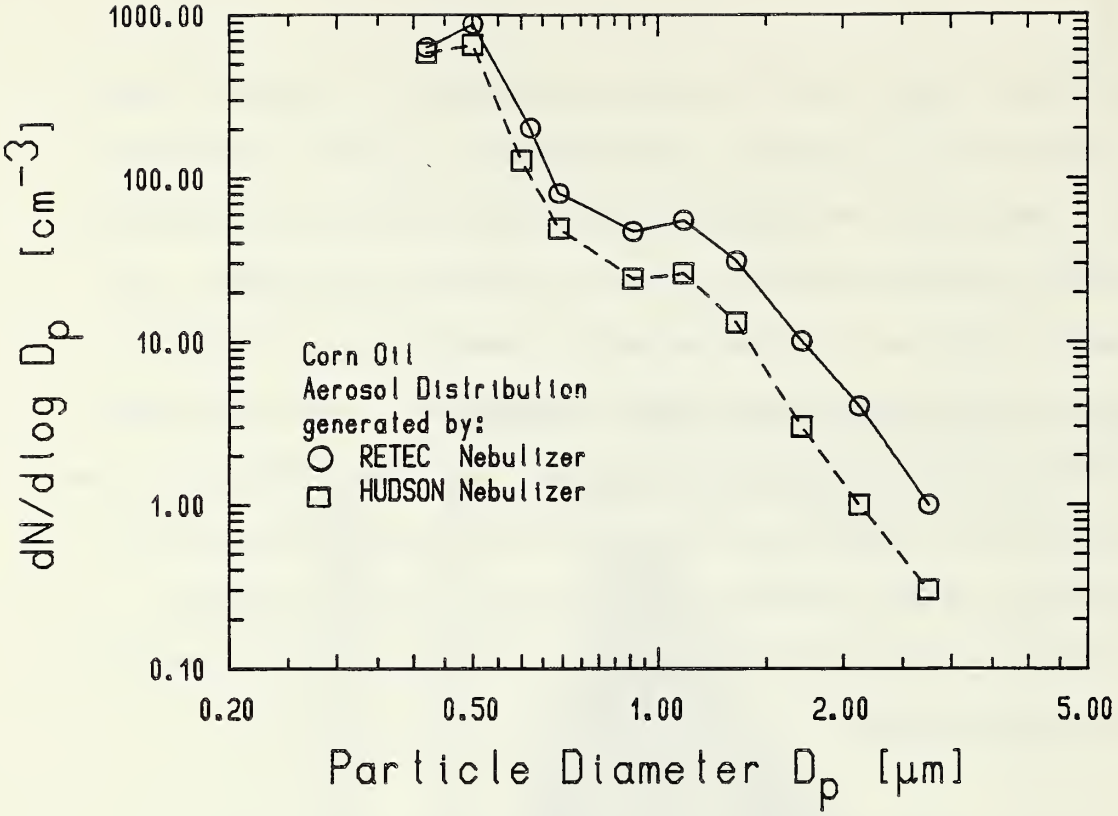


Figure 13. Size distribution of dry NaCl particles produced from aerosol generated by Handipak nebulizer at 2 x 10^5 Pa (30 psig).

The calculated droplet size distribution parameters are listed in Table 1. For the convenience of comparison, the parameters obtained in the first method are also tabulated. The DMPS measurement gives a much more reasonable geometric standard deviation than that from the laser OPC measurement. The calculated droplet size from the NaCl aerosol is generally larger than that from the oleic acid aerosol while the number concentration of the oleic acid aerosol is higher than that for the NaCl aerosol. These differences are to be expected considering the significant differences between the viscosities of the two liquids which affect the nebulization process. There is also the possibility of error in the case of NaCℓ, since the dried residue is measured rather than the droplet itself.

3.4 Characteristics of the Nebulizer and Liquid Used in the Prototype Fit Test Apparatus

The Hudson nebulizer was chosen for use in the prototype quantitative fit test apparatus. An operating pressure of 1.0×10^5 Pa (15 psig) was used for the nebulizer and corn oil was chosen as the aerosol source liquid for reasons discussed below. The size distribution was obtained using a Climet optical particle counter (model 208), which was calibrated with monosized polystyrene spheres. The calibration curve was corrected for the difference in refractive index from 1.59, the value for polystyrene spheres, to 1.45, the value for corn oil, based in part on theoretical calculations by Cooke and Kerker [4]. Unlike the laser optical particle counter discussed above, the Climet, which has a white light source, has a single valued response for the particle size range 0.4 to 3 μm [4]. The aerosol volume distribution plotted in figure 14 has a peak near 0.5 μm and a second peak near 1.2 μm. Data obtained with the Climet also clearly show that the Hudson nebulizer produces smaller droplets than does the Retec nebulizer (Fig. 14).



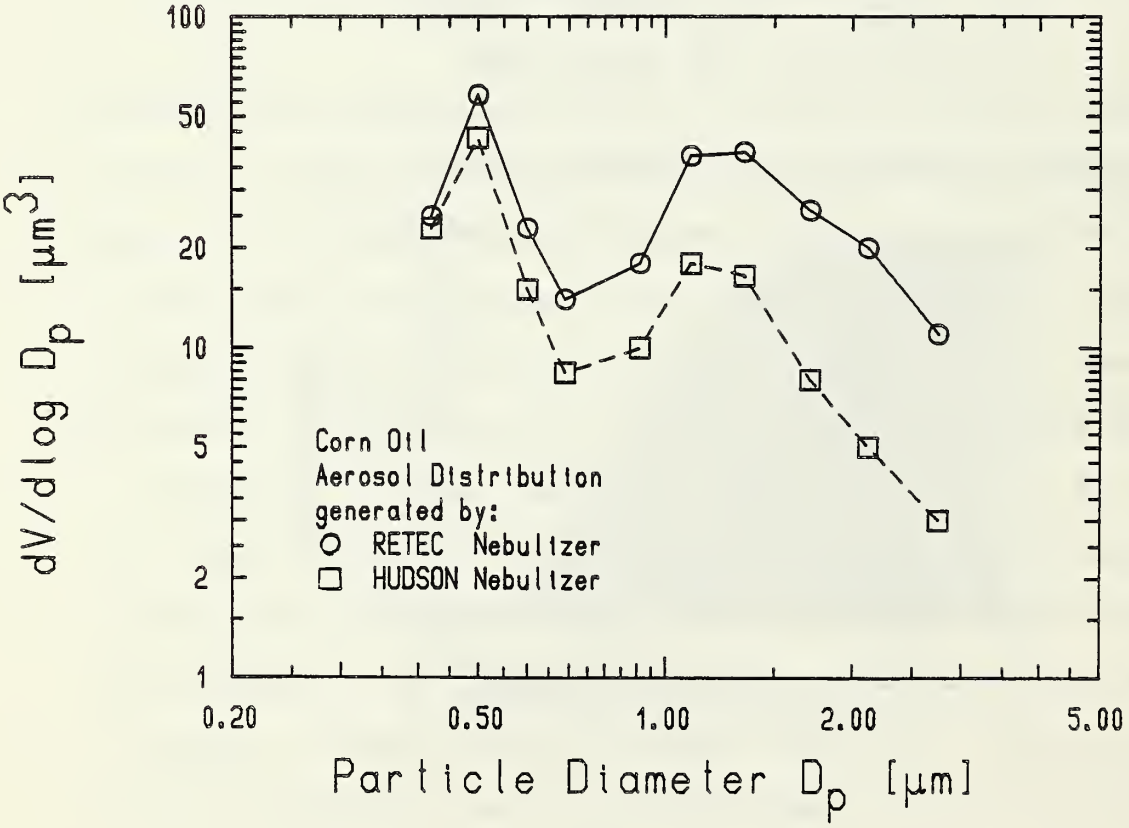


Figure 14. Number and volume distribution obtained with the Climet optical particle counter for corn oil aerosol.

The cumulative distributions plotted in figure 15 show that the mass median diameter obtained with the Andersen cascade impactor, 1.1 μm, is larger than the volume mean diameter obtained with the Climet, 0.7 μm. About 80% of the mass of the corn oil aerosol has a diameter less than 2 μm based on the impactor data while about 95% has a diameter less than 2 μm according to the Climet. The quantity σ_g obtained from a straight line fit to the Climet results plotted in figure 15, 1.9, agrees well with the values obtained with the Andersen impactor, 2.0, and with the differential mobility particle sizer, 2.0.

The nebulizer can be operated continuously for one hour at 1.0×10^5 Pa (15 psig) with corn oil before the liquid reservoir requires refilling. When the output from the nebulizer is diluted to a total flow of 50 ℓ/min, the aerosol concentration was found to be 485 mg/m^3. One problem with this nebulizer as well as a number of others is the leakage between the main housing of the nebulizer and the cap. The leakage of aerosol was greatly reduced by placing teflon tape at the interface of the housing and cap.

A literature survey was made to determine the best liquid for use in the nebulizer in regard to both physical properties and toxicity. We have obtained data on the following seven candidate liquids: glyceryl trioctanoate, glyceryl trioleate, glycerol, oleic acid, di(2-ethylhexyl) sebacate, corn oil, mineral oil, and polyethylene glycol. The physical properties of these liquids including density and viscosity are given in Table 2. Corn oil is currently the liquid recommended by the National Institute for Occupational Safety and Health (NIOSH) for respirator quantitative fit testing [5]. It appears that glyceryl trioctanoate would be a better choice than corn

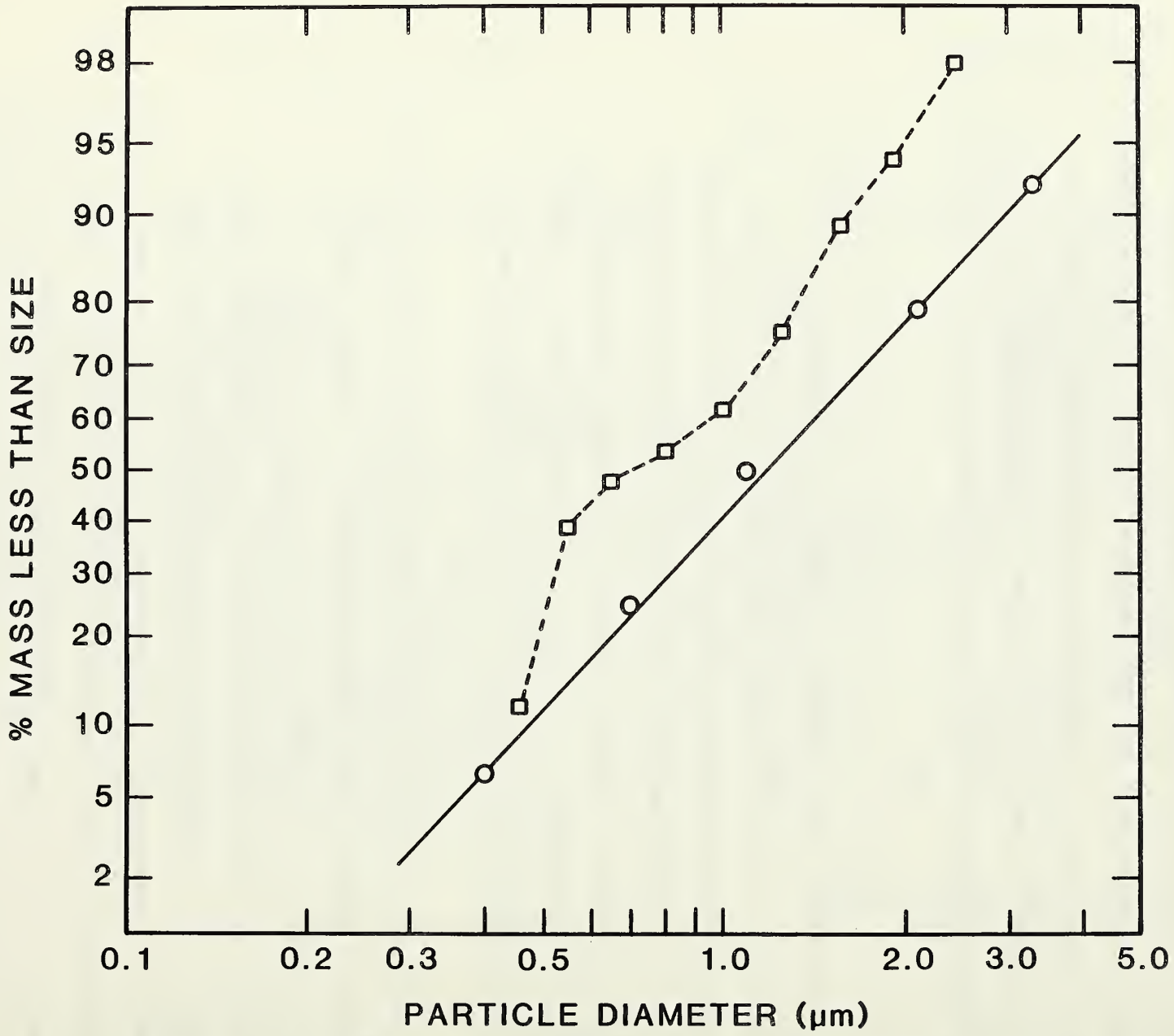


Figure 15. Accumulative size distribution of corn oil aerosol produced by the Hudson nebulizer based on measurements with the Andersen impactor (o) and the Climet optical particle counter (□).

Table 2. Physical Properties of Candidate Liquids for Fit Test Apparatus

Liquid	Boiling Point °C/mm Hg	Melting Point °C	Vapor Pressure ca °C	Water Solubility	Density g/cm^3	Viscosity cp	Refractive Index	Chem. Abstracts No.
glyceryl trioctanoate	233.1	10°	0.01 mm (128°C) 0.05 mm (179°C)	nil	0.9540 (20°C)	30.1±2 (0°C) 25.1±2 (99.8°C)	1.4482 (20°C)	538-23-8
glyceryl trioleate	235-240° @10 mm	5°		slight to nil	0.899 (40°C) 0.913 (20°C)	40.1 (17°C) 29.3 (99.8°C)	1.468 (20°C)	122-32-7
glycerol	290°/760 182°/20	17.8°		very soluble very hygroscopic	1.264 (20°C)	111 (83% aqueous solution)	1.475 (20°C)	56-81-5
di(2-ethylhexyl) sebacate	256°/5	-55°		nil	0.915	17.4	1.448	122-62-3
di(2-ethylhexyl) phthalate	350°/760 230°/5	-50°	1.2 mm(200°C)	nil	0.986	82 (20°C)	1.485	117-81-17
polyethylene glycol	broad range			variable, related to molecular weight	1.13	105 (25°C)	1.465	25322-68-3
mineral oil	> 370°C			nil	0.86			8012-95-1

oil for several reasons. First it is a pure compound with well defined properties unlike corn oil, which is a mixture of fatty acids (predominately linoleic acid), sterols, tocopherols, antifoaming agents, and antioxidants such as butylated hydroxyanisol (BHA). Secondly, it does not become rancid upon long exposure to air as does corn oil. Thirdly, while there is no definitive result at this time, it would appear that the toxic effects of glyceryl trioctanoate would be less than those of corn oil. A short discussion regarding our findings on the toxicity of the seven candidate liquids is provided in the appendix. Some of the undesirable characteristics of the corn oil would be removed if a major pure component of corn oil such as triolein were used instead of the corn oil. In any event, we have chosen to use corn oil in our study since it is the currently recommended liquid for respirator fit testing.

4. DESIGN OF PROTOTYPE FIT TEST APPARATUS

To test the concept of a fit test apparatus based on a smoke detector and a clinical nebulizer, we have assembled a prototype. The overall design of the apparatus is illustrated in figure 16. The diaphragm pump, which serves as a compressor and as a vacuum source, provides 1.0×10^5 Pa (15 psig) to the nebulizer. The bypass valves on the outlet and inlet to the pump are adjusted so that the outlet pressure is 1.0×10^5 Pa (15 psig) and so the sample flow rate from the face mask is 2 ℓ/min. The constancy of the pressure assures a constant output from the nebulizer.

The corn oil aerosol produced by the nebulizer is diluted with air from a blower to a concentration of about 500 mg/m^3 at a flow rate of 50 ℓ/min. This

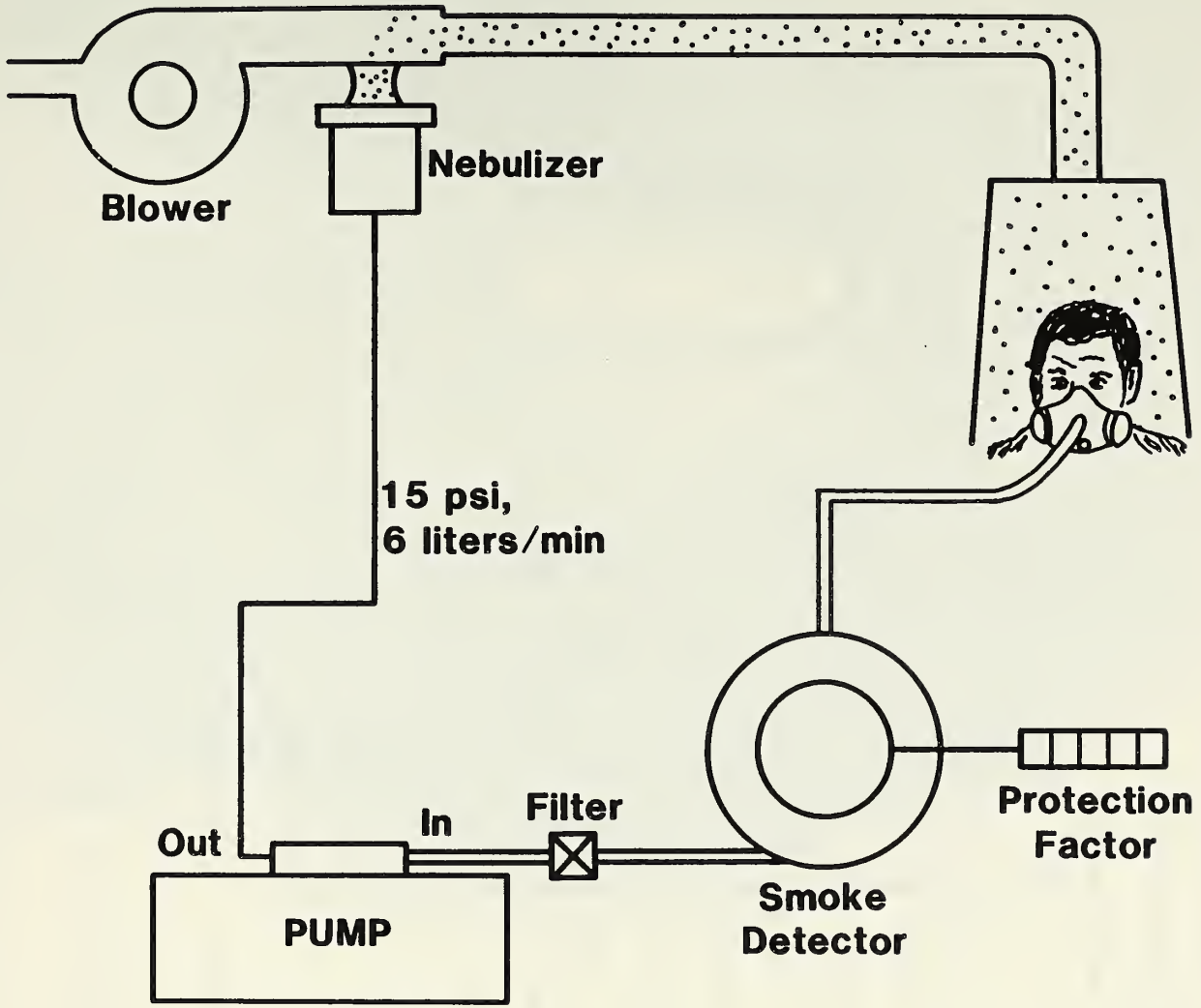


Figure 16. Schematic of quantitative fit test apparatus.

flow is directed into the hood type exposure chamber where the excess flow leaks out around the subject's shoulders.

The amount of leakage around the face seal is determined by drawing 2 ℓ/min of air from within the face mask into the cylindrical chamber (0.45 ℓ) containing the smoke detector (Fig. 17). The response time of the smoke detector positioned in the chamber is about 15 seconds.

The smoke detector operates off a 20 V DC power supply. The electrical diagram for the power supply is given in figure 18. A ten light LED display is used to monitor the face seal leakage. Each LED corresponds to a protection factor and the successive LED's are on a logarithmic scale. The protection factor is the ratio of the concentration of test aerosol in the hood to the concentration in the face mask. The higher the protection factor the better the fit. The signal from the smoke detector is off-set from the background signal and is inverted to a positive voltage by the electrical circuit shown in figure 19. This circuit also filters the smoke detector signal with a time constant of about 5 seconds to prevent rapid transients from affecting the LED display. The overall gain of the circuit is adjusted so that a 10 V output lights the first LED, which corresponds to a protection factor of 25. Provisions are made for adjusting both the gain and the off-set as indicated in figure 19. The protection factors (25, 50, 125, 450) corresponding to four of the LED's are indicated on the front panel (Fig. 20).

For ease in maintenance, the smoke detector/chamber, the blower, and the LED display with associated electronics are attached to the front panel of the chassis. Figures 21 and 22 present exterior and interior views, respectively,

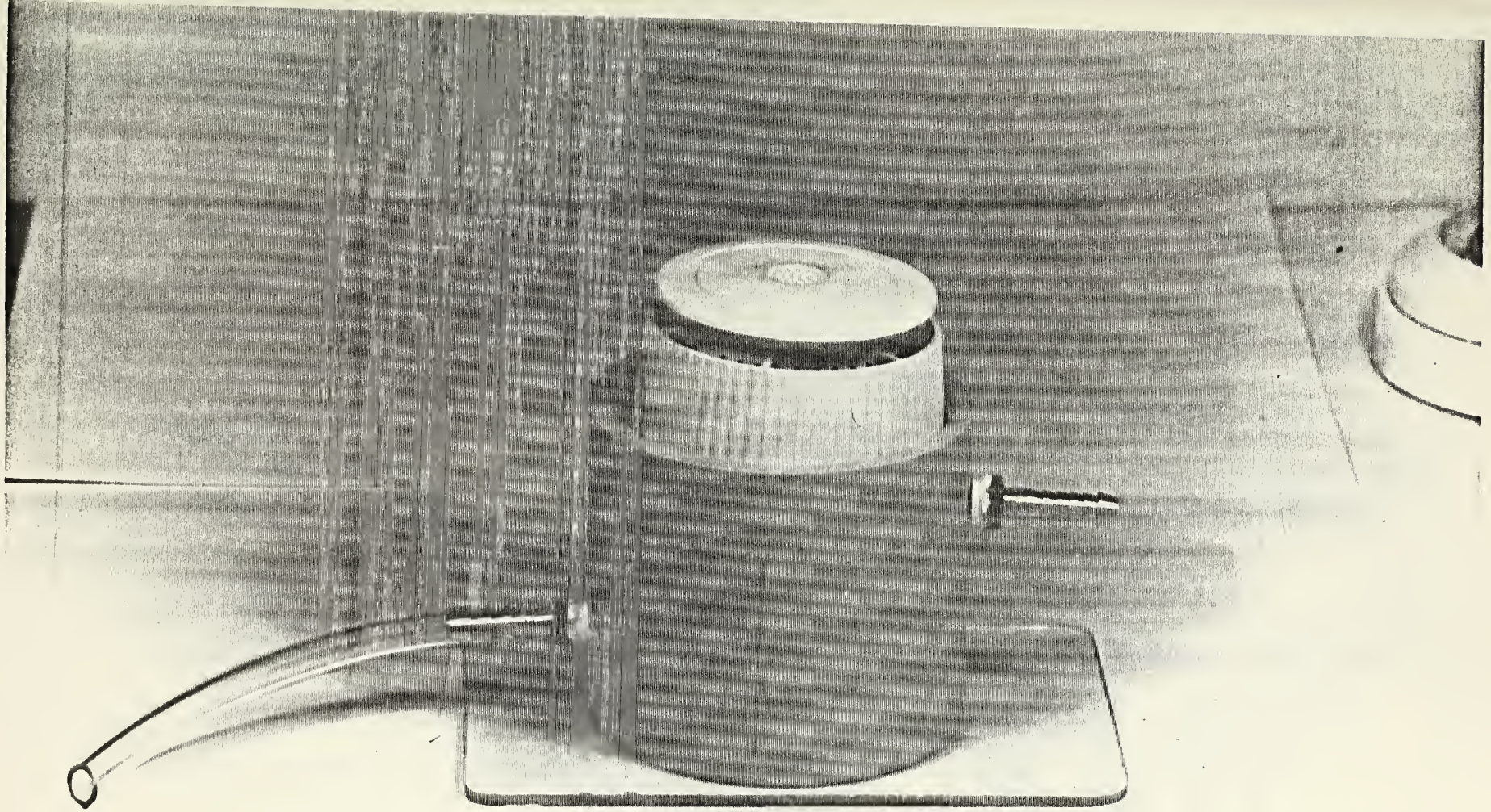


Figure 17. Photograph of smoke detector L-3 in the sampling chamber.

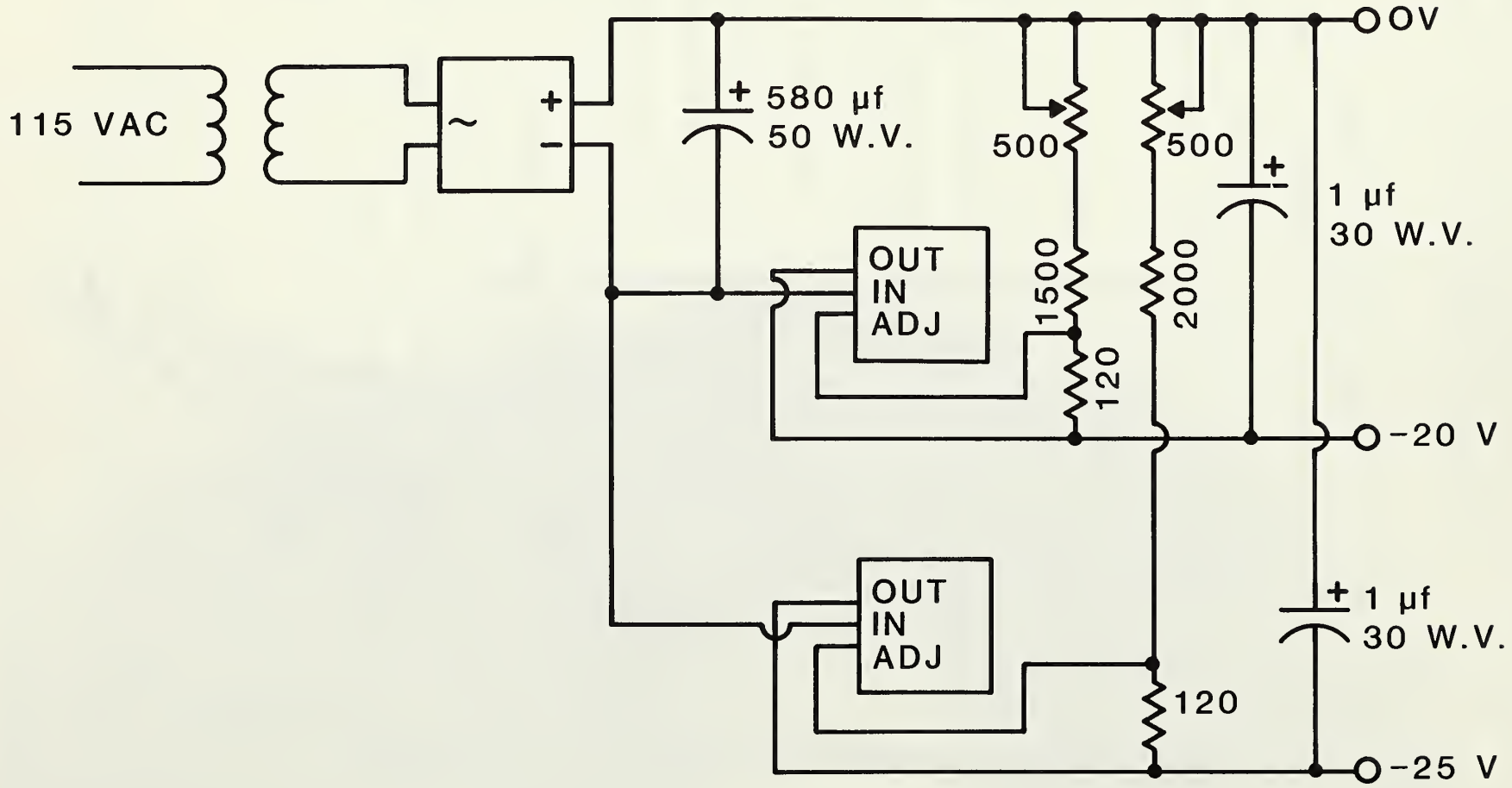


Figure 18. Power supply circuit for fit test apparatus.

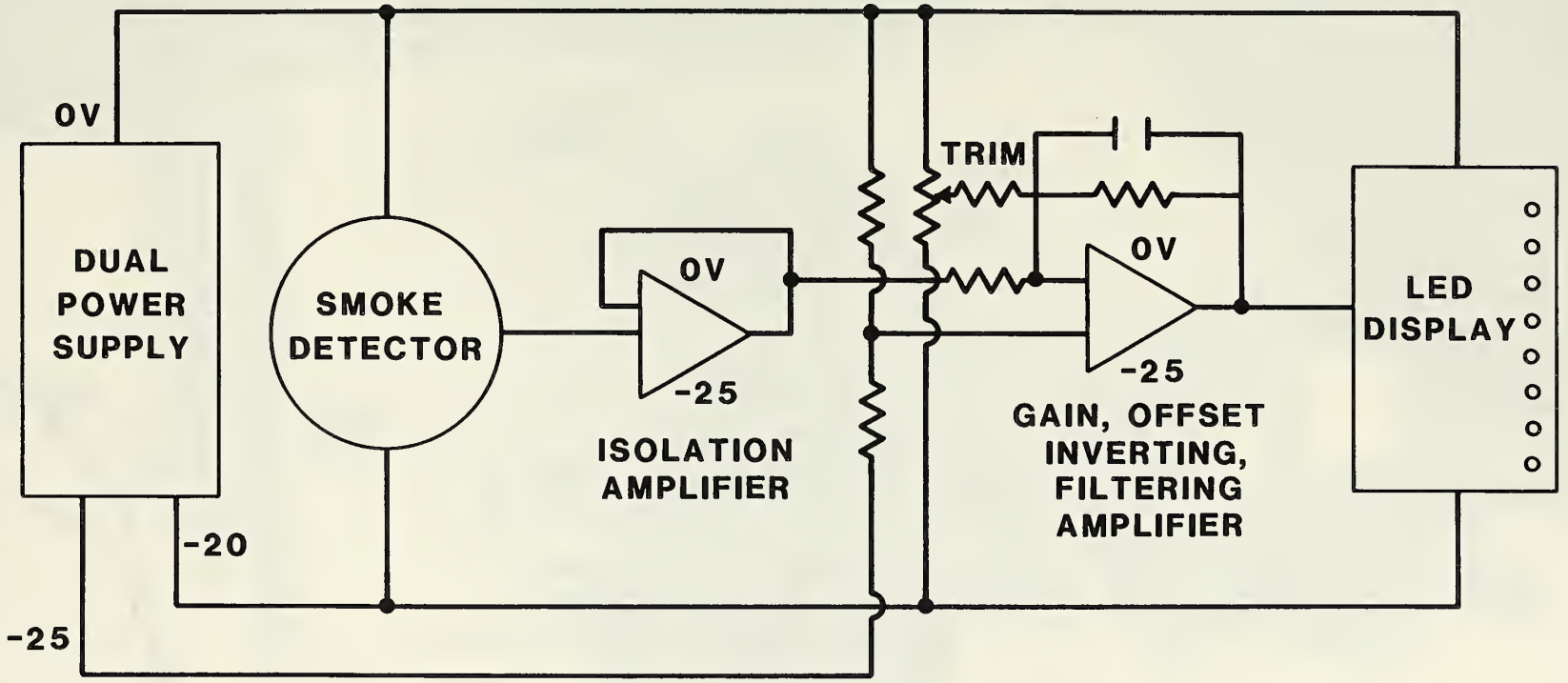


Figure 19. Circuit for monitoring the protection factor provided by the face mask.

Figure 20. LED display on front panel of prototype fit test apparatus.

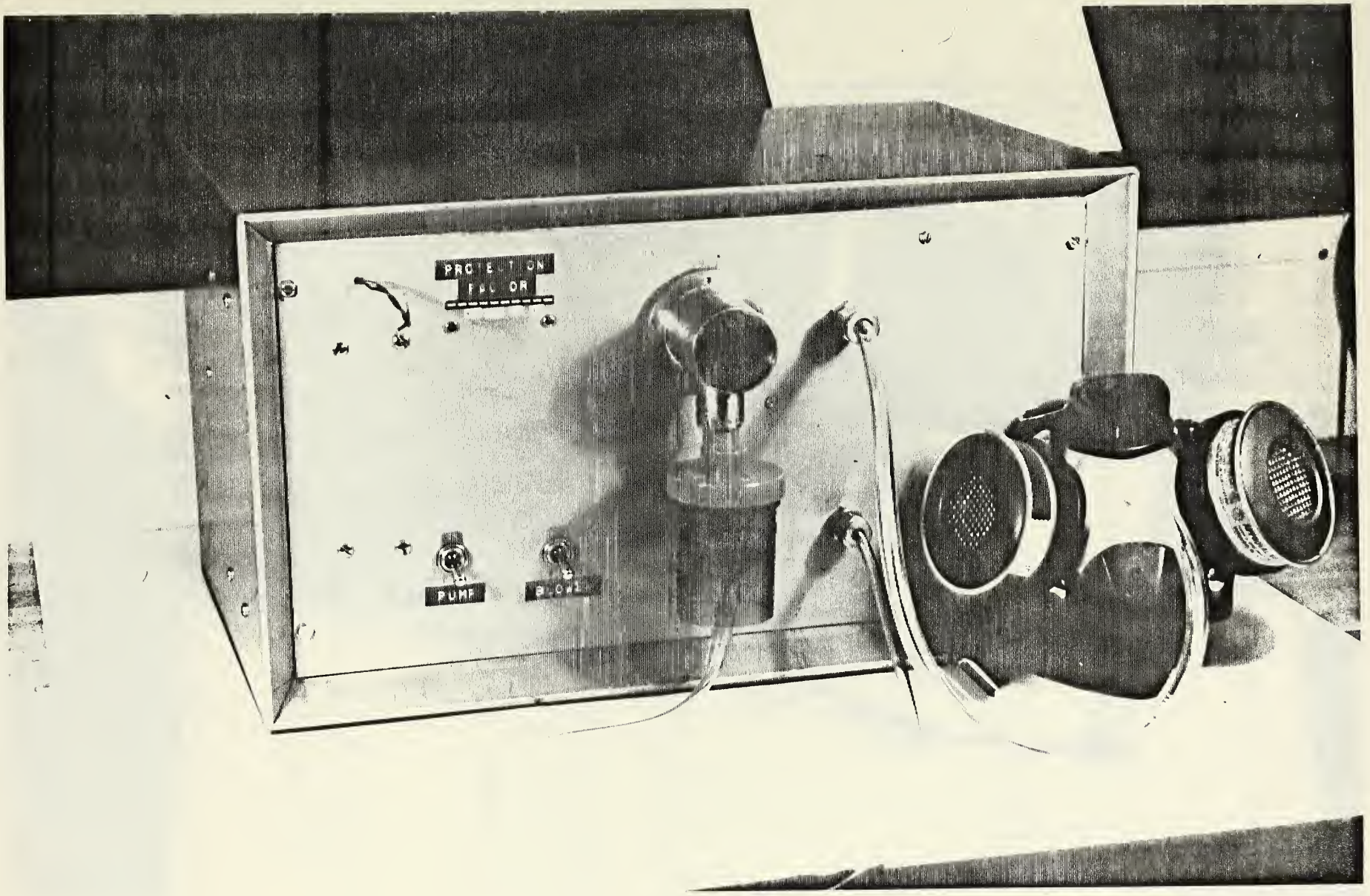


Figure 21. Exterior view of fit test apparatus.

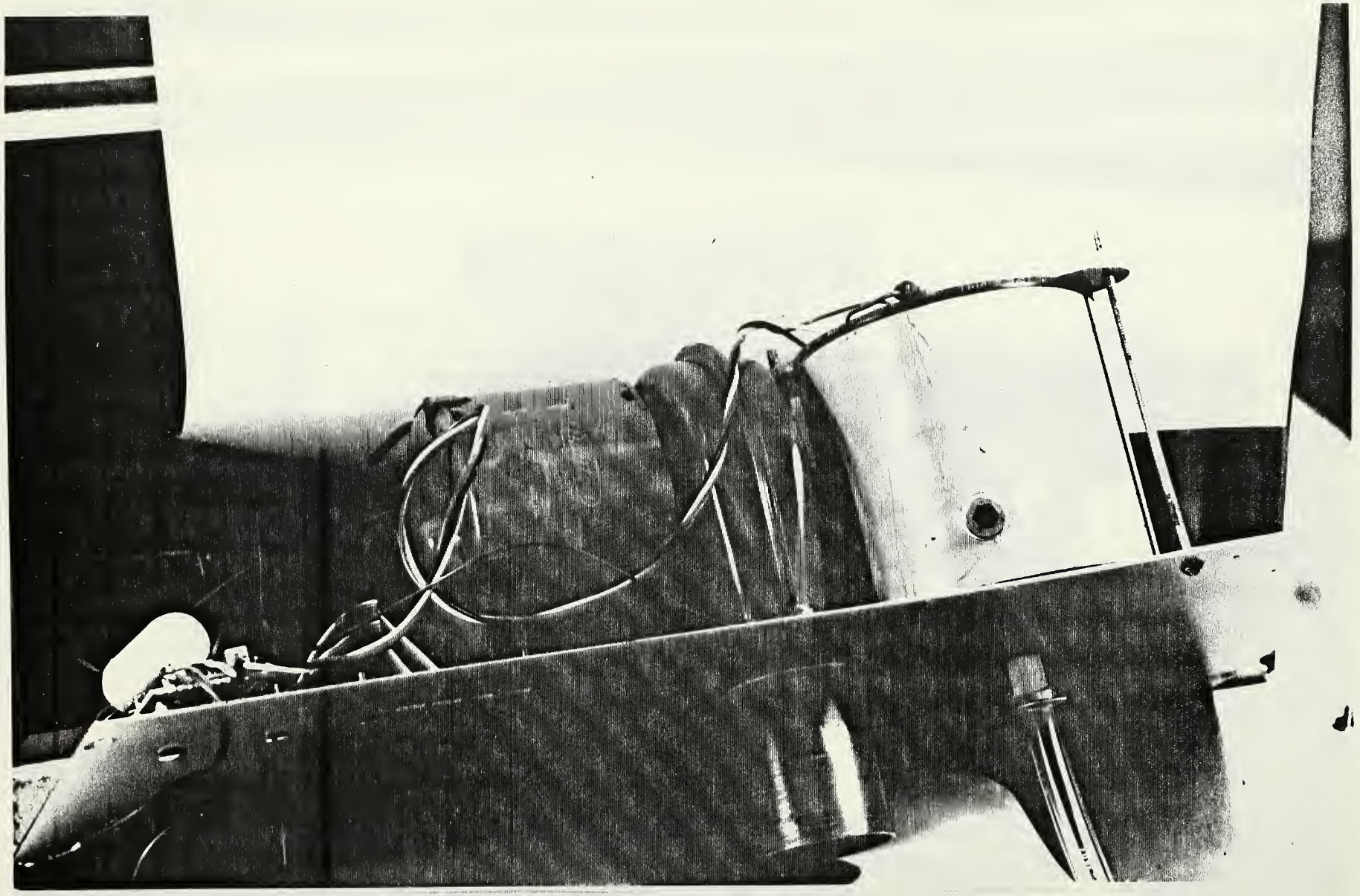


Figure 22. Interior view of fit test apparatus illustrating the attachment of the smoke detector chamber, blower, and LED display to the front panel.

of the prototype fit test apparatus. As shown in figure 21, the nebulizer is mounted on the exterior of the instrument for ease in refilling the liquid reservoir. A listing of the components is given in Table 3. The total cost of these components was about $300.

5. OPERATION OF PROTOTYPE FIT TEST APPARATUS

The intended operating procedure for the prototype fit test apparatus is as follows:

1. Fit mask per ANSI Z 80.2-1980.

2. Don the hood assembly.

3. Fill nebulizer with corn oil and insert nebulizer into tee connection.

4. Turn on blower and smoke detector with one switch and compressor with a second switch. (The compressor will not activate unless the blower is on so that high aerosol deposition in the tee assembly is minimized.)

5. Observe the protection factors indicated by the LED display as the subjects undergo the exercises specified in ANSI Z 80.2-1980.

With the assembled apparatus, we have recorded the detector output as a function of time as the corn oil aerosol is being diluted in the chamber. The numbers on the graph on figure 23 indicate the correspondence between protec-

Table 3. List of Components for Fit Test Apparatus[a]

1. Chassis - 43 x 28 x 24 cm steel with removable front and rear panel
2. Hudson nebulizer - 6 ℓ/min output at 15 psi
3. Cerberus RM 91 analog smoke detector
4. Thomas Compressor - 107 CA 183 up to 12 ℓ/min at a working pressure of 20 psig
5. Dayton Blower 2C782, 115 VAC squirrel cage blower
6. NSM 3915L LED Display - 10 LED display based on logarithmic gain
7. Hoke needle valve
8. Gelman pleated membrane filter (2 μm pore size)
9. Chamber for detector fabricated with 8.9 cm (3-1/2") diameter PVC pipe
10. T connector fabricated from brass to fit blower outlet and Hudson nebulizer
11. 20 volt power supply
12. Circuit for LED display
13. MSA Comfo Hood

[a]Certain commercial equipment and instruments are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation by the National Bureau of Standards, nor does it imply that the equipment identified is necessarily the best available for the purpose.

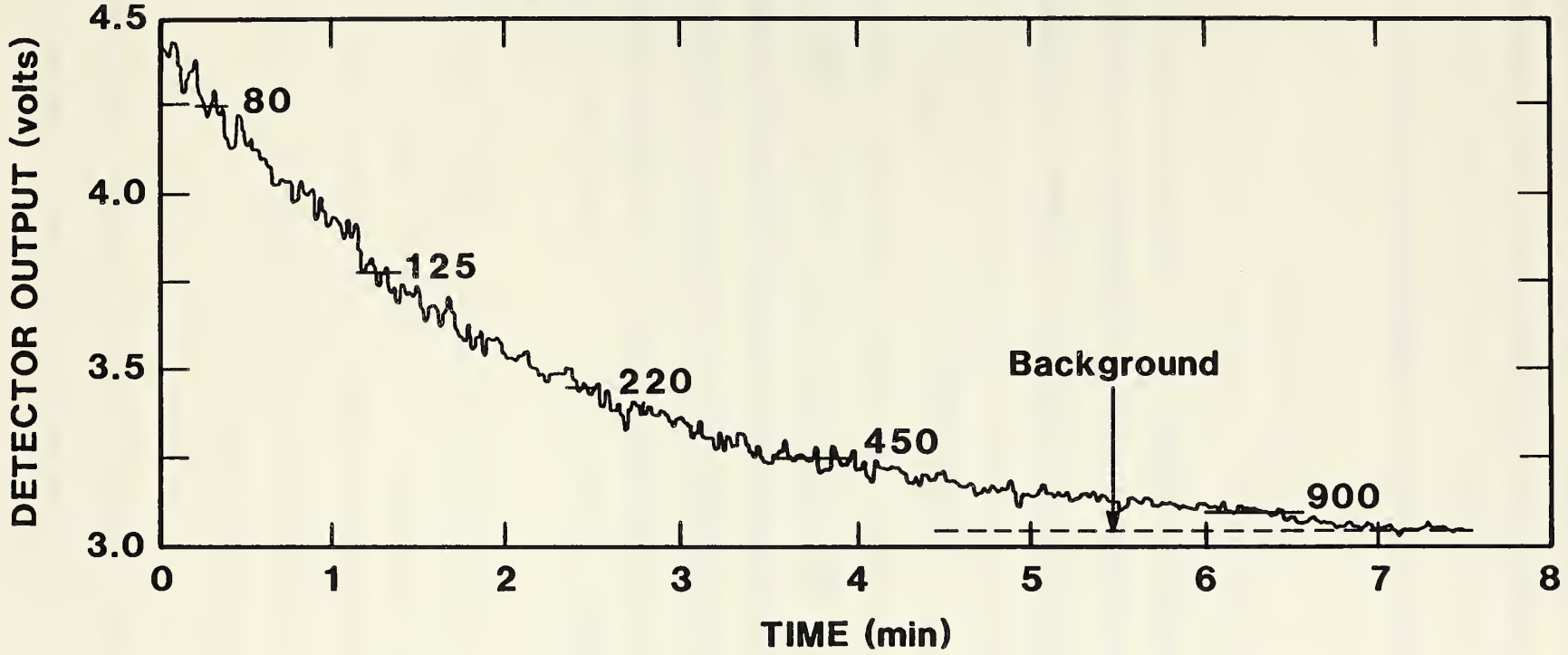


Figure 23. Correlation between detector output and protection factor.

tion factor and smoke detector output. As shown on the figure, a protection factor of at least 450 and perhaps as large as 900 may be discriminated from the background reading. Field testing will ultimately be required to define the highest protection factor that can be measured during routine testing.

6. SUMMARY AND DISCUSSION

By utilizing an analog smoke detector and a clinical nebulizer, both of which are mass produced, we have developed an inexpensive quantitative fit test apparatus with component parts costing less than $300. The apparatus is easy to use, and the design is such that a person should be able to test himself without an operator. One simply turns on the instrument and reads the protection factor indicated by the LED display. In contrast, the presently available quantitative fit test apparatuses require zeroing of the photomultiplier, interpretation of strip chart recordings, and skilled maintenance. The instrument manuals for these apparatuses are similar in complexity to state of the art aerosol instrumentation manuals. An equipment operator is always required for testing.

We anticipate that our newly developed fit test apparatus will be adequate for most routine applications. For very high protection factors or for special applications where small changes in the protection factor must be monitored, a more sensitive quantitative fit test apparatus such as the Dynatech Frontier apparatus should be used.

We have discussed several design changes in the smoke detector section including use of a smaller scattering angle and the use of shorter, more

intense LED pulse that could improve the smoke detector sensitivity to corn oil aerosol by a factor of 10 or more. This could increase the maximum protection factor measurable by the apparatus to 5000. We also indicated that the sensing element can be very small, as small as a penny, allowing the possibility of in situ monitoring of aerosol in the face mask itself.

In our apparatus we have used corn oil but with several reservations explained in section 3. Based on reviewing the literature and contacting toxicity experts, we recommend that glyceryl trioctanoate be considered a candidate liquid for quantitative respirator fit testing.

7. ACKNOWLEDGMENTS

This study was funded by the Occupational Safety and Health Administration. The authors thank S. Steele for his design of the power supply and circuitry for the LED display, T. Maher for his assistance in fabricating the quantitative fit test apparatus, and D. Chamberlain for his review of the toxicity data for various candidate liquids for use in the fit test apparatus.

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APPENDIX

SUITABILITY OF CANDIDATE LIQUIDS FOR QUANTITATIVE FIT TEST APPARATUS

Glyceryl Trioctanoate (trioctanoin)

The use of trioctanoin, also known as tricapryln and glyceryl tricaprylate, was suggested by W. Kluive from the National Institute of Environmental Health Studies because it is bland, is readily metabolized, and does not undergo oxidation to gummy products in ambient air.

Trioctanoin, the triester of glycerol and n-octanoic (caprylic) acid is a naturally occurring component of many seed oils, such as palm oil, that are extensively used as food oils, in pharmaceutical products, and cosmetics. It is also used as a carrier for drugs that are under evaluation for their pharmacological effects.

Kenneth Dooley from the National Center for Toxicological Research (NCTR) reported that trioctanoin is used as a carrier for injection studies. In three successive control studies with trioctanoin, the first resulted in no tumors (in mice or rats), the second resulted in one tumor in 24 animals, and the third study resulted in no tumors among the test animals. Since tumors occur occasionally in nonexposed animals, the trioctanoin was evaluated as quite safe. Gerd Reznik, an inhalation toxicologist with a special interest in pathology, stated that trioctanoin exposure by the usual routes (i.e., oral and i.v.) causes no damage to the liver. It was his opinion that there would be no adverse effects on tissue in the airways and lungs.

Glyceryl Trioleate (triolein)

Triolein is a major component of many vegetable and seed oils. It is a triester of glycerol and oleic acid, which is an 18-carbon straight-chain molecule with a double bond between the ninth and tenth carbon atoms. There is no data suggesting that triolein would cause any adverse effects. It does undergo a slow oxidation at the double bond at ambient temperature in the presence of air. This oxidation produces a gummy or resinous product that can result in clogging.

Glycerol

Glycerol is a water soluble, hygroscopic liquid that is a component of many naturally occurring vegetable oils including the two discussed above. Glycerol is metabolized as a food, has a pleasant taste, and is not irritating to the skin. One possible adverse effect of the substance was reported by Tyson Tilden of the University of Maryland Medical School. For those rare individuals who lack the enzyme glycerol kinase, glycerol is a neurotoxin. Our estimated maximum body load of 35 mg was of concern to Tilden. He suggested that the local instantaneous concentration at the cellular level in the lung could be high enough to cause problems for susceptible individuals. He indicated that there would be no problems for normal individuals.

While glycerol may be relatively safe, its hygroscopic nature is undesirable for a test aerosol. Also, the high viscosity of glycerol may affect the performance of an aerosol generator using this liquid.

Oleic acid

Oleic acid is a major component of olive oil, which has been used as a control substance for many studies involving the exposure of mice and rats by i.v., i.p., subcutaneous, and oral routes. According to Elizabeth Weisburger of the National Cancer Institute, no problems have arisen that were attributed to olive oil. However, no inhalation studies have been made.

While oleic acid is not reported to be harmful, the methyl ester (methyl oleate) is reported to be an experimental tumorigenic agent [6,7].

Di(2-Ethylhexyl)Phthalate, (Dioctyl Phthalate)

Krauskop [8] reported that dialkyl phthalates are relatively harmless by ingestion. The LD50 for rats by oral exposure is reported as about 30 g/kg by Patty [9]. Timofievskaya et al [10] conclude that dioctyl phthalate is non-toxic and nonirritant when inhaled or topically applied. In studies with mice and rats sponsored by the National Toxicology Program, dioctyl phthalate was found to be a confirmed carcinogen [11]. Therefore, it seems prudent to eliminate dioctyl phthalate from the list of candidate aerosol liquids.

Di(2-Ethylhexyl) Sebacate, (Dioctyl Sebacate)

Both dioctyl phthalate and dioctyl sebacate are widely used as plasticizers. Dioctyl sebacate has a low level of toxicity by oral, intravenous, and inhalation routes for various test animals [12]. There is no direct indication that it may be a carcinogen. It is currently being studied

as part of the 1983 FY study program for the National Toxicology Program. There is, however, indirect evidence that it may be a carcinogen. It has been reported that 2-ethyl-1-hexanol is a mutagen for certain Salmonela bacterial strains. It is thought that the carcinogenic behavior of di(2-ethylhexyl) phthalate and of di(2-ethyhexyl)adysate arises from the alcohol part of the molecule. Dioctyl sebacate has the same alcohol group, and thus one suspects that it will also turn out to be carcinogenic.

Another undesirable feature of dioctyl sebacate was that the Cadema nebulizers are attacked by dioctyl sebacate.

Corn Oil

No toxicity data were found for corn oil. One objection to corn oil is its susceptibility to air oxidation. The buildup of rancid oil in the plumbing of the fit test apparatus will necessitate cleaning. The fact that corn oil is not a pure compound is another disadvantage, since its properties may depend on the source or even the batch for a particular source.

Mineral Oil

Mineral oil is used as a carrier for oral ingested medicines. However, in the form of a mist at high concentration (100 mg/m^3), mineral oil causes permanent changes in the lungs including vacuoles of entrapped oil and oil-containing macrophages [13]. Mineral oil studies gave results that were "suggestive" of a carcinogenic effect [14]. Philip Albro of NIEHS was strongly opposed to use of mineral oil, saying that it is absorbed by the body

in greater extent than heretofore believed, and that it accumulates in the lymph nodes. As with corn oil, mineral oil has the disadvantage that is a mixture of compounds that may vary from one source to another.

Polyethylene glycol

Polyethylene glycol is a water-soluble synthetic polymer that is widely used in various pharmaceutical, food, and cosmetic products. Recent tests [15] indicate that polyethylene glycol may be carcinogenic.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

A quantitative respirator fit test apparatus was developed based on using a light-scattering type smoke detector for the sensing element and a clinical nebulizer for the aerosol source. The performance of three smoke detectors and nine clinical nebulizers considered for use in the final system are reported. Key design features of the apparatus include the generation of a corn oil aerosol concentration of 500 mg/m^3 at a flow rate of 50 ℓ/min and LED display for protection factors of 25, 50, 125, and 450. The total cost of the component parts for the apparatus is less than $300. This apparatus is designed to meet the need for a low cost, easy to use instrument for quantitatively monitoring a respirator's fit to a worker's face.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

corn oil aerosols; face masks; nebulizers; occupational safety; protection factor; quantitative fit test; respirators; smoke detectors

13. AVAILABILITY

☒ Unlimited
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