

A New, Automated Method for Testing Particulate Respirators

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Abstract

We have developed a new system for the automated testing of particulate respirator filters employing a condensation nucleus counter (CNC) for particle detection. Counting efficiencies of up to 99.99999+ % can be measured by using the CNC for aerosol monitoring both upstream and downstream from the respirator. The system also measures flowrate and pressure drop through the filter. The system is sensitive, stable, and automated so as to provide for better confidence. A reproducibility study on high-efficiency filters gave an average filter efficiency of 99.9960% with a standard deviation of 10×10^{-4} . The accuracy gained and reproducibility obtained appear superior to other available testing systems.

Introduction

The purpose of this paper is to describe a new automated method for testing particulate respirator filters and to show its capabilities by presenting data collected by the system. The system described is extremely sensitive and stable for long periods of time. The data analysis microcomputer system controls the testing regime thus assuring consistency and confidence. The data include filter efficiency, flowrate, and graphic display capabilities. The system shows excellent reproducibility with system resolution up to 99.99999+ %.

In the past, the predominant methods for testing respirator efficiencies were gravimetric techniques using silica dust and photometric techniques using DOP aerosols. These methods have some disadvantages. They are time consuming, have limited resolution, and have inherent inaccuracies. In addition, DOP has been implicated as a possible human carcinogen. Thus, more flexible

methods must be developed that allow for the testing of aerosols of various composition and particle size. A respirator filter efficiency test system (FETS), which can be used for virtually any submicron-sized aerosol, has been developed. This system, which gives count percent penetration resolution up to 99.99999+ %, employs a continuous flow condensation nucleus counter (CNC). Previously, a quantitative respirator fit testing system employing a CNC was developed by Willeke et al. (1981). Willeke's results indicated that the CNC system could be used for a variety of aerosols and that it was preferable to the photometer used with DOP aerosols. Further, Willeke noted that although the CNC gave a count efficiency as compared to a light scattering efficiency, the two methods correlated at a ratio of 1.64 with a correlation coefficient of 0.967 over the penetration range of 0 to 8%.

* Mention of company names does not imply endorsement by NIOSH.

An instrumentation system that measures respirator particulate filter efficiencies using a CNC was developed by TSI and supplied to NIOSH. In addition to testing efficiencies, the system measures respirator flowrates and pressure drops. The three parameters are monitored over time to obtain respirator loading data. Up to three respirators can be tested simultaneously and automatically. The instruments are interfaced to a dedicated microcomputer system that monitors, reads, and controls the instruments. Extensive data analysis and presentation is done by the microcomputer system, including cross-correlations between the various tested parameters.

Description of TSI Filter-Efficiency-TestSystem

Condensation Nucleus Counter

The CNC has been previously described by Agarwal and Sem (1980) and is schematically shown in Fig. 1. Its main components are the saturator tube, condensor tube, and sensor.

The availability of a continuous flow single-particle-counting CNC (TSI Model 3020) makes a new method for particulate respirator filter testing possible. The CNC can measure concentrations as high as 10^7 particles/cm³, and when using its

single-particle-counting capability, can measure concentrations down to 10^{-2} particles/cm³. When used to measure the particle concentrations both upstream and downstream of a filter, the CNC's large dynamic range allows count filter efficiencies as high as 99.99999+ % to be measured. By using the CNC, numerous submicron challenge aerosols can be used, and respirators can be tested at low concentrations while still obtaining meaningful results.

A special feature of the CNC is that it has two modes of operation:

I. Count Mode. At concentrations below 1000 particles/cm³, electrical pulses generated by light scattered from individual droplets are counted. The photodetector output signal passes through a noise filter and a Schmit triggering circuit, resulting in a 5-volt pulse for each droplet pulse. The 5-volt pulses are counted for a specified time period and converted to particle concentration, with the specified time period depending on particle concentration to keep statistical count accuracy.

II. Photometric Mode. At particle concentrations above 1000 particles/cm³, the circuit measures the total light scattered from all the droplets present in the viewing volume at any time. The photodetector output passes

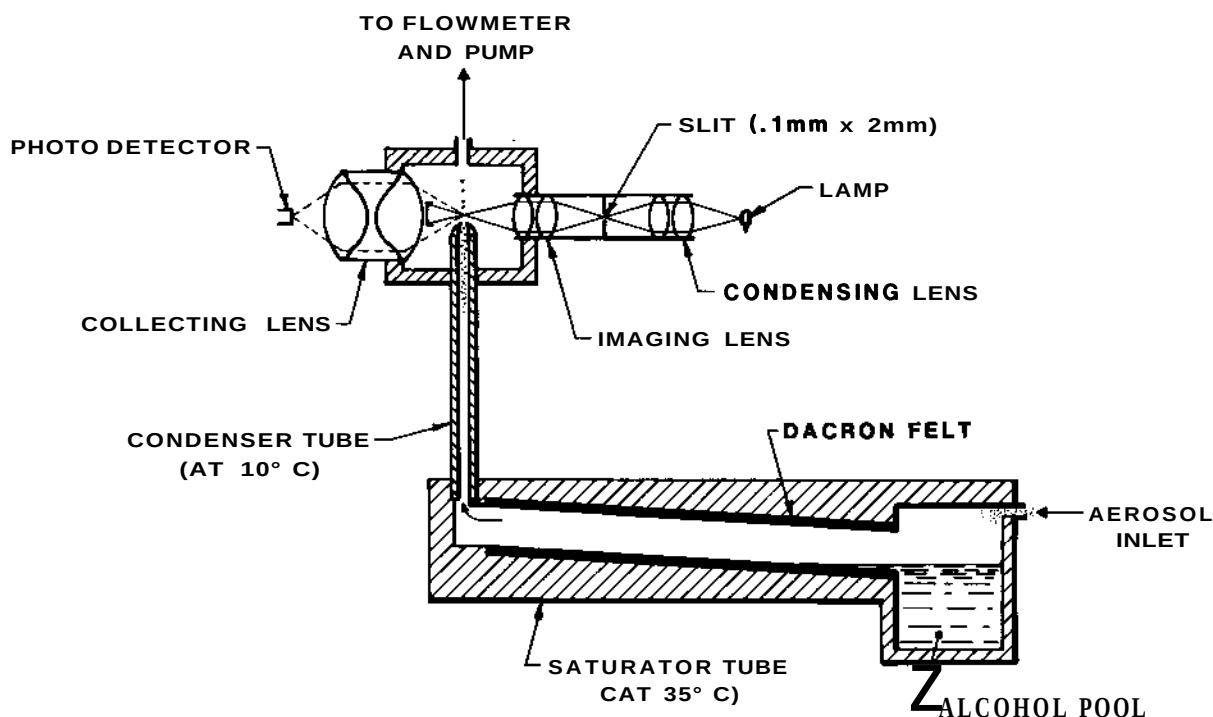


Figure 1. Schematic of condensation nucleus counter.

through an 8-segment linearizer circuit which provides a voltage signal linearly proportional to the particle number concentration (Fig. 2).

Respirator Testing System

Because of the CNC's dynamic range of 10^9 , it is possible to build a respirator testing system that can measure efficiencies much higher than previously possible. Also, due to the sample holder's design either individual filters or a complete respirator can be tested. The basic method used for testing the respirators is shown in Fig. 3. The CNC is used to sequentially measure particle concentrations upstream and downstream of the respirator. A schematic of the complete respirator testing system is shown in Fig. 4.

The flow through the system starts with the stainless steel test chamber. There is an inlet at the

top of the chamber for the challenge aerosol, and an exit at the back of the chamber leading to a high efficiency filter for excess challenge aerosol. There are five ports on the bottom of the chamber. Three are for the filters to be tested, the fourth is for measuring the challenge aerosol concentration, and the fifth is for the differential pressure transducer used to measure the pressure drop across the respirators.

The flow path from each of the three filter sampling ports branches, with one line going to a high efficiency filter, thermal mass flowmeter (TSI Model 2011B), control valve, and vacuum pump. The other line goes to a port on the switching valve (TSI Model 3042). The chamber concentration sampling port also branches, with one line leading to the vacuum pump in the switching valve and the other line leading to the first port on the switching valve. The output of the switching



Figure 2. TSI Model 3020 condensation nucleus counter.

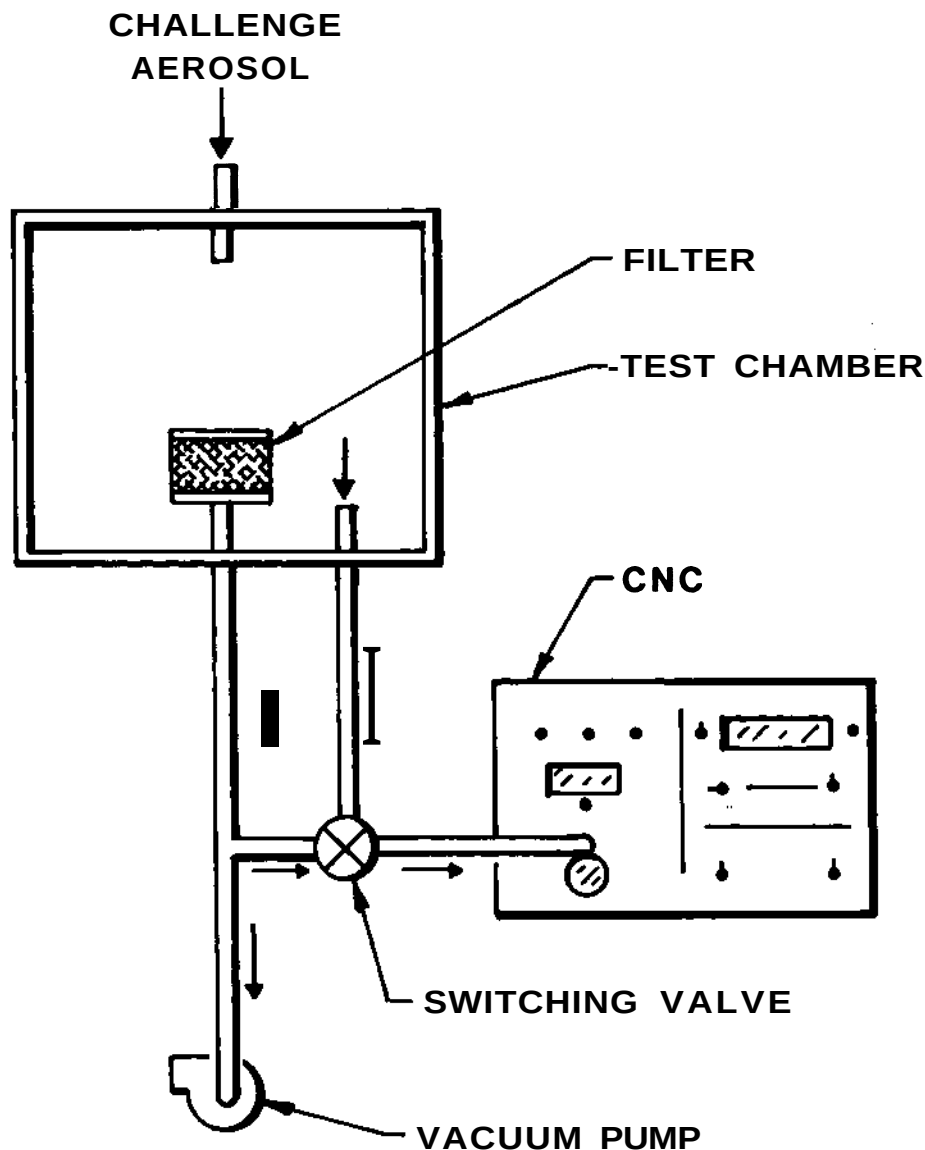


Figure 3. Operating principle of respirator test system.

valve leads to the second side of the pressure transducer and the inlet of the CNC. A photo of the complete respirator testing system is shown in Fig. 5.

Programmable Test Procedure and Data-Analysis System

A microcomputer system controls the respirator tester. The CNC, switching valve, flowmeters, and pressure transducer all interface to the microcomputer system. The microcomputer system consists of an Apple II Plus microcomputer,

Apple Disk II Drive and controller card, IDS Prism 80 Printer, Grappler printer interface card, Zenith video monitor, California Computer Systems A/D card and real-time clock card, and a 16K memory card for additional memory. In addition, special control electronics were designed and built for the system. The microcomputer system programs and controls the test procedure. The microcomputer system controls the switching valve and reads the CNC, flowmeters, and pressure transducer outputs, along with keeping track of time. The computer does extensive data analysis, including cross-correlations between the various tested parameters. Automatic sampling over time periods

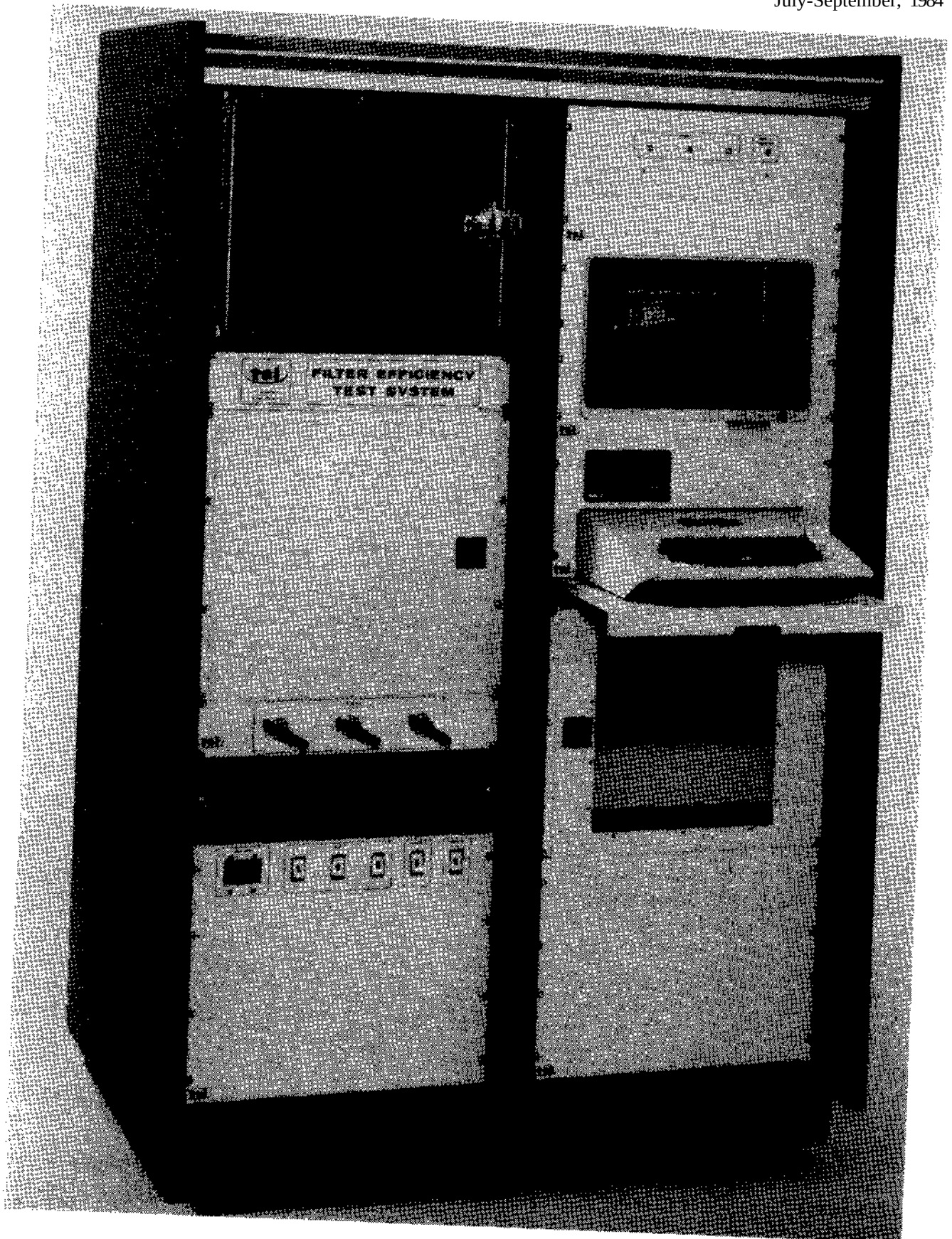


Figure 5. TSI filter efficiency test system.

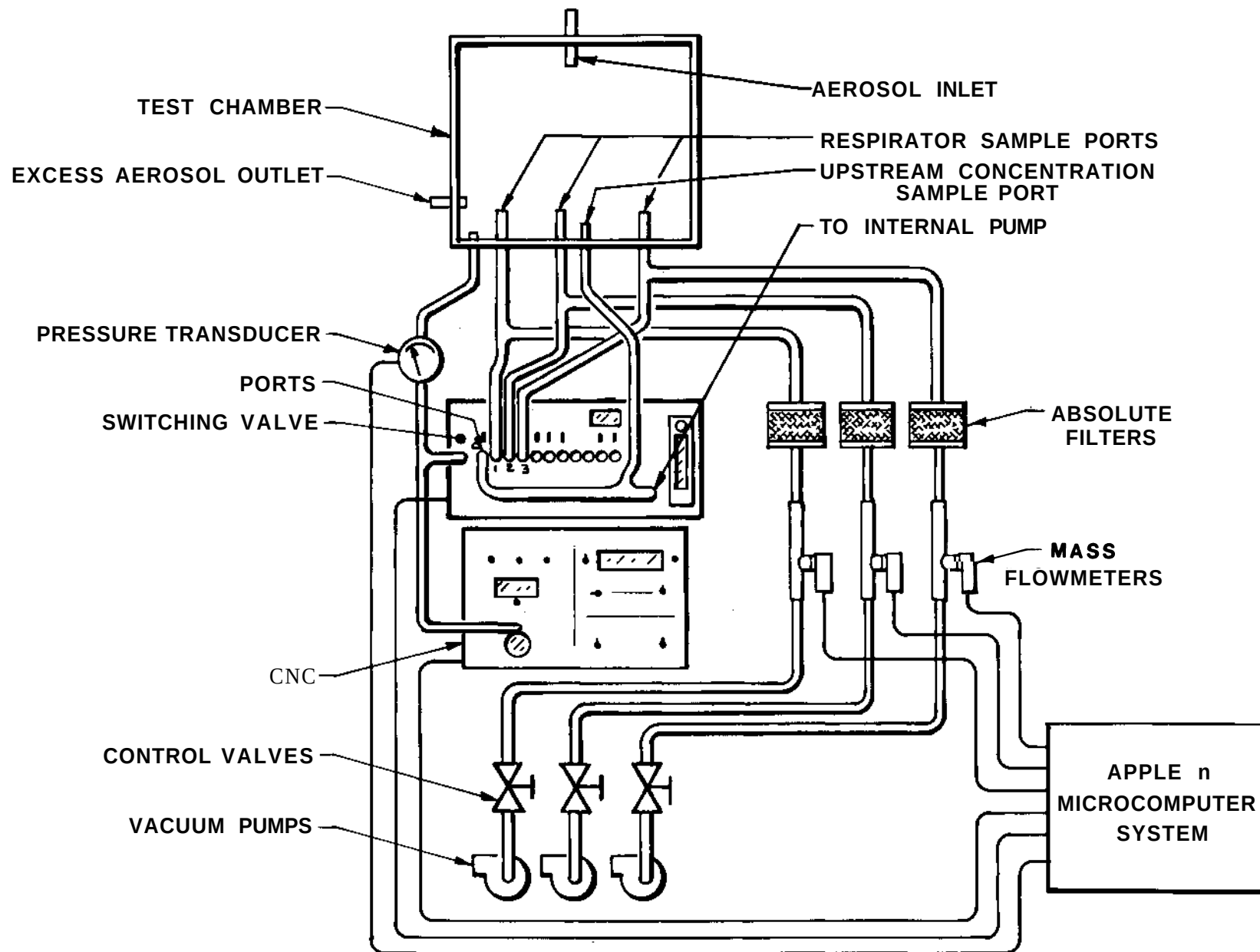


Figure 4. Schematic of TSI filter efficiency test system.

as long as 6-1/2 days is possible using the micro-computer system.

Experimental Procedure

The TSI filter efficiency test system was evaluated against commercially available high-efficiency filters to determine the instrument's reproducibility. Also, some work was done to determine whether this instrument was sensitive enough to monitor small changes in penetration as a function of flowrate. The filters employed were certified filters recommended for use against dusts, fumes, mists, and radionuclides and had efficiencies of greater than 99.97% (DOP). These filters were selected in an effort to minimize variation among test filters.

The challenge aerosol was sodium chloride and was generated with a model AP-6310G NaCl aerosol generator manufactured by Sibata Science Technology Ltd. This generator supplies airborne particles by atomizing a 10% NaCl distilled water

solution into a mist, dispersing the mist, and subsequently drying the particles. Contained within the instrument is a mist classifying impactor stage (3-mm spacing) that regulates the aerosol's size and distribution. Finally, the aerosol was passed through a krypton-85 radioactive source (TSI Model 3054) to neutralize the aerosol.

A single lot of a commercially available high efficiency filter was tested in this study over a period of one month. The filters were challenged with the NaCl aerosol for durations of up to 90 minutes. A continuous flow of 16, 42.5, or 85 l/min was employed for a single filter cartridge, and the sampling was automatically performed periodically according to the sampling scheme.

The aerosol size and size distribution were determined with a TSI Model 3030 electrical aerosol size analyzer according to the procedures of Liu et al. (1974, 1975). The sampling was performed at the point of entrance into the aerosol chamber compartment of the FETS. The NaCl aerosol size ranged from a count mean diameter of 0.058 to 0.074 μm with a geometric standard deviation of less than 1.77.

Results and Discussion

The results from this study showed that all filters had an efficiency of greater than 99.97% when tested against the NaCl challenge aerosol at the various flowrates. Some of the typical test data obtained during a reproducibility study at 85 l/min is shown in Fig. 6. As can be seen from this printout, the microcomputer keeps track of the chamber concentration, concentration downstream of each respirator, time of day and date, flowrate, pressure drop, respirator efficiency, and penetration.

The FETS includes graphics capabilities. Plots of the various parameters versus time and cross-correlations between pressure and flowrate, efficiency and flowrate, efficiency and pressure drop, penetration and flowrate, and penetration and pressure drop are possible. Graphics of test data are presented in Figs. 7 through 11. Figure 7 shows a plot of the chamber concentration versus time; Fig. 8 shows flowrate versus time for filter #3; Fig. 9 shows pressure drop versus time for filter #3; Fig. 10 shows the percent penetration versus time for filter #1; Fig. 11 shows the percent efficiency versus time for filter #1. It can be easily seen for this high-efficiency filter that as the filter

loads, the filter's efficiency improves but the pressure drop across the filter increases.

The data from a reproducibility study at 85 l/min flowrate confirmed that this test system is capable of monitoring filter efficiencies with great precision. In fact, by employing the CNC for aerosol concentration measurements upstream and downstream of the respirator, efficiencies of 99.99999+ % can be measured with great reproducibility as shown in Table 1, where the results for 19 filters from the same lot are presented. Table 1 also shows the means and standard deviations for the percent penetration and the percent efficiency.

The standard deviation as noted in Table 1 is 10×10^{-4} for the percent penetration and efficiency. Alternatively, one could calculate the relative standard deviation for the penetration to be 25%. It must be noted, however, that these variabilities are a maximum or upper limit and constitute the total variability, which consists of two parts. The first is that induced by the instrumental variation and the second arises from filter to filter variability. Unfortunately, these two are not separable.

TSI FILTER EFFICIENCY TEST SYSTEM

TEST START TIME 14:37 03

TUESDAY

05 / 31 / 83

FILTER #1:

FILTER #2:

FILTER #3:

	TIME (MIN)	CHAMBER CONC (#/CC)		FLOW (L/MIN)	DELTA P (IN H2O)	FILTER CONC (#/CC)	PENE. (%)	EFFIC (%)
1	0:00	1604500	1	86.35	1.391	59.825	0.003728	99.996272
			2	83.64	1.659	76.565	0.004771	99.995229
			3	83.60	1.651	63.0775	0.003931	99.996069
3	0:12	1280500	1	85.65	1.416	44.47	0.003472	99.996528
			2	83.46	1.682	44.895	0.003506	99.996494
			3	83.41	1.674	37.185	0.002903	99.997097
5	0:24	1323000	1	85.31	1.440	39.065	0.002952	99.997048
			2	83.64	1.709	37.175	0.002809	99.997191
			3	83.41	1.711	37.6525	0.002845	99.997155
7	0:36	2473000	1	84.12	1.475	26.42	0.001068	99.998932
			2	83.64	1.747	26.8475	0.001085	99.998915
			3	83.23	1.757	19.0825	0.000771	99.999229
9	0:48	1429000	1	84.12	1.507	18.875	0.001320	99.99868
			2	83.64	1.784	19.11	0.001337	99.998663
			3	83.41	1.804	15.03	0.001051	99.998949
11	1:00	1328000	1	84.12	1.545	11.1925	0.000842	99.999158
			2	83.64	1.829	15.7325	0.001184	99.998816
			3	83.41	1.854	9.2825	0.000698	99.999302
13	1:12	2033000	1	86.00	1.575	9.112500	0.000448	99.999552
			2	83.46	1.890	21.3225	0.001048	99.998952
			3	83.23	1.907	5.207	0.000256	99.999744

Figure 6. TSI filter efficiency test-system data sheet.

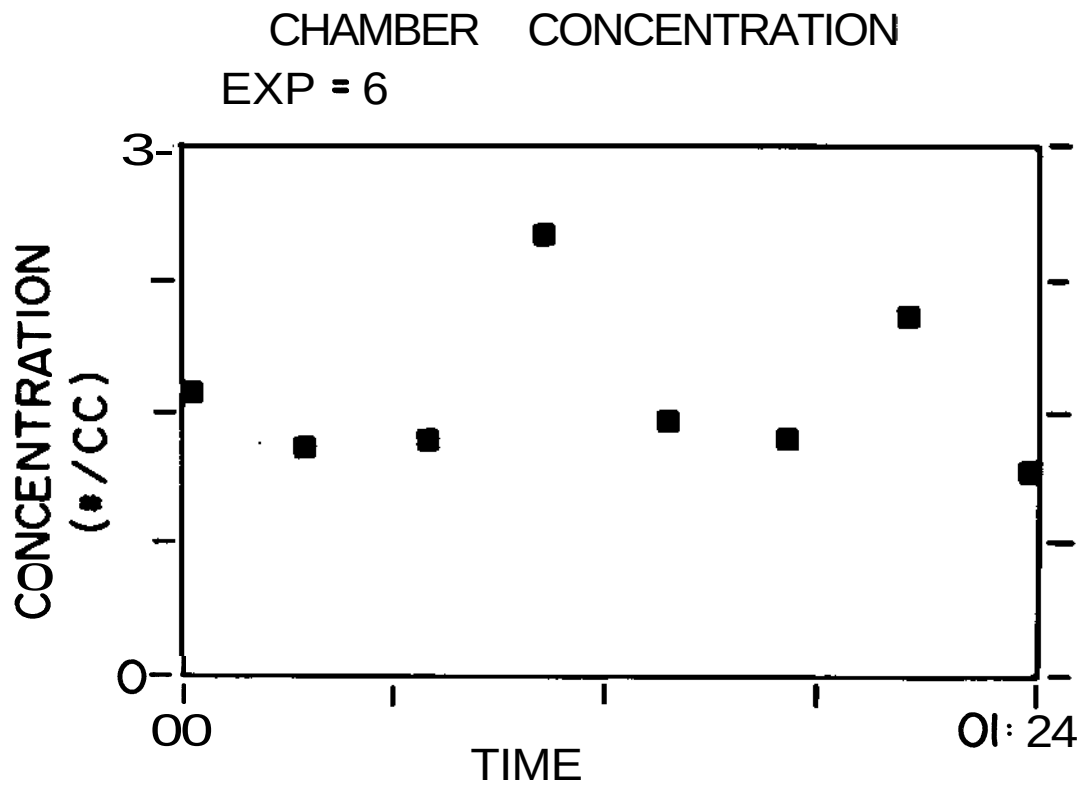


Figure 7. Plot of chamber concentration versus time.

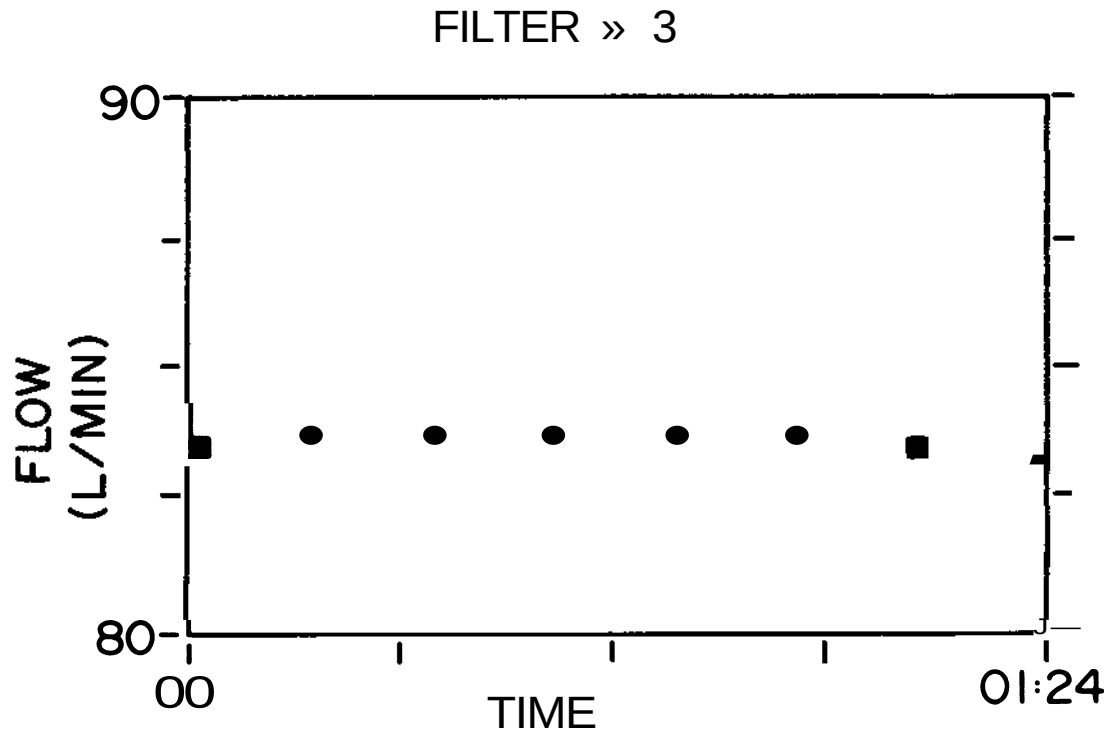


Figure 8. Plot of flowrate versus time for filter #3.

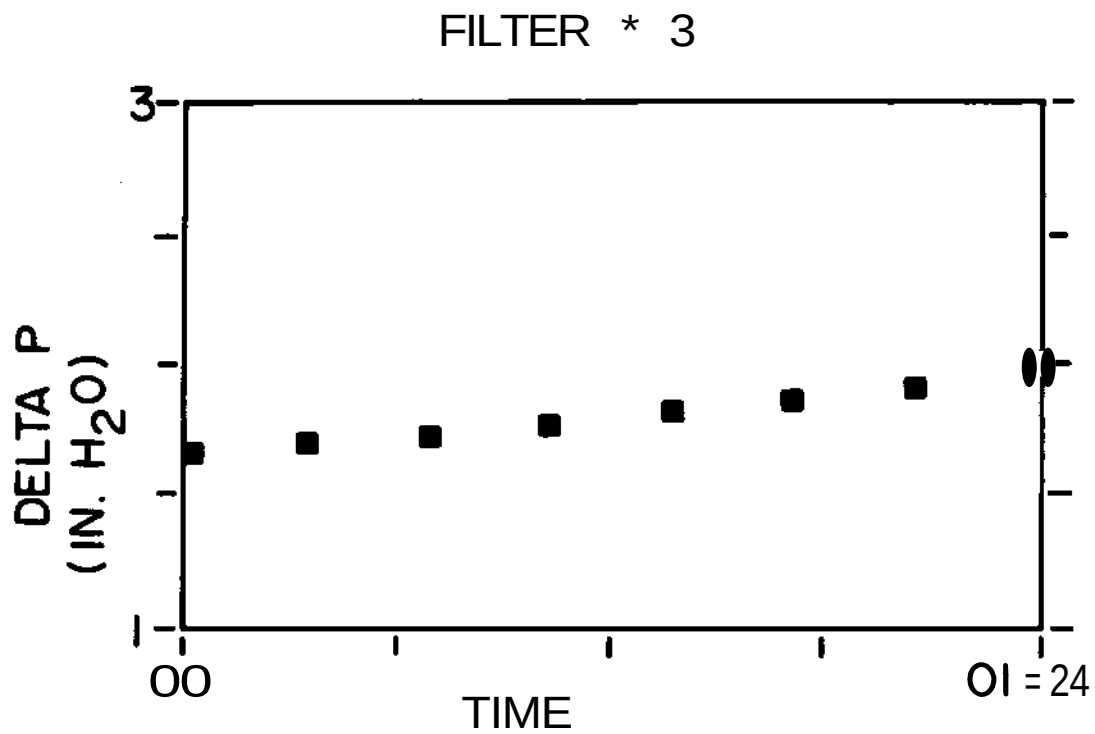


Figure 9. Plot of pressure drop versus time for filter #3.

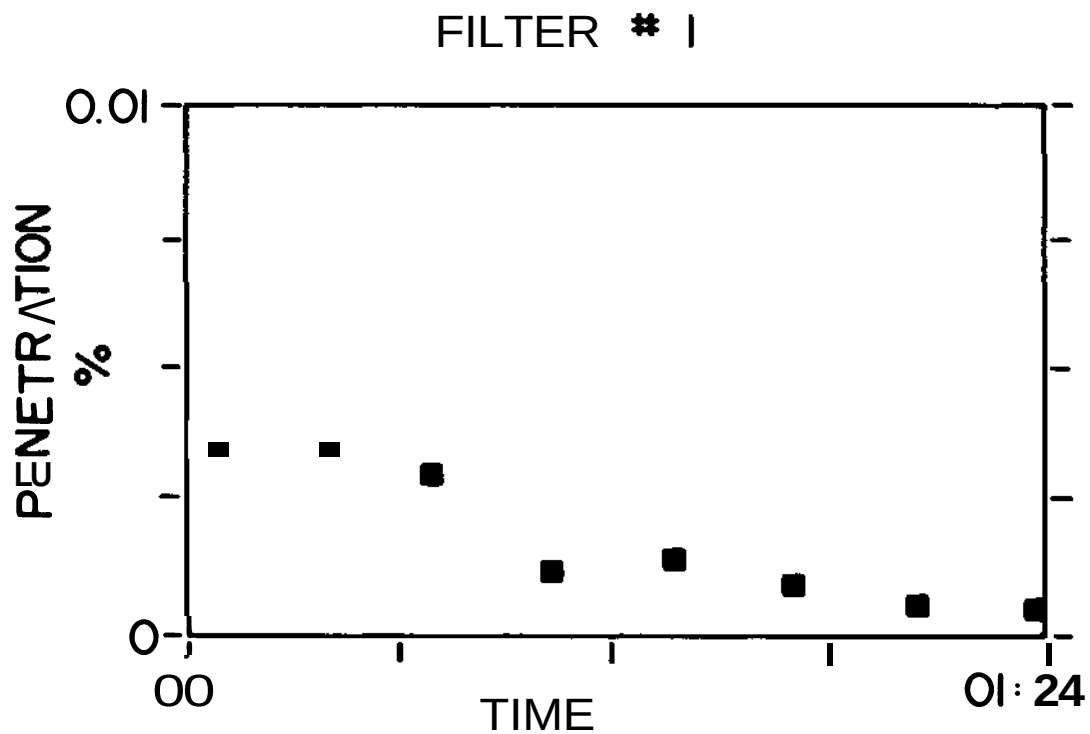


Figure 10. Plot of percent penetration versus time for filter #1.

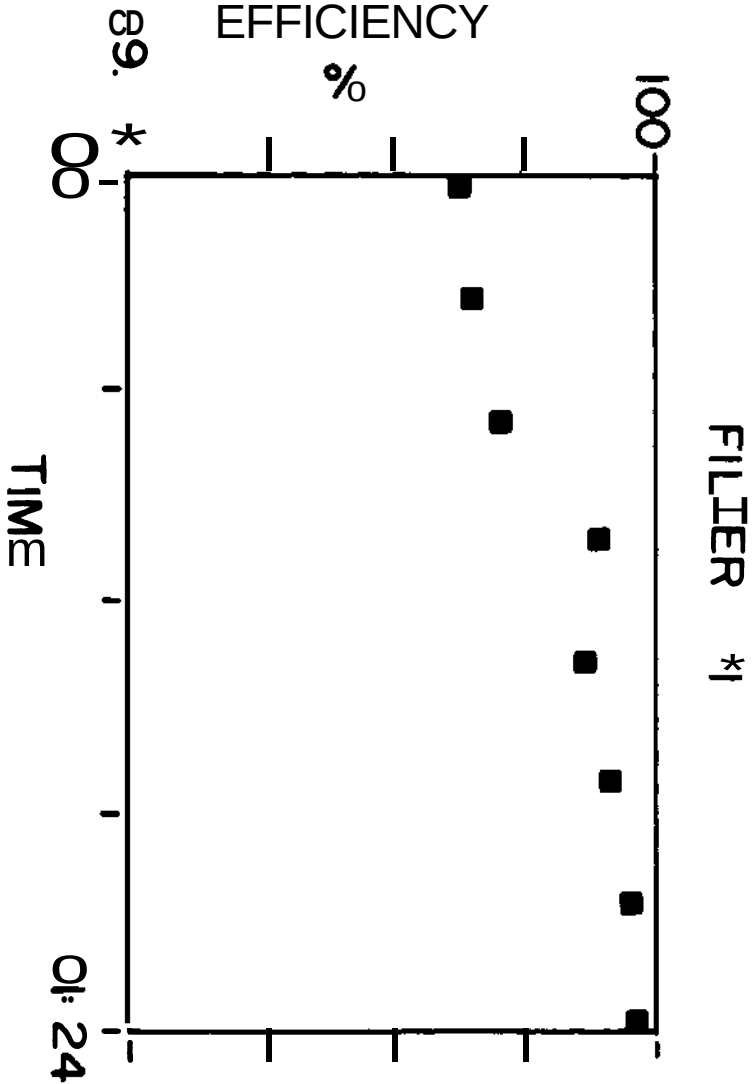


Figure 22. Plot of Filtration efficiency versus time for filter #2.

Table 1. Reproducibility study of high-efficiency filters at 85 l/min flow rate.

Sample No.	Chamber con. (#/cc)	Flow (l/min)	Δ P (in. H ₂ N	Downstream		Penetration (%)	Efficiency
				filter conc. (#/cc)			
1	248800	84.79	1.407	232.53	53.06 × 10 ⁻⁴	88.894384	
2	249800	84.83	1.406	201.03	40.45 × 10 ⁻⁴	88.888885	
3	249800	84.13	1.326	104.6	45.85 × 10 ⁻⁴	88.885895	
4	3476500	84.43	1.394	76.03	22.82 × 10 ⁻⁴	88.887798	
5	3476500	84.35	1.376	82.225	23.36 × 10 ⁻⁴	88.887664	
6	3476500	84.13	1.446	83.1123	3.90 × 10 ⁻⁴	88.887632	
7	1020300	83.4*	1.363	38.1723	37.40 × 10 ⁻⁴	88.88626	
8	1020300	83.82	1.04	63.275	62.00 × 10 ⁻⁴	88.8838	
9	1020500	83.78	1.410	38.2375	38.33 × 10 ⁻⁴	88.886183	
10	1171500	87.04	1.526	56.8175	48.48 × 10 ⁻⁴	89.885251	
11	1171500	84.00	1.495	48.255	39.48 × 10 ⁻⁴	98.886052	
12	1171500	83.97	1.402	48.9075	42.60 × 10 ⁻⁴	88.88574	
13	1604500	86.35	1.391	59.825	37.28 × 10 ⁻⁴	88.886272	
14	1604500	83.84	1.656	76.565	47.71 × 10 ⁻⁴	88.885229	
15	1604500	83.80	1.624	63.0775	9.31 × 10 ⁻⁴	88.886069	
16	1881000	83.29	1.430	83.825	2.31 × 10 ⁻⁴	88.990768	
17	1981000	83.87	1.480	85.3075	3.06 × 10 ⁻⁴	99.985692	
18	2378000	83.07	1.411	116.5	8.99 × 10 ⁻⁴	89.985101	
19	2633000	83.45	1.492	90.37750	34.32 × 10 ⁻⁴	89.986568	

1.780

Standard deviation

40 × 10⁻⁴

10 × 10⁻⁴

99.985

10 × 10⁻⁴

Table 2. Filter efficiency as a function of flowrate for high-efficiency filters.

Filter sample No.	Chamber conc. (#/cc)	Flow (l/min)	A P (in. H ₂ O)	Downstream filter conc. (#/cc)	Penetration (%)	Efficiency (%)
1	3287500	16.29	0.2239	0.355	1.0 X 10 ⁻⁵	99.99999
2	3287500	16.22	0.2214	0.2905	0.08 X 10 ⁻⁵	99.999992
3	2633000	16.29	0.2189	0.6495	2.40 X 10 ⁻⁵	99.999976
4	3903000	41.92	0.6155	31.87	8.167 X 10 ⁻⁴	99.999184
5	3903000	41.53	0.6338	25.29	6.47 X 10 ⁻⁴	99.999353
6	2378000	42.35	0.6220	19	7.98 X 10 ⁻⁴	99.999202
7	2633000	42.25	0.6347	0.5685	0.21 X 10 ⁻⁴	99.999979

Table 2 presents the data obtained at flowrates of 16 l/min and 42.5 l/min through the same single filters. Table 3 summarizes this data. As can be seen, the efficiencies increase as the flowrate is reduced, with the order of magnitude of the penetration changing. This is what one would expect for this type of filter. Data of this type is easily obtainable with the TSI FETS due to its reliable flow adjustment capabilities and enhanced sensitivity over other detectors. It should be noted that these filters have an efficiency significantly greater than 99.97% for the NaCl challenge aerosol even at a flowrate of 85 l/min, which is much higher than the flows used for certifying these filters when tested with DOR. However, it is extremely important to remember

that the TSI FETS gives a number concentration efficiency whereas the DOP instrument's output is a function of the amount of light scattered by the aerosol. For this reason, the efficiencies are not directly comparable, but require extensive correlative procedures.

Table 3. Summary of filter efficiency data as a function of flowrate.

Flow (l/min)	Mean penetration	Mean efficiency
16	0.000014	99.999986
42.5	0.000570	99.999429
85	0.004037	99.995963

Conclusions

A new system has been developed for the automated testing of particulate respirator filters using a CNC for the particle detector. By using a CNC for the aerosol measurements upstream and downstream of the respirator, count efficiencies up to 99.99999+ % can be measured. Along with measuring efficiencies, the system measures flowrate and pressure drop. The system can measure three intact respirators or the respirator filters simultaneously. Any challenge aerosol can be used, and respirators can be tested at low challenge aerosol concentrations while still obtaining

meaningful results. The system is sensitive, stable, and automated so as to provide for better confidence. It is envisioned that the TSI filter efficiency test system could be routinely employed for the quality control of filter media as well as research applications due to its enhanced sensitivity and versatility. Also, since this system allows for the continual monitoring of the percent of penetration with time, one gains added valuable information regarding filter loading and its ultimate effect on aerosol penetration.

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