Section 3

Evaluation of the Effectiveness of Air-Purifying Respirator Cartridges in Removing MDI Aerosols from Air

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SUMMARY

Respirator cartridge efficiency tests were conducted with four models of respirator cartridge using laboratory-generated test atmospheres containing diphenyl methane-4,4'-diisocyanate (MDI). The respirator cartridge models were the Cabot/AO R51A (organic vapor), Cabot/AO R91A (organic vapor/ dust, mist filter), Cabot/AO R51HE (organic vapor/ high efficiency filter), and 3M 6001/5010 (organic vapor/ dust, mist filter). The MDI test atmospheres were generated using both spray- and condensation-aerosol formation techniques. MDI concentrations covered the range of 48-9000 µg/m^3 and aerosol particle size (MMAD) was within the range of 0.9-2.5 µm. The test results led to the following conclusions:

- Organic vapor cartridges without a particulate filter were not effective at removing MDI aerosols from air (34% mean removal efficiency for predominantly aerosol atmospheres, 330-9000 µg/m^3; 81% mean removal efficiency for predominantly vapor atmospheres, 48-63 µg/m^3).
- Organic vapor cartridges with dust/mist (DM) or high efficiency (HEPA) filters effectively removed greater than 99% of MDI aerosol and vapor in all test atmospheres.
- Formation of MDI aerosols was evident even at very low (<100 µg/m^3) total MDI concentrations.

INTRODUCTION

Respiratory protection is often used to control inhalation exposures to diisocyanates. Appropriate respiratory protection may consist of an air-supplying respirator or, in certain situations, an air purifying respirator. Ideally, an air-purifying respirator with an end-of-service-life indicator (ESLI) should be used, but none currently exist. One of the pieces of information necessary in supporting both the use of air-purifying respirators in appropriate situations and the development of an appropriate ESLI is data demonstrating the ability of the air-purifying element (cartridge, canister, or filter) to remove the diisocyanate from air. For 2,4-toluenediisocyanate (TDI), such data has been published[1], but for diphenyl methane-4,4'-diisocyanate (MDI) the data do not exist. Further, the MDI case is complicated by the fact that MDI is likely to be present in both aerosol and vapor form in the air. Because of this, an organic vapor cartridge in combination with a particulate filter would be the best candidate air purifying element; data is needed to verify that this combination does effectively trap MDI in both vapor and aerosol forms and to establish the level of effectiveness of an organic vapor cartridge without a filter in trapping MDI aerosol.

EXPERIMENTAL

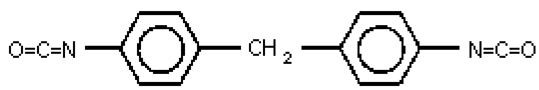
TEST SUBSTANCES

The test substances for this study were polymeric MDI (CAS Registry Number 9016-87-9) and 4,4'-MDI (CAS Registry Number 101-68-8). The analyte of interest for both test substances was 4,4'-MDI.

The polymeric MDI (PAPI* 27) was obtained from The Dow Chemical Company, Freeport, TX (lot 95923). The polymeric MDI test substance was determined[2] to be within product specifications of 40-50% 4,4'-MDI.

The 4,4'-MDI test substance was obtained from Eastman Kodak Company, Rochester, NY. (lot 32377340). The purity was determined[3] to be 98.2%.

The structure of 4,4'-MDI is given below:



Molecular Weight: 250.26

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TEST CARTRIDGES

The respirator cartridges tested are described in Table 1. All of the cartridges are for twin-cartridge, full- or half-face air-purifying respirators that are NIOSH-certified and commercially available in the United States. The cartridge models were chosen to provide both commonly used examples from a variety of manufacturers and a series of types from one product line to evaluate any differences in effectiveness between dust/mist filters, high-efficiency (HEPA) filters, and organic vapor cartridges without filters. The cartridges were obtained from S&E Industrial Supply Company, Inc., Midland MI and were tested as received from the vendor.

TEST APPARATUS AND METHODS

Cartridge Exposure Chamber

Respirator cartridges were exposed to test atmospheres of MDI in air using a 1-m^3 inhalation toxicology exposure chamber constructed of stainless steel and Teflon-lined glass (Figure 1). The test atmosphere from the aerosol generator (described below) was drawn through the chamber using an exhaust blower. The total flow through the chamber was adjusted to approximately 200 L/min using a balancing valve on the exhaust. Stainless steel access tubes (1" diameter) built into the bottom and sidewalls of the chamber were used as sampling ports for the test atmosphere. HEPA-filtered laboratory air was used as the makeup feed to the entrance of the chamber; the temperature and relative humidity (RH) ranged from 20-23°C and 40-60 %RH, respectively.

Test Atmosphere Generation - Spray Aerosol Technique

High concentration test atmospheres containing MDI aerosol were generated from polymeric MDI (liquid) and dry, compressed air using a Schlick model 970 two-component spray nozzle (Orthos, Inc., Schaumburg, IL). The resultant aerosol was passed through a cyclone to reduce the quantity of particles greater than 10 µm and was then diluted with make-up air to the concentration of 5,000-9,000 µg/m^3 (equivalent to 490-880 ppb) 4,4'-MDI as it entered the chamber.

Test Atmosphere Generation - Condensation Aerosol Technique

Lower concentration test atmospheres containing MDI aerosol were generated from 4,4'-MDI (solid) using a High Capacity Condensation Aerosol Generator (In-Tox Products, Inc., Albuquerque, NM). The condensation aerosol generator (Figure 2) operates by heating a sample of the solid MDI in a glass boat to produce a vapor atmosphere at elevated temperature (75-130°C), then cooling the atmosphere with dilution streams to initiate condensation. The resultant aerosol was then diluted to the chamber concentration of 40-1200 µg/m^3 (equivalent to 39-120 ppb) 4,4'-MDI with make-up air as it entered the chamber.

Test Atmosphere Characterization - MDI Concentration

The concentration of MDI in the chamber test atmosphere was evaluated using several techniques. For the high concentration (spray generation) studies, gravimetric measurements of total aerosol concentration as well as chemical (derivatization) analyses of 4,4'-MDI concentration were made. For the lower concentration (condensation aerosol generation) studies, only chemical analyses were conducted and a direct-reading isocyanate monitor was used for real-time observations of concentration changes.

Chemical Analysis Method

The atmosphere was monitored for 4,4'-MDI using an adaptation of OSHA Method 47[4, 5]. The method involved drawing air through a glass fiber filter which had been coated with an amine to derivatize the MDI to a stable urea. The urea was subsequently desorbed from the filter and analyzed by high performance liquid chromatography with ultra violet detection (HPLC/UV). The amine used was 1,2-pyridyl piperazine (1,2-PP; CAS [34803-66-2], obtained from Aldrich Chemical Co., Milwaukee, WI). Diethyl phthalate (DEP; CAS [84-66-2], obtained from Aldrich Chemical Co., Milwaukee, WI) was also included in the filter coating to enhance the derivatization of MDI aerosols. Glass fiber filters (Type AE, Gelman, Inc., Ann Arbor, MI) in 13-mm, 37-mm and 47-mm sizes were used for various types of sampling. The filters were coated by adding aliquots of a stock solution of 1,2-PP and DEP in acetonitrile to the filter and letting it air-dry. The 13-mm filters (P/N 66073, Gelman, Inc., Ann Arbor, MI) were coated with ≈2 mg of 1,2-PP and ≈5 mg of DEP; the other filter sizes were loaded similarly in proportion to their respective surface areas.

Following sampling, the filters were desorbed in 5-10 mL (depending on filter size) of a solution of $\approx 2 \times 10^{-5}$ M 1,2-PP in acetonitrile. Aliquots of the desorbed sample solution were analyzed by HPLC/UV. Details of the analytical conditions are given below:

Column:	YMC Basic; 250 mm × 4.6 mm i.d. stainless steel, 5 µm particle size (YMC Inc., Wilmington NC)
Eluent:	Acetonitrile: 0.1N ammonium acetate (pH adjusted to 6.0), 1:1 v/v; 2 mL/min
Injection Size:	20-25 µL
Detection:	UV, 254 nm, range = 0.0001
Quantitation Limit:	0.1 µg 4,4'-MDI per mL of desorbed sample solution

High Concentration (Spray Generation) Studies

Gravimetric measurements of total aerosol concentration were made using 47-mm diameter, 0.45-µm pore size, Teflon filters (Gelman, Inc., Ann Arbor, MI). The filters were preweighed, placed in a stainless-steel housing which had a 1/4"o.d. × 30" copper probe attached to the inlet of the housing. The probe was placed through the sampling port in the bottom of the chamber and chamber air was drawn through at a rate of approximately 30 mL/min for periods of 100-400 minutes using a battery-operated personal sampling pump (Model 224, SKC Inc., Pittsburgh, PA). Following sampling, the filters were re-weighed using a microbalance (Mettler, Inc.).

Using a similar housing and probe, total 4,4'-MDI concentration (vapor + aerosol) measurements were made with the chemical derivatization analysis method during the high concentration runs. A 37-mm glass fiber filter coated with 1,2-PP (≈16 mg) and DEP (≈44 mg) was used to sample the atmosphere at 30 mL/min for periods of 100-400 minutes. The filters were desorbed and analyzed as described earlier.

Low Concentration (Condensation Aerosol Generation) Studies

Total 4,4'-MDI concentration in the test chamber atmosphere was determined using the chemical derivatization analysis method described earlier with 13-mm filters held in a polypropylene syringe filter housing (P/N SX00-013-00, Millipore Corp., Bedford, MA). Air was sampled at a flow rate of 1 L/min using a battery-operated personal sampling pump (Model 224, SKC Inc., Pittsburgh, PA). This technique was preferable for the low concentration studies because the extra capacity of the 37-mm filters was not needed and the small size of the 13-mm filter housing allowed its introduction directly to the chamber through the sample ports, eliminating the need for a sampling probe.

Real-time monitoring of the chamber MDI concentration was also conducted for the lower concentration studies using a paper-tape direct reading instrument (MDI AutoStep, GMD Systems, Inc., Hendersonville, PA). The instrument was used with a Teflon sample probe (1/4" o.d. × 30") attached which was inserted through the chamber sample port. The instrument readings were not used as definitive, but only to monitor changes in the chamber atmosphere and to make adjustments in the condensation aerosol generator.

Test Atmosphere Characterization - Particle Size Distribution

High Concentration (Spray Generation) Studies

Particle size distribution was characterized in the high concentration studies using a seven-stage Marple cascade impactor (Model 266, Anderson, Inc). The first six stages consisted of uncoated 1" glass plates while the last stage was a 47-mm glass fiber filter which had been coated with 1,2-PP (≈26 mg) and DEP (≈72 mg). The impactor was connected to the chamber for sampling through a port on the bottom of the chamber (Figure 1). Following sampling, the seven stages were desorbed and analyzed for 4,4'-MDI as described earlier. The MDI analysis data for each stage was then treated with a probit analysis technique to yield the mass median aerodynamic diameter (MMAD) for the test atmosphere.

Low Concentration (Condensation Aerosol Generation) Studies

Since the particle size for the condensation aerosol atmosphere used in the low concentration experiments was anticipated to be smaller, an annular diffusional denuder (ADD; Model URG-2000, URG Corp., Carrboro, NC) was employed for characterizing the MDI particle size distribution. The ADD and its use in characterizing particulate atmospheres has been described in detail elsewhere[6]. Basically, the ADD consists of a cyclone with a 2.5 µm cut-point, followed by a 2-section frosted glass tubular annulus which was coated with 1,2-PP, followed in turn by two 37-mm 1,2-PP-/DEP-coated filters in series contained in a filter housing (Figure 3). The ADD was connected to the bottom port of the chamber for sampling; air was sampled at a flow rate of 3

L/min using a battery-operated personal sampling pump (Model 224, SKC Inc., Pittsburgh, PA). Following sampling, the filters were desorbed as described earlier. The cyclone was rinsed with a 2-mL aliquot of the 1,2-PP desorbing solution, followed by duplicate 2-mL acetonitrile rinses and a single 1-mL acetonitrile rinse. All of the rinses were combined for analysis. The glass annulus was rinsed with a 2-mL aliquot of acetonitrile followed by a 3-mL aliquot; the aliquots were combined for analysis. The desorption solutions from the various sampler sections were all analyzed by HPLC/UV as described earlier. The results obtained from the ADD describe the MDI mass distribution in three categories: particles > 2.5 µm (cyclone), particles <2.5 µm (filter) and vapor (glass annulus). An example of ADD sampling results for a low-concentration test atmosphere is shown in Table 2.

Test Cartridge Holder

The test cartridges were mounted on a holder that consisted of three AO/Cabot respirator face piece mounts and one 3M 6000 series bayonet mount attached to a 1' × 1' × 1/2" polyethylene plate. This configuration allowed one replicate of each type of respirator cartridge to be tested simultaneously. The holder was situated inside the chamber and the outlet of each respirator mount was connected by a 3/8" o.d. Teflon tubing to a vacuum manifold outside the chamber which drew the test atmosphere through the cartridge (Figure 1). Each line had a rotameter with a needle valve so that the flow through each cartridge could be controlled at 32 L/min. Each cartridge outlet line had a tee in it outside the chamber through which the breakthrough monitoring samples were taken.

Cartridge Breakthrough Monitoring

The cartridge exit air was monitored for 4,4'-MDI using the chemical derivatization analysis method described earlier with 13-mm filters held in a polypropylene syringe filter housing (P/N SX00-013-00, Millipore Corp., Bedford, MA). Air was sampled at a flow rate of 1 L/min using a battery-operated personal sampling pump (Model 224, SKC Inc., Pittsburgh, PA). The 13-mm filter housing was connected directly to the cartridge line sampling tee in the high concentration experiments.

For the low concentration experiments, a 1/8" o.d. Teflon tube of sufficient length to reach the cartridge outlet ($\approx$2 m) was added to the front of each filter housing. During sampling, this tube was threaded through the sample tee and up the cartridge exit line to the exit port of the respirator. When the samples were desorbed, the front cowling of the filter housing with the attached tube was rinsed with desorbing solution and the rinse was added to the rest of the sample solution.

For the high concentration test runs, cartridge breakthrough sampling was continued for 24h or until 10 µg/m^3 4,4'-MDI was reached in the cartridge exit stream, whichever occurred first. Individual breakthrough samples were taken in consecutive 10-60 minute time periods during the test run. For the low concentration test runs, cartridge exposure was continued for 24h; individual breakthrough samples were taken for several 16-240 minute time periods during the test run.

RESULTS AND DISCUSSION

The summary results are presented and discussed below for the two sets of experiments conducted; high concentration (spray generation) studies and low concentration (condensation aerosol generation) studies. The complete data for all runs is included as Appendix A.

HIGH CONCENTRATION (SPRAY GENERATION) STUDIES

Strategy

Initially, tests were carried out using high concentration test atmospheres generated from sprayed polymeric MDI (as described earlier). Mean 4,4'-MDI concentration in the test atmosphere for the high concentration runs was 7300 µg/m^3 (range: 5300-9000 µg/m^3) while the MMAD was 2.13 µm (range: 1.6-2.4 µm). At this concentration, a very high proportion of MDI aerosol would be expected since the maximum vapor concentration of MDI obtained in laboratory atmosphere generation experiments at 25°C has been reported as about 100 µg/m^3[6].

Cartridge Breakthrough Test Results

The 10 µg/m^3 breakthrough time results for each cartridge are shown in Table 3. The individual cartridge breakthrough sample results, expressed as percent of test atmosphere breaking through the cartridge as a function of elapsed exposure time, are shown in Figures 4 and 5 for the two cartridge types where breakthrough was observed. The organic vapor cartridge (Cabot/AO R51A) showed breakthrough to a level of about 100 µg/m^3 in the first 10-minute cartridge exit stream sample. After 100 minutes of exposure to the test atmosphere, the cartridge exit stream of Cabot/AO R51A had reached a concentration representing 50-80% breakthrough of the test atmosphere. Results for the Cabot/AO R91A organic vapor/dust/mist cartridge showed that 10 µg/m^3 breakthrough was reached after a mean time of 200 min; the maximum breakthrough observed in the 400-min test runs was 3-3.5% of the test atmosphere level. The cartridge with the highest filter efficiency class (HEPA), the Cabot/AO R51HE, as well as the 3M 6001A/5010 showed very low MDI concentrations in the cartridge exit samples; all samples represented MDI breakthrough of <0.08% of the test atmosphere.

Discussion

This initial high concentration testing clearly showed that organic vapor cartridges without a particulate filter were ineffective at removing MDI aerosols. The addition of a dust/mist prefilter improved the cartridge's aerosol removal efficiency considerably, although it appears from the Cabot/AO R91A and 3M 6001A/5010 results that dust/mist filters from different manufacturers may differ in their efficiency with small particles. The HEPA filter/organic vapor combination gave the best MDI aerosol removal performance. These findings are consistent with the particulate test requirements used in the U.S. by the National Institute for Occupational Safety and Health (NIOSH) for approval of respirator cartridges[7]. These requirements ensure a 99% minimum efficiency for dust, mist filters and a 99.97% minimum efficiency for HEPA filters. The presence of aerosols of even smaller particle size than in the present study could further accentuate the efficiency differences between dust, mist and HEPA filters noted here.

LOW CONCENTRATION (CONDENSATION AEROSOL GENERATION) STUDIES

Strategy

After reviewing the results from the initial high-concentration test runs, a new set of experiments was designed to evaluate the performance of the cartridges at the lower MDI concentrations more likely to be encountered in actual workplace situations (approximately 1-10 times the 51 µg/m^3 TLV® for MDI). At these concentrations MDI vapor would form a much larger proportion of the total MDI concentration. As described earlier, a condensation aerosol generator was used with undiluted 4,4'-MDI to produce the test atmosphere; an annular diffusional denuder (ADD) was used to characterize the distribution of particles and vapor. The cascade impactor was also used to characterize particle size in two of the higher-concentration condensation aerosol test runs. The characterization results for the condensation aerosol test runs are summarized in Table 4.

A consideration of the spray-generated test results led to the conclusion that the major mechanism of MDI removal by the cartridge from the test atmosphere was mechanical filtration of the aerosol particles. Unlike vapor diffusion, diffusion of aerosol particles in the short residence time in the cartridge sorbent bed will not lead to the numerous surface interactions necessary for efficient adsorption. Because of this, the time-course of breakthrough (which is important in organic vapor sorption mechanisms of respirator cartridge operation) was considered to be of less importance than determining a 'filtration efficiency' for each cartridge. Therefore, cartridge exit samples were not taken consecutively throughout the test run, as in the earlier spray-generated work, but rather at intervals throughout the test run. The apparent 'breakthrough curve' behavior seen for the Cabot/AO R51A and R91A in the spray runs (see Figures 4 and 5) was suspected to be a result of loss of MDI in the cartridge exit stream to the walls of the lines leading to the sampling filter. This possible source of loss was eliminated in the condensation aerosol runs by the addition of a 1/8" Teflon lead-in tube which was analyzed with the sample (see the Experimental section). The validity of this approach of using a filtration efficiency model rather than a vapor adsorption model for the removal of MDI from air by respirator cartridges is demonstrated by the results for the Cabot/AO R51A shown in Table 5. These results show that the cartridge efficiency (defined as the percent of the test atmosphere concentration removed by the cartridge) was the same in the first exit stream sample (0-15 min exposure time) as in the last sample of the run (1415-1434 min exposure time).

Cartridge Breakthrough Test Results

The results of the test runs (expressed as cartridge efficiency) for the MDI condensation aerosol tests are summarized in Table 6. The results are listed in order of increasing test atmosphere concentration, and can be grouped into two concentration ranges: a range where a significant portion of the MDI concentration would be expected to be vapor and a range where the predominant form of MDI concentration would be expected to be aerosol.

Discussion

The results for the Cabot/AO R51A organic vapor cartridge show much better efficiency in the predominantly vapor test runs (mean efficiency = 81%) when compared to that for the predominantly aerosol runs (mean efficiency = 34%). The fact that approximately 20% of the test atmosphere passes the R51A cartridge even at the low concentrations confirms the ADD data indicating that a sizable portion of the MDI in the test atmosphere was in the aerosol form (see Table 4). The MDI vapor present appears to be adsorbed effectively on the charcoal bed of the respirators since all of the other OV respirators with particulate filters showed efficiencies of 99% or greater. The results also demonstrate the difference in efficiency between the two OV/DM respirators noted in the spray-generated tests; the Cabot/AO R91A showed detectable amounts of MDI in the exit stream in all but the lowest concentration while the 3M 6001/5010 (like the Cabot/AO R51HE OV/HEPA) showed no detectable breakthrough in any of the exit stream samples.

CONCLUSIONS

- Organic vapor cartridges without a particulate filter were not effective at removing MDI aerosols from air (34% mean removal efficiency for predominantly aerosol atmospheres, 330-9000 μg/m^3 ; 81% mean removal efficiency for predominantly vapor atmospheres, 48-63 μg/m^3).
- Organic vapor cartridges with dust/mist (DM) or high efficiency (HEPA) filters effectively removed greater than 99% of MDI aerosol and vapor in all test atmospheres.
- Formation of MDI aerosols was evident even at very low (<100 μg/m^3) total MDI concentrations.

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5. Levine, S. P., et al., Critical Review of Methods of Sampling, Analysis, and Monitoring for TDI and MDI, Am. Ind. Hyg. Assoc. J. 56:585 (1995)
6. Rando, R. J. and H. G. Poovey: Dichotomous Sampling of Vapor and Aerosol of Methylene-bis- (Phenylisocyanate) [MDI] with an Annular Diffusional Denuder, Am. Ind. Hyg. Assoc. J. (55)(8): 716-721 (1994).
7. United States Code of Federal Regulations: 30CFR 11.140 (1972).

Table 1.
Respirator Cartridges Tested Against MDI

Respirator Manufacturer[1]	Cartridge/Filter Model Number(s)	NIOSH/MSHA Approval Type(s)[2]	Lot Number Used
AO/Cabot	R51A cartridge	OV	102791
AO/Cabot	R91A cartridge	OV, DM, Paint	081291
AO/Cabot	R51HE cartridge	OV, HEPA, Paint	93250

Table 2.
Example Annular Diffusional Denuder Results from MDI Condensation Aerosol Test Atmosphere Characterization: Chamber Run 95-5.

ADD Section	Particle Size Interval	μg/m^3 MDI	% in Interval
Cyclone	> 2.5μm	12	2.9
First AD	Vapor	42	10.1
Second AD	Vapor	<0.04	<0.01
First Filter	<2.5μm	360	87.0
Second Filter	<2.5μm	<0.04	<0.01
	Total:	414	100
	Results from 13mm filter sample taken at the same time:	410	

Table 3.
Results of Respirator Cartridge Breakthrough Testing with Spray-Generated MDI Aerosol Test Atmospheres (5300-9000 μg/m^3 (Mean=7300), MMAD = 2.13 μm)

Cartridge	Type[1]	10 μg/m^3 (0.977 ppb) Breakthrough Time (min)
Cabot/AO R51 HE	OV/HEPA	>1440
3M 6001/5010	OV/DM	>1440
Cabot/AO R91A	OV/DM	200
Cabot/AO R51A	OV	<10

1

OV = organic vapor
DM = dust, mist
HEPA = high efficiency particulate

Table 4.
Test Atmosphere Characterization Results from MDI Condensation Aerosol Test Runs

		Annular Diffusional Denuder Results (% of mass in interval)			Cascade Impactor Results	
Test Run	μg/m³ MDI (TWA)	Particle, >2.5μm	Particle, <2.5μm	Vapor	MMAD (μm)	84% of mass less than (μm):
1	63	<0.3	15.4	84.6	-	-
2	48	2.1	17.0	80.9	-	-
3	1200	-	-	-	-	-
4	330	1.4	84.0	14.6	0.89	1.25
5	650	2.9	87.0	10.1	0.92	1.34

Table 5.
Example Cartridge Efficiency Results from an MDI Condensation Aerosol Test Run.

Test Cartridge: Cabot/AO R51A

Mean MDI Concentration: 650 μg/m³

Elapsed Time Interval(min)	Test Atmosphere MDI Conc. (μg/m³)	Exit Stream MDI Conc. (μg/m³)	Cartridge Efficiency
1 to 15	622	367	41%
1005 to 1020	408	275	33%
1415 to 1434	357	235	34%
		Mean:	36%
		RSD:	12%

Table 6.
Summary of Cartridge Efficiency Results from MDI Condensation Aerosol Test Runs

		Cartridge Efficiency			
MDI Conc. ($\mu g/m^3$)	Predominant MDI Form	AO R51A (OV)[1]	AO R91A (OV/DM)	3M 6001/5010 (OV/DM)	AO R51HE (OV/HEPA)
48	Vapor	75%	>99.9%	>99.9%	>99.9%
62	Vapor	86%	99.2%	>99.8%	>99.8%
330	Aerosol	30%	99.3%	>99.98%	>99.98%
650	Aerosol	36%	99.1%	>99.98%	N/A
650	Aerosol	36%	N/A	N/A	N/A
1200	Aerosol	35%	99.6%	>99.96%	>99.96%

N/A = not applicable (cartridge not run under this condition)

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OV = organic vapor
DM = dust, mist
HEPA = high efficiency particulate

Figure 1. Respirator Test Chamber

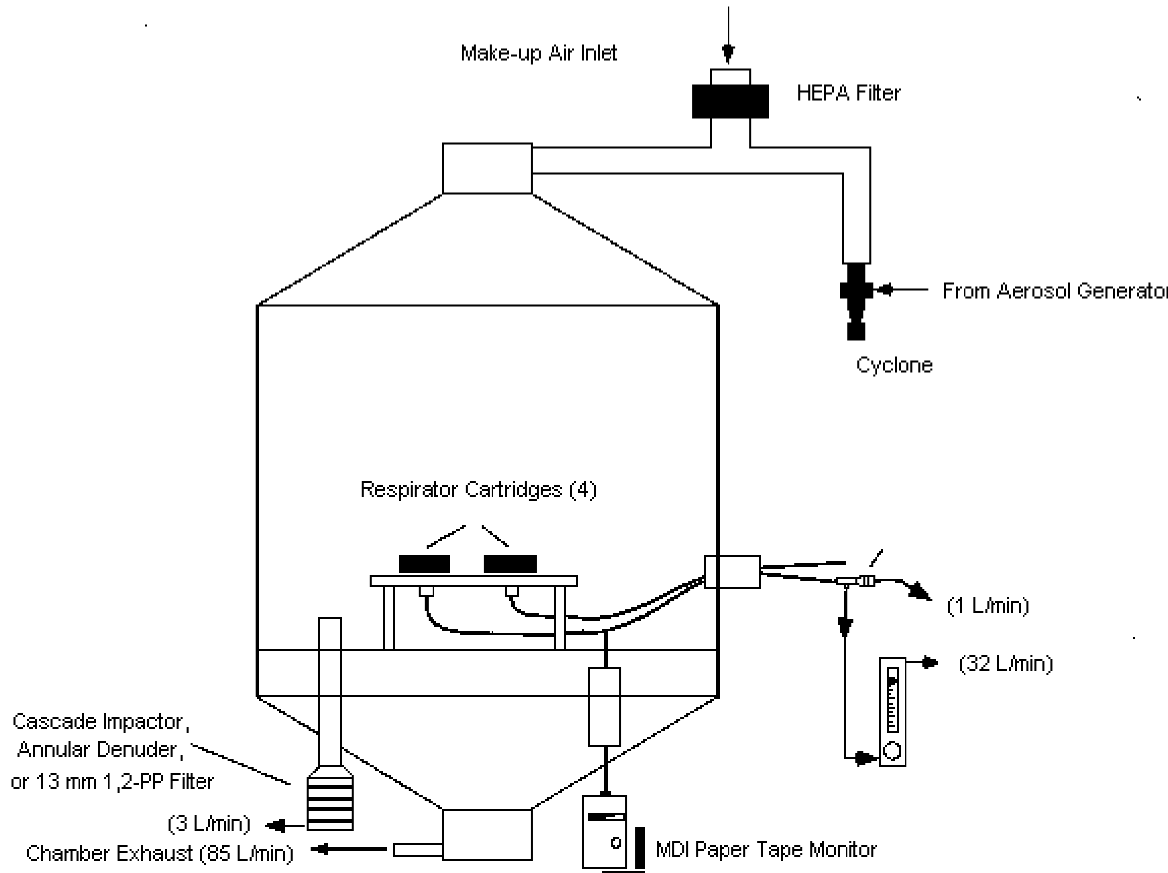

Figure 2. Condensation Aerosol Generator

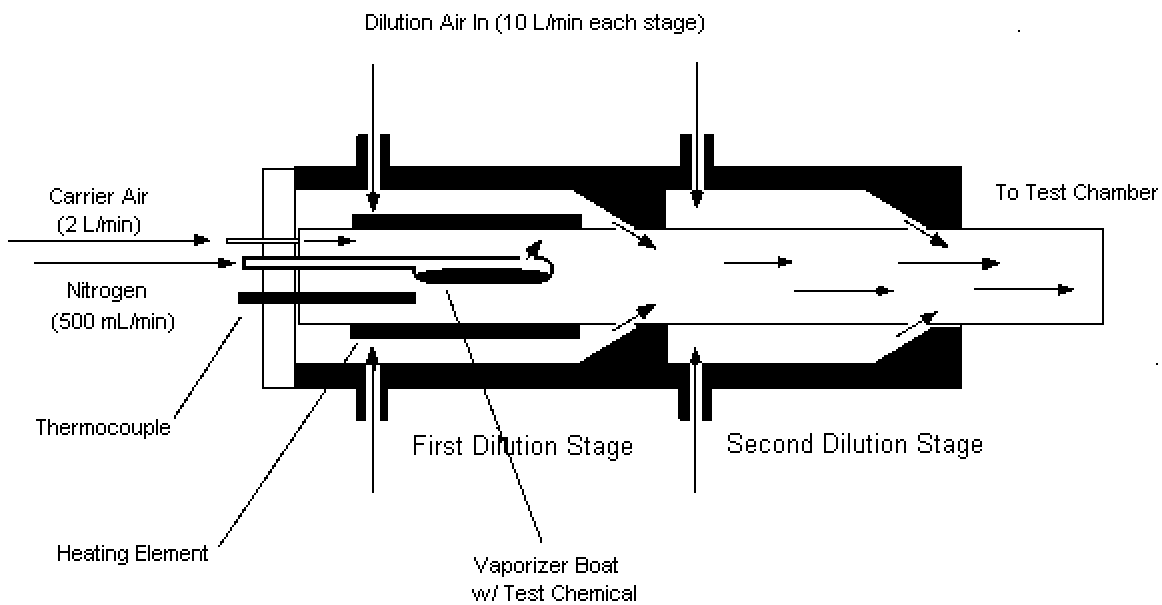

Figure 3. Diagram of the Annular Diffusional Denuder (ADD) Sampler

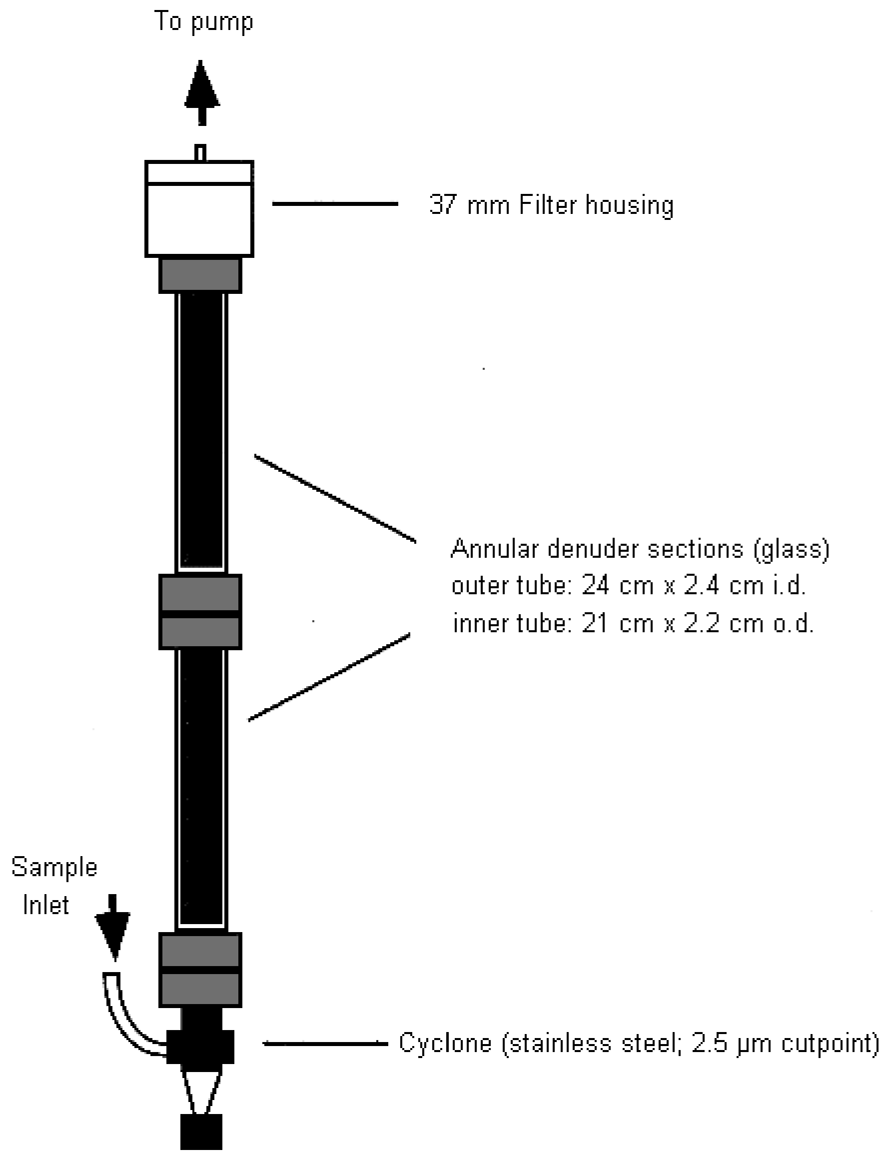

Figure 4. Breakthrough Results for AO/Cabot R51A OV Cartridge with High Concentration MDI Aerosol Atmosphere (7050 μg/m³, MMAD = 2.13 μm)

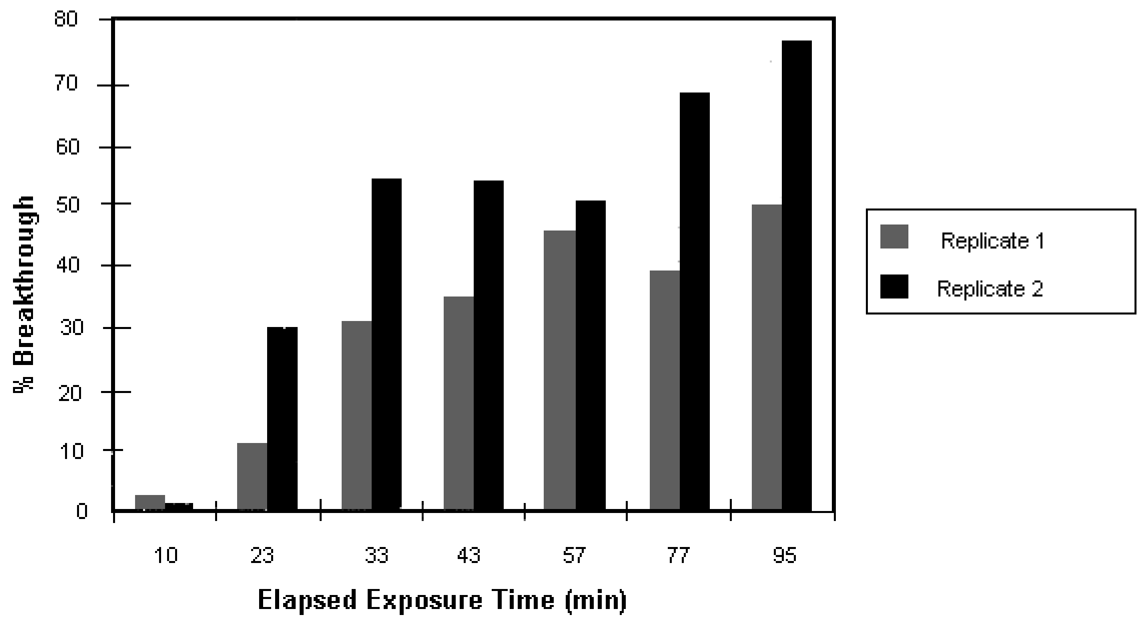

Figure 5. Breakthrough Results for AO/Cabot R91A OV/DM Cartridge with High Concentration MDI Aerosol Test Atmosphere (8500 μg/m³, MMAD = 2.13 μm)