

AUTHORS

Saulius Trakumas^{a,c}Klaus Willeke^aTiina Reponen^aSergey A. Grinshpun^aWarren Friedman^b

^aAerosol Research and Exposure Assessment Laboratory, Department of Environmental Health, University of Cincinnati, P.O. Box 670056, Cincinnati, OH 45267-0056;

^bOffice of Lead Hazard Control, U.S. Department of Housing and Urban Development, 451 7th St. SW (P 3206), Washington, DC 20410;

^cCurrent address: SKC Inc., 863 Valley View Road, Eighty Four, PA 15330; E-mail: SKCSaulius@SKCinc.com

Comparison of Filter Bag, Cyclonic, and Wet Dust Collection Methods in Vacuum Cleaners

In this study, methods were developed for comparative evaluation of three primary dust collection methods employed in vacuum cleaners: filter bag, cyclonic, and wet primary dust collection. The dry collectors were evaluated with KCl test aerosols that are commonly used in filter testing. However, these aerosols cannot be used for evaluating wet collectors due to their hygroscopicity. Therefore, the wet collectors were evaluated with nonhygroscopic test particles. Both types of test aerosol indicated similar collection efficiencies in tests with dry collectors. The data show that high initial collection efficiency can be achieved by any one of the three dust collection methods: up to 50% for 0.35 μm particles, and close to 100% for 1.0 μm and larger particles. The degree of dependence of the initial collection efficiency on airflow rate was strongly related to the type and manufacturing of the primary dust collector. Collection efficiency decreased most with decreasing flow rate for the tested wet collectors. The tested cyclonic and wet collectors showed high reentrainment of already collected dust particles. After the filter bag collectors had been loaded with test dust, they also reemitted particles. The degree of reentrainment from filter bags depends on the particulate load and the type of filter material used. Thus, the overall particle emissions performance of a vacuum cleaner depends not only on the dust collection efficiency of the primary collector and other filtration elements employed, but also on the degree of reentrainment of already collected particles.

Keywords: collection efficiency, cyclone, emission, filter bag, lead-based paint abatement, vacuum cleaner, wet collector

Vacuum cleaners are commonly used for regular cleaning of surfaces in industrial and commercial buildings, in homes, and for special purposes such as lead-based paint hazard control cleanup.^(1,2) Dust from the surface being cleaned is picked up through the nozzle of the vacuum cleaner, and most of it is captured by the dust collection components installed in the vacuum cleaner. Some of the dust may penetrate through the primary dust collectors and will then be expelled to the ambient air or be captured by the final high efficiency particulate air (HEPA) filter, if installed. The amount of dust that penetrates through the vacuum cleaner depends on the efficiency of the dust collection components installed in the device. Use of a less efficient dust collector leads to a higher dust emission level, and vice versa. Thus, the dust removal efficiency of a vacuum cleaner

affects the indoor environmental quality after vacuum cleaning.^(3–5)

It has been shown that household and industrial vacuum cleaners with a final HEPA filter installed in the exhaust airflow initially remove close to 100% of 0.3 μm and larger particles.^(6–8) The lifetime of the expensive final HEPA filter depends on the performance of the primary dust removal element of the vacuum cleaner: a less efficient primary collector will cause higher dust loading on the final HEPA filter.⁽⁸⁾ Thus, the efficiency of the primary dust collector affects the loading of the final HEPA filter in the vacuum cleaner and its replacement frequency during use.

The three principal methods used for primary dust removal in vacuum cleaners are dust collection in a disposable filter bag (filter bag collector), dust removal by centrifugal motion

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(cyclonic collector), and dust removal by impingement into water (wet collector). Once a filter bag is filled with collected dust, it is disposed of and replaced by a new one, typically costing \$1 to \$3.⁽⁹⁾ No such replacement cost is incurred with cyclonic and wet collectors. In a cyclonic collector the collected dust is removed from the chamber; in a wet collector the soiled water is replaced by fresh tap water. Because the effluent airflow from a wet dust collector is humid, the standard test techniques for evaluating dry dust collectors cannot be used.

The test techniques and procedures developed and employed in this study permit direct comparisons among the three dust collection methods. To do so, the initial collection efficiencies were measured and compared for filter bag, cyclonic, and wet dust collectors. Dust reentrainment from these collectors was also evaluated after initial loading of each collector with the same amount of test dust.

EXPERIMENTAL MATERIALS AND METHODS

Filter Bag, Cyclonic, and Wet Dust Collection in Vacuum Cleaners

Each vacuum cleaner is equipped with a primary dust collector that removes and collects most of the dust from the airstream going through the device. One or more additional filtration elements may be installed in the vacuum cleaner for further dust removal and protection of the air mover components from dust. The purpose of the final HEPA filter, if installed, is to assure that virtually no particles are emitted to the ambient air environment. Figure 1 schematically shows the three principal dust collection methods employed in vacuum cleaners.

The filter bag (Figure 1A) is the most commonly used primary dust collector in vacuum cleaners.⁽¹⁰⁾ Usually, filter bags are made from fibrous filter media. According to filtration theory, particles in the airstream may deposit on the fiber surfaces due to diffusion, interception, inertial impaction, or gravitational settling.^(11,12) The contribution of each of these filtration mechanisms to the overall filtration efficiency depends on parameters such as particle size, filter material, and the airflow velocity through the filter.^(11,12) Accumulated dust on a filter medium may increase the pressure drop across the filter and thus affect the filtration characteristics.⁽¹¹⁻¹³⁾ Therefore, a loaded filter bag must be replaced with a new one. The filter bags available from the manufacturers have different filtration efficiencies. A vacuum cleaner collects dust more efficiently when a filter bag with higher efficiency is installed,⁽⁸⁾ unless the higher efficiency bag significantly reduces the airflow through the vacuum cleaner. Filter bags are widely used in canister and upright vacuum cleaners.

Recently, more companies have marketed vacuum cleaners with cyclonic dust collection. A typical cyclonic dust collector is schematically shown in Figure 1B. It is also used in either canister or upright vacuum cleaners. In this type of collector, the dust containing airflow is drawn into a cylindrical chamber, in which it swirls downward and then leaves the chamber upward through a central tube.^(14,15) Swirling particles with sufficient inertia are deposited onto the inner surface of the cylinder due to the inertial (centrifugal) forces on them. The efficiency of particulate collection depends on such parameters as the airflow rate through the device, the size of the cylinder, and the dimensions of the inlet and outlet tubes.^(15,16) Periodically, the collected dust is removed and the surfaces of the cyclone are cleaned.

The third method of dust collection in vacuum cleaners is impingement into water (Figure 1C). It appears that only canister-type vacuum cleaners are available with this type of collector. In a

wet collector, particles are impacted into a reservoir filled with water.^(14,17,18) As in all inertial collection devices, the velocity of the airflow and particle size are the most important parameters.⁽¹⁵⁾ A mist separator is usually installed above the wet collector to prevent droplets from the bubbling water to affect the performance of the air mover and motor. As with cyclonic collectors, wet collectors do not include elements that need to be replaced periodically with new ones, except the water, after it has become dust-laden.

Description of the Vacuum Cleaners Tested

Six different brands of household vacuum cleaners were tested in this study, two each of the filter bag, cyclonic, and wet dust collection types. The characteristics of these devices are summarized in Table I. The labeling for the type of motor placement was introduced and schematically shown in a previous publication.⁽⁸⁾ Type II indicates that the air mover is placed after the primary dust collector. In Type IIa the motor emissions are combined with the effluent airflow from the primary dust collector, whereas in Type IIb the motor emissions are separate from the effluent airflow coming from the primary dust collector. In previous studies five different filter-equipped vacuum cleaners were evaluated.^(7,8) Two of these were used for the present comparison tests with cyclonic and wet collectors. To help the reader desiring more information on filter-containing vacuum cleaners, the labeling for the filter collectors (FC) in the present publication is the same as in the previous publications.

Vacuum cleaner FC3-UP (ca. \$160) was an upright vacuum cleaner with a filter bag as the primary dust collector. The filter bag had about 2000 cm² (~2.2 ft²) in filtration surface, and consisted of three layers of fibrous filter material. The motor was preceded by a small prefilter. A final HEPA filter captured the motor-emitted particles and the dust particles not removed previously by the filter components. The maximum flow rate through this device, Q_{IN} , was 60 ft³/min, when operated with all filters installed. In vacuum cleaner FC4-CAN (ca. \$650), the filter bag collector was installed in a canister. It also contained a small motor prefilter and a final HEPA filter. The filter bag had about 1400 cm² (~1.5 ft²) in filtration surface and consisted of a single layer of fibrous material. Additional information on the performance of these two vacuum cleaners can be found in previous publications.^(7,8)

Two vacuum cleaners with cyclonic collectors (CC) were evaluated in this study: upright CC1-UP (ca. \$170) and canister CC2-CAN (ca. \$300). Vacuum cleaner CC1-UP contained a chamber for the collection of large dust particles and a cyclone. The uncollected particles were removed in one of the subsequent dust collectors: a cyclone afterfilter, a small motor prefilter, and a final HEPA filter. The HEPA filter also removed the particulate motor emissions. Vacuum cleaner CC2 contained a dual cyclone, a fine metal grid for motor protection, and a final HEPA filter for removing the remaining dust particles and the particulate motor emissions.

In both wet collectors (WC) tested in this study (\$1200–\$1400), the water container was placed in a canister. In vacuum cleaner WC1-CAN the container was filled with 1.9 L (2 quarts) of tap water. Water droplets in the effluent air were removed by a mist separator before entering the air mover. Particles passing out of the wet collector were captured by a final HEPA filter. An additional filter removed particles from the motor emissions. Vacuum cleaner WC2-CAN employed 3.8 L (1 gallon) of water. A mist separator was also installed before the air mover. A small final

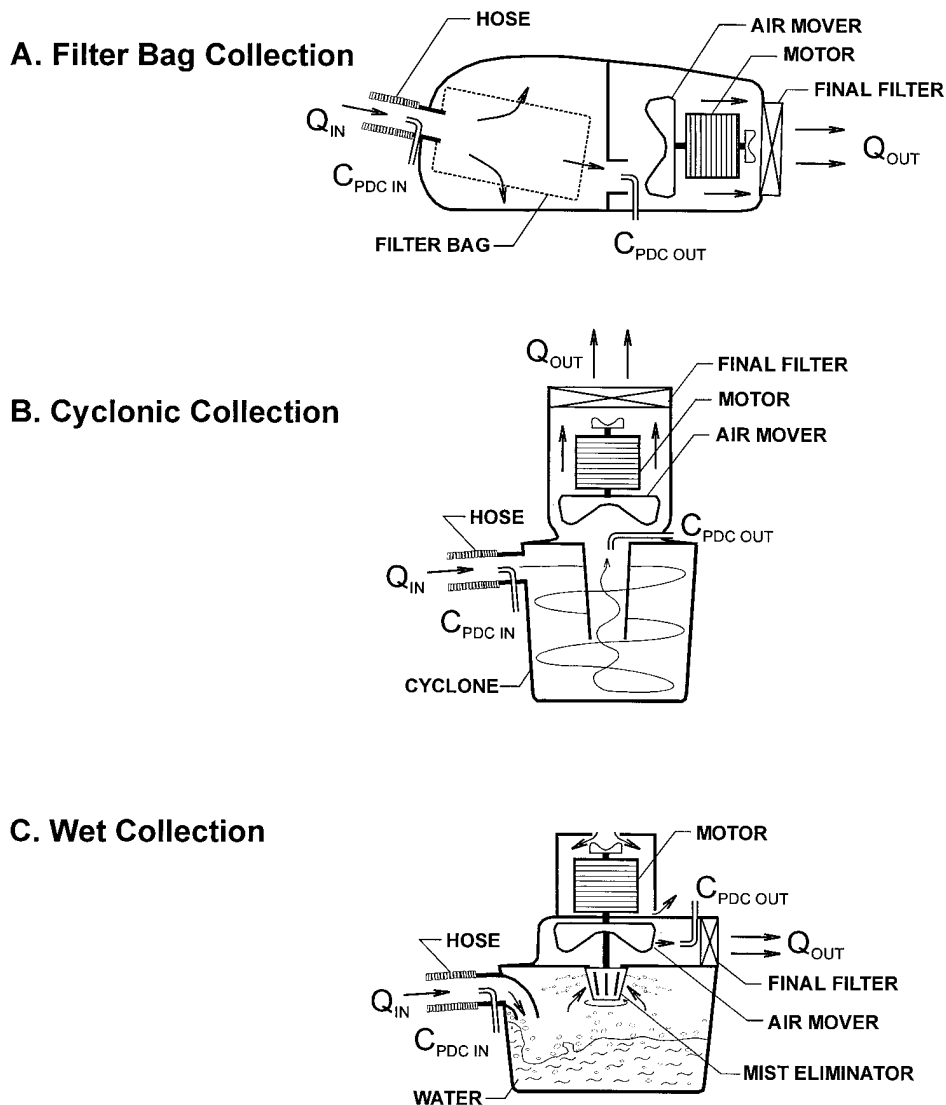


FIGURE 1. Schematic of the three principal dust collection methods used in vacuum cleaners. The final filters on some vacuum cleaners, including the ones used in this study, are HEPA filters. PDC = primary dust collector.

filter (not HEPA), installed after the air mover, collected previously uncollected particles. The motor emissions were separate from the effluent airflow coming from the primary dust collector and were not filtered.

Data presented in the last column of Table I show the pressure drop at the outlet of primary dust collectors tested, $\Delta P_{PDC\ OUT} = P_{PDC\ OUT} - P_{AMBIENT}$. The lowest pressure drop was registered at the outlet of wet collectors WC1 and WC2. The value of

TABLE I. Characteristics of Tested Vacuum Cleaners

Label	Category	Primary Collector Type	Motor Placement Type ^A	Final HEPA	Maximum Flowrate, Q , ft ³	Pressure Drop, $\Delta P_{PDC\ OUT}$ ^B , inch H ₂ O
FC3-UP	upright	filter bag	Ila	yes	60	23
FC4-CAN	canister	filter bag	Ila	yes	80	27
CC1-UP	upright	cyclone	Ila	yes	50	32
CC2-CAN	canister	cyclone	Ila	yes	40	54
WC1-CAN	canister	wet	Ilb	yes	62	16
WC2-CAN	canister	wet	Ilb	none	56	18

^ATest labels correspond to those used in the previous publication "Particle Emission Characteristics of Filter-Equipped Vacuum Cleaners" by S. Trakumas, K. Willeke, S.A. Grinshpun, T. Reponen, G. Mainelis, and W. Friedman, *AIHAJ* 62:482-493 (2001).

^B $\Delta P_{PDC\ OUT} = P_{PDC\ OUT} - P_{AMBIENT}$.

$\Delta P_{\text{PDC OUT}}$ measured for cyclonic collectors was 2 to 3 times higher than the pressure drop at the outlet of wet collectors. The values of pressure drop across the filter bags appear to be between the ones measured for wet and cyclonic collectors, respectively.

Test Methods

Measuring the Initial Collection Efficiency of Different Primary Dust Collectors

The primary dust collectors of six different vacuum cleaners were first evaluated as to their initial collection efficiency. The term *initial* reflects the collection efficiency of a clean dust collector; that is, when new filter bags are installed in the filter collectors, all dust is removed from the cyclonic collectors, and clean water is put into the wet collectors.

The initial collection efficiency of the primary dust collectors (PDC) was measured through probed testing.^(7,8) Identical probes were installed at the primary dust collector inlet and outlet, as shown in Figure 1. The aerosol concentrations in the airflow entering the primary dust collector, $C_{\text{PDC IN}}$, and leaving it, $C_{\text{PDC OUT}}$, were simultaneously measured with optical particle size spectrometers (model 1.108, Grimm Technologies, Douglasville, Ga.). The vacuum cleaner was connected through a hose (no nozzle was used) to a clean air supply system⁽⁷⁾ and was operated for 30 min before each test. During the next 10 min, the background aerosol concentration was registered in the airflow leaving the primary dust collector, while there was no test aerosol input. The aerosol generator was then activated, and concentrations $C_{\text{PDC IN}}$ and $C_{\text{PDC OUT}}$ were measured three times during a 4-min period. The collection efficiency, E , of the primary dust collector was calculated by Equation 1:

$$E = \left(1 - \frac{C_{\text{PDC OUT}} - C_{\text{BACKGROUND}}}{C_{\text{PDC IN}}} \right) 100\% \quad (1)$$

The average collection efficiency and standard deviation were calculated from three measurements of $C_{\text{PDC IN}}$ and $C_{\text{PDC OUT}}$.

As indicated earlier, the dust collection efficiencies for the filter bag, cyclonic, and wet collectors depend on the airflow rates through them. When a vacuum cleaner is used in dusty environments, the airflow through it can decrease due to loading with dust particles on the different dust removal components. The airflow through a vacuum cleaner also depends on the type of nozzle used and the characteristics of the surface being cleaned.⁽⁸⁾ To assess how the airflow rate affects the collection efficiency of the different primary dust collectors, they were tested at their normal flow rates and at half of those flow rates. The flow rate was reduced by decreasing the rotational speed of the vacuum cleaner motor.

The filter bag and cyclonic collectors were tested with potassium chloride (KCl) test aerosol, which is commonly used for dry filter efficiency testing.⁽¹⁹⁾ These test aerosols were also used in previous studies.^(7,8) The KCl particles were dispersed by a three-jet Collison nebulizer (BGI, Waltham, Mass.) from a 0.5% KCl solution, and were dried by the addition of dry, particle-free air. Because of their ability to absorb water, salt particles such as KCl can change in size very rapidly when exposed to environments with high relative humidity.⁽²⁰⁾ Thus, such particles are not suitable for evaluating wet collectors. Dry Arizona road test dust, aerosolized by a Vilnius Aerosol Generator (CH Technologies, Westwood, N.J.), was used for evaluating the wet collectors. Polydisperse Arizona road test dust can be aerosolized as a dry powder and is typically used to calibrate dust monitors.⁽²¹⁾ For comparison purposes the cyclonic collectors were tested with both types of aerosol.

Measuring the Reentrainment of Particles from Primary Dust Collectors after Loading with Dust

The dust collection process in a vacuum cleaner with a wet collector is similar to the removal of particles from the sampled airstream in a liquid impinger, which is primarily used for sampling bioaerosol particles.⁽²²⁾ In both cases the aerosol is impacted into a liquid, which bubbles violently as the air escapes and particles are trapped in the liquid. It has been shown that an impinger is not only a collector, but also an aerosol generator;^(14,17,18) that is, some of the particles collected by the liquid eventually reentrain into the effluent airflow because of the violent bubbling. In a vacuum cleaner with a wet collector, a mist separator (fast rotating vanes) is usually installed above the bubbling liquid to keep the larger droplets and particles from leaving the wet collector. Testing was deemed necessary to check for potential passage of already collected particles through the mist separator. The primary collectors of filter-containing and cyclone-containing vacuum cleaners were also examined for possible reentrainment of already collected particles.

At the start of each experiment, the vacuum cleaner was connected through a hose to the filtered air supply system.⁽⁷⁾ After 10 min, a different hose was connected to the vacuum cleaner and 5 g of Arizona road test dust were delivered to the primary collector by moving the hose inlet over 5 g of the test dust, which had been distributed over a smooth surface of 400 cm². The purpose of this procedure was to feed the same amount of test dust into each primary collector being tested in a manner similar to normal dust pickup in a vacuum cleaner. After all of the 5 g of test dust was entrained into the vacuum cleaner, the filtered air supply was reconnected to the vacuum cleaner through a clean hose. The hose for dust delivery was different from the hose for the clean air supply to ensure that particle reentrainment after loading could originate only in the primary dust collector. The dust delivery operation lasted about 50–55 sec, including 20 sec for the hose reconnection. The aerosol concentration $C_{\text{PDC OUT}}$ was registered by one of the optical particle size spectrometers every 6 sec for 70 min (10 min before test dust loading and 60 min after the loading).

In earlier studies the authors showed that ambient aerosol may leak into the vacuum cleaner through potential leak sites in the nozzle and in the primary filter compartment.^(7,8) In the present study, all vacuum cleaners were tested without nozzles to minimize the influence of potential leakage in the nozzle component on the measured aerosol concentrations in the vacuum cleaner. The degree of ambient aerosol leakage into the primary filter compartment was assessed by measuring $C_{\text{PDC OUT}}$ before loading the primary dust collector with test dust while the vacuum cleaner was connected to the clean air supply system. The aerosol concentration in the air surrounding the vacuum cleaner being tested was also monitored before and after each experiment to prove that the registered changes of $C_{\text{PDC OUT}}$ after loading with test dust were not caused by changes in leakage from the ambient air environment.

RESULTS AND DISCUSSION

Comparison of the Initial Collection Efficiencies for the Different Primary Dust Collectors

Filter Bag Collection

Figure 2 shows the initial collection efficiencies for the two filter bags serving as the primary dust collectors in vacuum cleaners

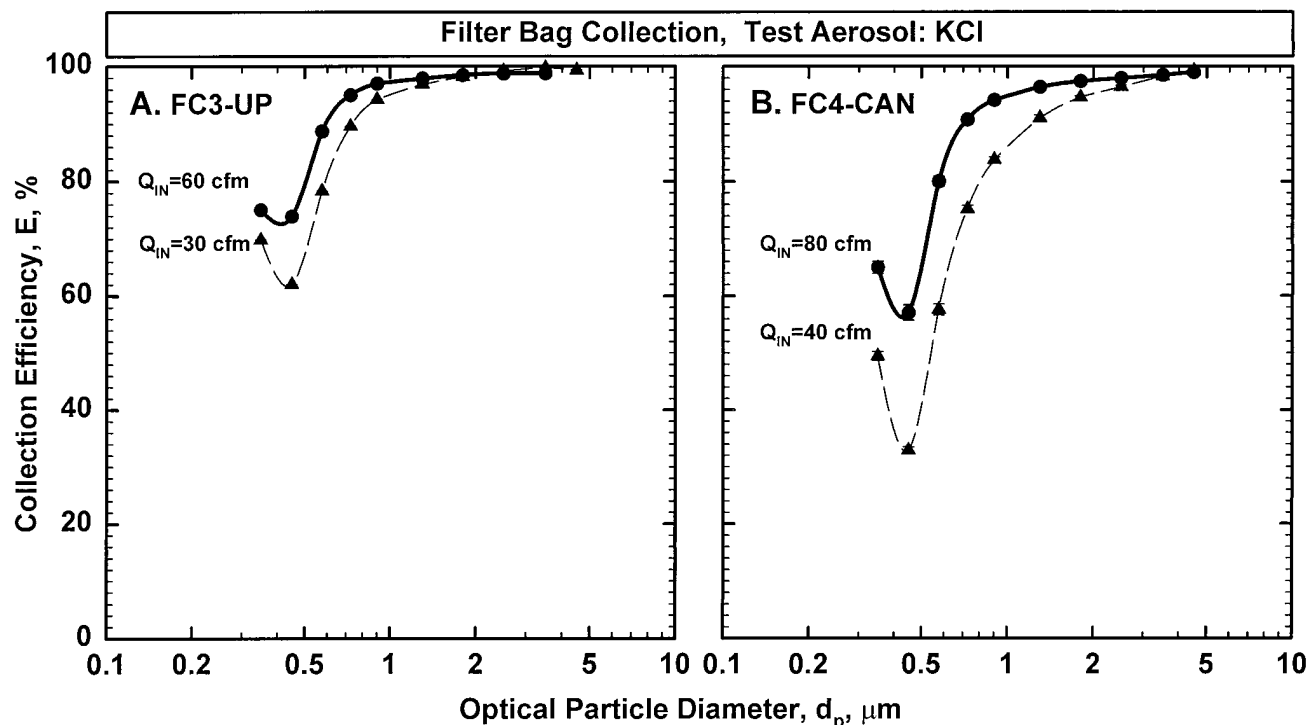


FIGURE 2. Effect of airflow rate on the initial collection efficiency of the filter bags in vacuum cleaners FC3-UP and FC4-CAN. Tests were conducted at 100 and 50% of maximum airflow rate through each vacuum cleaner.

FC3-UP and FC4-UP. These tests were performed with KCl test aerosol. The data presented in Figure 2A are for the filter bag installed in upright vacuum cleaner FC3-UP. The filtration velocity through this filter bag, V_F , was 14.2 cm/sec (~ 5.6 inches/sec) at the maximum flow rate through the vacuum cleaner of 60 ft^3/min . At half of this flow rate, $Q_{IN} = 30 \text{ ft}^3/\text{min}$, and $V_F = 7.1 \text{ cm/sec}$ (~ 2.8 inches/sec). As can be seen from Figure 2A, about 72% of the test particles 0.35 to 0.45 μm and more than 98% of the particles larger than 2.0 μm are collected when $Q_{IN} = 60 \text{ ft}^3/\text{min}$ (solid curve with circles). At $Q_{IN} = 30 \text{ ft}^3/\text{min}$, the initial collection efficiency for KCl particles is lower in the size range from 0.35 to about 2.0 μm (dashed curve with triangles). Such a decrease in collection efficiency with decreasing filtration velocity is typical for fibrous filters.^(11,13) The dip in the collection efficiency curves is due to decreasing particle collection by diffusion and increasing particle collection by impaction and interception, as the particle size increases.⁽¹¹⁾ The particle size, d_p , is the optical equivalent diameter of KCl particles, as measured by the optical particle size spectrometer, which was calibrated with standard polystyrene latex spheres (Bangs Laboratories, Fishers, Ind.).

The collection efficiency curves shown in Figure 2B are for filter bags installed in the canister of vacuum cleaner FC4-CAN. At maximum airflow rate, when $Q_{IN} = 80 \text{ ft}^3/\text{min}$, the filtration velocity was $V_F = 27 \text{ cm/sec}$ (~ 10.6 inches/sec). The collection efficiency for test particles smaller than 2.0 μm was lower for the primary filter collector of vacuum cleaner FC4-CAN (Figure 2B, solid curve) than for the filter bag of vacuum cleaner FC3-UP (Figure 2A, solid curve), when the vacuum cleaners were operated at their maximum flow rate. Particles larger than 2.0 μm were collected with similar efficiency in both cases. The collection efficiency of the filter bag in FC4-CAN decreased over almost the

entire monitored particle size range when the flow rate was decreased to half of its maximum value ($Q_{IN} = 40 \text{ ft}^3/\text{min}$, $V_F = 13.5 \text{ cm/sec} \approx 5.3$ inches/sec, dashed curve in Figure 2B).

As seen in Figure 2, the collection efficiency of FC3 decreased less than that of FC4 when the flow rate was reduced to half of its maximum value. This figure also shows that, at both airflow rates, the primary filter bag of vacuum cleaner FC3-UP collected particles more efficiently than the filter bag of FC4-CAN. As indicated earlier, the filter bag of vacuum cleaner FC3-UP consisted of three layers of fibrous filter material, whereas the filter bag of FC4-CAN consisted of only one layer. When examined under an optical microscope, the fiber diameters of the two inner filter layers of FC3 were found to be noticeably smaller than those of FC4. The different manufacture of the filter materials and the different number of filter layers resulted in the higher performance of FC3 versus FC4, although the filtration velocity at maximum airflow rate for vacuum cleaner FC3-UP was about of vacuum cleaner FC4-CAN.

Cyclonic Collection

Figure 3 shows the collection efficiencies for the cyclonic collectors in upright vacuum cleaner CC1-UP (Figure 3A) and in the canister vacuum cleaner CC2-CAN (Figure 3B). Similar to the test procedure for the filter bag collectors (Figures 2A and B), the cyclonic vacuum cleaners were also tested at their maximum flow rates and at half of these values. The solid circles and triangles in Figures 3A and 3B are for tests with KCl particles. The open diamonds and squares in these figures represent the tests with dry Arizona road dust.

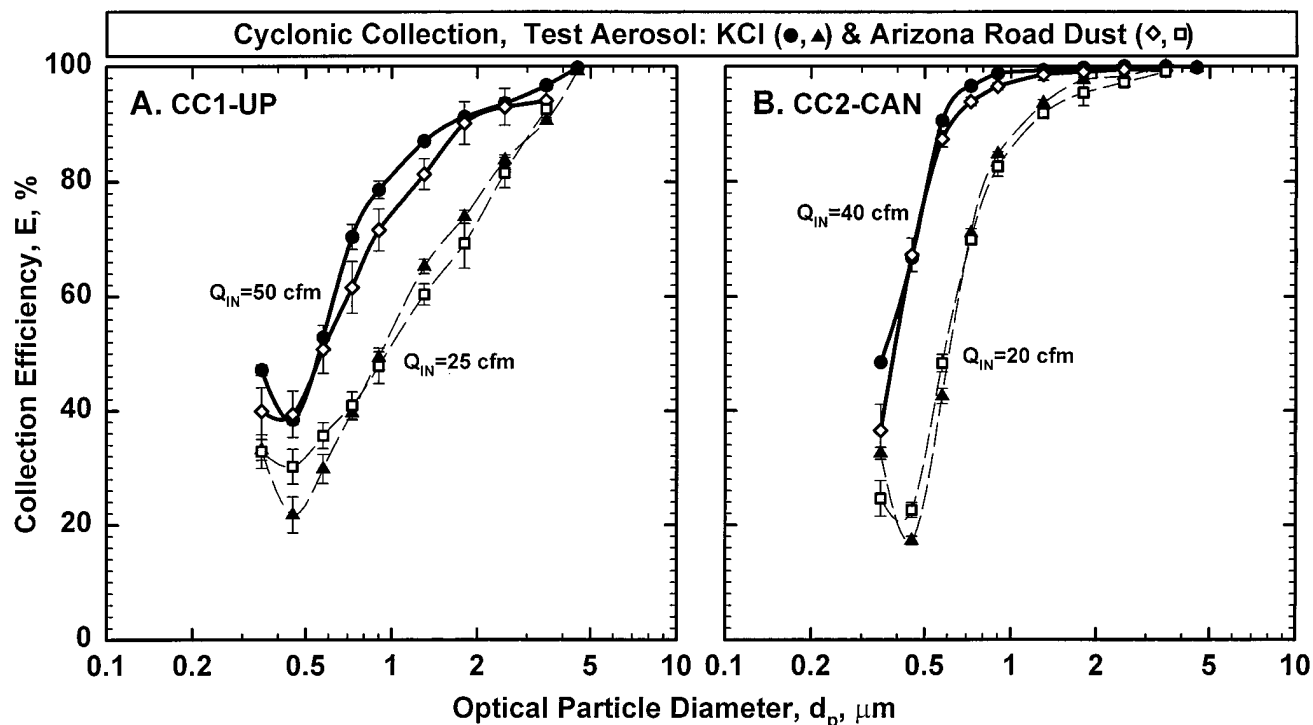


FIGURE 3. Effect of airflow rate and type of test particles on the initial collection efficiency of the cyclonic collectors in vacuum cleaners CC1-UP and CC2-CAN

When operated at its maximum flow rate of 50 ft³/min (Figure 3A, solid circles), the cyclonic collector of vacuum cleaner CC1-UP removed less than 40% of 0.5 μm KCl particles. Its collection efficiency approached 100% only for 4.5 μm and larger particles. Thus, the cyclonic collector CC1 was less efficient than the filter bag collectors FC3 and FC4. When the airflow rate through CC1 was decreased to 25 ft³/min, the collection efficiency also decreased significantly (solid triangles). A decrease in dust collection at the lower flow rate was expected, because the centrifugal forces moving particles to the inner wall of the cyclone decrease with decreasing airflow rate.⁽¹⁵⁾ The performance at maximum flow rate for the cyclonic collector in CC2-CAN (Figure 3B) was much better, comparable with that of the filter bag in FC3-UP (Figure 2A). The curve with solid circles in Figure 3B shows that about 48% of 0.35 μm KCl particles and close to 100% of KCl particles larger than 1.0 μm are collected, when vacuum cleaner CC2-CAN was operated at its maximum flow rate $Q_{IN} = 40$ ft³/min. Similar to CC1, cyclonic collector CC2 also retained significantly fewer particles over the entire particle size range when the airflow rate through it decreased (Figure 3B, solid triangles). Comparison of the distinctly different collection efficiencies for the two cyclonic collectors demonstrates that construction differences play an important role in their performance.

The open diamonds and squares in Figure 3 show the collection efficiencies for these cyclonic collectors when measured with dry Arizona road dust. The data obtained with Arizona road dust have greater vertical error bars because of the greater fluctuations in aerosol concentration when dry dust was dispersed from a powder.⁽²³⁾ The performance curves obtained with the two types of test particles have similar shapes and values for each vacuum cleaner at the specified flow rates. The small differences are probably

due to the different morphologies and light-scattering characteristics between KCl particles and Arizona road dust.⁽²⁴⁾ The authors conclude from the data of Figure 3 that either KCl (dispersed from a liquid solution) or Arizona road dust (dispersed in a dry form) may be used to test the collection efficiency of vacuum cleaners. Arizona road dust data from wet collectors, therefore, can be directly compared with KCl data from filter-bag or cyclonic collectors.

Wet Collection

Figure 4 shows the collection efficiencies for the wet collectors in the canisters of vacuum cleaners WC1-CAN and WC2-CAN. In this case, particles are retained by impinging them into water. Following the recommendations of the manufacturers, the containers of WC1 and WC2 were filled with 1900 mL (2 quarts) and 3800 mL (1 gallon) of water, respectively. To start the experiments with particle-free water, only filtered, deionized water was used. The solid curves with open diamonds in Figure 4 represent the collection efficiency data for the wet collectors when tested with Arizona road dust at their maximum flow rates. The dashed curves and open squares are for half the maximum flow rate. As seen, the wet collector WC1 removed about 63% of 0.35 μm test particles and more than 96% of particles larger than 0.7 μm, when $Q_{IN} = 62$ ft³/min (Figure 4A). The collection efficiency of WC2 was less than 60% for 0.35 μm particles, and only particles larger than 1.5 μm were removed with higher than 98% efficiency (Figure 4B). Thus, the initial filtration efficiency of the wet collector in WC1-CAN was comparable with that of the filter bag in FC3-UP and the cyclonic collector in CC2-CAN, when these vacuum cleaners were operated at their maximum flow rates. The initial filtration

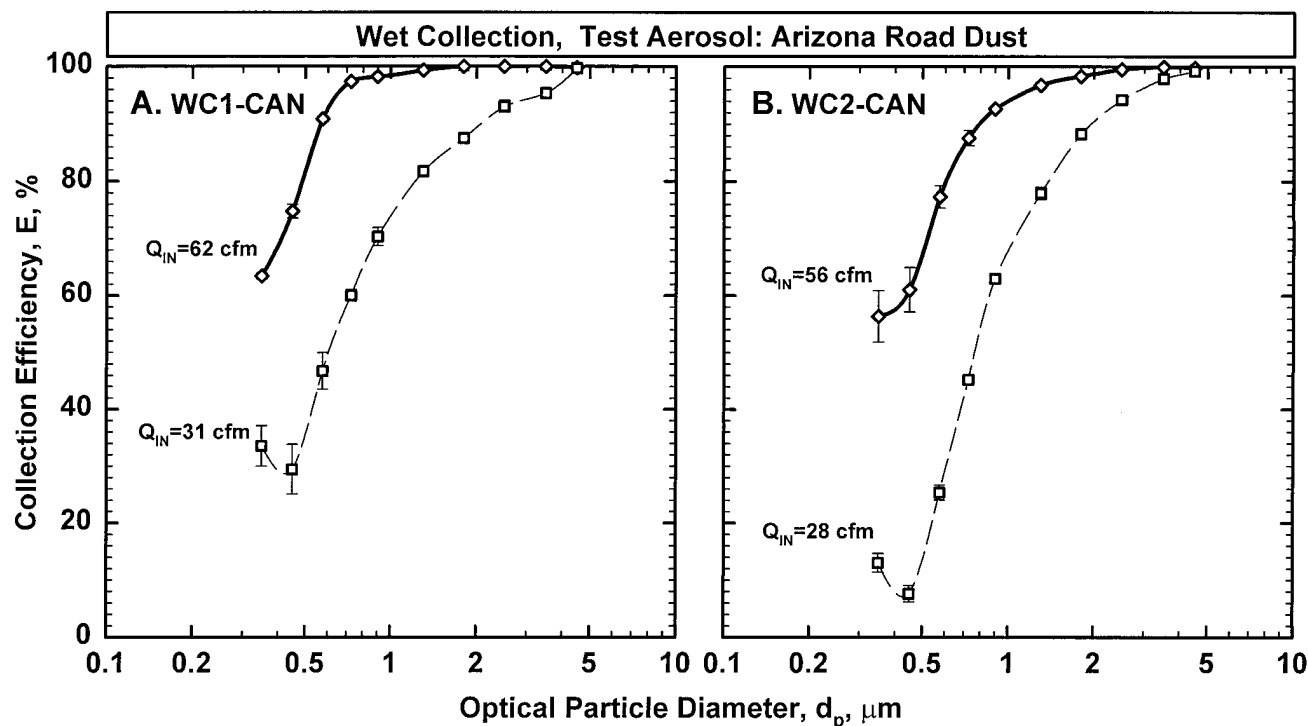


FIGURE 4. Effect of airflow rate on the initial collection efficiency of the wet collectors in vacuum cleaners WC1-CAN and WC2-CAN

efficiency of the wet collector in WC2-CAN is comparable with that of the filter bag in FC4-CAN.

Collection efficiency was significantly decreased in both wet collectors at half of the maximum flow rate (dashed curves in Figure 4): Only about 30% of particles smaller than $0.50\ \mu\text{m}$ were collected by the wet collector WC1, and about 10% of these particles were collected by the wet collector WC2. A decrease in collection efficiency was expected because of the lower force of particle impingement into water at a decreased flow rate through the vacuum cleaner. Although a decrease in flow rate is expected in filter collectors as they become loaded with dust, little change in flow rate is expected in a wet collector unless a final HEPA filter is installed and gets loaded significantly. However, decrease of the liquid level due to water evaporation during vacuum cleaner operation may change the collection efficiency in a wet collector.

Reentrainment of Dust from the Primary Collectors after Loading with Test Dust

Time Dependence of Dust Reentrainment

Figure 5 shows the aerosol concentrations of dust reentrainment from the different primary dust collectors during 1 hour after loading the collectors with 5 g of Arizona road test dust. The total aerosol concentrations in the size range from 0.3 to about $20\ \mu\text{m}$, $C_{PDC\ OUT}$, were measured in 6-sec time intervals in the air leaving the primary dust collector. The aerosol concentrations prior to $t=0$ correspond to the aerosol concentrations measured at the outlet of the primary dust collector before it was loaded with test dust. As the test dust was loaded into the primary dust collector during $t=0$ to 1 min, the aerosol concentration at the outlet of the primary dust collector, $C_{PDC\ OUT}$, reached a maximum. During the subsequent 10 min, the aerosol concentration decreased significantly in the effluent flow from each of the dust collectors.

However, the magnitude of dust reentrainment after $t=10$ min was different for each dust collector: The lowest particle reentrainment was registered for the filter-bag collectors (Figures 5A and B); it was higher for the wet collectors (Figures 5E and F), and highest for the cyclonic collectors (Figures 5C and D).

The different initial aerosol concentrations (before $t=0$) reflect the different levels of ambient aerosol leakage into each collector, as also shown in a previous publication.⁽⁷⁾ To ensure that the output concentration, measured after 60 min, is not affected by changes in ambient aerosol concentration, the latter was monitored before and after each experiment. In all experiments the average ambient aerosol concentration never changed by a factor exceeding 1.2 between $t=0$ and 60 min. Figures 5C and 5D show that the aerosol concentrations at the outlet of both cyclonic collectors 60 min after loading them with 5 g of dust were a factor of 100 higher than before $t=0$. The measured aerosol concentrations before $t=0$ and at $t=60$ differed by a factor of about 10 for filter bag collector FC3 (Figure 5A) and for both wet collectors (Figures 5E and F). These differences can be attributed entirely to particle reentrainment from the collectors, not to increases in the ambient aerosol concentration. The time traces shown in Figure 5 are for single experiments. Similar traces were recorded during three repeats for each collector.

Ten minutes after dust loading, the initial level of $C_{PDC\ OUT}$ was regained only for the filter bag of vacuum cleaner FC4-CAN (Figure 5B). This indicates that all of the collected dust remained inside the collector, and none of the previously collected particles were reentrained after $t=10$ min. Similar performance was expected for the filter bag of FC3-UP. However, Figure 5A shows that the aerosol concentration at the outlet of this filter bag was still about 10 times higher at $t=60$ min than prior to dust loading. This finding is particularly surprising, because the initial collection

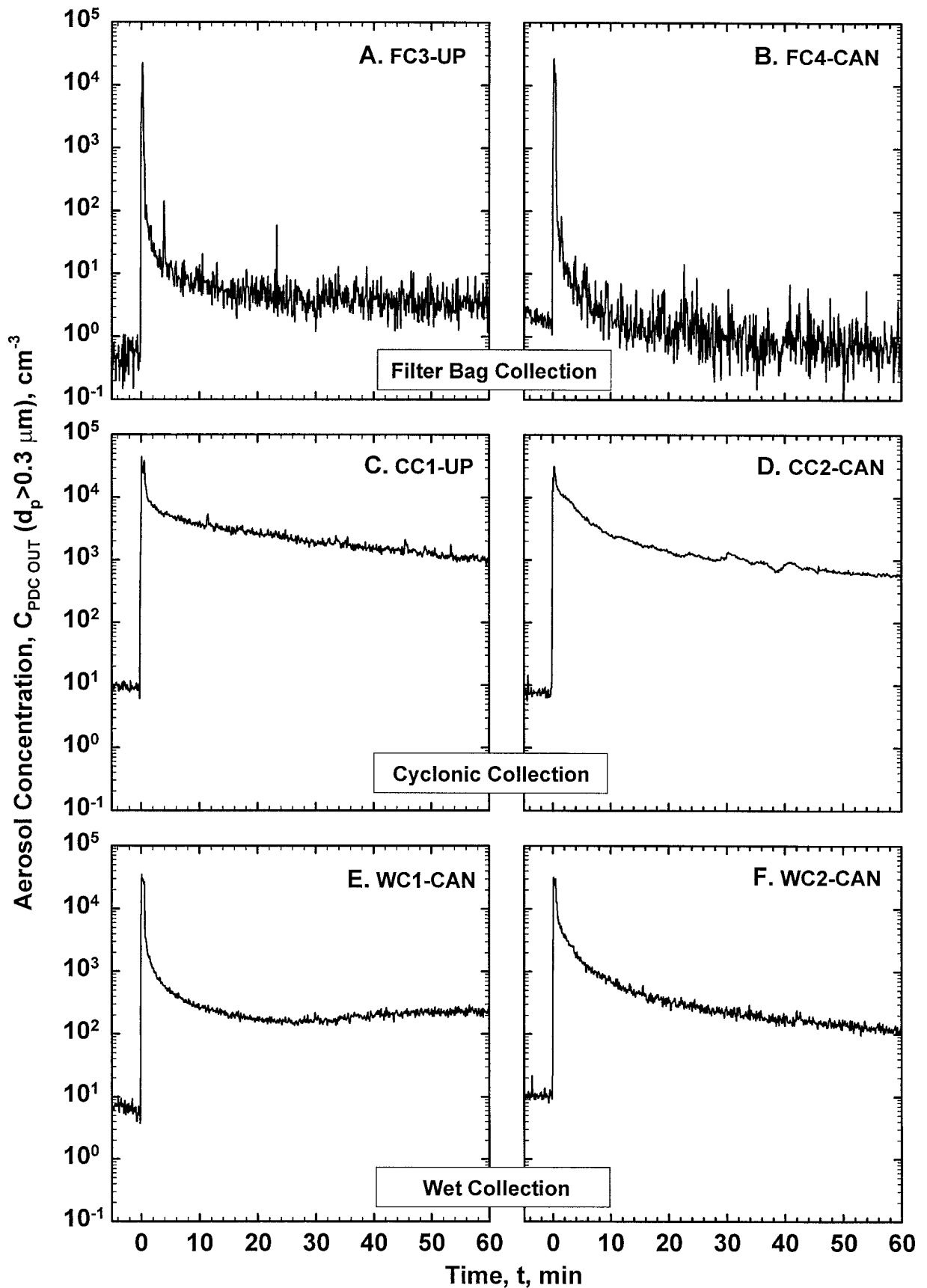


FIGURE 5. Time dependence of dust reentrainment from different primary dust collectors (PDC) after loading with 5 g of Arizona road test dust

efficiency of the filter bag in FC3-UP was higher than in FC4-CAN (Figure 2). Several replicates with vacuum cleaner FC3-UP resulted in traces similar to the one shown in Figure 5A, even after all potential leak sites in FC3-UP were sealed with adhesive. Visual observation confirmed that a considerable amount of the test dust had penetrated through the filter bag. A layer of dust was found on the inner walls of the bag compartment, and the color of the filter bag was darker than before the test. (No change in color was observed for the filter bag of FC4-CAN.) The color of the filter bag of FC3 was not uniform, but was interspersed with lighter areas and spots. This indicates that the dust particles were not evenly distributed on the inner surface of the filter bag and that the filtration velocity was not the same across the entire filter medium. One possible explanation for the higher aerosol concentration at the filter bag outlet after 60 min, compared with the aerosol concentration measured before $t=0$ min, is that air turbulence inside the bag reentrains dust particles, swirls them around, and then passes some of them through the less than 100% efficient filter medium.

Sixty minutes after loading, the aerosol concentrations at the outlets of the cyclonic collectors (Figures 5C and D) were still about 100 times higher than before loading these collectors with 5 g of dust. The continuous flow of air over the particle deposit (resulting in aerodynamic drag on the particles) and the impaction of particles onto the deposits (resulting in scouring) may be the cause for the high particle reentrainment.⁽²⁵⁾ In both cyclonic vacuum cleaners considerable dust deposits were observed on the inner walls of the compartment downstream of the cyclonic collector.

After the same time period of 60 min, the aerosol concentrations in the outlets of the mist separators downstream of the wet collectors in vacuum cleaners WC1-CAN and WC2-CAN were about 30 times (Figure 5E) and 10 times (Figure 5F) higher, respectively, than prior to dust loading. Since liquid impingers for aerosol sampling utilize the same collection principle as vacuum cleaners with wet collectors and have been observed to reaerosolize already collected particles,^(14,17,18) the authors postulate that already collected particles in the wet collectors WC1 and WC2 were reaerosolized through violent bubbling in the liquid reservoir; that is, the liquid reservoir acted as a dust collector and disperser.

The initial aerosol concentrations measured at the outlets of both wet collectors were about 10 cm^{-3} (Figures 5E and F, before $t=0$). These concentrations ($d_p \geq 0.3 \text{ }\mu\text{m}$) included mineral residues and water droplets that had passed through the mist separator. It was concluded that the increased aerosol concentrations after the addition of test particles to the water were due to reaerosolization of some of these test particles (Figures 5E and F, $t>0$). When the liquid reservoir was filled with tap water instead of filtered, deionized water, the aerosol concentrations measured at the outlets of the wet collectors were higher; that is, the mineral residues from evaporated water droplets increased the aerosol concentrations.⁽²⁶⁾ The slight increase in aerosol concentration for WC1 after $t=30$ min was due to the decreasing amount of water in the collector. Here again, the impinger analogy helps explain this observation: As the liquid evaporated in an impinger, the remaining particles in the liquid were concentrated, resulting in higher aerosol concentrations in the airflow leaving the impinger.⁽²⁷⁾ After about 70 min of operation, the initial water volume of 1.9 L in WC1 was reduced to about 1.3 L. In collector WC2 the water volume was reduced from 3.8 to 2.9 L.

Particle Size Distributions of Dust Reentrained after Loading

In Figure 6, the particle size distributions are shown for specific time periods of the time traces in Figure 5. The beginning of dust

loading corresponds to the first measured time interval of 6 sec when $C_{\text{PDC OUT}}$ increased significantly, as registered by the optical particle size-spectrometer. The curves with solid circles in Figures 6A and 6B represent the particle concentrations registered during the first minute ($t=0$ to 1 min) after loading with Arizona road test dust. Because very unstable aerosol concentrations were registered downstream of the cyclonic and wet collectors right after loading, the curves for these collectors (solid triangles) represent the more stable aerosol concentrations measured starting slightly later, during $t=0.6$ to 1 min (Figures 6C-F). The curves with open circles correspond to the aerosol concentrations measured during the second minute ($t=1$ to 2 min); the curves with open squares are for the sixth minute ($t=5$ to 6 min); and the open triangles represent the aerosol concentrations measured at the end of the experiment ($t=60$ to 61 min).

The total aerosol concentrations measured during the first minutes after dust loading were higher than $2000 \text{ particles/cm}^3$ for all collectors. The manufacturer of the optical particle size spectrometer recommends this level as the highest aerosol concentration for measurement with this device. When the aerosol concentration is high, particle coincidence in the view volume of the device may result in the counting of two or more particles as one, thus lowering the indicated aerosol concentration. The actual aerosol concentrations in Figures 5 and 6 may therefore be higher than shown during the first 5 min. However, since the goal of these experiments was to semiquantitatively compare the reentrainment from the different dust collectors, there was no attempt to lower the aerosol concentrations by dilution with clean air. If a correction were applied to the aerosol concentrations during the first minutes, it would be approximately the same for all collectors, because the high aerosol concentration registered after loading was somewhat similar during all experiments (see Figures 5A-F).

As seen in Figure 6A, $C_{\text{PDC OUT}}$ for the filter bag collector of FC3-UP decreased more or less monotonically over the entire particle size range (curves with solid and open circles). The aerosol concentration measured at $t=1$ to 2 min was about 100 times lower than the one measured immediately after dust loading. During the next 4 min, $C_{\text{PDC OUT}}$ further decreased about four times. From $t=6$ to 61 min, it decreased by an additional factor of about 2. A similar sharp decrease of the aerosol concentration at the filter bag outlet was measured for FC4-CAN during the second minute after loading (Figure 6B). In this case, in contrast to the data for FC3-UP (Figure 6A), the aerosol concentration $C_{\text{PDC OUT}}$ for particles smaller than $1.0 \text{ }\mu\text{m}$ decreased more rapidly with particle size. During the first minute after dust loading and throughout the rest of the experiment, considerably lower aerosol concentrations for particles above $3.0 \text{ }\mu\text{m}$ were registered at the filter bag outlet of FC4-CAN than at the filter bag outlet of FC3-UP. At the end of the experiment, only particles smaller than $0.7 \text{ }\mu\text{m}$ were reentrained from the filter bag of FC4-CAN.

With both cyclonic collectors (Figures 6C and D) similar decreases in $C_{\text{PDC OUT}}$ were registered during each 60-min test. However, it can be seen that fewer particles of size larger than $2.0 \text{ }\mu\text{m}$ were reentrained from the cyclone of CC2-CAN than from the cyclone of CC1-CAN; that is, cyclone CC2 retained more of the large particles.

The data for the wet collectors (Figure 6E and F) show that during the second minute after dust loading $C_{\text{PDC OUT}}$ decreased more for collector WC1 than for collector WC2. The reverse was observed between the sixth and sixty-first minutes: $C_{\text{PDC OUT}}$ decreased more for wet collector WC2, resulting in almost the same $C_{\text{PDC OUT}}$ levels at the end of the experiment for both wet collectors. In vacuum cleaner WC1-CAN more of the larger particles

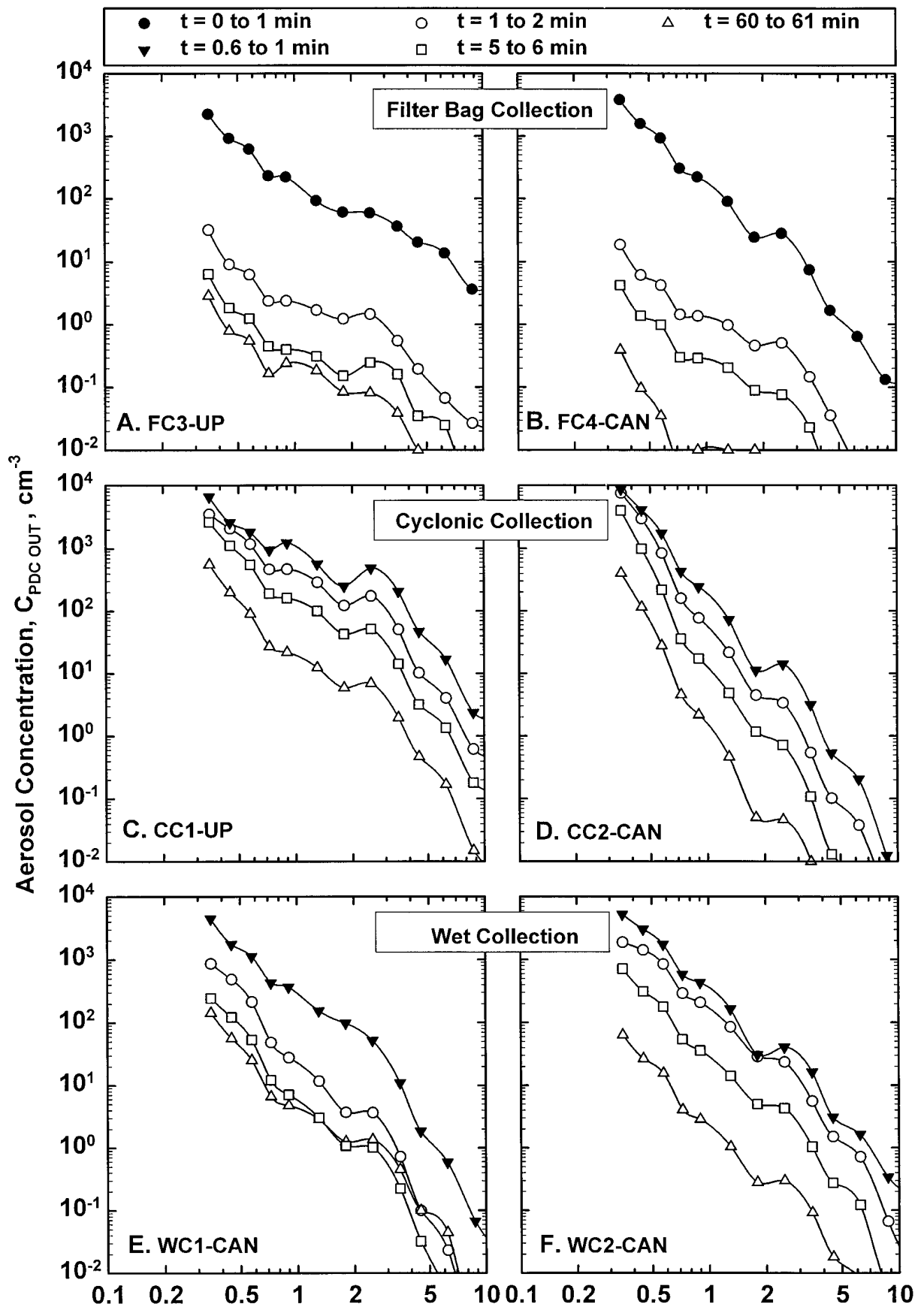


FIGURE 6. Size distributions of particles reentrained from different primary dust collectors at different times after loading with 5 g of Arizona road test dust

($d_p > 2.0 \mu\text{m}$) were reentrained during the sixty-first minute than during the sixth minute. This is probably due to the decreased level of water in the collector of WC1-CAN.

CONCLUSIONS

Comparison of different primary dust collection methods employed in vacuum cleaners has shown that the same high initial collection efficiency can be achieved by either filter bag, cyclonic, or wet dust collection. For each type of collection device, the collection efficiency depends on the design of the collector. In general, the collection efficiency of cyclonic and wet collectors decreases more significantly than that of bag filters when the primary collector and other dust collection components become loaded with dust and the airflow rate through them decreases. All of the tested cyclonic and wet collectors were found to reentrain already collected particles. The amount of reentrainment was lowest for filter bags.

Based on the limited number of vacuum cleaner models in this study, one cannot conclude that one method is consistently superior over the others. On the other hand, differences in collection efficiency curves of individual models within and between method types were discernible and, in most cases, significant. Preference of one type of vacuum cleaner over another also depends on the specific design of the vacuum cleaner, including parameters such as weight, ruggedness, ease of operation, and the number of filtration elements.

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