

OZONE-REMOVAL EFFICIENCIES OF ACTIVATED CARBON FILTERS AFTER MORE THAN THREE YEARS OF CONTINUOUS SERVICE

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ABSTRACT

This paper evaluates the efficiency with which commercial charcoal filters remove ozone. Three different applications have been examined: a test plenum, an air handler providing outside air to a Class 100 clean room, and a plenum downstream of an air handler providing outside air to another Class 100 clean room. After 37 months, the charcoal in the test plenum has decreased in removal efficiency from 95% to 90%. After 37 months, the charcoal servicing the first clean room has decreased in efficiency from 85% to 60%. After 24 months, the charcoal servicing the second clean room is still removing 95% of the ozone in the airstream. The charcoal filters associated with the test plenum and the second clean room are better protected from submicron particles than those associated with the first clean room. The accumulation of fine particles on the charcoal appears to influence service life. This work is an extension of the preliminary results (20 months of service) that were reported for the filters associated with the test plenum and the first clean room (Weschler et al. 1993).

INTRODUCTION

Ground-level ozone (O_3) has both acute and chronic health effects (Lippmann 1989). It also can contribute to the damage of sensitive materials, including cultural artifacts (Shaver et al. 1983) and electronic equipment (ISA 1985). The National Ambient Air Quality Standard (NAAQS) for ozone is 120 parts per billion (ppb). In 1989, 67 million people lived in areas that exceeded this standard (NRC 1992). These figures reflect the fact that most major metropolitan regions in the continental United States exceed the NAAQS.

Indoor settings offer some protection from outdoor ozone, but the amount of protection decreases with increasing air exchange rates. Indoor O_3 concentrations approach 50% of outdoor levels at air exchange rates on the order of three to four air changes per hour (ACH) (Weschler et al. 1989), depending on the rate at which O_3 is scavenged by

indoor surfaces. At higher air exchange rates, indoor levels are an even greater fraction of outdoor levels. If the recommendations presented in ANSI/ASHRAE 62, *Ventilation for Acceptable Indoor Air Quality* (ASHRAE 1989), are followed, high air exchange rates are expected in locations where the occupant densities are high (e.g., classrooms, conference centers, auditoriums, theaters, restaurants, transportation waiting areas, etc.). High air exchange rates also are encountered in buildings that use direct evaporative cooling. Indeed, a recent study by Stock and Venso (1990) reports indoor O_3 concentrations that are a large fraction of outdoor levels in such buildings. Additionally, large air exchange rates are encountered in facilities that use high velocity exhaust hoods (e.g., semiconductor and biotechnology laboratory buildings).

If ozone can be removed from the ventilation air, it is possible to have elevated air exchange rates without concomitant elevated indoor/outdoor (I/O) ozone ratios. Charcoal filters have been advocated for such applications. However, there is a scarcity of literature evaluating charcoal's ability to remove ozone from an airstream. Although there are studies that have measured indoor and outdoor ozone levels in museums that contain carbon filters in the heating, ventilating, and air-conditioning (HVAC) systems (Cass et al. 1988), the authors know of only one extensive study explicitly designed to measure the ability of charcoal to remove ozone from ventilation air (Shair 1981). Since May 1990, the authors have been evaluating commercial charcoal filters for the removal of O_3 in buildings with mechanical ventilation systems. This paper updates results presented in Weschler et al. (1993). In that paper, measured removal efficiencies were reported for ozone (and other pollutants) for a test plenum and an actual facility employing charcoal filtration. Those results covered the first 20 months of charcoal use. In this paper, ozone-removal efficiencies are presented for the same filters after they have been in continuous use for more than 37 months. Results also are presented for an additional test site—a facility where charcoal filters have been in use for 24 months.

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EXPERIMENTAL

Test Plenum

The test plenum is approximately 7.5 ft (2.3 m) long. The first five feet (1.5 m) are rectangular (24 in. by 12 in. inner diameter [i.d.]). The next foot is cylindrical, tapering from the rectangular section to the final section, which is 1.5 ft (.46 m) long and 14 in. (.36 m) in diameter. The average airflow through the plenum is 600 cfm (0.28 m³/s). The plenum contains 30% particulate filters, followed by 85% filters (ASHRAE dust-spot rating, ANSI/ASHRAE 52.1-1992 [ASHRAE 1992]). Downstream of the particulate filters is a "half" filter cell that contains six individual carbon panels arranged in a zig-zag configuration within the 24-in. by 12-in. housing. Each panel (24 in. by 29 in. by 1 in.) holds 7.5 lb (3.4 kg) of virgin coconut shell activated carbon (4 × 8 mesh) rated at 60% wt carbon tetrachloride activity (ASTM 3467-89). The test duct was initially operated with and without charcoal filters. Since mid-August 1990, the charcoal filters servicing the test plenum have been in continuous use. Ozone concentrations have been measured upstream (at the intake of the test duct) and downstream (two inches beyond the charcoal filters).

Upstream of the test plenum, an ozone generator and a small mixing fan were used to occasionally elevate ozone concentrations above ambient levels. Ambient indoor ozone, with no deliberate additions, also has been used to evaluate the removal efficiencies.

Clean Room #1

Clean room #1, a Class 100 device-fabrication facility, is located at an office-laboratory complex in Red Bank, New Jersey, approximately 27 air-miles from Manhattan and 6.5 air-miles west of the Atlantic Ocean. This clean room has a floor area of 4,543 ft² (423 m²), and indoor air is exchanged with outdoor air at a rate of 30 air changes per hour (ACH). Following the initial benchtop studies, 24 "half" filter cells (each containing 45 lb [20 kg] of activated carbon) were installed in the air-handling unit servicing clean room #1. This air-handling unit treats *only* outside air; no recirculated air passes through the unit. The airflow through this unit is 21,700 cfm (10.2 m³/s). Filters with ASHRAE dust-spot ratings of 30% were installed upstream of the carbon filters, and filters with a rating of 85% were installed downstream of the carbon filters. The installation occurred on July 20, 1990. In the course of this study, O₃ concentrations were simultaneously monitored inside clean room #1 and outdoors.

Clean Room #2

Clean room #2, a Class 100 lithography facility, is located within the same office-laboratory complex as clean room #1. It is significantly smaller than the other facility,

with a floor area of 352 ft² (33 m²). The air exchange rate is high, 64 ACH, reflecting the use of high-velocity exhaust hoods in a relatively small room. In September 1991, two "full" filter cells (each containing 90 lb [41 kg] of activated carbon) were installed in the plenum that provides outdoor air to this facility. The volumetric flow rate through these filters is 3,000 cfm (1.4 m³/s). Filters with an ASHRAE dust-spot rating of 30%, followed by filters with a rating of 85%, as well as cooling coils, are located upstream of the carbon filters. O₃ concentrations were measured a few inches upstream and downstream of the charcoal filters.

Ozone Measurements

The sampling details for ozone have been presented elsewhere (Weschler et al. 1989). In brief, ozone concentrations were measured with ultraviolet (UV) photometric analyzers (wavelength: 254 nm; range: 0 to 500 ppb; precision: ±1% or 1 ppb, whichever is greater). For the initial plenum studies, conducted in 1990, separate instruments were used for upstream and downstream O₃ measurements. Separate instruments also were used for the indoor and outdoor measurements associated with clean room #1. In each case, the instruments were interfaced to personal computers; data were collected at one-minute intervals and stored on magnetic media. In addition to the raw data, the average and standard deviations of the previous 30 readings (half-minute intervals) were recorded every 15 minutes. For the upstream-downstream plenum measurements made in 1993 and the analogous measurements made for the charcoal filters servicing clean room #2, a single instrument was used. This instrument was interfaced to a computer and a three-port solenoid valve; the latter was used to alternate sampling between upstream and downstream on a 15-minute cycle. At the start of each downstream or upstream cycle the sampling line was purged for 10 minutes, O₃ values were then read at 30-second intervals for the next 5 minutes and, finally, the average of the 10 readings was recorded.

RESULTS

Benchtop Studies

When commercial charcoal filters were initially installed in the plenum (May 1990), their measured removal efficiency for O₃ was 95% (Weschler et al. 1993). For challenge concentrations varying from 20 to 300 ppb, this removal efficiency was independent of O₃ concentration. After two years of service, the removal efficiency had declined only slightly, to 92%. After more than three years of service, the filters were still quite effective. Figure 1a shows upstream and downstream ozone concentrations for the week of July 9, 1993. Figure 1b shows ozone-removal efficiencies versus upstream ozone concentrations for the period from July through July 22, 1993. The removal efficiencies are calculated as $(1 - [D/U])$, where D is the downstream O₃ concentration.

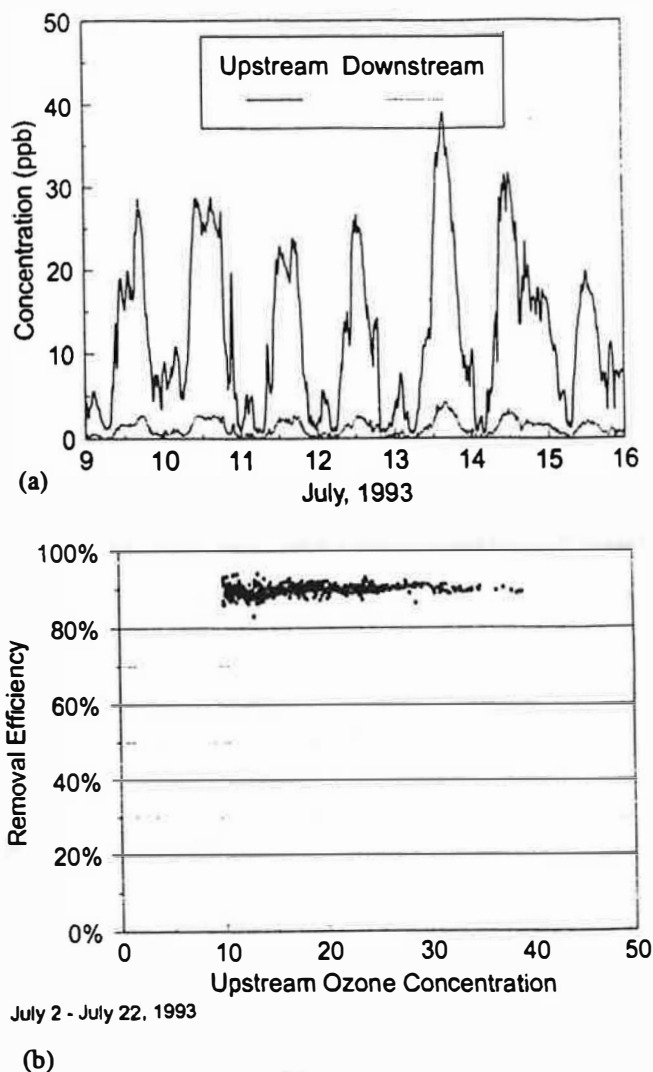


Figure 1 Evaluation of charcoal filters contained in the test plenum. Results shown are after 37 months of continuous use. (a) Upstream and downstream ozone concentrations (ppb). (b) Removal efficiencies ($1 - [D/U]$) versus upstream ozone concentrations.

tration and U is the upstream O_3 concentration. Only intervals when the upstream concentrations are not changing quickly and that are greater than 10 ppb are plotted. In Figures 1a and 1b, the upstream concentrations are simply the existing indoor ozone levels at the time of measurement. (The indoor ozone concentrations at the plenum location are a significant fraction of those outdoors [Weschler et al. 1989].) The median removal efficiency in Figure 1b is close to 90%. Hence, over a period of more than three years of continuous operation, the ozone-removal efficiency of the charcoal in the plenum has declined from 95% to 90%.

Clean Room #1 Studies

Figure 2a shows indoor and outdoor O_3 concentrations for the week of July 3, 1990, in clean room #1—prior to the

installation of the charcoal filters. At this time, indoor levels were a significant fraction of the outdoor level reflecting the large air exchange rate (outdoor air) at the facility. Figure 2b shows indoor and outdoor O_3 concentrations for the week of August 1, 1990, just after the installation of the charcoal filters. The indoor O_3 levels were not only a small fraction of the outdoor values, indicating that the charcoal filters were removing a large amount of the O_3 contained in the ventilation air. Figure 2c shows indoor and outdoor O_3 concentrations for the week of August 1, 1993—more than three years after the installation of the charcoal filters. It is apparent that the indoor levels are closer to the outdoor levels than they were in 1990; the ozone-removal efficiency of the charcoal filters at this location has declined. Figure 3 shows indoor O_3 concentrations divided by the concurrent outdoor O_3 concentration (I/O) versus the outdoor O_3 concentration for four separate periods. The first period is July 1990, prior to the installation of the charcoal filters; the second is August 1990, shortly after charcoal installation; the third is August 1991, 13 months after charcoal installation; and the fourth is August 1993, 37 months after charcoal installation. (I/O values are only plotted for those periods when the outdoor concentration is relatively constant; hence, the y-axis is labeled “steady-state I/O .”) The plots in Figure 3 illustrate that the I/O value for a given period is relatively constant over a large range of outdoor ozone concentrations (from 10 to 120 ppb). Prior to charcoal installation, the I/O ratio had a median value of 0.67 (the open circles in Figure 3). Just after charcoal installation, the I/O ratio has decreased dramatically; the median value is 0.12 (the solid circles in Figure 3). Thirteen months after charcoal installation, the I/O ratio has a median value of 0.12 (the asterisks in Figure 3). Thirty-seven months after charcoal installation, the I/O ratio has a median value of 0.32 (the squares in Figure 3). The superposition of the data points for the second and third periods (solid circles and asterisks) indicates that there was no detectable decrease in filter efficiency during the first 13 months of charcoal use. However, the subsequent increase in the I/O ratio to 0.32, after 37 months of service, indicates a moderately decreased performance (see “Discussion” section).

Clean Room #2 Studies

In September 1991, charcoal filtration was provided for a second clean room at the office-laboratory complex. The charcoal filters servicing this site were situated in such a way that O_3 concentrations could be monitored immediately upstream and downstream of the filters, similar to the benchtop experiments incorporating the test plenum. This is a more direct measurement of filter removal efficiency than trying to calculate removal efficiencies from I/O values. Due to instrument constraints, the first measurements at this site were not made until August 1993. Figure 4 shows upstream and downstream O_3 concentrations for

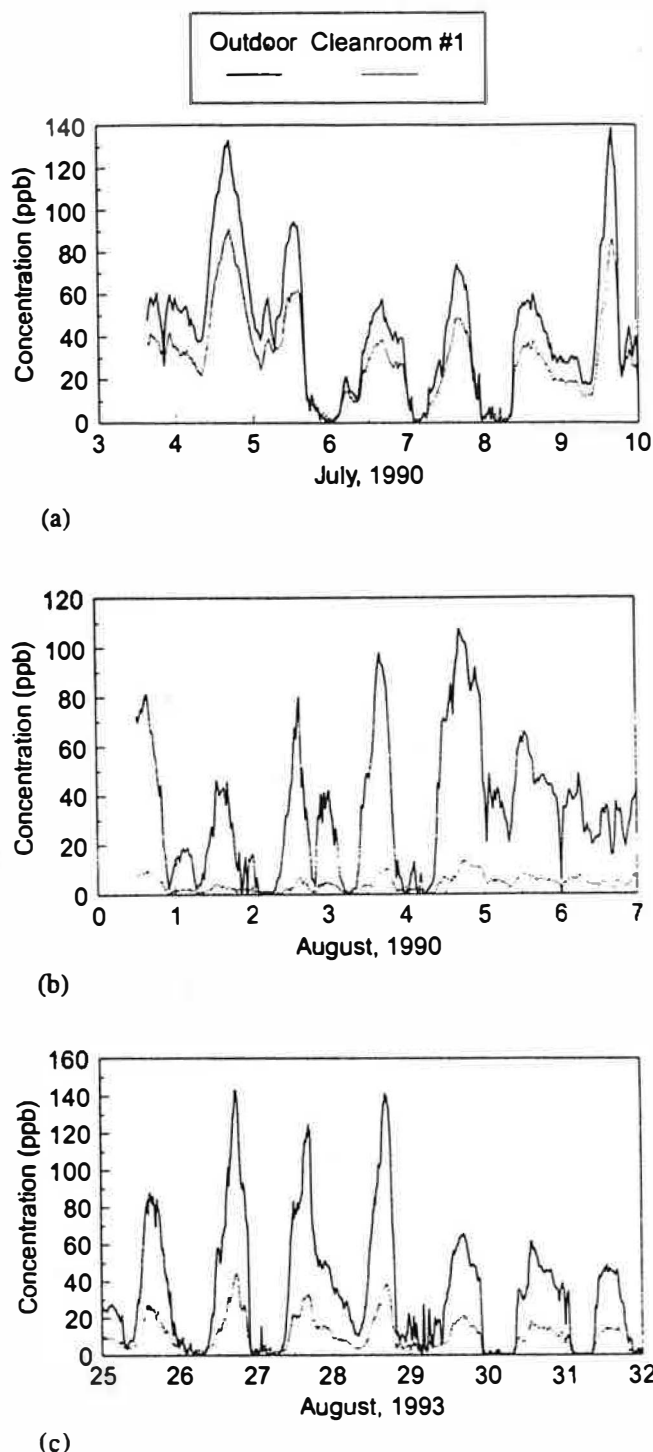


Figure 2 Outdoor (solid line) and indoor (dashed line) ozone concentrations (ppb) measured in clean room #1. (a) Shortly before charcoal filters were installed in the air-handling unit. (b) Shortly after charcoal filters were installed in the air-handling unit. (c) Thirty-seven months after charcoal filters were installed in the air-handling unit.

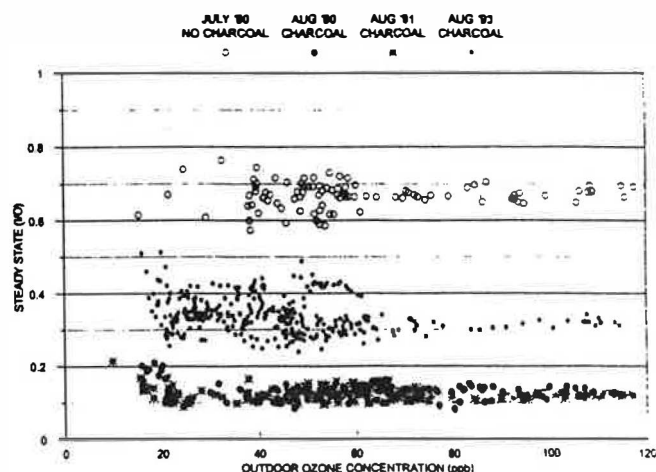


Figure 3 Steady-state indoor/outdoor ozone ratios before (○), immediately after (●), 13 months after (*), and 37 months after (■) the charcoal filters were installed in the air-handling system for the clean room.

week of September 15, 1993. It is apparent that concentrations downstream are much less than those upstream. Figure 4b shows O_3 removal efficiencies versus upstream O_3 concentrations for the period from September 14 to October 5, 1993. (As was done in the benchtop studies, the plotted points have an upstream concentration greater than 10 ppb and cover periods when the concentration is not changing rapidly.) The median value is approximately 95%. Hence, after two years of continuous service, the charcoal filters servicing clean room #2 are removing 95% of the O_3 in the airstream.

DISCUSSION

Calculated O_3 Removal Efficiencies for Clean Room #1

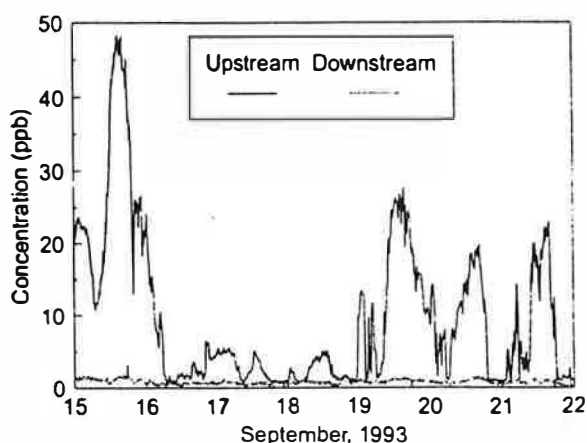
The charcoal filters servicing clean room #1 are situated in a location where it would be difficult to directly measure upstream and downstream ozone concentrations. As a substitute, simultaneous indoor and outdoor O_3 concentrations have been measured for clean room #1. From the ratio of the indoor and outdoor (I/O) ozone concentrations, it is possible to calculate the removal efficiencies for the charcoal servicing this site. The calculations are accomplished using a one-compartment mass-balance model. Given the operational parameters of the HVAC system that services clean room #1 (continuous fan operation, no recirculated air, negligible infiltration of untreated air, and no known indoor sources of O_3), the I/O value for O_3 , under steady-state conditions, is given by

$$I/O = E_x(1 - F_x)/(v_d(A/V) + E_x) \quad (1)$$

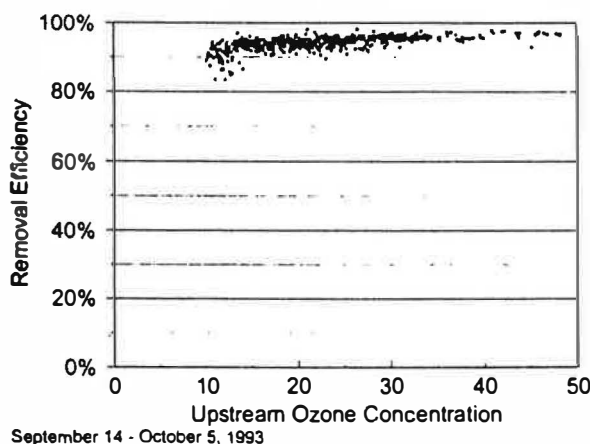
where

- E_x = air exchange rate (in clean room #1, $E_x = 30 \text{ h}^{-1}$, i.e., 30 ACH);
- F_s = fractional efficiency of the carbon filters for the removal of O_3 ; and
- $v_d(A/V)$ = rate at which O_3 is removed by indoor surfaces (the product of the deposition velocity and the surface-to-volume ratio); in clean room #1, the measured value is $2 \times 10^{-3} \cdot \text{s}^{-1}$ or 7.2 h^{-1} (Nazaroff et al. 1993).

As outlined in the "Results" section, Figure 3 presents steady-state I/O values for ozone in clean room #1 for different periods in the service life of the charcoal. Substituting these values in Equation 1 yields removal efficiencies, F_s , for each of these periods. Immediately after charcoal



(a)



(b)

Figure 4 Evaluation of charcoal filters servicing clean room #2. Results shown are after 24 months of continuous use. (a) Upstream and downstream ozone concentrations (ppb). (b) Removal efficiencies ($1 - [D/U]$) versus upstream ozone concentrations.

was installed at this location, the calculated removal efficiency was 85%. After 13 months of service, there had been no detectable change in the removal efficiency; it was still 85%. However, in the next 24 months of service, the calculated removal efficiency declined from 85% to 60% (i.e., after 37 months of continuous service, the removal efficiency was 60%).

Comparisons Among the Three Studies

Table 1 lists the measured and calculated ozone-removal efficiencies, at different times, for the charcoal filters in the test plenum, as well as the charcoal filters servicing clean rooms #1 and #2. After 37 months of service, the removal efficiency of the filters in the test plenum has decreased only slightly, from 95% to 90%. On the other hand, the filters servicing clean room #1 have decreased in efficiency from 85% to 60% over a similar 37-month interval. In the case of clean room #2, the only measured value for the removal efficiency is after 24 months of service. This value, 95%, is equal to that measured in the plenum when the charcoal filters were first installed. Presumably, the removal efficiency of the filters servicing clean room #2 was close to 95% immediately following installation (i.e., similar to those in the test plenum) and the efficiency has not decreased significantly in the intervening two years of continuous use.

In comparing these results, it is important to appreciate varying factors that may affect the efficiencies and service lives of the charcoal filters. Table 2 summarizes two such factors: the normalized airflow (i.e., the airflow per unit mass of charcoal) and the position of the charcoal filters relative to other elements in the air-handling system.

The normalized airflows vary from 13.3 cfm/lb ($0.014 \text{ m}^3/\text{s} \cdot \text{kg}$) of charcoal for the filters in the test plenum, to 20.1 cfm/lb ($0.021 \text{ m}^3/\text{s} \cdot \text{kg}$) for the filters servicing clean room #1, to 16.7 cfm/lb ($0.017 \text{ m}^3/\text{s} \cdot \text{kg}$) for the filters servicing clean room #2. Hence, during the same length of service, a pound of charcoal in the air handler for clean room #1 is exposed to one-and-a-half times more air than a pound of charcoal in the test plenum. This may partially explain the observation that the filters servicing clean room #1 have decreased in efficiency faster than those in the test plenum. Furthermore, because of the higher flow rate per unit mass of charcoal, the amount of time that filtered air is in contact with the surface of the charcoal is proportionately less for clean room #1 compared to the test plenum. The decreased contact time, coupled with some filter bypass for the 24 "half" filter cells servicing clean room #1, may explain the difference in initial removal efficiencies between clean room #1 and the test plenum (85% versus 95%).

The position of the charcoal filters relative to the particulate filters is important since soiling of activated carbon filters by submicron particles can significantly degrade filter performance (Raber 1991). The air entering the test plenum is indoor air that has already passed through

TABLE 1
Ozone-Removal Efficiencies

Time in Service	Test Plenum	Cleanroom #1*	Cleanroom #2
0 months	95%	85%	-
13 months	-	85%	-
24 months	92%	-	95%
37 months	90%	60%	-

* Calculated from measured indoor/outdoor ratios using Equation 1.

the building's particulate filters; this air then passes through 30% and 85% particulate filters associated with the plenum (see Table 2) before encountering the charcoal. The air entering the air handler for clean room #1 is untreated outdoor air and subsequently passes through only 30% particulate filters before encountering the charcoal; the charcoal filters are located upstream of the 85% filters and the cooling coils (see Table 2). Hence, the charcoal filters servicing clean room #1 are continuously exposed to a much higher concentration of submicron particles than are the filters in the test plenum. This, in turn, is also expected to contribute to a faster degradation in removal efficiencies for the charcoal servicing clean room #1 compared with that in the test plenum.

In the arrangement for clean room #2, the charcoal filters are located near the end of the plenum that delivers outdoor air to the clean room, downstream of the 30% and 85% particulate filters and the cooling coils (see Table 2). The removal efficiency of the charcoal filters has remained quite high (95%) after 24 months of service. Presumably, this reflects efficient removal of fine particles upstream of the charcoal filters and a lower normalized flow rate than that experienced by the filters in the air handler for clean room #1. It will be instructive to monitor the removal efficiency of these same filters after they have been in service for 37 months.

Given that the filters for clean room #2 are downstream of the cooling coils, the relative humidity of the airstream passing through these filters tends to be quite high during the summer. When the warm, humid summer air is cooled to 58°F (16°C), the relative humidity approaches 100% immediately upstream of the charcoal filters. The effect of the elevated humidity on O₃ removal efficiency has not been determined. However, as will be discussed in a future paper, the elevated humidity is expected to decrease the removal efficiency for volatile organic compounds and increase the removal efficiency for sulfur dioxide.

There is an additional difference among these three charcoal installations. The filters in the test plenum experience a relatively constant temperature (70°F to 74°F) throughout their service life. The filters in the air handler

TABLE 2
Normalized Airflows through Charcoal Filters and Position of Charcoal Filters Relative to Particulate Filters and Cooling Coils

	Airflow/Weight of Charcoal	Position of Charcoal Filters
Test Plenum	13.3 cfm/lb	30%, 85%, charcoal
Cleanroom #1	20.1 cfm/lb	30%, charcoal, 85%, cooling coils
Cleanroom #2	16.7 cfm/lb	30%, 85%, cooling coils, charcoal

for clean room #1 experience variable outdoor temperatures (-5°F to 100°F). The filters that service clean room #2 experience a constant temperature of 58°F since they are situated downstream of the cooling coils that condition the supply air. At present, we do not know if these different (in relation to temperature) environments measurably influence the ability of charcoal filters to remove O₃.

Comparisons with Other Studies

The authors are aware of only one other extensive evaluation of charcoal filters for the removal of O₃. This study was conducted by Shair (1981) and used the same type of commercial charcoal filters employed in the current study. The charcoal filters were installed in an "auxiliary filtration system" located upstream of the main ventilation system that serviced a laboratory on a university campus in California. To extend the life of the charcoal filters and conserve energy, outdoor air passed through the auxiliary system only when the outdoor ozone concentration exceeded 80 ppb; at other times, the outdoor air passed directly into the main ventilation system. As a result of this arrangement, the charcoal filters were in service for about 1,200 hours per year.

The auxiliary filtration contained nine "full filter cells" of charcoal (810 lb [367 kg]); the airflow through the charcoal filters was 14,000 cfm (6.5 m³/s); hence, the normalized airflow was 17.3 cfm/lb (.017 m³/s·kg) of charcoal. This is less than the normalized airflow experienced by the charcoal servicing clean room #1 (20.1 cfm/lb [.021 m³/s·kg]) and close to the normalized airflow experienced by the charcoal servicing clean room #2. The only particulate filters upstream of the charcoal filters were 30% filters. As previously noted, this arrangement provides little protection from soiling by fine-mode particles. In this regard, the arrangement resembles that for the filters servicing clean room #1 and differs significantly from that for the test plenum or clean room #2 (see Table 2).

The initial O₃ removal efficiency measured in Shair's study was 95%. At the end of the first, second, and third years of operation, the removal efficiencies were 95%, 80%,

and 50%, respectively. These values are similar to those measured for the filters servicing clean room #1 (see Table 1). In both cases, no significant decrease in performance was observed during the first year of operation. After three years of operation, the relative decrease in removal efficiency was slightly greater in Shair's study (95% to 50%) than for clean room #1 (85% to 60%).

Despite these similarities, there are two important differences between these trials, and each is expected to affect filter life. First, the charcoal filtration system in the California laboratory was only operating 1,200 hours per year, whereas the filtration systems in the current study were operating 8,760 hours per year. Second, Shair's filtration system is located in Pasadena, California; the current system is located in Red Bank, NJ. Compared with Red Bank, Pasadena has much higher airborne concentrations of fine particles and various organic compounds (especially during the time when Shair's studies were conducted—1975-1978). The service life of activated charcoal filters is affected by the accumulation of fine particles, semi-volatile organic compounds, and volatile organic compounds in the charcoal's pores. (Total exposure to ozone is not expected to have a major effect on filter life.) These two differences—yearly operating hours and pollutant levels—apparently counteract one another, with the net result that the observed service lives are comparable.

It is significant that in both the California study and the clean room #1 study, the charcoal filters had only marginal protection from fine particles. In the cases of the test plenum and clean room #2, the additional protection from fine particles (85% particulate filters) appears to have significantly slowed the decline in removal efficiency of the charcoal filters.

Recently, a report was issued that describes the ability of chemically treated filters to remove ozone and other gas-phase pollutants (Kelly and Kinkead, 1993). The filters evaluated were dry processed carbon composite (DPCC) adsorbers "of both the 1413 and 1073 designations. . . . The former incorporate reagents specific for the removal of formaldehyde; the latter incorporate reagents specific for the removal of sulfur dioxide, nitrogen dioxide and ozone." These filters were arranged in series (1073 followed by 1413) in a test plenum. During an 80-hour test, the filters were challenged with a mixture of pollutants, including O_3 . The upstream O_3 concentration averaged 118 ppb during the 80-hour test. The downstream O_3 concentration was not statistically different from zero. Hence, in this 3.3-day test, the filters demonstrated a high removal efficiency for O_3 "even at very low contaminant levels." This study was not designed to evaluate filter life. However, the authors note that there was no loss in efficiency during the test. The chemically treated filters depend on irreversible chemical reactions for the removal of ozone and, hence, these results cannot be directly compared with those of the current study. However, this is another example of successful O_3 removal at challenge concentrations typical of polluted urban areas.

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CONCLUSIONS

The efficacy of charcoal filters for O_3 removal has been evaluated in benchtop studies and in two separate air-handling systems for Class 100 clean rooms (clean rooms #1 and #2). The results demonstrate that commercial charcoal filters, properly sized, can efficiently remove O_3 from the outdoor air in mechanically ventilated buildings. After 37 months of continuous use, charcoal filters in a test plenum remove 90% of the O_3 in the airstream (initial efficiency—95%). After the same length of time, charcoal filters servicing clean room #1 remove 60% of the O_3 in the airstream (initial efficiency—85%). In the case of clean room #2, charcoal filters continue to remove 95% of the O_3 in the airstream after 24 months of continuous service. In each application, the removal efficiencies are independent of O_3 concentrations, which range from 20 to 140 ppb. These results are consistent with those reported in an earlier study by Shair (1981).

The effective service life of the charcoal filters is expected to depend on both the rate at which air flows through the charcoal and the rate at which airborne contaminants, such as submicron particles, accumulate on the adsorption media. Together these factors shorten the service life of the charcoal filters in the air handler of clean room #1 compared with those in the test plenum; the filters for clean room #1 process a greater volume of air per unit mass of charcoal and are not as efficiently protected from submicron particles as those in the test plenum. In contrast, the filters servicing clean room #2 are better protected from soiling by submicron particles than those servicing clean room #1.

In metropolitan regions with severe photochemical pollution, charcoal filtration offers an effective means of controlling indoor O_3 , especially in facilities with high air exchange rates. The studies described in this paper will continue in an effort to better understand the factors that influence the service life of charcoal filters. The authors are also in the process of updating the measurements of removal efficiencies for selected volatile organic compounds at each of these charcoal installations.

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DISCUSSION

Bill Mele, Manager of Technical Services, Super-Tech Filter, Denver, CO: With reasonable particulate prefiltration, the efficiency of the carbon for catalytic removal of O₃ was apparently unaffected. Are you suggesting that the loading of the carbon by other gas-phase contaminants has no effect on O₃ removal or has the carbon been ineffective in removing or retaining these other contaminants?

Charles J. Weschler: The former—that the loading of activated carbon by other gas-phase contaminants has little effect on O₃ removal. Indeed, we know from measurements not reported in the text that, as of November 1993, the VOC loading for the charcoal servicing cleanroom #1 was 4.7% of the original charcoal weight, and the VOC loading for the charcoal servicing cleanroom #2 was 3.6% of the original charcoal weight. These loadings are close to the expected saturation level for VOCs, yet the filters continue to remove O₃ with efficiencies of 60% and 95%, respectively.

Douglas VanOsdell, RTI, Research Triangle Park, NC: You noted decreases in O₃ removal efficiency with time and attributed those decreases to fine particle blinding or similar

effects. Was enough known about pressure drop changes during the same period to distinguish between some kind of capacity change (blinding) and a buildup in pressure drop that led to increased bypassing/nonuniform flow that manifests itself as decreased efficiency?

Weschler: Yes, enough was known about the pressure drop changes to distinguish between the two possibilities presented. The decrease in O₃ removal efficiency with time was most pronounced for the charcoal filters servicing cleanroom #1. The air-handling unit that contains these charcoal filters uses gauges to monitor the pressure drops across the 30% particulate filters, the charcoal filters, and the 85% particulate filters. Over the 3+ years since the charcoal filters were installed, the largest changes in pressure drop have been associated with the particulate filters (which are replaced when the pressure drop exceeds a given value). There has been a small increase (~0.15 inches of water) in pressure drop across the charcoal filters, but not enough to cause bypass. In the case of cleanroom #2, no significant decrease in O₃ removal efficiency has been observed, so bypass/nonuniform flow is a moot point. In the case of the plenum, the

unit contains the charcoal panels in such a fashion that bypass is highly unlikely. Furthermore, as was the case for cleanroom #2, little decrease in O₃ removal efficiency has been observed.

Bruce R. Weir, Manager, Systems Applications International, San Rafael, CA: What are the potential effects of using (as Shair [1981] did) a sensor for detection of ozone and thus using the charcoal filter only when ozone levels are high?

Weschler: Shair's arrangement, in which the charcoal filters are placed in an auxiliary filtration system and this system is utilized only when the outdoor O₃ levels exceed some predefined value, extends the service life of the charcoal filters and saves energy. The former benefit is especially important if the charcoal filters are not well protected from soiling by airborne particles (see text). However, this approach requires a reliable (and hence somewhat costly) O₃ sensor, as well as available space for an auxiliary filtration system.