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Life Cycle Valuation of Gas-Phase Filters for Ozone Removal

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SUMMARY
During the development of standards such as *ASHRAE 62.1-2010* and *ASHRAE 189.1-2009*, committee discussion about the outdoor ozone concentrations that should trigger ozone filtration has been influenced by the perceived cost of ozone filtration. This work reviews several activated carbon filters currently available for ozone filtration including carbon loaded non-woven pleats, cassettes with internal V-banks, granular loaded honeycomb trays in a V-bank formation, and adsorbents extruded into open honeycomb matrices. The analysis includes a comparison of gas-phase filter properties and life cycle costs over a 4 year period. The results show that currently available ozone filtration technology may increase the ventilation air filtration system annual cost by approximately $170 to $540 USD for a 3398 m^3/hr (2000 ft^3/min) outdoor air system (with one outlier at $1900). These costs may be reasonable when considering the occupant health and productivity benefits of controlling ozone for indoor environments.

IMPLICATIONS
Ozone and related by-products are considered harmful to occupant health. This paper evaluates the additional cost of ozone filtration devices for an air handling system. The results can be used by industry standard setting organizations and end users whose objective is to control indoor exposure to elevated ozone concentrations.

KEYWORDS
Ozone Filtration, Gas-Phase Filters, Life Cycle Cost, IAQ, Indoor Environment

INTRODUCTION

Two ASHRAE standards require ozone filtration under certain conditions – *ASHRAE Standard 62.1-2010 Ventilation for Acceptable Indoor Air Quality* and *ASHRAE Standard 189.1-2009 Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings*. Both standards require ozone filtration of ventilation air when outdoor air conditions exceed limit values. *ASHRAE 62.1-2010* is less stringent, only requiring filtration when the most recent 3-year average of the fourth-highest daily maximum 8-hour average exceeds 0.107 ppm. *ASHRAE 189.1-2009* requires ozone filtration whenever the building is located in an area designated as "non-attainment" – in the United States this is when the 3-year average of the fourth-highest daily maximum 8-hour average exceeds 0.075 ppm.

One influential factor discussed within these standard body committee meetings has been the cost of ozone filtration requirements. If the ozone filtration is too stringent, it may place a financial burden on facility owners and managers that is considered excessive. Therefore, limiting the number of counties and percent of the population that must use ozone filtration limits the financial impacts of that standard. However, the United State Environmental

Protection Agency's (US EPA) National Ambient Air Quality Standards (NAAQS) monitoring station data estimates that 119 million people (39%) of the US population live in areas where the ozone concentration exceed the NAAQS and are considered as non-attainment areas (USEPA Green Book, 2010).

Ozone Filtration

Activated carbon filters (hereafter referred to as carbon) are commonly known as ozone removal filters. This is due to their relatively high capacity and operational removal efficiency for ozone. Gundel referenced the theoretical stoichiometric limit capacity of 2.7 g/g (ozone/carbon) (Gundel, 2002). That work reviewed several experimental results showing average capacities in the range of 0.2-0.34 g/g at 50% efficiency for granular carbon beds and carbon loaded non-woven pleats. These capacities were suggested to be independent of other gaseous contaminant presence. Shair performed a study on a bulk media (tray) system which operated at efficiencies equal to or greater than 50% for a three year period with intermittent use (Shair, 1981). Other studies, which will not be detailed here, have shown properly designed systems or products containing carbon to remove ozone with efficiencies greater than 50% over extended periods of time (Beko, 2007). More recent information on carbon filter ozone removal efficiency has also shown the average ozone removal efficiency of many products similar to the pleated products in this paper as above 50% (Camfil Farr). If there are concerns about the ozone filtration efficiency of a certain product, users should request performance data from the manufacturer.

METHODS – LIFE CYCLE COSTS

Filter Arrangement

The base system for the life cycle costs was a hospital system handling 3398 m^3/hr (2000 ft^3/min) using MERV 8 prefilters and MERV 14 final filters. Hospitals house sensitive populations, are typically located in urban areas, have more stringent IAQ standards than typical buildings, and are therefore more likely to apply ozone filtration. Figure 1 is a schematic of an example filtration setup including the location of potential gas-phase filters. The particulate filter location is as prescribed by *ASHRAE Standard 170-2008 Ventilation of Health Care Facilities*.

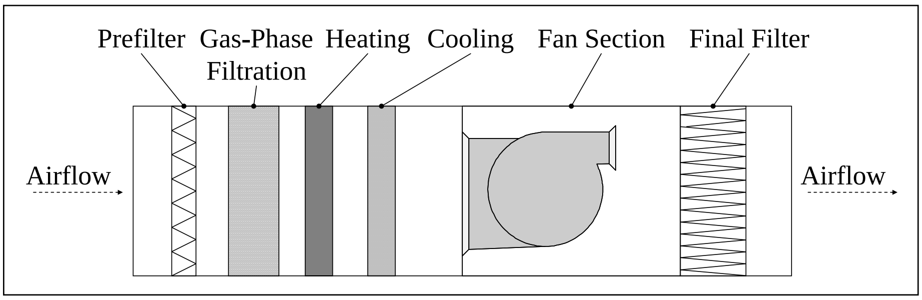

Figure 1. Schematic of an example hospital air handling system. The life cycle costs used this setup as its basis

Filtration Devices and Systems Evaluated

Carbon filtration devices marketed for ozone filtration vary from non-woven pleats containing small size carbon (20x50 mesh) to V-bank trays or cassettes containing bulk granular carbon (0.16 inch nominal particle size). The authors reviewed the products and system arrangements described in Table 1. The BASE column serves as the basis of the analysis. It has no carbon filtration and all costs are compared against that system. The products included non-woven pleated filters containing carbon, bag filters containing carbon, extrusions of carbon matrices, honeycombs filled with bulk carbon in a V-bank, and cassettes (modules) holding V-banks of bulk carbon. They are arranged in order of increasing carbon content representing 3398 m^3/hr (2000 ft^3/min) systems. Each system arrangement includes a MERV 8 pre-filter and MERV 14 final filter or a carbon filter which can also fulfil one of those purposes.

The carbon pleat and carbon bag filters of Table 1 are combination filters with particulate and gaseous contaminant removal capabilities. The carbon matrix, honeycomb V-bank, and cassette V-bank filters are not combination filters intended solely for the removal of gaseous contaminants. They cannot serve as a particulate filters.

Table 1 – Carbon Filter Products & Systems Evaluated (each system provides 3398 m^3/hr (2000 ft^3/min))

Group	**Property**	**BASE**	**51 CP**	**102 CP**	**533 CB**	**305 CP**	**51 CM**	**102 CM**	**305 HC**	**457 CV**
System Overview	Prefilter [D]	STD (8)	-	-	STD (8)	-	STD (8)	STD (8)	STD (8)	STD (8)
	Gas-Phase [D]	-	GPF (7)	GPF (7)	GPF (13)	GPF (8)	GPF (-)	GPF (-)	GPF (-)	GPF (-)
	Final Filter [D]	STD (14)	STD (14)	STD (14)	-	STD (14)	STD (14)	STD (14)	STD (14)	STD (14)
Carbon Filter Product	Carbon (kg)	-	0.8	1.2	1.6 [H]	3.5	3.9	9.8	10.9	27.2
	Depth (mm)	-	51	102	533	305	51	102	305	457
	Hardware [E]	-	-	-	-	-	Frame	Frame	Frame	Housing
	Life (months)[F]	-	1.4	2.1	2.8	6.2	6.8	17.2	19.2	47.9
Filter Prices [A]	Prefilter	A	-	-	A	-	A	A	A	A
	Gas-Phase	-	C	1.2C	12.7C	7.4C	4.2C	7C	4.4C	12.8C
	Final Filter	13.4A	13.4A	13.4A	-	13.4A	13.4A	13.4A	13.4A	13.4A
	Hardware	-	-	-	-	-	B	B	B	11.5B
Pressure Drops (Pa) [B]	$Pre_{initial}$	82	-	-	82	-	82	82	82	82
	Pre_{final}	249	-	-	249	-	249	249	249	249
	Gas-Phase $_{initial}$	-	90	75	139	107	75	149	62	87
	Gas-Phase $_{final}$	-	299	249	374	374	75	149	62	87
	$Final_{initial}$	149	149	149	-	149	149	149	149	149
	$Final_{final}$	374	374	374	-	374	374	374	374	374
	System Operating [G]	366	388	379	361	426	441	516	428	453
Replacement Labor (hours)[C]	Prefilter	0.5	-	-	0.5	-	0.5	0.5	0.5	0.5
	Gas-Phase	-	0.5	0.5	0.25	0.5	0.25	0.25	0.25	1.0
	Final Filter	0.25	0.25	0.25	-	0.25	0.25	0.25	0.25	0.25

Abbreviations for filter types are as follows: CB = Carbon Bag Filter, CM = Extruded Carbon Matrix Filter, CP = Carbon Pleat Filter, CV = Cassette V-Bank, HC = Honeycomb V-bank. All properties shown in the table above are from manufacturer's literature or from calculations stated in the footnotes.

[A] Actual filter prices are not provided to protect manufacturers. Filter prices used are typical prices for filters to handle 3398 m^3/hr (2000 ft^3/min) obtained by contacting sources of each material on the open market.

[B] Pressure drops are at 500 feet per minute (fpm)

[C] System is a 3398 m^3/hr (2000 ft^3/min) housing (one 610x610 mm filter). The filter replacement schedule allows the final filter change out at the same time as prefilters and therefore does not need any additional time for reaching the location of the air handler. Thus, the labor for the final filter is less.

[D] STD indicates a standard pleat prefilter or standard minipleat final filter. GPF indicates the gas phase filter (filter with carbon). In some cases, the gas-phase filter (GPF) also serves as the system prefilter or system final filter. The MERV is indicated in parenthesis.

[E] Frame indicates the need for a standard frame and clips; housing indicates the need for a front access housing. It is assumed that the existing air handler has space for these items.

[F] Annual Carbon Consumption: 6.8 kg (15.03 lb). Based on average ozone concentrations of 0.035 ppm in cooler months and 0.05 ppm in warmer months for a relatively clean environment (Weschler, 2000). Considered constant volatile organic compound (VOC) concentration of 50 microg/m^3. Carbon capacities were 30% by weight for ozone based on work in VOC controlled and non-VOC controlled studies which suggested VOC concentrations do not impact the ozone capacity (Gundel, 2002). The carbon capacity for VOCs was 50% by weight to estimate the time at which the carbon may become saturated with VOCs and must be removed from service. The shorter of the two was used to estimate the lives shown here.

[G] System Operating pressure drop is the total system initial pressure drop plus one third of the difference between initial and final pressure drops. This mimics the pressure drop encountered by the system during most of the filter life.

[H] Carbon mass based on 250 g/m^2 loading estimated on filter

Assumptions

The life cycle valuation used the assumptions in Table 2. The system size was a 3398 m^3/hr (2000 ft^3/min) system running 24 hours per day, 365 days per year. The electricity rate, inflation percentages, motor efficiency, drive efficiency, and fan efficiency are as displayed. The energy requirements for each system were calculated based on the system operating pressure drop per Equation 1.

Table 2 – Assumptions for Life Cycle Costs

Parameter	**Value**
Airflow (m^3/hr)	3398
Efficiency – Drive (%)	90
Efficiency – Fan (%)	80
Efficiency – Motor (%)	95
Electricity Cost ($/kWh)*	0.08
Inflation – Labor (%)	3
Inflation – Media (%)	3
Inflation – Power (%)	3
Replacement Labor Cost ($/h)	25
Operating Hours (hours)	8760

* Represents an average electricity cost in the United States

$$energy\ \ consumption\,(kWh) = \frac{Q \times \Delta P \times t}{eff_{fan} \times eff_{motor} \times eff_{drive} \times 1000} \tag{1}$$

ΔP = pressure drop in Pa
eff = efficiency of fan, motor, and drive, respectively
Q = volumetric flow rate, m^3/sec
t = time in hours

RESULTS – LIFE CYCLE COSTS

The life cycle costs compared systems by an average annual cost in terms of dollars per unit of airflow (m^3/hr or ft^3/min) including the following items: energy, filter replacements, additional hardware required for the ozone filtration, filter replacement labor, and the total of all these items as “Annual Total Filtration Cost”. This was done by calculating a life cycle cost over a 4 year period and subsequently dividing by 4 to obtain an average annual cost. The cost of the BASE system using only particulate filters was subtracted from these results to obtain the “Increase over BASE,” which is the additional cost of the ozone filtration. Table 3 summarizes these results.

Table 3 – Life Cycle Cost Comparisons for the BASE and Ozone Filtration Systems – 4 Year Average

Group	Property	BASE	51 CP	102 CP	533 CB	305 CP	51 CM	102 CM	305 HC	457 CV
Airflow & ΔP	(m^3/hr)	3398	3398	3398	3398	3398	3398	3398	3398	3398
	(Pa)	366	388	378	362	425	440	515	428	452
Annual Energy	(kWh)	4419	4678	4561	4370	5130	5311	6213	5160	5461
	(\$/(m^3/hr))	0.11	0.12	0.11	0.11	0.13	0.13	0.15	0.13	0.13
Annual Filter Replacement	Prefilter	4	-	-	4	-	4	4	4	4
	Gas-Phase	-	8.6	5.7	4.3	2.0	1.7	0.7	0.6	0.3
	Final Filter	1	1	1	-	1	1	1	1	1
	Total (\$/(m^3/hr))	0.03	0.12	0.10	0.60	0.19	0.11	0.09	0.06	0.07
Annual Hardware	Additional Hardware (\$/(m^3/hr))	-	-	-	-	-	-	-	-	0.02
Annual Replacement Labor	Prefilter (hr)	0.5	-	-	0.5	-	0.5	0.5	0.5	0.5
	Gas-Phase (hr)	-	0.5	0.5	0.25	0.5	0.25	0.25	0.25	1.0
	Final Filter (hr)	0.25	0.25	0.25	-	0.25	0.25	0.25	0.25	0.25
	Total (\$/(m^3/hr))	0.02	0.03	0.02	0.02	0.01	0.02	0.02	0.02	0.02
Annual Total Filtration Cost	Total (\$/(m^3/hr))	0.16	0.27	0.24	0.73	0.32	0.27	0.26	0.21	0.24
	Increase Over BASE (\$/(m^3/hr))	-	0.11	0.08	0.57	0.16	0.11	0.10	0.05	0.08

Assumptions are as follows: 0.08 \$/kWh, Labor = \$25/hr, 3% inflation per year, Drive Efficiency = 90%, Fan Efficiency = 80%, Motor Efficiency = 95%, Operating Hours = 8760

Abbreviations for filter types are as follows: CB = Carbon Bag Filter, CM = Extruded Carbon Matrix Filter, CP = Carbon Pleat Filter, HC = Honeycomb V-bank, CV = Cassette V-Bank

DISCUSSION

The annualized total system impact of adding ozone filtration ranges from 0.05 to 0.16 \$/(m^3/hr) (0.08 to 0.27 \$/(ft^3/min)) depending on the system constraints and the filter chosen (with one outlier at 0.57 \$/(m^3/hr) or 0.97 \$/(ft^3/min)). These constraints may include available space in the air handler, available pressure loss, required efficiency, and desired maintenance schedule. The minimum value of 0.05 \$/(m^3/hr) (0.08 \$/(ft^3/min)) will cost a hospital using a 3398 m^3/hr (2000 ft^3/min) outdoor air handler approximately \$170 per year. In relationship to the overall operational cost of the air handler and the health impacts of ozone, this is reasonable.

The filter prices used in this analysis are estimated to be market sale prices. The actual market may result in different sale prices in different regions. Additionally, the life of the ozone filters (carbon filters) is affected by actual contaminant concentrations and may differ from what was used in this paper. Both of these items can cause different results than shown above. Finally, there is uncertainty in the efficiency of many gas phase filters. The references used in this paper showed many carbon filters were able to achieve efficiencies above 50% for extended periods of time. However, confirmation of ozone efficiencies should be obtained when installing filters to meet code requirements.

CONCLUSIONS

The ideal ozone control solution will have the lowest (or even zero) pressure drop penalty, site acceptable ozone removal efficiency, infinite life, and extreme ease of retrofit. No such filter exists currently and facilities must use the listed filters in this paper or similar ones to meet ozone filtration requirements. The additional system cost of such ozone filtration may range from 0.05 to 0.16 \$/(m^3/hr) (0.08 to 0.27 \$/(ft^3/min)), \$170 to \$540 USD for a 3398 m^3/hr (2000 ft^3/min) outdoor air system. Options in this range can provide a reasonable solution to meet filtration requirements in ozone nonattainment regions or other areas where it is required by code.

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