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**Cost Analysis of Activated Carbon vs. Photocatalytic Oxidation  
for Removing VOCs from Indoor Air**

by

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## ABSTRACT

A cost comparison has been conducted of 1 m<sup>3</sup>/s indoor air cleaners using granular activated carbon (GAC) vs. photocatalytic oxidation (PCO), for treating a steady-state inlet volatile organic compound (VOC) concentration of 0.3 mg/m<sup>3</sup>. The commercial GAC unit was costed assuming that the inlet VOCs had an average carbon sorption affinity. A representative model PCO unit for indoor air application was designed and costed, assuming an above-average VOC oxidation rate from the literature. The analysis shows that, for the assumptions used here, the PCO unit would have an installed cost more than 12 times greater, and an annual cost more than 6 times greater, than the GAC unit. It also suggests that a dramatic reduction in the PCO costs cannot likely be achieved solely by improvements in reactor configuration; rather, an improved catalyst would be needed, significantly increasing rates and reducing illumination requirements relative to the catalysts reported in the literature. GAC costs could increase significantly if the VOCs to be removed were more poorly sorbed than the average used in this analysis. PCO would be more competitive at higher VOC concentrations representative of industrial applications.

## INTRODUCTION

Granular activated carbon (GAC). VOCs in indoor air are varying mixtures of individual compounds, each typically present at concentrations well below 1 ppmv. While several types of air cleaners might be considered for removing VOCs from indoor air, the type most commonly assumed for removing general VOC mixtures is based on physical adsorption on GAC (1). When such a VOC air cleaner is mounted in the ducting of the heating, ventilating, and air-conditioning (HVAC) system, a typical configuration involves panel beds, commonly 1.2 to 2.5 cm thick, containing the GAC. These panels are typically arrayed across the ducting cross section in a zig-zag pattern in order to increase the panel surface area and reduce gas velocity through the panel, thus increasing gas residence time in the GAC bed and reducing pressure drop.

Several uncertainties exist regarding the long-term VOC removal performance of GAC air cleaners, and of the maintenance required in order to maintain that performance. One issue is that a GAC bed designed to remove sub-ppmv VOC concentrations could quickly become loaded to capacity (and cease to be effective) if it were exposed to many spikes in VOC levels, as might occur from repeated chemical spills, floor waxing, or idling of delivery trucks beside outdoor air intakes. Another issue is that GAC can be ineffective on VOCs having fewer than four atoms (excluding hydrogen), some of which are only weakly adsorbed on carbon. This problem could be exacerbated if the weakly sorbed compounds are in a mixture with strongly sorbed VOCs that displace them from the carbon surface. These issues could significantly impact the design of the GAC unit (i.e., the mass of carbon required), and/or the required maintenance (i.e., the frequency with which the carbon must be replaced).

For these reasons, as well as other site-specific considerations, building operators needing to control indoor VOC levels tend to favor ventilation or source management (e.g., source removal) techniques, rather than air cleaning.

Another issue with GAC units is that the sorbed VOCs are not destroyed, but simply remain on the carbon. These VOCs might ultimately be released into the environment -- into the air if the carbon is regenerated, or into a landfill.



There is extensive experience with carbon adsorption in industrial applications (2), where inlet VOC concentrations are higher and where the costs associated with operating and maintaining deep carbon beds can be absorbed. However, there is very little experience with GAC in indoor air applications, where pressure drop limitations necessitate very shallow beds, and where extensive maintenance may not be practical.

**Photocatalytic oxidation (PCO).** Dilute concentrations of aqueous or airborne organics can be oxidized over a solid semiconductor catalyst when the catalyst is illuminated by electromagnetic radiation containing the appropriate energy to cause electrons in the semiconductor to jump from the valence to the conduction band. Commonly, the selected semiconductor photocatalyst is titanium dioxide ( $\text{TiO}_2$ ), and, correspondingly, the wavelength of the radiation must be shorter than 400 nm [in the ultraviolet (UV) range]. The electron jump enhances catalytic activity, so that the photocatalyst is able to achieve -- at ambient (or near-ambient) temperature -- an oxidation reaction that could require perhaps 1,000 °C to achieve purely thermally, and 350 °C or more to achieve thermocatalytically.

PCO as a means for the oxidation of organics in aqueous and gaseous waste streams has been extensively studied over the past two decades (3, 4). The studies of gaseous streams have usually focussed on VOC concentrations in the range of 10 to 1,000 ppmv, representative of industrial waste streams. However, some recent studies have addressed the sub-ppmv levels representative of indoor air applications (5, 6), and increasing attention has been devoted to the possible utilization of PCO technology as a competitor to GAC for indoor VOC air cleaners.

A PCO air cleaner could address two of the issues raised above regarding GAC units. A PCO unit would not become saturated with organics (and become ineffective) upon repeated spikes in concentration. On the contrary, the PCO unit could well become even *more* effective (in terms of percentage VOC removal) for the duration of the spike, if the oxidation rate increases with concentration (e.g., according to first-order kinetics); the unit would then return to normal performance once the spike passed. In addition, if (ideally) the PCO unit completely oxidized the organics, there would be no secondary release of these organics into the environment.

Of course, there are uncertainties that exist regarding PCO, just as there are with GAC. The feed organics do not oxidize directly to carbon dioxide and water; the PCO process results in the production of organic intermediates, some of which can be of greater concern than the original organic. Analogous to GAC, mixtures of individual organics might interfere with the PCO unit's performance on any one compound, since the different species (and their intermediates) will be competing for sites on the catalyst surface. With the need for UV lamps in the PCO reactor, it is apparent *a priori* that the PCO reactor will be more complex and more energy intensive than the GAC unit. Assuming that the catalyst will need to be periodically regenerated and occasionally replaced, there would be a secondary waste stream from the PCO unit, as from the GAC unit.

Finally -- because PCO units represent a developmental process -- there is a greater degree of uncertainty regarding their long-term performance and costs. With GAC units, there is substantial industrial experience demonstrating the technology, even if this experience does not all directly support indoor air applications. With PCO units, there is no such extensive industrial background.

**Objective of this analysis.** The objective of the current analysis is to compare the installed costs and the annual costs of indoor VOC air cleaners based on both GAC and PCO technology, using practical hardware configurations and operating procedures that might realistically be applied in the HVAC systems of commercial buildings. This analysis is intended to suggest the costs that generally might be associated with the use of air cleaning as a method for indoor VOC removal, and the economic potential for PCO as an alternative to GAC for indoor air applications.

## GENERAL COSTING ASSUMPTIONS

The key assumptions used in this analysis, applicable to both the GAC and PCO units, are summarized in Table 1.

The conventional wisdom is that occupants typically begin perceiving indoor VOC concentrations as a problem when they reach about 0.5 to 1 mg/m<sup>3</sup>. Accordingly, the VOC generation rate assumed in Table 1 was selected such that -- with the assumed outdoor air ventilation rate -- an indoor



concentration greater than  $1 \text{ mg/m}^3$  would result when no air cleaner is operating. The air cleaner is to be designed to reduce this concentration by 85%, to  $0.3 \text{ mg/m}^3$  (about 0.07 to 0.17 ppmv) -- below the limit where the VOCs typically become perceived as a problem. This reduction is to be achieved assuming that the building air makes seven passes through the air cleaner per hour.

The VOC air cleaner is assumed to be located in the return air ducting just prior to the central air handler and coils, and to be operating at return air temperature. But it is downstream of the particulate filter protecting the air handler and coils. Thus, the pre-existing particle filter also serves to protect the charcoal and the photocatalyst panels from blinding, and is assumed to protect the catalyst and the UV lamps in the PCO unit from being deactivated by a coating of dust. For this analysis, it is assumed that the pre-existing particulate filter does not have to be upgraded to one having increased efficiency on fine particles, in order to further protect the potentially sensitive catalyst and lamps.

Commonly, particulate (and gaseous) filters for HVAC systems are sold in modules capable of handling about  $1 \text{ m}^3/\text{s}$ , and having a cross section of about 0.6 by 0.6 m. For air handlers moving greater flows, these modules are combined into banks. Accordingly, in this analysis, the costs have been estimated for air cleaners having a capacity of  $1 \text{ m}^3/\text{s}$ , and both the installed and the annual costs are expressed as cost per cubic meter per second. Scaleup to capacities larger than  $1 \text{ m}^3/\text{s}$  should be approximately linear, within the uncertainties of this analysis.

## DESIGN AND ASSUMPTIONS FOR THE GAC UNIT

The GAC unit that was costed in this analysis is illustrated in Figure 1. The illustrated configuration is representative of some units being offered commercially for indoor air applications. The cost estimates here address only the elements shown in solid lines in the figure.

The design details for this GAC unit -- along with the key assumptions used in this cost analysis -- are presented in Table 2.

The GAC unit dimensions and equipment costs are based on vendor literature and quotes (Farr Co., El Segundo, CA). Three labor hours are assumed for installation. The carbon bed is assumed to sorb 100% of the entering VOCs initially, with the bed being replaced at the point of 30% breakthrough, providing an average per-pass removal over the bed lifetime greater than the 82% that is needed to achieve the 85% reduction in zone concentration. The mass of VOC that will be removed by the bed prior to 30% breakthrough -- which will depend heavily upon the specific organic compounds and their concentrations in the entering mixture -- was estimated from limited available data on several individual organics (10, 11). The specific capacity used here --  $0.025 \text{ g VOC/g carbon}$  at 30% breakthrough -- is the capacity for 0.1 ppmv (inlet) hexane at 50% relative humidity, extrapolated from data at 0.4 ppmv reported in one study (11). The capacity for hexane appears to be at about the median for VOCs having four or more atoms (excluding hydrogen), based on limited information at inlet concentrations of 10 ppm and lower (11, 12).

Assuming a maximum acceptable loading of  $0.025 \text{ g/g}$ , the 41-kg carbon bed will have to be replaced at 3-month intervals under the conditions assumed here. Two labor hours are assumed to be required to remove and replace the carbon inside the panels. The assumption that the spent carbon can be placed in a municipal landfill (at  $\$0.10/\text{kg}$ ) appears reasonable, based on current Federal regulations (13). If, instead, the spent carbon were classified as hazardous, this disposal cost (including transport) would increase to about  $\$5.60/\text{kg}$  (disposal contractor quote).

## DESIGN AND ASSUMPTIONS FOR THE PCO UNIT

Although some firms market PCO units for industrial (and even indoor air) applications, insufficient information is available regarding these proprietary designs to enable their use in a rigorous cost analysis here. Accordingly, it was necessary to develop a reasonable "model" PCO reactor design as part of this study. The model PCO design developed here is undoubtedly different from those being offered commercially. However, the model design contains the same illuminated catalyst surface area and same amount of UV illumination that commercial units would have to contain, based on published data, and it provides fairly efficient contact between the gas stream and illuminated  $\text{TiO}_2$ . Thus, the model should represent indoor air PCO costs adequately for the purposes of this comparison.



A variety of PCO reactor configurations have been considered over the years, including: packed beds (14); fluidized beds (14, 15, 16); transport reactors (14); fiber optic cable configurations (17, 18); and what will be referred to here as "panel reactors" (5, 6, 14, 19, 20, 21, 22). The panels in the panel reactors would consist of fairly open support structures having a low pressure drop and a good optical depth, which would serve as a substrate on which the  $\text{TiO}_2$  would be deposited. The stream to be treated would flow through the panels. Among the panel structures that have been considered are: ceramic honeycombs (20), ceramic monoliths penetrated by square channels (21, 22), ceramic foams (5, 6, 19), and fiberglass mesh (23).

It was decided that the PCO unit designed here would be a panel reactor of essentially the same configuration as the GAC unit in Figure 1. The carbon bed panels shown in Figure 1 would be replaced by either ceramic foam panels or square-channeled monolith panels, coated with the catalyst. This zig-zag design provides a significant  $\text{TiO}_2$  surface area per unit reactor volume, creates a fairly low pressure drop, and is similar to filter configurations already familiar to the HVAC industry. The zig-zag panel configuration will degrade the distribution of UV radiation into the interior of the substrate. But for this estimate, it will be assumed that the optical depth into the substrate will be the same as if the panels were all vertical, an assumption favoring the PCO system.

To assess how many banks of such panels would be required to treat sub-ppmv VOC concentrations, it was first necessary to evaluate the published data regarding the kinetics for PCO of various organic compounds.

**Reaction rates.** The rate at which an organic compound will be oxidized over the catalyst depends on a large number of variables. Among these are: 1) the nature and concentration of the specific compound; 2) the intensity of UV illumination; and 3) the moisture concentration in the air stream. The rate is also dependent on the reactivity of the  $\text{TiO}_2$  catalyst being used (including the effects of any enhancing agents), and on the effectiveness with which illuminated catalyst surface is exposed to the air stream (which, in turn, is heavily dependent on reactor design).

To select an average reaction rate for reactor design in this study, data were analyzed from published experimental studies involving PCO of individual gaseous organics in low concentrations (below 500 ppm) in air streams at ambient temperature (5, 6, 16, 19, 22, 24, 25, 26, 27, 28, 29). These studies addressed differing values of the variables listed in the preceding paragraph, so that the reported results are often not directly comparable. To express the results from these different studies on comparable terms, the analysis here attempted to convert all of the results to a common form:

*the differential reaction rate at 1 ppmv of the organic compound, under an illumination of 1 mW UV per geometric  $\text{cm}^2$  of illuminated  $\text{TiO}_2$  area, expressed as  $\mu\text{mol/hr}$  of the compound oxidized per geometric  $\text{cm}^2$  of illuminated  $\text{TiO}_2$  area.*

The results of this analysis are summarized in Table 3.

The geometric square centimeters of  $\text{TiO}_2$  surface area includes only the gross surface coated by the catalyst, when the catalyst is deposited on a substrate. When pure  $\text{TiO}_2$  pellets are used, it is the gross exterior surface of spheres having the average diameter of the catalyst pellets. The geometric area does not include the internal porosity of the  $\text{TiO}_2$ , which, together with the exterior surface of the 20 nm primary  $\text{TiO}_2$  particles, provides a surface of about  $50 \text{ m}^2/\text{g}$  as supplied by the vendor (30). Nor does it include the internal porosity of the substrate.

The rate used here is normalized based on the geometric surface area, rather than on the mass of catalyst as is common in heterogeneous catalytic reactor design (31). Studies suggest that perhaps only the top  $2 \mu\text{m}$  of the catalyst layer participates in the photocatalytic reaction (32), suggesting that surface area rather than mass is a more meaningful measure of catalyst capacity. Further, only the illuminated portion of the surface area is considered, since most studies show that, at room temperature, essentially no oxidation occurs in the absence of illumination.

The various studies cited in Table 3 addressed VOC concentrations ranging between 0.3 and 500 ppmv, and illumination intensities ranging between 0.6 and  $7 \text{ mW}/\text{cm}^2$  of  $\text{TiO}_2$  area. The reaction rates shown in the table were adjusted to the reference concentration of 1 ppmv by assuming that the rate is first order with respect to the VOC concentration over this range. The rates were adjusted to the



reference intensity of  $1 \text{ mW/cm}^2$  by assuming that the rate is proportional to intensity to the power 0.6. This exponent is suggested by experience (3, 5, 19, 24) for intermediate values of intensity.

The rates in Table 3 might be in error by a factor of 3 or greater, due to the number of assumptions that had to be made in converting the literature data to the common units being used here. The more significant sources of uncertainty include:

- 1) Difficulty in estimating the total geometric catalyst surface area and the fraction that was illuminated, for studies where the catalyst was not deposited on a well-defined surface.
- 2) Use of first-order kinetics to extrapolate the various reported reaction rates to the estimated differential rate at 1 ppmv. First-order kinetics are consistent with the commonly assumed Langmuir-Hinshelwood rate equation at very low VOC concentrations. However, some investigators (5, 6, 32) have shown that -- depending upon the values of the constants in the Langmuir-Hinshelwood equation -- this first-order assumption might result in predicted rates at 1 ppmv that are low for some individual VOCs, when the data used for the extrapolation were collected at concentrations above perhaps 10 to 100 ppmv.
- 3) Neglecting the effect of moisture on the rates. Much of the data are at moisture concentrations below 8,000-16,000 ppmv, corresponding to the recommended 30 to 60% relative humidity for indoor space (7, 33). Due to data limitations, no attempt was made here to extrapolate the oxidation rates to a moisture content representative of the higher levels encountered indoors. Increasing moisture to 8,000 ppmv and above can have varying impacts on rate, depending on the specific VOC (5, 6, 16, 24, 34).

Another important limitation of Table 3 is that these data often appear to address only the rates of disappearance of the primary organic compound in the feed stream, not the rate of complete oxidation. Many studies show that the decay of some compounds often results in the formation of intermediate organics that, in turn, oxidize more slowly than the feed compound (19, 26, 28, 29). For the purposes of this PCO cost analysis, the (optimistic) assumption will be made that the rates in Table 3 represent the decomposition of the VOC all the way to carbon dioxide and water.

It will also be assumed that the presence of mixtures of VOCs will not significantly reduce the rates shown in the table for the individual compounds.

As shown in Table 3, the oxidation rates can vary by 2 orders of magnitude from one VOC to another, even among the fairly limited number of individual compounds represented on this list. The design of a PCO would depend upon the specific VOCs that are expected in the feed. If the VOC mixture in the feed is unknown or variable, as will usually be the case, one might conservatively design the PCO reactor based upon the slowest rates in the table (less than  $0.01 \mu\text{mol/hr/cm}^2$ ).

*For this analysis, a differential oxidation rate of  $0.12 \mu\text{mol/hr per cm}^2$  of illuminated  $\text{TiO}_2$  (at 1 ppmv and  $1 \text{ mW/cm}^2$ ) will be assumed for the VOC mixture. This is towards the higher end of the range in Table 3, favoring the PCO system.*

**PCO reactor design.** Based upon this reaction rate, the model PCO unit is illustrated in Figure 2. Key design features and assumptions are presented in Table 4. In the following discussion, it is assumed that the ceramic foam catalyst support panels are used, although similar results are achieved using the square-channel monolith support.

Given the inlet concentration of  $0.3 \text{ mg/m}^3$  at steady state, and assuming that the differential reaction rate decreases according to first-order kinetics as the oxidation progresses, it is computed that seven banks of catalyst panels would be required to achieve the 82% per-pass reduction that is needed.

To provide the illumination intensity of  $1 \text{ mW/cm}^2$ , UV bulbs totalling 1,500 W (input) are required between panel banks (750 W for each face of each bank), if the bulbs are 25% efficient and if the reactor walls are designed to reflect all incident radiation back onto the catalyst. A single tubular 1,500 W medium-pressure mercury bulb is located between each pair of panel banks, with the bulbs in front of the first bank and behind the seventh being operated at 750 W. In practice, multiple bulbs would be preferred between panel banks, to improve UV distribution; single bulbs were assumed to reduce costs. These 1,000-hour bulbs cost \$75 apiece, and their associated ballasts \$400 apiece (Votarc Technologies, Inc., Fairfield, CT). Less expensive, longer-lived commercial bulbs providing the needed



intensity could not be identified. The power consumption by all of the bulbs in the reactor totals 10,500 W, raising the air temperature by 9 C°. An additional 1,050 W is consumed by the ballasts.

The cost of the 2-cm-thick catalyst-coated foam panels in large quantities was derived from quotes provided by three vendors of ceramic foams (Hi-Tech Ceramics, Inc., Alfred, NY; Selee Corp., Hendersonville, NC; and Ultramet, Pacoima, CA), with and without the TiO<sub>2</sub> coating applied; and from estimates by a catalyst vendor (Degussa Corp., Ridgefield Park, NJ) for applying catalyst coatings to substrates. The cost of \$90 per panel was derived from these estimates as a reasonable figure for bulk quantities, although it does not coincide with the quote from any one vendor. This analysis assumes that the foam panels can be manufactured with the desired dimensions for this price, although structural considerations for such porous foams currently limit individual panels to smaller cross-sections and/or greater thicknesses.

No definitive data could be found suggesting the frequency with which the photocatalyst would have to be regenerated or replaced, although some research papers refer to the need for periodic regeneration. Given that the catalyst will be encountering fine dust as well as a variety of potentially deactivating gaseous contaminants, the arbitrary selection of 6 months between regenerations, and 5 years between complete replacements, was felt to be optimistic. Considering possible alternative methods of *in-situ* and off-site regeneration, a potentially optimistic estimate of 2½ labor hours (plus minimal materials and utilities) per regeneration per panel bank was derived for use here.

A particulate filter is added at the end of the PCO reactor as a safety precaution to capture TiO<sub>2</sub> particles that might be released from the panels, since TiO<sub>2</sub> dust is a potential occupational carcinogen at high concentrations. This should not be a serious threat from PCO reactors; hence, only an ASHRAE 30 pleated filter -- which would be inefficient on micron-sized particles (35) -- is included here. The filter will also protect the HVAC air handler in the event of any deterioration of the foam.

## COST RESULTS

The results of this cost analysis are summarized in Tables 5 and 6.

**Installed costs.** As shown in Table 5, the estimated installed cost for the PCO unit is over 12 times that of the GAC unit. This results from the high cost of the PCO reactor and catalyst, and from the increase in HVAC cooling capacity required to remove the heat added by the UV bulbs.

The illuminated catalyst surface area and the amount of illumination in this model reactor are based on literature data, and cannot be reduced unless the catalyst is improved. With the literature catalysts, the only apparent approach for significantly reducing model reactor costs would be to improve the foam panel configuration used in the model, providing more illuminated TiO<sub>2</sub> per unit reactor volume at lower cost. It seems doubtful that such configuration improvements could reduce the installed cost of the model PCO by a factor greater than perhaps 2. Thus, to achieve the 12-fold PCO cost reductions necessary to make PCO competitive with GAC under the assumptions used in this study, a substantial improvement in catalyst performance would be required, to achieve greater VOC destruction with less catalyst surface area (and to thus reduce the number of panel banks and the number of bulbs).

Installed costs for the GAC unit would increase dramatically if multiple carbon panel banks were required, as could be required if GAC were to be used to capture VOCs less easily adsorbed than hexane. Some VOCs having fewer than four atoms (excluding hydrogen) have a sorption capacity on carbon 1 to 3 orders of magnitude lower than that of hexane (12).

The \$9,290 installed cost of the PCO reactor, excluding catalyst, was estimated using the uninstalled cost of: seven GAC reactors, excluding carbon (33% of the installed reactor cost); eight UV bulbs and ballasts (41%); and the final particle filter (2%), based on vendor quotes (Flanders Filters, Inc., Washington, NC). The estimate for fabrication and installation, source of the greatest uncertainty, accounts for only the residual 24% of the total cost. These latter estimates were derived using the installed costs of galvanized steel ducting (36), for the connecting sections between the panel banks and for the ballast housing, and an additional 14 labor hours for sheet metal work and electrical wiring.

Labor costs for the installation (and PCO fabrication) were obtained from Means (36). The required increases in cooling capacity were estimated by modeling each of the air cleaners in different



climates using the DOE-2 building energy model (37) in an office building for which the model input files were already available (9). The incremental costs for enlarged HVAC air handlers and cooling units were estimated by computing the incremental installed cost per kilopascal of static pressure, or per kilowatt of cooling capacity, from comparing alternative units in Means. The air cleaner was charged only for the number of kilopascals or kilowatts that it adds, realizing that, in practice, increases in fan or cooling requirements can require step changes up to the next larger size of fan or cooling unit.

**Annual costs.** As shown in Table 6, the annual costs associated with the PCO unit are more than 6 times greater than those for the GAC unit. The two largest contributions to the annual PCO costs, responsible for over half of the cost, result solely from the UV bulbs: electricity, to operate the bulbs and the cooling unit that removes the bulb heat from the air stream; and bulb replacement. The primary contributor to the annual GAC costs is the replacement of the carbon.

Improved PCO reactor configurations cannot reduce the UV wattage requirement, if literature catalysts are used and if an illumination of about 1 mW per cm<sup>2</sup> of illuminated TiO<sub>2</sub> must be maintained. Only an improved catalyst, necessitating fewer square centimeters of catalyst surface area and fewer watts per square centimeter, would sufficiently reduce the bulb energy and replacement costs. Less expensive, longer-lived bulbs would also reduce replacement costs.

If the carbon replacement frequency and/or the carbon mass in the GAC unit had to be increased -- because the VOCs present in the air stream included more weakly sorbed compounds, or because frequent VOC spikes caused the organics loading on the carbon to reach capacity more rapidly -- annual GAC costs could increase significantly.

## CONCLUSIONS

1. With the assumptions used in this analysis -- including the assumption that the inlet VOCs have an average sorption affinity for the carbon and an above-average oxidation rate over the photocatalyst -- the PCO reactor has an installed cost over 12 times greater, and an annual cost over 6 times greater, than those of the GAC sorber.
2. The high costs for the PCO reactor result from the large catalyst surface area, and the illumination of this large area, that is required based on average kinetics from the literature. Improvements in reactor configuration -- to present this large catalyst surface to the air stream and the UV radiation in a more effective manner than in the model reactor used here -- can be expected to provide only moderate reductions in installed PCO costs and even lesser reductions in annual costs. Only a significantly improved catalyst, to provide faster oxidation rates with less catalyst area and less illumination, can dramatically reduce PCO costs for a given VOC.
3. Changes in the assumptions used here -- e.g., to include inlet VOCs that are more weakly sorbed on the carbon -- would lead to significant increases in costs (and/or significant reductions in performance) for either the GAC or the PCO unit.
4. PCO would become more cost competitive at high concentrations, since oxidation rates tend to increase with concentration, and the carbon bed would become loaded to capacity more quickly.

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Table 1 General assumptions used in the cost analysis.

| <u>Parameter</u>  | <u>Assumed Value</u>   |
|---|--|
| Building outdoor air ventilation rate<br>(mechanical plus infiltration) | 10 L/s of outdoor air per person (7)   |
| VOC concentration in outdoor air  | Zero   |
| Building occupancy  | 14 m <sup>2</sup> floor area per person (7)  |
| Indoor air recirculation rate through<br>air handler (and air cleaner)  | 7 air changes per hour   |
| VOC generation rate inside building                                     | 5 mg VOC/hr per m <sup>2</sup> floor area (which would<br>result in an indoor concentration of 2 mg/m <sup>3</sup> ,<br>or about 0.5 to 1.1 ppmv, in the absence<br>of an air cleaner) |
| Required VOC removal efficiency   | Air cleaner must reduce indoor concentration<br>by 85% relative to what it would have been<br>in the absence of the air cleaner  |
| Nature of installation  | New building; no retrofit costs  |
| Year of installation  | 1996   |
| Escalation (inflation) rate   | 5%   |
| Interest rate   | 8%   |
| Equipment lifetime and depreciation                                     | 10-year lifetime, straight-line depreciation   |
| Insurance and real estate taxes   | 2% of original investment per year (8)   |
| Cost of electricity   | \$0.0473/kWh plus demand charge of \$9.96/kW<br>for usage rates greater than 10 kW (9)   |
| Air cleaner operating hours   | 308 hours per month (off overnight, weekends)  |

Table 2 Design specifications and costing assumptions for the GAC unit.

| <u>Parameter</u>                              | <u>Assumed or Computed Value</u>                           |
|---|--|
| Number of activated carbon panels             | 12   |
| Dimensions of each panel                      | 0.3 x 0.6 m, 2.5 cm thick                                  |
| Total mass of granular carbon in unit         | 41 kg  |
| Total air flow through unit                   | 1 m <sup>3</sup> /s, superficial velocity 2.5 m/s          |
| Face velocity through panels                  | 0.4 m/s  |
| Total pressure drop across unit               | 250 Pa (from calculations and laboratory data)             |
| Equipment cost of GAC unit, including carbon  | \$1,100 uninstalled (vendor quote)                         |
| Cost of housing to mount unit in duct         | \$100 per m <sup>3</sup> /s uninstalled (vendor quote)     |
| Cost of replacement carbon (coconut shell)    | \$6.60/kg (vendor quote)                                   |
| Disposal of spent carbon (municipal landfill) | \$0.10/kg (typical for collection and landfilling)         |
| Inlet VOC concentration at steady state       | 0.3 mg/m <sup>3</sup> (about 0.07 to 0.17 ppmv)            |
| Outlet VOC concentration at steady state      | Zero initially; 0.09 mg/m <sup>3</sup> at 30% breakthrough |
| Mass loading of VOC (inlet 0.1 ppmv, 50% RH)  | 0.025 g VOC/g carbon, 30% breakthrough (11)                |
| Carbon replacement frequency                  | Every 3 months, at 30% breakthrough                        |



Table 3. Reaction rates for photocatalytic oxidation of various individual VOCs, expressed on a common basis, estimated from available literature data.

| <u>Compound</u>   | <u>Differential Reaction Rate at 1 ppmv*</u> | <u>References</u>  |
|-------------------|--|--------------------|
| Trichloroethylene | 0.05 - 0.2                                   | 16, 19, 26, 27, 32 |
| Formaldehyde      | 0.01 - 0.4                                   | 5, 6, 24           |
| Acetone           | 0.006  | 24                 |
| Benzene           | 0.007  | 28                 |
| Toluene           | 0.02 - 0.05                                  | 5, 6               |

\* Rate expressed as  $\mu\text{mol/hr}$  of VOC oxidized per geometric  $\text{cm}^2$  of illuminated  $\text{TiO}_2$  surface area, at a UV illumination intensity of 1 mW per geometric  $\text{cm}^2$  of illuminated  $\text{TiO}_2$ .

Table 4 Design specifications and costing assumptions for the PCO unit (ceramic foam panels).

| <u>Parameter</u>  | <u>Assumed or Computed Value</u>   |
|---|--|
| Nature of panels  | Ceramic foam, 4 pores/cm, 2 $\mu\text{m}$ $\text{TiO}_2$ coating   |
| Dimensions of each panel                                | 0.3 x 0.6 m, 2 cm thick  |
| Number of catalyst panels per bank                      | 12   |
| Total air flow through unit                             | 1 $\text{m}^3/\text{s}$ , superficial velocity 2.5 m/s   |
| Face velocity through panels                            | 0.4 m/s  |
| Inlet VOC concentration at steady state                 | 0.3 $\text{mg}/\text{m}^3$ (about 0.07 to 0.17 ppmv)   |
| Outlet VOC concentration at steady state                | 0.05 $\text{mg}/\text{m}^3$ (82% removal per pass)   |
| Reaction rate   | 0.12 $\mu\text{mol/hr}/\text{cm}^2$ illum. $\text{TiO}_2$ at 1 mW/ $\text{cm}^2$ $\text{TiO}_2$  |
| UV illumination intensity                               | 1 mW per $\text{cm}^2$ of illuminated $\text{TiO}_2$   |
| Total surface area in ceramic foam                      | 22.8 $\text{cm}^2$ per $\text{cm}^3$ of foam (6)   |
| Optical depth of foam                                   | Fraction of surface which is illuminated drops exponentially from 100% at illuminated face to near zero at 1 cm depth (6); so 38% of the total area to 1 cm depth is illuminated |
| Number of panel banks in reactor                        | 7  |
| Total pressure drop across reactor                      | 80 Pa (incl. 5 Pa across each bank, per vendors)   |
| UV bulb efficiency                                      | 0.25 W UV output (<400 nm) per W input   |
| Input power to UV bulbs (medium-pressure mercury bulbs) | 750 W per face of each 12-panel bank<br>(10,500 W total to reactor, excl. ballast)   |
| Air temperature rise caused by bulbs                    | 9 $^\circ\text{C}$   |
| Bulb lifetime   | 1,000 operating hours  |
| Cost of catalyst panels (support + $\text{TiO}_2$ )     | \$90 per panel (derived from vendor quotes)  |
| Catalyst regeneration frequency                         | Every 6 months (arbitrary)   |
| Catalyst replacement frequency                          | Every 5 years (arbitrary)  |



Table 5 Installed costs of GAC and PCO VOC air cleaners.

| <u>Cost Item</u>   | <u>Installed Cost (\$ per m<sup>3</sup>/s capacity)</u> |                 |
|--|---|-----------------|
|  | <u>GAC Unit</u>   | <u>PCO Unit</u> |
| Reactor (excluding carbon or catalyst)   | \$ 850  | \$ 9,290        |
| Initial charge of carbon or catalyst   | 470   | 7,560           |
| Enlarged central air handler (to handle increased static pressure)                                 | 60  | 20              |
| Increased cooling coil capacity (to handle added heat from enlarged air handler and from UV bulbs) | 150   | 2,010           |
|  | <hr/>   | <hr/>           |
|  | \$1,530   | \$18,880        |

Table 6 Annual costs of GAC and PCO VOC air cleaners (average over 10 years).

| <u>Cost Item</u>  | <u>Annual Cost (\$/year per m<sup>3</sup>/s capacity)</u> |                 |
|---|---|-----------------|
|   | <u>GAC Unit</u>   | <u>PCO Unit</u> |
| <i>Operating costs</i>  |   |                 |
| Electricity (for increased fan static pressure, cooling load, UV bulbs) | \$ 100  | \$ 4,890        |
| <i>Maintenance</i>  |   |                 |
| Replacement of carbon   | 1,680   | --              |
| Regeneration of catalyst  | --  | 1,760           |
| Disposal of spent carbon or catalyst                                    | 20  | ~0              |
| Replacement of UV bulbs   | --  | 2,700           |
| Replacement of PCO final filter   | --  | 20              |
| <i>Indirect expenses</i>  |   |                 |
| Depreciation of equipment (10 years)                                    | 150   | 1,130           |
| Depreciation of catalyst (5 years x 2)                                  | --  | 1,750           |
| Insurance and real estate taxes   | 30  | 380             |
| Interest on capital (installed cost)                                    | 60  | 760             |
|   | <hr/>   | <hr/>           |
|   | \$2,040   | \$13,390        |



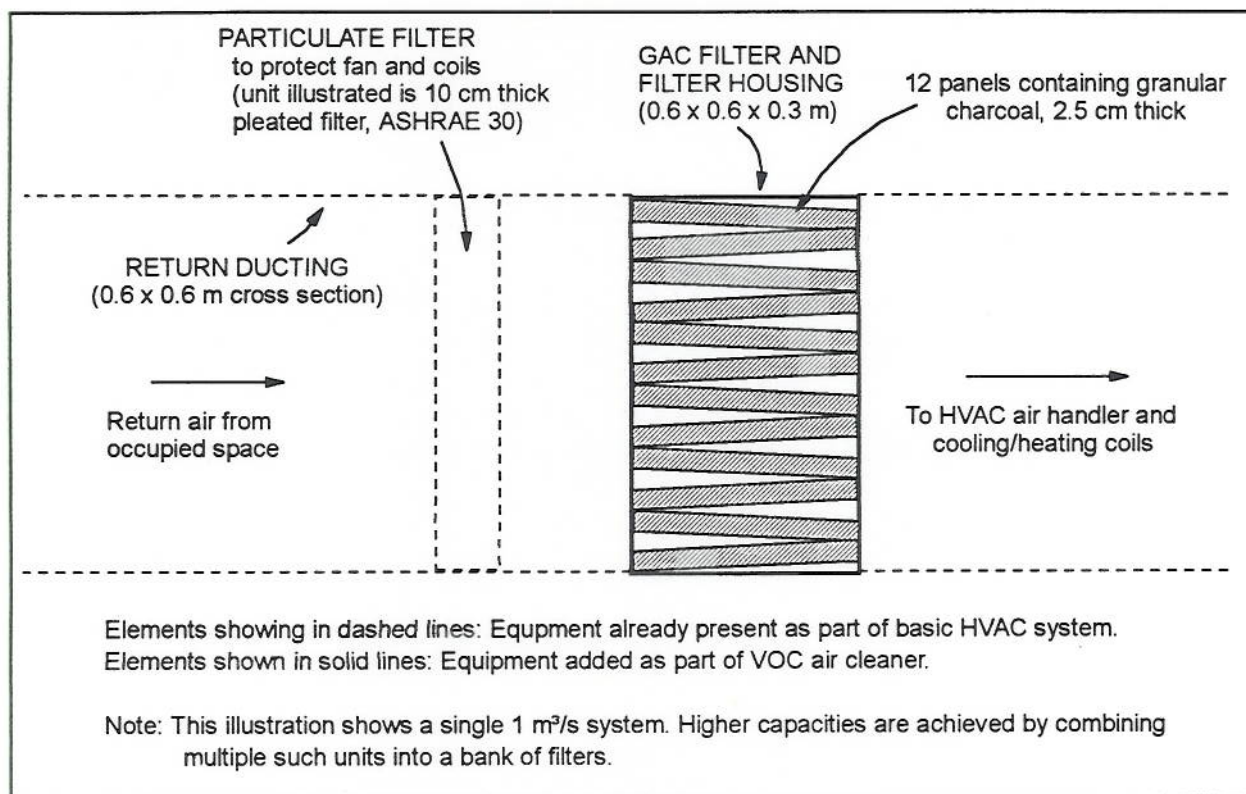


Figure 1. Granular activated carbon VOC air cleaner (side view).

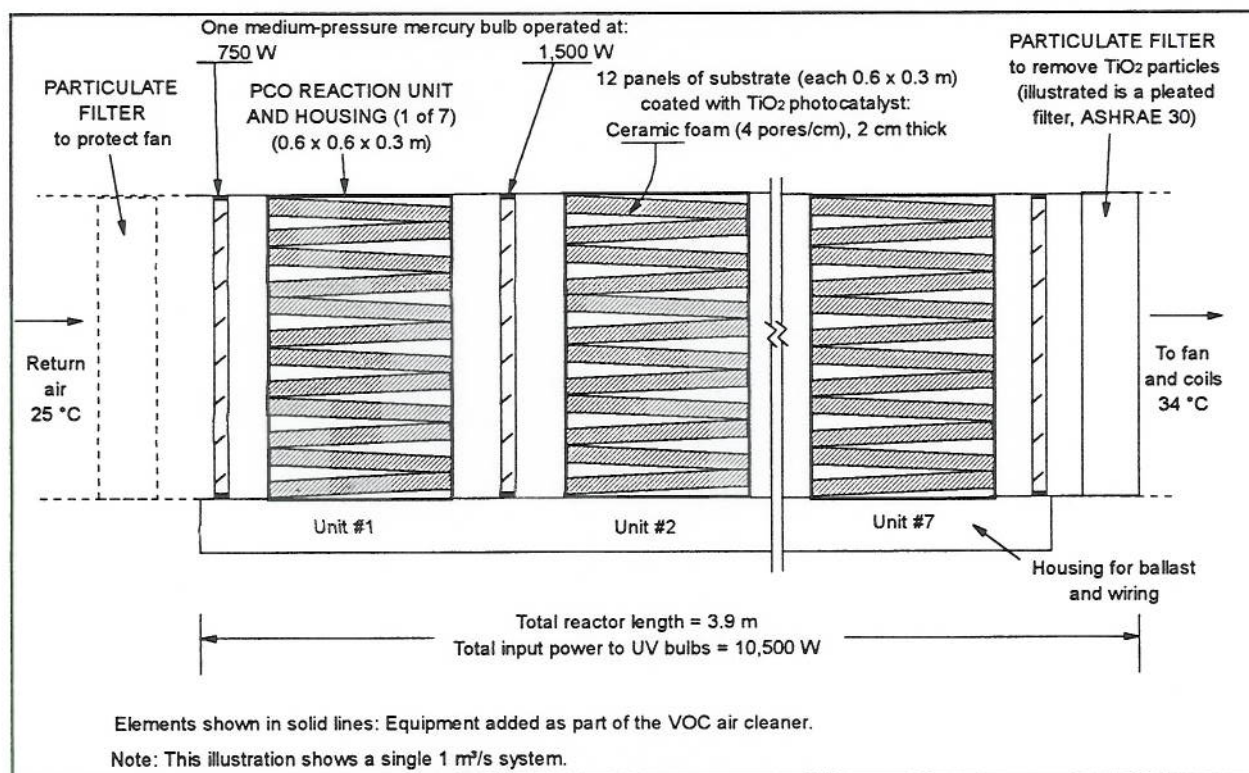


Figure 2. Model photocatalytic oxidation VOC air cleaner (side view).