

Cost Analysis of Activated Carbon Versus Photocatalytic Oxidation for Removing Organic Compounds from Indoor Air

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ABSTRACT

A cost comparison has been conducted of 1 m³/sec indoor air cleaners using granular activated carbon (GAC) versus photocatalytic oxidation (PCO) for treating a steady-state inlet volatile organic compound (VOC) concentration of 0.27 mg/m³. The commercial GAC unit was costed assuming that the inlet VOCs had a reasonable carbon sorption affinity, representative of compounds having four or more atoms (exclusive of hydrogen). A representative model PCO unit for indoor air application was designed and costed, using VOC oxidation rate data reported in the literature for the low inlet concentration assumed here, and using a typical illumination intensity. The analysis shows that, for the assumptions used here, the PCO unit would have an installed cost more than 10 times greater, and an annual cost almost seven times greater, than the GAC unit. It also suggests that PCO costs cannot likely be reduced by a factor greater than 2–4, solely by improvements in the PCO system configuration and reductions in unit component costs. Rather, an improved catalyst having a higher quantum efficiency would be needed, increasing reaction rates and reducing illumination requirements relative to the catalysts reported in the literature. GAC costs would increase significantly if the VOCs to be removed were lighter and more poorly sorbed than assumed in this analysis.

IMPLICATIONS

Due to the large amounts of ultraviolet (UV) energy and catalyst surface areas required, PCO units are likely to be very expensive for removing VOCs from indoor air. Unless improved catalysts can be developed that substantially reduce energy and surface requirements, PCO is not likely to increase the utilization of air cleaners for indoor VOC control, or to challenge GAC as the most common VOC air cleaning method. Cost will likely limit PCO to specialized indoor applications where GAC is not an option (e.g., because the specific compound is poorly sorbed on carbon).

INTRODUCTION

While several types of air cleaners might be considered for removing volatile organic compounds (VOCs) from indoor air, the type most commonly assumed for removing general VOC mixtures involves physical adsorption on granular activated carbon (GAC).¹ There is extensive commercial 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 little experience with GAC in indoor air applications, where pressure drop limitations necessitate very shallow beds, and where extensive maintenance may not be practical. The sorption capacity of carbon tends to decrease significantly for organic compounds having fewer than four atoms (exclusive of hydrogen). The limited use of GAC in indoor air applications could be due, in part, to uncertainty regarding the removal performance and maintenance requirements of shallow carbon beds when the indoor VOC mixture is expected to contain light organics.

Photocatalytic oxidation (PCO) is an alternative VOC air cleaning approach that has been under development over the past two decades,^{3,4} and that could offer the potential for removing the lighter organic compounds that are not effectively adsorbed on carbon. This developmental process utilizes a solid semiconductor photocatalyst—commonly titanium dioxide (TiO₂)—that, when illuminated with ultraviolet (UV) light, can promote oxidation of airborne organics at room temperature. This same oxidation reaction would require perhaps 1,000 °C to achieve purely thermally, and 350 °C or more to achieve thermocatalytically. Most PCO studies to date on airborne organics have focused on VOC concentrations in the range of 10–1,000 ppmv, representative of industrial waste streams. However, some recent studies have addressed the sub-ppmv levels representative of indoor air applications.^{5,6} There do not appear to be many (if any) commercial PCO installations for treating gaseous streams, either

in industrial or indoor air applications. However, there are a number of vendors marketing proprietary PCO reactors.

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 in-duct hardware configurations and operating procedures that might realistically be applied in the heating, ventilation, and air conditioning (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 overall configuration envisions a building zone being conditioned by an HVAC system that recirculates the zone air at seven air changes per hour (representing a typical cooling/heating load), and that provides outdoor

Table 1. General assumptions used in the cost analysis.

Parameter	Assumed Value
Building outdoor air ventilation rate (mechanical plus infiltration)	10 L/sec of outdoor air/person ⁷
VOC concentration in outdoor air	Zero
Building occupancy	14-m ² floor area/person ⁷
Indoor air recirculation rate through air handler (and air cleaner)	7 air changes/hr
VOC generation rate inside building	5 mg VOC/hr/m ² floor area (which would result in an indoor concentration of 2 mg/m ³ , or about 0.5–1.1 ppmv, in the absence of an air cleaner).
Required VOC removal efficiency	Air cleaner must reduce indoor concentration by 85% to 0.3 mg/m ³ (about 0.07–0.17 ppmv)
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/yr ⁸
Cost of electricity	\$0.0473/kWh plus demand charge of \$9.96/kW for usage rates greater than 10 kW
Air cleaner operating hours	273 hr/month (off overnight, weekends)
HVAC system characteristics	Packaged variable air volume system; cooling electric input ratio = 0.34-W electric input per W cooling output; overall fan efficiency = 0.6; cooling capacity 20 kW/m ³ /sec, fan static pressure = 870 Pa, in absence of air cleaner.

ventilation air at a rate of 10 L/sec/person. Inside the zone is a steady source of generic VOCs releasing 5 mg VOC/hr/sq m of floor area—fairly high for a steady source. With the assumed ventilation, this source would result in a steady-state indoor concentration of 2 mg/m³ in the absence of an air cleaner.

The air cleaner is to be designed to reduce the zone concentration by 85%, to 0.3 mg/m³ (about 0.07–0.17 parts per million by volume (ppmv), depending upon molecular weight). This reduction requires a per-pass VOC removal efficiency of 82%, given that the zone air makes seven passes through the air cleaner per hour. The inlet concentration to the air cleaner (0.27 mg/m³, or about 0.10 ppmv) is less than the zone concentration; the air cleaner is assumed to be mounted in the return air ducting downstream of the point where the recirculated zone air is diluted with incoming outdoor air.

The VOC air cleaner is located just prior to the central air handler and coils, and is 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, to further protect the air cleaner.

Commonly, particulate (and gaseous) filters for HVAC systems are sold in modules capable of handling about 1 m³/sec, and having a cross section of about 0.6 × 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 m³/sec, and both the installed and the annual costs are expressed as cost per cubic meter per second. Scale-up to capacities larger than 1 m³/sec 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—involving a series of 2.5-cm-thick GAC panels in a V-bank arrangement—is representative of many 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 the GAC cost analysis—are presented in Table 2.

The GAC unit dimensions and equipment costs are based on vendor literature and quotes (Farr Co., El

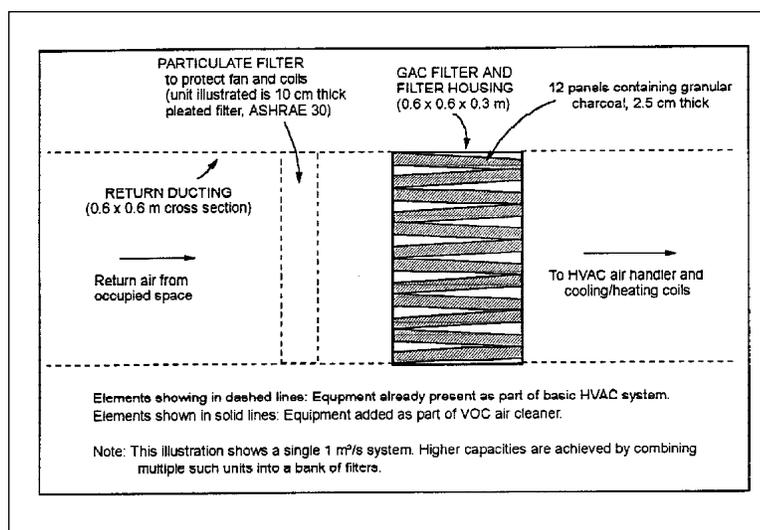


Figure 1. Granular activated carbon VOC air cleaner (side view).

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

Parameter	Assumed or Computed Value
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 airflow through unit	1 m ³ /sec (capable of treating 190-m ² floor area under Table 1 assumptions); superficial (approach) velocity 2.5 m/sec
Face velocity through panels	0.4 m/sec
Total pressure drop across unit	250 Pa (see text for derivation)
Equipment cost of GAC unit, including carbon	\$1,100 uninstalled (Farr Co., El Segundo, CA)
Cost of housing to mount unit in duct	\$100/m ³ /sec uninstalled (derived from vendor quote)
Cost of replacement carbon (8 x 16 mesh activated coconut shell)	\$6.60/kg (Charcoal Service Corp., Bath, NC)
Disposal of spent carbon (municipal landfill)	\$0.10/kg (typical for collection and landfilling)
Inlet VOC concentration at steady state	0.27 mg/m ³ (about 0.10 ppmv)
Outlet VOC concentration at steady state	Zero initially; 0.08 mg/m ³ at 30% breakthrough
Mass loading of VOC on carbon (0.10 ppmv VOC, 50% RH in inlet)	0.020 g VOC/g carbon at 30% breakthrough ¹⁰
Carbon replacement frequency	Every 3.7 months, at 30% breakthrough

Segundo, CA). Three labor hours are assumed for installation; labor rates were obtained from Means Mechanical Cost Data.⁹ 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 required 82%.

The mass of VOC that will be adsorbed by the bed prior to 30% breakthrough significantly impacts the GAC cost estimates, determining the mass of carbon that is required and the frequency with which it will have to be replaced. Carbon sorption capacity depends heavily upon the specific organic compounds and their concentrations in the entering mixture. It was decided to base this estimate on organic compounds that have a reasonable sorption capacity (i.e., that have four or more atoms exclusive of hydrogen). Based on limited information for various VOCs at inlet concentrations of 10 ppmv and lower,¹⁰⁻¹² the capacity for hexane appears to be at about the median for such compounds at very low concentrations.

Accordingly, the VOC sorption capacity shown in Table 2—0.020 g VOC/g carbon at 30% breakthrough—is the capacity for hexane on 8 x 16 mesh coconut shell carbon at the inlet conditions assumed for this study (0.10 ppmv, 50% relative humidity (RH), room temperature).

This value is extrapolated from data reported by VanOsdell et al.¹⁰ with this same carbon, humidity, and temperature, and with inlet hexane concentrations close to the inlet assumed here. The sorption capacities reported in that reference (0.10, 0.060, and 0.032 g/g for inlets of 10.8, 2.3, and 0.40 ppmv, respectively) were extrapolated logarithmically to 0.10 ppmv. Thus, 0.020 g/g should be a fair measure of the performance that can be expected with hexane at the conditions assumed in this analysis.

It is noted that the capacity for compounds having fewer than four atoms (exclusive of hydrogen) can sometimes be one or more orders of magnitude poorer than that for hexane. It is also noted that, in practice, the VOCs entering an air cleaner will be a mixture, the composition of which can vary with time; some of the individual compounds in this mixture might impact the sorption performance of others. The assumption that this mixture will behave, on average, like pure hexane is a convenience for this analysis.

Assuming a maximum acceptable loading of 0.020 g/g, the 41-kg-carbon bed will have to be replaced at 3.7-month intervals under the conditions assumed here (which require removal of about 800 mg/hr VOCs, 273 hr/month). Two labor hours are assumed to be required to remove and replace the carbon inside the panels. The assumption that the spent carbon (containing 2% organics by weight) can be placed in a municipal landfill (at \$0.10/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/kg (disposal contractor quote).

Given the assumed panel thickness and face velocity, and the particle size of the carbon, this GAC unit will create a pressure drop of about 250 Pa in the HVAC ducting, assuming no gas bypassing. This pressure drop is obtained from standard industry curves for 8×16 mesh carbon beds (Barnebey & Sutcliffe Corp., Columbus, OH), and from independent calculations for flow through fixed beds of granular solids.¹⁴ Some GAC vendors use coarser carbon (4 × 8 or 4 × 10 mesh) in indoor air applications, which would reduce this pressure drop to about 125 Pa. However, since the VOC sorption capacity data used above were obtained using 8 × 16 mesh carbon, the pressure drop associated with the finer carbon was used in this analysis. Reducing the pressure drop to 125 Pa would decrease the GAC installed costs presented later by 7%, and the annual costs by 3%.

The pressure drop across the GAC unit increases energy consumption by the central air handler and potentially necessitates a fan that can produce a higher static pressure. Also, the increase in fan energy adds heat to the airstream, increasing the cooling load during cooling periods (or reducing the heating load during heating periods). This results in a net increase in annual coil energy consumption and an increase in required cooling coil capacity. These increases in energy consumption and cooling capacity were estimated by modeling the air cleaner using the DOE-2 building energy model,¹⁵ addressing an office building for which the model input files were already available¹⁶ and considering a range of climates.

The incremental costs for enlarged HVAC air handlers and cooling units were estimated by computing the incremental installed cost per kPa of static pressure, or per kW of cooling capacity, from comparing alternative units in Means.⁹ The air cleaner was charged only for the number of kPa or kW that it adds, realizing that, in practice, increases in fan or cooling requirements can require a step change up to a fan or cooling unit of the next larger increment in commercial capacity.

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.

Following a review of PCO reactor configurations that have been considered in the published literature,¹⁷ 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 panels of ceramic foam substrate, coated with the catalyst. UV bulbs would be positioned in the front and rear of the panel beds to illuminate the catalyst.

The model PCO design developed here is undoubtedly different from those being offered commercially. It includes some apparent drawbacks; for example, the V-bank panel configuration will degrade the distribution of UV radiation into the interior of the substrate matrix. However, it provides fairly efficient contact between the gas stream and illuminated TiO₂, providing a significant illuminated surface area per unit reactor volume, and it results in a fairly low pressure drop. Thus, the model should represent indoor air PCO costs adequately for the purposes of this comparison, and should effectively illustrate the significant cost centers associated with these units.

To design the model PCO reactor for this comparison, it is necessary to define two key design parameters which will have a substantial impact on the size and cost of the unit. These parameters are the oxidation rate for sub-ppmv VOC inlet concentrations, and the UV illumination intensity, incident on the catalyst surface, that is required to achieve this oxidation rate. These parameters dictate the required amount of catalyst surface area (the number of panel beds) and the number of bulbs (the UV power consumption).

PCO Oxidation Rate

The rate at which an organic compound will be oxidized over a photocatalyst depends on a number of variables. Key among these are (1) the nature of the specific compound, (2) its concentration, and (3) the intensity of UV illumination.

To select a representative 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 airstreams at ambient temperature.^{5,6,18-27} These studies addressed differing values of the variables listed in the preceding paragraph, and different experimental reactor configurations, 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/geometric cm² of illuminated TiO₂ area, expressed as μmol/hr of the compound oxidized/geometric cm² of illuminated TiO₂ area.

The results of this analysis are summarized in Table 3.

The geometric square centimeters of TiO₂ surface area includes only the gross surface area of substrate coated by

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

Compound	Differential Reaction Rate at 1 ppmv ^a	References
Trichloroethylene	0.05 - 0.2	18, 19, 23, 24, 27
Formaldehyde	0.01 - 0.3	5, 6, 21
Acetone	0.006	2
Benzene	0.007	25
Toluene	0.02 - 0.07	5, 6

^aRate expressed as $\mu\text{mol/hr}$ of VOC oxidized/geometric cm^2 of illuminated TiO_2 surface area, at a UV illumination intensity of $1 \text{ mW/geometric cm}^2$ of illuminated TiO_2 .

the catalyst, excluding the internal porosity of the substrate or of the TiO_2 itself. The rate is normalized based on the geometric surface area, rather than on the mass of catalyst as is common in heterogeneous catalytic reactor design.²⁸ Studies suggest that perhaps only the top $2 \mu\text{m}$ of an opaque catalyst layer participate in the photocatalytic reaction,²⁷ 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 $7 \text{ mW/geometric cm}^2$ of 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 entire range. The rates were adjusted to the reference intensity of 1 mW/cm^2 by assuming that the rate is proportional to intensity to the power 0.6. This exponent is suggested by experience^{3,5,19,21} for intermediate values of intensity.

The greatest potential source of error in converting the literature data to the common units in Table 3 probably arises from the assumption that the reaction rate is first order over the entire range. The single-component form of the Langmuir-Hinshelwood rate equation, commonly used in interpreting PCO data, predicts that the reaction rate would approximate first order at very low concentrations, and would transition to zero order at higher concentrations, when the availability of reaction sites on the catalyst surface becomes controlling. The concentration range over which the transition occurs will vary with the compound. However, the values that have been reported in the literature for the chemical rate constants and the adsorption coefficients for various compounds^{5,6,20,21,26,27} indicate that the transition will com-

monly occur around 1–10 ppmv. When rates measured at 20–100 ppmv are extrapolated down to 1 ppmv assuming first-order kinetics over the entire range—and this includes most of the numbers in Table 3—the predicted rate at 1 ppmv might be low by an order of magnitude if, in fact, the rate is actually zero order over much of the range.

Accordingly, only those data from Table 3 that were obtained at 3 ppmv or less were used in deriving the differential rate at 1 ppmv used in this analysis. These data include 21 discrete measurements of the rate for toluene^{5,6} at RHs between approximately 30 and 60% (yielding a mean of $0.042 \mu\text{mol/hr/cm}^2$ with a standard deviation of 0.016), and 12 measurements for formaldehyde^{5,6} (mean = $0.179 \mu\text{mol/hr/cm}^2$, $\sigma = 0.070$). All of these measurements were obtained with experimental reactors utilizing ceramic foam catalyst substrates, as in the model reactor assumed here.

In the absence of other data, the average of these means for toluene and formaldehyde was used here in the design of the PCO reactor. The resulting differential oxidation rate is $0.11 \mu\text{mol/hr/geometric cm}^2$ of illuminated TiO_2 (at 1 ppmv and $1 \text{ mW/geometric cm}^2$).

The assumption that the complex VOC mixture entering the PCO unit will behave, on average, like a mixture of toluene and formaldehyde (with neither compound influencing the oxidation of the other) is a convenience required for this analysis. Also, it is being assumed that the inlet VOC mixture is being completely oxidized to carbon dioxide and water at this average rate, with no intermediate products of incomplete oxidation remaining in the airstream.

UV Illumination Intensity

As indicated previously, the rate data reported in the literature were obtained with illumination intensities ranging between 0.6 and $7 \text{ mW/geometric cm}^2$ incident on the catalyst surface. These intensities reflect a fairly low quantum efficiency, commonly on the order of 1–10%. Apparently, a large fraction of the UV photons do not create reactive electron-hole pairs in the catalyst, and/or the electrons and holes recombine without contributing to catalysis. Also, the PCO of an organic compound might involve a number of intermediate steps consuming a number of photons.

Reaction rate varies with light intensity to an exponent between 0.5 and 1, with the exponent approaching 1 at low intensities.³ Thus, reducing the design intensity in the reactor would reduce the reaction rate, correspondingly increase the amount of catalyst surface area that is required for a given degree of oxidation, and potentially achieve only a modest (if any) reduction in total UV energy consumption.

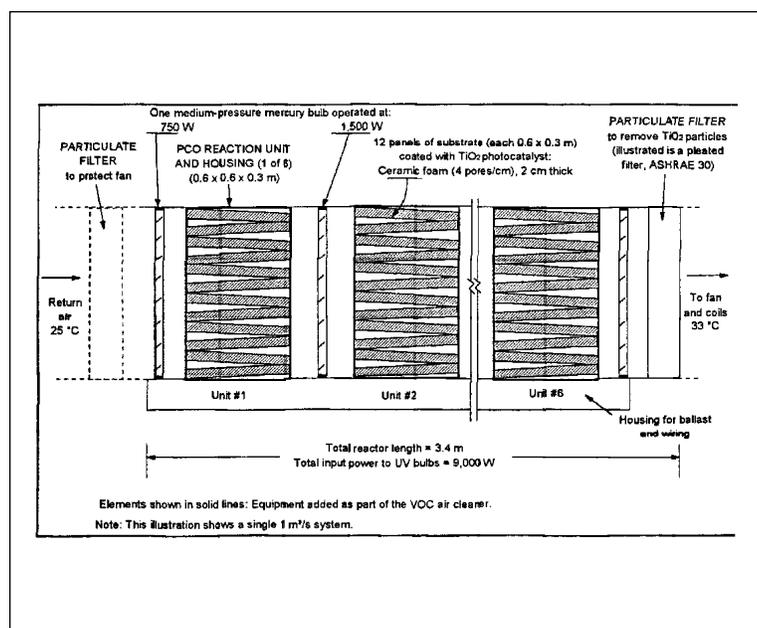


Figure 2. Model photocatalytic oxidation VOC air cleaner (side view).

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

Parameter	Assumed or Computed Value
Nature of panels	Ceramic foam, 4 pores/cm, 2 μm TiO_2 coating
Dimensions of each panel	0.3 \times 0.6 m, 2-cm thick
Number of catalyst panels per bank	12
Total airflow through unit	1 m^3/sec , superficial (approach) velocity 2.5 m/sec
Face velocity through panels	0.4 m/sec
Inlet VOC concentration at steady state	0.27 mg/m^3 (about 0.10 ppmv)
Outlet VOC concentration at steady state	0.05 mg/m^3 (82% removal per pass)
Reaction rate at 1 ppmv inlet	0.11 $\mu\text{mol}/\text{hr}/\text{cm}^2$ illum. TiO_2 at 1- mW/cm^2 TiO_2
UV illumination intensity	1 $\text{mW}/\text{geometric cm}^2$ of illuminated TiO_2
Geometric surface area of ceramic foam	22.8 cm^2/cm^3 of foam ⁶
Optical depth of foam	Fraction of geometric 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	6
Total pressure drop across reactor	75 Pa (incl. 5 Pa across each bank, per vendors)
UV bulb efficiency	0.25-W UV output (<400 nm) per W input (Voltarc Technologies, Inc., Fairfield, CT)
Input power to UV bulbs (medium-pressure mercury bulbs)	750 W per face of each 12-panel bank (9,000 W total to reactor, excluding ballast)
Overall quantum efficiency	About 0.1%
Air temperature rise caused by bulbs	8 °C
UV bulb and ballast cost	\$75/bulb, \$400/ballast (Voltarc Technologies, Inc.)
Bulb lifetime	1,000 operating hr (Voltarc Technologies, Inc.)
Cost of catalyst panels (support + TiO_2)	\$90/panel (derived from vendor quotes)
Catalyst regeneration frequency	Every 6 months (arbitrary)
Catalyst replacement frequency	Every 5 years (arbitrary)

In view of these considerations, the model PCO reactor here was designed to provide an incident intensity of 1 mW/cm^2 of illuminated surface, a representative value.

PCO Reactor Design

Based upon the oxidation rate and the illumination intensity selected above, the model PCO unit is illustrated in Figure 2. Key design features and assumptions are presented in Table 4.

Given the inlet concentration of 0.27 mg/m^3 at steady state, it is computed that six banks of catalyst panels would be required—providing 2.3×10^6 geometric cm^2 of illuminated surface—to achieve the 82% per-pass reduction that is needed.

The required number of panel banks is calculated through an iterative mass balance around each bank, computing the outlet concentration based upon the inlet concentration to that bank and the average reaction rate through the bank. The average reaction rate—at the average of the inlet and outlet concentrations for the bank—is computed assuming that the differential rate of 0.11 $\mu\text{mol}/\text{hr}/\text{cm}^2$ at 1 ppmv decreases linearly with concentration, according to first-order kinetics.

The computed number of panel banks is inversely proportional to the reaction rate, as would be expected. Doubling the 0.11- $\mu\text{mol}/\text{hr}/\text{cm}^2$ design rate would decrease the number of banks to three; reducing it by half would increase the number to about 12.

To provide the incident illumination intensity of 1 mW/cm^2 , UV bulbs totaling 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 sixth being operated at 750 W. In practice, multiple bulbs would be preferred between panel banks to improve UV distribution and operating reliability; single bulbs were assumed to reduce installed costs. These high-intensity bulbs have an operating lifetime of only 1,000 hr, and cost \$75 each; their associated ballasts cost \$400 each (Voltarc Technologies, Inc., Fairfield, CT). Less expensive, longer-lived commercial bulbs capable of practically providing the necessary intensity in the available space could not be identified. The power

consumption by all of the bulbs in the six-bank reactor totals 9,000 W, raising the air temperature by 8 °C. An additional 900 W is consumed by the ballasts. At the low VOC inlet concentration, the overall quantum efficiency through the reactor is about 0.1%.

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 TiO₂ coating applied; and from estimates by a catalyst vendor (Degussa Corp., Ridgefield Park, NJ) for applying catalyst coatings to substrates. The cost of \$90/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. According to the vendors, the pressure drop across these foam panel banks should be low (5 Pa/bank) at the design face velocity.

The installed cost of the PCO reactor, excluding the catalyst, was derived using the uninstalled cost of six GAC panel reactors excluding the carbon (obtained at a volume discount); the uninstalled cost of the UV bulbs and ballasts; and fabrication and installation costs. The fabrication and installation costs were derived using: the installed costs of galvanized steel ducting for the connecting sections between the panel banks and for the ballast housing, computed according to Means;⁹ and an additional 13 labor hours for sheet metal work and electrical wiring.

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 six months between regenerations, and five years between complete replacements, was felt to be optimistic. Considering possible alternative methods of in situ and off-site regeneration, a rough estimate of 2.5 labor hours (plus minimal materials and utilities) per regeneration per panel bank was derived for use here.

The impacts of the PCO air cleaner on the HVAC air handler and cooling coils were estimated using the DOE-2 model, as discussed previously for the GAC unit. With the PCO unit, there will be less impact on the air handler (since the pressure drop across the PCO air cleaner is much less), but there will be a greater impact on the cooling coils (due to the heat generated by the UV bulbs), and there will be energy consumption by the bulbs.

COST RESULTS

Installed Costs

As shown in Table 5, the estimated installed cost for the PCO unit is over 10 times that of the GAC unit. This results from the high cost of the PCO reactor and catalyst, and from the significant increase in HVAC cooling capacity required to remove the heat added by the UV bulbs and ballasts.

Most of the installed cost of the PCO reactor excluding catalyst (\$8,090) results from vendor quotes for the uninstalled components (the panel reactors and the bulbs/ballasts). The fabrication and installation costs—the source of the greatest uncertainty in this estimate—amount to only 25% of the total reactor cost. Thus, the reactor cost would not appear to be unreasonably inflated. The catalyst cost estimate results directly from vendor quotes—72 foam panels at \$90 each—and thus would seem to be reasonable.

Sensitivity analysis for GAC. If the VOCs to be removed were assumed to be lighter compounds having only one-tenth of hexane's sorption capacity on carbon, one option for maintaining the desired removal in a 1-m³/sec GAC system would be to install 10 of the reactors in Figure 1 in series. As a first approximation, this would increase each of the GAC cost elements in Table 5 by a factor of 10, and the total GAC installed cost would increase to a value approaching the cost of the PCO unit. Thus, depending upon the nature of the compounds to be sorbed, the cost of the GAC unit could increase substantially.

Sensitivity analysis for PCO. The reaction rate of 0.11 μmol/hr/cm² at 1 ppmv and 1 mW/cm², derived from the literature data, determines the required illuminated catalyst surface area and the bulb wattage, regardless of PCO system design. If this rate is fixed, no innovations in reactor

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

Cost Item	Installed Cost (\$/m ³ /sec capacity)	
	GAC Unit	PCO Unit
Reactor (excluding carbon or catalyst)	\$ 850	\$ 8,090
Initial charge of carbon or catalyst	470	6,480
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	1,720
	<u>\$1,530</u>	<u>\$16,310</u>

design would enable the illuminated surface area or the wattage to be reduced below the amounts used in the model reactor. Thus, unless the reaction rate can be increased, the only apparent approaches for significantly reducing PCO system costs are improving the reactor configuration, to compress more square centimeters of illuminated TiO₂ into a smaller reactor volume, relative to the model; or reducing the unit costs of the reactor components, such as the foam substrates or the bulbs.

Assume in the extreme that—through design innovations—illuminated surface area could be compressed so efficiently that the required number of panel banks could hypothetically be reduced to zero while still providing the required catalyst surface. Assume that the reactor could be shrunk to a size that would accommodate only one panel bank. The same wattage of UV bulbs and ballasts would still be required, but assume that—through negotiations with lighting vendors—the purchase price of these items could be reduced by 50% per watt. Under these most optimistic assumptions, the \$8,090 cost of the reactor in Table 5 would be reduced to \$2,500/m³/sec, and the \$6,480 cost of the catalyst would be reduced to zero. The \$16,310 total cost of the system (including the cooling coil and air handler modifications) would thus be reduced to about \$4,200/m³/sec, a fourfold decrease.

The other major contributor to the installed costs in Table 5—the cost of increased cooling capacity—cannot be reduced unless the reaction rate can be increased. As long as the reactor requires sufficient power to illuminate 2.3 × 10⁶ geometric cm² of catalyst at 1 mW/cm²—as dictated by the rate derived from the literature—the bulbs and ballasts will necessarily be generating 9,900 W of heat, even if design innovations could hypothetically reduce to zero the number of panels required to provide that area. Thus, 9,900 W will still have to be removed by the cooling coils.

Thus, even under the most optimistic assumptions regarding design innovations and reduced component costs, PCO will continue to be a relatively expensive process—on the order of \$4,200/m³/sec installed—due in large part to the high energy requirements. Even with these optimistic assumptions, the PCO installed cost would still have to be reduced by an additional factor of almost 3 to equal the estimated cost of the GAC unit in Table 5. Such additional cost reductions can be achieved only through increased reaction rates, significantly reducing surface area and, especially, UV power requirements.

The PCO installed cost decreases approximately linearly with decreases in the required catalyst surface area and UV power. The area and power decrease inversely with reaction rate. Thus, even with extremely optimistic assumptions regarding system design innovation and reduced component costs, the PCO reaction

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

Cost Item	Annual Cost (\$/yr/m ³ /sec capacity)	
	GAC Unit	PCO Unit
<i>Operating costs</i>		
Electricity (for increased fan static pressure, cooling load, UV bulbs)	\$ 100	\$ 4,440
<i>Maintenance</i>		
Replacement of carbon	1,360	—
Regeneration of catalyst	—	1,510
Disposal of spent carbon or catalyst	20	~0
Replacement of UV bulbs	—	2,370
Replacement of PCO final filter	—	20
<i>Indirect expenses</i>		
Depreciation of equipment (10 yr)	150	980
Depreciation of catalyst (5 yr × 2)	—	1,500
Insurance and real estate taxes	30	330
Interest on capital (installed cost)	60	650
	\$1,720	\$11,800

rate at 1 ppmv would still have to be increased almost threefold, to about 0.3 μmol/hr/cm² at 1 mW/cm², to match the GAC cost estimate. With the base-line costs of the model PCO reactor in Table 5, the rate would have to be increased more than 10-fold, to over 1 μmol/hr/cm² at 1 mW/cm². These required reaction rates are as fast as, or faster than, the fastest individual measured rate shown in Table 3.

Improved catalysts will be necessary to achieve these faster rates. To provide the faster rates, with the corresponding substantial reduction in power requirements, the improved catalyst will have to offer higher quantum efficiencies, above the value (~0.1%) at the conditions assumed here. A greater percentage of the UV photons must become effective in oxidizing VOC molecules, or PCO will remain an energy-intensive and expensive process.

Annual Costs

As shown in Table 6, the total annual cost associated with the PCO unit is almost seven times greater than that for the GAC unit.

The two largest contributions to the annual PCO cost, 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 airstream; and bulb replacement. The PCO catalyst regeneration cost is high—despite a fairly simple regeneration procedure—due to the number of catalyst panels involved. And PCO indirect costs are high because the installed cost is so high. The primary contributor to the annual GAC costs is the replacement of the carbon.

Sensitivity analysis for GAC. If the VOCs were assumed to have only one-tenth of hexane's sorption capacity, then—to maintain performance—it would be necessary to increase the mass of carbon in the GAC unit or the carbon replacement frequency (or some combination of the two) by a factor of 10. In either case, the carbon replacement and disposal costs in Table 6 would be increased by a factor of 10. The impact on the other GAC cost elements in the table would depend upon the extent to which mass versus replacement frequency were increased. But, as a rough approximation, it appears that the total annual GAC cost would increase by a factor of about 10, making GAC more expensive than PCO.

Sensitivity analysis for PCO. The UV input power and the cooling energy required to remove the resulting bulb-generated heat—which are essentially entirely responsible for the \$4,440/yr cost of electricity for the PCO unit in Table 6—are fixed based upon the reaction rate derived from literature data. Thus, this major cost component cannot be reduced—regardless of any innovations in reactor or lighting configuration—unless improved catalysts are developed that reduce illumination requirements.

The \$2,370/yr cost of bulb replacement in this 9,900-W reactor could conceptually be reduced by a factor of 10—a savings of about \$2,130/yr—if it were possible to use low-pressure bulbs having a 10,000-hr lifetime in place of the 1,000-hr-medium-pressure bulbs. If arrangements with bulb manufacturers reduced the purchase price per bulb by 50%, this would provide an additional savings of \$120/yr, reducing the total bulb replacement cost to \$120/yr.

If the installed cost of the PCO unit could be reduced from \$16,310 to \$4,200 through design innovations and reduced component costs, under the optimistic assumptions discussed previously, then the indirect expenses listed in Table 6, which are all based on the installed cost, would be reduced accordingly. The catalyst depreciation cost would be eliminated altogether, since the panel banks were hypothetically reduced to zero. The total indirect costs would be reduced by \$2,960/yr, from \$3,460 to \$500/yr.

Regarding catalyst regeneration costs, some PCO vendors claim that they can produce the catalyst so inexpensively that one might replace the catalyst instead of regenerating it. If this were possible, the \$1,510 annual regeneration cost in Table 6 would drop to zero. Of course, the cost of fresh catalyst—included as an indirect expense under “depreciation of catalyst” in Table 6—would necessarily increase under those circumstances. But such an increase is not included in this sensitivity analysis, since the catalyst cost is ideally assumed to be zero.

If it were optimistically assumed that all of the possible savings listed above could be achieved, the annual cost for the PCO system would decrease more than two-fold, from \$11,800 to about \$5,100/yr/m³/sec. Thus, even under the most optimistic combination of assumptions regarding design innovations and reduced component costs, the PCO system remains expensive if the reaction rate at 1 ppmv cannot be increased above the value of 0.11 $\mu\text{mol/hr/cm}^2$ at 1 mW/cm² derived from the literature.

The \$5,100/yr/m³/sec calculated under the extremely optimistic assumptions above would have to be reduced by an additional factor of 3 to equal the estimated annual cost for the GAC unit. The annual costs for the base-line model PCO reactor in Table 6 would have to be reduced by a factor of 7. As discussed above for the installed costs, the PCO annual costs decrease approximately inversely with the reaction rate. Thus, the reaction rate would have to be increased three- to sevenfold, to over 0.3–0.7 $\mu\text{mol/hr/cm}^2$, to match the GAC estimate.

These required rates are faster than the fastest rate in Table 3, and would thus necessitate a catalyst superior to those reported in the literature.

CONCLUSIONS

- (1) With the assumptions used in this analysis, the PCO reactor has an installed cost over 10 times greater, and an annual cost almost seven times greater, than those of the GAC adsorber.
- (2) Changes in the assumptions for the GAC unit, to include VOCs not effectively sorbed on carbon, can increase GAC installed and annual costs to levels comparable to (or higher than) the PCO unit.
- (3) However, even with the most optimistic assumptions regarding possible PCO system design innovations and component cost reductions, it does not appear possible to reduce the PCO installed and annual costs by a factor greater than 2–4, if the catalyst performance reported in the literature cannot be improved. Even with reductions by a factor of 2–4, PCO would still be sufficiently expensive such that it would not likely be widely accepted for general indoor air applications.
- (4) To reduce PCO costs by a factor greater than 2–4, it is necessary to reduce the large catalyst surface area—and the corresponding large UV power consumption—computed in this analysis. The high surface area and power requirements are dictated by the oxidation kinetics obtained from the literature, and cannot be reduced by reactor design innovations and reductions in component costs.

- (5) Thus, only an improved catalyst having a greater quantum efficiency—capable of providing faster oxidation rates, and of reducing catalyst area and UV power requirements—can reduce PCO costs by a factor greater than 2–4. To reduce PCO installed and annual costs by a factor of 10, the improved catalyst would have to provide oxidation rates faster than the fastest rates reported in the current literature, even if this improved catalyst were accompanied by the most optimistic system design innovations and component cost reductions.

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