REVIEW OF BIOFILTRATION AND ITS IMPLICATIONS FOR CLIMATE CHANGE

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ABSTRACT

Biofiltration systems have been used for treating odor emissions from municipal wastewater treatment plants and treating emissions of volatile organic compounds (VOCs) from industrial operations. Increasingly, biofiltration is seen as a viable alternative to thermal oxidation because of lower operating cost and reduced emissions of carbon dioxide, NOx, SOx, and particulate matter (PM). In this regard, biofiltration is a logical fit for the global demands of reduced carbon dioxide emissions. However, current biofiltration systems suffer from several disadvantages: (1) significantly lower rates of treatment than high temperature destruction; (2) water usage concerns, especially with the looming global water shortages; (3) concerns about how to monitor the efficacy of the system in real-time; and (4) limited understanding on nutrient requirements, etc.

In this paper, the various types of biofilter systems will be reviewed to provide a clear understanding of their advantages and disadvantages. Experience with current full-scale installations will be presented to provide operating issues for industries substituting biofiltration for catalytic and chemical oxidation. Further, the disadvantages mentioned above for biofiltration will be addressed to give a clear understanding of the main issues involved, and their possible solutions. Finally, evaluation of biofiltration systems in terms of climate change will be detailed, to gain a better fit between federal policy and biofilter technology capabilities and limitations.

INTRODUCTION

Stating that there will be no more "dragging heels" by the federal government, President Obama, in late January directed the EPA to reconsider its denial of California's request to regulate carbon emissions. President Barack Obama's climate czar said the EPA will soon determine that carbon-dioxide emissions represent a danger to the public and propose new rules to regulate emissions of the greenhouse gas from a range of industries. Legal experts say designating carbon dioxide a public danger could open up any emitters to legal challenge.

Another recent consideration is the concept of “water footprint”, which is an indication of both direct and indirect water use[1]. The water footprint is the volume of fresh water used to produce and operate the technology, summed over the various steps of production and operation.

MULTIPHASE BIOSYSTEM

Treatment of odors and volatile organic compounds (VOCs) has been traditionally achieved using thermal oxidizers. In recent years, regenerative thermal oxidizers have been installed which maximize heat recovery and attempt to maximize the use of combustion energy from organic contaminants. However, they also have substantially higher emissions of carbon dioxide from the combustion of natural gas, when compared to biological treatment approaches. In recent years, biofilters have been used for odor and VOC treatment, which emit carbon dioxide only from the mineralization of the contaminants[2]. However, most biofilters use water to a greater extent than thermal treatment methods, mainly to keep the biomedia wet and make up evaporative losses. Hence, while the carbon dioxide emissions from biofilters are much less than oxidizers, their water footprint is larger.

In the literature, different terms have been used to denote various kinds of bioreactor devices. In a common Biofilter, the incoming contaminated gas is pre-humidified, and the organisms reside on a solid surface of the biomedia, where the degradation of the compounds occurs. In a Biotrickling Filter, water is recirculated through the biomedia bed, thereby humidifying the gas stream and providing water to the organisms attached to the surface of the biomedia. In another approach, the term Bioscrubber has been used when water, containing organisms from an activated sludge water treatment system, for example, is recirculated through the biomedia, providing active organisms for contaminant degradation in the gas phase. Major advantages/disadvantages of these various designs are summarized in Table 1.

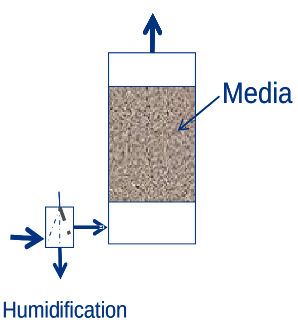
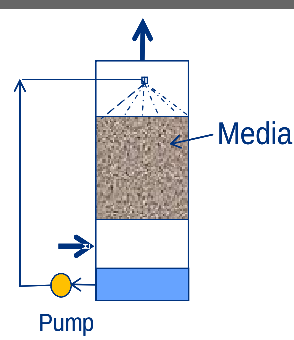
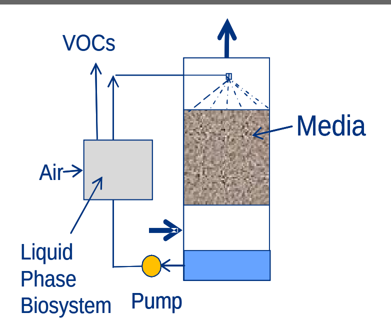
MULTIPHASE BIOFILTER

The MultiPhase Biofilter[3] overcomes all the disadvantages of conventional biotreatment devices by treating the incoming contaminants in the phase (liquid or gas) in which the contaminant would normally reside, depending on its inherent properties. For example, a highly volatile compound exhibiting low water solubility will concentrate in the gas phase, and will be treated mainly in the gas phase. A highly water soluble compound with low volatility will concentrate in the water phase and will be treated in the water phase. Most compounds with intermediate volatility and water solubility will be treated in both the gas and water phases, depending on their natural partitioning. Biofilters and Biotrickling Filters attempt to treat all the contaminants in the gas phase, whereas conventional Bioscrubbers delegate the treatment of the water soluble fractions of the contaminants to an external treatment system, often with design flaws that can either partially re-entrain the contaminants into the ambient environment due to air-sparging, or allow the contaminants to accumulate and exit through the water. Further, none of these systems – biofilter, biotrickler, or bioscrubber -- are designed to handle particulate matter in the gas phase, treat “condensables” that are typically high molecular weight and can be water-insoluble compounds such as terpenes and tars, or handle the dissipation of heat if the incoming gas stream is above the normal operating temperature of aerobic organisms, which generally operate in a range from 50^{o}F to 105^{o}F.

Figure 1 shows one application of the MultiPhase Biofilter where incoming gas is sprayed with water in the incoming duct to humidify the gas, and achieve some evaporative cooling simultaneously settling large particulates in the gas phase. The gas then enters the central duct flowing downward, and turning 180 degrees to enter the biofilter bed from the bottom. Additional water is sprayed inside the central duct, allowing greater removal of smaller particles that are still too heavy to be carried upward by the gas flow as it turns upward through the biofilter bed. The particulate is forced to fall into the liquid sump below for treatment. Water soluble compounds and condensables, such as terpenes and tars, will enter the liquid sump, while compounds which have high volatility and low water solubility, will remain in the gas phase and will be treated in the biofilter bed.

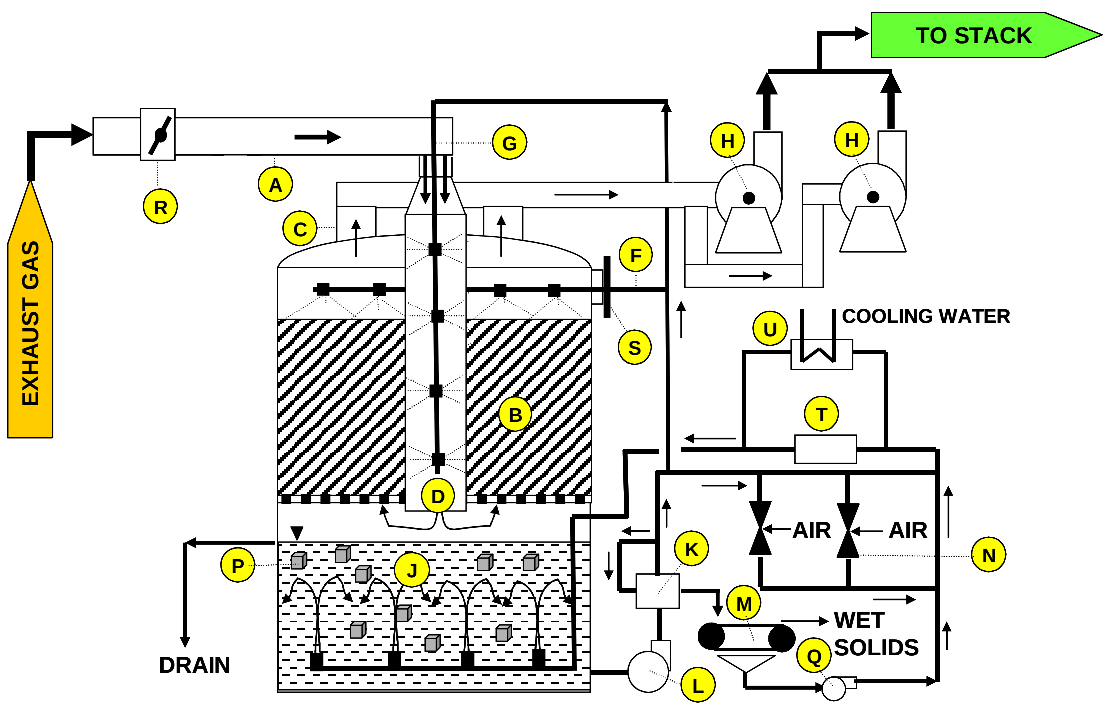
The MultiPhase Biosystem uses a ceramic biofilter media that enables a wide variety of microorganisms to adhere to its outer and inner surfaces, providing a high surface area contact between the contaminated gas phase and the active biofilms. The biofilms generally consist of complex communities of dozens of interacting living microorganisms, that include species such as *Pseudomonas putida, Rhodococcus* sp., *Arthrobacter paraffineus,* etc. The diversity of the active biofilms depends on the types of chemical compounds treated in the biosystem.

Table 1. Advantages and disadvantages of common biotreatment systems.

Biofilters	Biotrickling Filters	Bioscrubbers
Advantages		
		
• Simple design requiring no water recirculation • Pre-humidification removes some of the large particulates in the gas phase	• Trickling water flow can be used to humidify the air, provide nutrients, such as nitrogen, phosphorus and minor elements, and maintain pH within the bed • Water flow can also be used to slough-off excessive biomass growth from the media, provided the media is open enough to allow this biomass to exit the bed • Water recirculation also provides organisms suspended in the water	• Has all the advantages of a Biotrickling Filter • Use of an external supply of living organisms makes the system more robust against starvation, when no organics are present in the incoming air • Water-soluble compounds are mainly treated in the external system, from where the water is taken

Disadvantages		
• Inability to handle biomass growth inevitable in biodegradation of organics, resulting in clogging of media • Inability to provide nitrogen, phosphorus and other minor nutrients for effective biodegradation • Inability to handle small particulate matter in the gas phase • Larger molecular weight compounds, such as terpenes, tars accumulate in the bed and clog up the biomedia • Partial removal of water soluble compounds in the pre-humidifier, resulting in generation of contaminated water	• Water soluble compounds in the gas phase accumulate in the recirculating water and reentrain into the exit air at the top of the bed, thereby giving lower treatment efficiency • Generally, if the biomedia is small, biomass clogging can occur, in spite of the water flow • Larger molecular weight, water-insoluble compounds, such as terpenes, tars, accumulate in the water and eventually clog the biomedia • Particulate matter in the gas phase clogs up the bed	• Water-soluble compounds which are volatile re-entrain into the air if the external system is an air sparged, open activated sludge basin • Particulate matter in the gas phase can clog up the biomedia bed in spite of the water flow • Higher molecular weight, water-insoluble compounds can accumulate in the bed causing clogging of the biomedia • Clogging due to biomass growth can occur if the biomedia is not properly designed to handle this growth • High inlet gas temperature can result in gradual heating of the external water treatment system

Figure 1. Schematic of MultiPhase BioSystem operated at a major wood products company



The main advantages of the MultiPhase Biofilter when compared to conventional biofilters, biotrickling filters and bioscrubbers are summarized in Table 2.

Table 2. Summary of the advantages of the MultiPhase Biofilter

Issue	MultiPhase Biofilter
Presence of solids in inlet gas	Transferred to water phase by spraying of inlet gas, transferring to the liquid sump, and then filtered out of the recycle flow by an automatic backwash filter
Presence of condensable compounds in inlet gas	Transferred to water phase by spraying of inlet gas, transferring to the liquid sump where it is emulsified by the bacteria's biosurfactants and biotreated
Clogging of biofilter media by biomass growth and small particles	Biomedia allows water to flow through it allowing it to backwash by the water sprayed on top of the biofilter section, and the sloughed off biomass is decayed in the liquid sump to recycle nutrients
Starvation of active biomass when system is shutdown	Growth of bacteria in liquid sump becomes a continuous supplier of acclimated bacteria to the biofilter section.
Generation of contaminated water from the biofilter (large water footprint)	Treatment of water in the liquid sump minimizes water blowdown, reduces water footprint, and supplies acclimated bacteria to biofilter
High inlet gas temperature	Use of evaporative cooling in inlet gas flow cools the gas

FOOTPRINT ANALYSIS

The footprint of any pollution treatment technology can be categorized into two types: (1) Equipment footprint; and (2) Operational footprint. Equipment footprint is associated with the manufacture of the equipment itself, such as vessels, biomedia, etc. for biofilters and vessel; or insulation, burners, etc. for thermal oxidizers. Operational footprint is associated with the equipment operation, including water consumption for biofilter operation or carbon dioxide emissions for thermal oxidizers.

The operational footprint can be categorized into three main types: (1) carbon; (2) water; and (3) energy. (1). Carbon footprint for biofilters is substantially lower than for thermal oxidizers, which use additional natural gas to maintain destruction temperatures. (2). The water footprint for biofilters is larger than biotrickling filters, mainly due to water blowdown from biofilters. All biological treatment systems humidify the inlet gas stream. Depending on the gas flow rate, temperature and inlet gas humidity, the water loss due to inlet gas humidification is inevitable. In the MultiPhase Biofilter design, if there are solids present in the inlet gas, then subsequent solids filtration will also result in some water loss. In any case, the operational footprint of biofilters is bigger than thermal oxidizer systems, and smaller than all types of chemical scrubbers. (3). The energy footprint of thermal oxidizer systems far exceeds the corresponding footprint for biofilters, mainly due to natural gas consumption. Consumption of natural gas significantly increases the operating cost of thermal oxidizers.

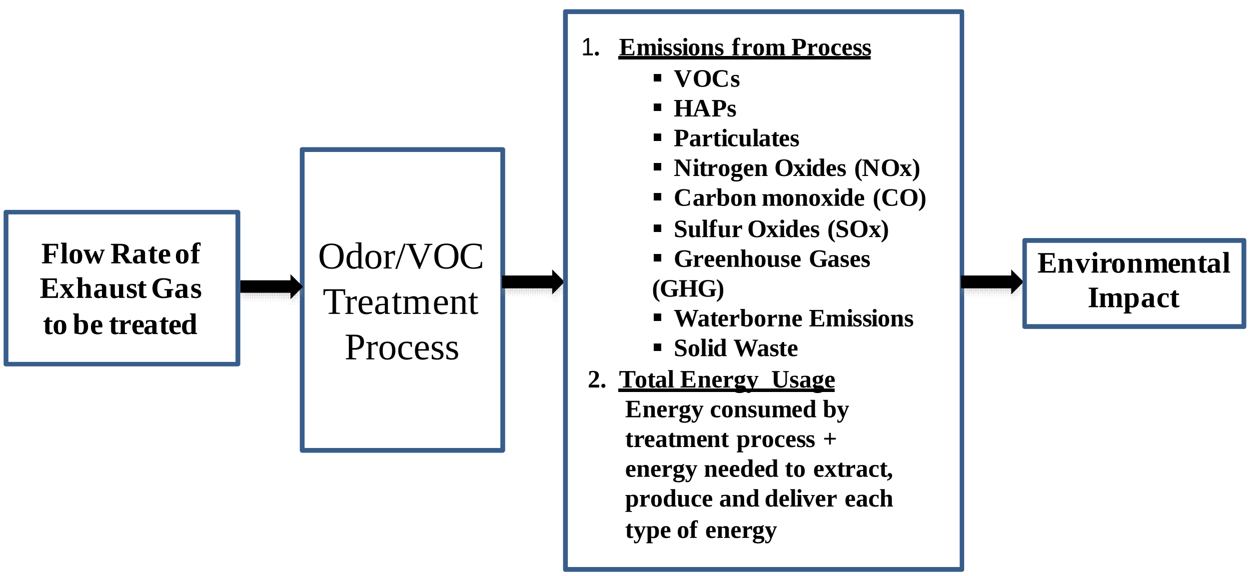
Even when the inlet VOC concentrations are high to achieve a self-sustained combustion condition, variations in inlet VOC composition results in natural gas need and hence increased operating cost.

LIFE CYCLE INVENTORY ANALYSIS

Life cycle assessment[4] is an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and material uses and releases to the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment include the entire life cycle of the product, process or activity, encompassing extracting and processing raw material; manufacturing; transportation and distribution; use, reuse, maintenance; recycling and final disposal.

In this paper, Life Cycle Inventory Analysis (LCIA) will be based on the energy consumption and environmental emissions from the treatment process. The environmental emissions that will be considered in this analysis are: energy usage, emission of volatile organic compounds, carbon dioxide, carbon monoxide, nitrogen dioxide, particulates, wastewater COD and generation of solid wastes. The emissions are normalized on the basis of yearly operation and flowrate (scfm) of exhaust gas treated. Each treatment process can be represented by an Input-Output representation, shown in Figure 1, in which the inlet parameter is the exhaust gas flow rate and the outlet being the emissions considered in the life cycle inventory analysis.

Figure 2. Input-Output Representation of the Odors/VOC Treatment Process.



Input-Output analysis shows how the inputs to the treatment process are linked to its eventual environmental impact. This formulation can be expressed as follows:

$$E = LCE*I \qquad (1)$$

where E = Emissions (E1, E2, E3….E10) expressed or converted to lbs/yr, where
E1 is Energy Usage; E2 is Solid Waste emission; E3 is VOC emissions; E4 is HAP emissions, E5 is Particulate emissions; E6 is Nitrogen oxides emissions; E7 is Carbon monoxide emissions; E8 is Sulfur oxides emissions; E9 is Green House Gases (GHG) emissions; and E10 is water borne emissions. E1, E10 explained next section.
LCE = Life Cycle Emissions (LCE) coefficients (LCE1, LCE2, LCE3, LCE4, LCE5, LCE6, LCE7,LCE8,LCE9,LCE10) defined for each treatment process in Table 3
I = Inlet (Exhaust gas flowrate in scfm)

The Environmental Impact (EI) can be written as follows:

$$EI = EIC*E \qquad (2)$$

where EI = Environmental Impact which is the total weighted emissions from the treatment process in Kg of emissions/year
EIC = EIC1, EIC2, …EIC10 = Environmental Impact Coefficients, which are weights assigned to each emission (ranging from 0 to 1) based on user's local importance associated with each emission, such that the sum of all ten weights assigned to each emission is 1.0
E = Emissions defined as in equation (1) above

Combining equations (1) and (2) we get

$$EI = LCE1*EIC1*E1+LCE2*EIC2*E2+LCE3*EIC3*E3+ LCE4*EIC4*E4+ + LCE5*EIC5*E5+ LCE6*EIC6*E6+ LCE7*EIC7*E7+ LCE8*EIC8*E8+ + LCE9*EIC9*E9+ LCE10*EIC10*E10 \qquad (3)$$

where EI = Life Cycle Emission Impact, given as lbs of Total Emissions/year for the pollution treatment technology.

Using the Life Cycle coefficients (LCE1, …LCE10) for any treatment process, the environmental impact (EI) and total yearly cost can be used to compare various treatment options. This is an important departure from considerations of only total cost, which is being used presently to compare various treatment options. Considering only total cost overlooks the environmental emissions and their consequent impact, which is a serious shortcoming of decision making based solely on immediate and narrow economic analysis.

For thermal oxidizer systems and compost biofilters, the Life Cycle Emission (LCE) coefficients were obtained from Sauer et al.[5], who conducted a life-cycle inventory analysis for the American Forest and Paper Association for evaluating the environmental burdens of various treatment options for the wood products industry. Two types of treatment technologies were considered: (1) Thermal treatment systems, which included Regenerative Thermal Oxidizers (RTO) and Regenerative Catalytic Oxidizers (RCO) and (2) Biological treatment systems, which

MULTIPHASE BIOSYSTEM

included natural media (compost) biofilters (BFC). In the present study, the data presented earlier[5] was extended to include the MultiPhase Biofilter (MB), which uses synthetic media instead of compost.

There is considerable variability in the generation of the Life Cycle Emission (LCE) coefficients for compost biofilter, MultiPhase Biofilter, RTO and RCO treatment systems. This is mainly due to the fact that the LCE coefficients depend on the type of wood product produced at the plant (variations in materials and processes used), source of waste gas (e.g. press vent, dryer), condition of the waste gas (temperature, composition, etc.), proper installation, operation and maintenance of the treatment system and effect of other ancillary emission controls, such as scrubbers, cyclones, wet ESPs that are used in addition to the Odor/VOC treatment system.

Table 3 gives the Life Cycle Emissions (LCE) coefficients for the four treatment technologies considered for the woods products industry, namely compost biofilters (BFC), MultiPhase Biofilter (MB), RTO and RCO. The table gives the range of the coefficient and the median value in brackets. The emissions considered are: (1) Total energy usage (E1), which includes the energy consumed by the treatment process at the plant and the energy required to extract, produce and deliver each type of fuel used in the treatment process; (2) Solid Waste emissions (E2); (3) Emission of Volatile Organic Compounds (VOCs) (E3) which includes the emissions from the treatment system as well as the non-source emissions for materials and fuels for operation of the treatment system; (4) Emission of Total Hazardous Atmospheric Pollutants (HAPs) (E4) from the treatment technology and the non-source HAPs for the materials and fuels used in the treatment process; The primary HAPs for the treatment process were methanol and formaldehyde, with acetaldehyde, also commonly found, at lower levels; The primary non-source HAPs were hydrochloric acid, hydrofluoric acid, formaldehyde and other aldehydes; Mercury, another important non-source HAP was not considered since its amounts were too small; (5) Emission of Particulates (E5); (6) Emission of Nitrogen Oxides (NO_x) (E6); (7) Emission of Carbon monoxide (CO) (E7); (8) Emission of Sulfur Oxides (SO_x) (E8) mainly from the treatment system and non-sources; (9) Emission of Greenhouse Gases (GHG) (E9) expressed in pounds of carbon dioxide equivalents, which are calculated from fossil CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions and global warming potentials for these gases published by the Intergovernmental Panel on Climate Change (IPCC); and (10) Water borne emissions (E910) which includes emissions only from the treatment system; Thermal oxidizers do not generate any wastewater; Compost Biofilters (BFC) generate significantly more wastewater than the MultiPhase Biofilter (MB), mainly due to effective water treatment and recycle in the MultiPhase Biofilter design, while most compost biofilters have no water treatment within the treatment process.

Please note again: all of the values except for the MultiPhase Biofilter (MB) were calculated by Sauer et al.[5] Furthermore, the following values are over the life-cycle of the systems and not a snapshot of operating conditions.

Table 3. Life Cycle Emissions (LCE) coefficients for four treatment systems: Compost Biofilter (BFC), MultiPhase Biofilter (MB), Regenerative Thermal Oxidizer (RTO) and Regenerative Catalytic Oxidizer (RCO). Median values are given in brackets. Values for the Compost Biofilter (BFC), Regenerative Thermal Oxidizer (RTO) and Regenerative Catalytic Oxidizer (RCO) have been taken from Sauer et al [5].

Emission	Compost Biofilter (BFC)	MultiPhase Biofilter (MB)	Regenerative Thermal Oxidizer (RTO)	Regenerative Catalytic Oxidizer (RCO)
Energy Usage (MMBtu/year/scfm)	0.25-0.75 (0.51)	0.25-0.75 (0.50)	0.5-3.25 (2.70)	1.0-2.25 (1.60)
Solid Waste (lbs/year/scfm)	12-23 (17)	6 – 10 (8)	11 – 47 (32)	20 – 27 (23)
VOC Emissions (lbs/year/scfm)	0.4-0.8 (0.6)	0.4-0.8 (0.6)	0.8-1.1 (1.0)	1-1.8 (1.3)
HAP Emissions (lbs/year/scfm)	0-0.7 (0.4)	0-0.7 (0.4)	0.1-1.0 (0.6)	0.2-0.6 (0.4)
Particulate Emissions (lbs/year/scfm)	Very low (0)	Very low (0)	0.4-0.6 (0.5)	0.6-1.0 (0.8)
Nitrogen Oxides (NOx) (lbs/year/scfm)	Very low (0)	Very low (0)	1.1-3.5 (2.6)	0.4-0.8 (0.6)
Carbon Monoxide (CO) (lbs/year/scfm)	Very low (0)	Very low (0)	0.38-3.21 (2.2)	0.8-1.2 (1.0)
Sulfur Oxides (SOx) (lbs/year/scfm)	0.5-0.8 (0.7)	0.5-0.8 (0.7)	1.0-4.75 (3.0)	1.3-3.3 (2.2)
GHG Emissions (lbs CO2 equiv/year/scfm)	60-100 (71)	40-80 (60)	100-400 (353)	150-270 (213)
Water borne Emissions (gallons/year/scfm)	10-30 (20)	3-8 (5)	Very low (0)	Very low (0)

The Environmental Impact (EIC) coefficients serve two purposes. Firstly, it converts all the emission numbers in Table 3 into the same units, namely lbs of Emissions/year/scfm, and secondly, it attempts to give relative weights or importance to the various emissions.

For example, Energy Usage has units of MMBtu/year/scfm. This is converted to lbs of Methane equivalent/year/scfm as follows: lbs of Methane equivalent/year/scfm = MMBtu/year/scfm x (10^6 Btu/MMBtu)*17 (lbs Methane/lbmole Methane)/(1028 Btu/scf Methane)*(359 scf/lbmole Methane) = 46.1 lbs Methane/year/scfm.

Similarly, Waterborne Emissions in gallons/year/scfm are converted to lbs wastewater/year/scfm by multiplying by 8.34 lbs/gallon wastewater.

The relative importance of each emission is achieved by assigning a weight to each emission, ranging from 0 to 1.0, such that the sum of all these weights is 1.0. So if we give equal importance to each emission, then each weight will be 0.1, since we have a total of 10 emissions. In this case, the Environmental Impact Coefficient (EIC) coefficients will become:

EIC1 = 0.1*46.1 = 4.61 (4)
EIC2 = EIC3 = EIC4 = EIC4 = EIC5 = EIC6 = EIC7 = EIC8 = EIC9 = 0.1 (5)
EIC10 = 8.34*0.1 = 0.834 (6)

Depending on the emphasis given to the various emissions by local authorities, the user can choose appropriate values of the Environmental Impact coefficients. For example, in California, emissions of VOCs, HAPs, nitrogen oxides, carbon monoxide, sulfur oxides and particulate emissions might given much more importance than Greenhouse Gases or other emissions. Hence, in this case, the following Environmental Impact Coefficients could be selected:

EIC1 = 0.025*46.1 = 1.153
EIC2 = EIC9 = 0.025
EIC3 = EIC4 = EIC5 = EIC6 = EIC7 = EIC8 = 0.1
EIC10 = 0.025*8.34 = 0.209

For the case studies below, we assume equal weighting.

CASE STUDIES

Case 1: Regenerative Thermal Oxidizer[6]

Total process exhaust rate is 150,000 acfm from four individual dryers, operating at a temperature of 125 deg F, with an average ambient temperature of 50 deg F. The dryers may not all operate at the same time due to product changeovers, etc. The utilization rate for the dryers is 75%. When solvents are being evaporated in a dryer, the dyer exhaust is directed to the VOC Treatment Process. When the processes are all operating, the exhaust gas flow rate is 112,500 scfm. The normal production schedule is 24 hrs/day, 5.5 days/week, and 50 weeks/year. The total maximum pounds of solvent evaporation from the four dryers is 756.3 lbs/hr. The solvents that are evaporated are a mixture of toluene, methyl ethyl ketone, ethyl acetate and heptanes and the average heating value is 15,120 Btu/lb. Natural gas cost is assumed to be $3.90/MMBtu and electrical cost is 7.5 cents/kWh. The minimum destruction efficiency desired is 97%.

To achieve the required destruction efficiency, the thermal oxidizer must operate at a destruction temperature of 1530 deg F. A regenerative thermal oxidizer is selected in this case to maximize heat recovery. The air pressure drop is estimated to be 25 inches water column at the design airflow. An additional 5 inches water column is required for the process collection ductwork. An average system pressure drop of 26 inches water column, exhaust blower efficiency of 75% and 0.9 power factor are assumed for this analysis[6].

To provide a redundant fan, three exhaust fans at 75,000 scfm are recommended. The estimated total project cost to provide the thermal oxidizer, collection exhaust duct work, controls, engineering and installation is $13.5 million. The estimated exit temperature for the gases with 95% thermal efficiency is 195 deg F.

Since the inlet solvent loading is variable, the actual amount of natural gas needed can range from 10 to 45 times the calculated natural gas requirements.[6] Relying on published literature, using a factor of 20 we get[6]:

Natural gas requirements = (285,000 Btu/hr x 20)/((1028 Btu/scf)*60 min/hr) = 92 scfm
Yearly cost of natural gas for destruction of VOCs = (285,000 Btu/hr x 20) x $3.90/1,000,000 Btu x 6600 hr/yr = $146,718/yr
Btu/hr for recirculation = 1,096,875 Btu/hr
Btu/hr for combustion air = 298,640 Btu/hr
Total natural gas consumption for standby operation = ((1,096,875 + 298,640)/60)/1028 Btu/scf =22.6 scfm
Total estimated cost of natural gas = $157,494/yr
Estimated electricity for inlet gas blowers = 589 KWh
Yearly cost of electricity = $264,182
Total estimated energy cost per year for natural gas and electricity: $421,676
Using equation (1) and the values from Table 3, we get the following emissions E:
E = [2.70 32 1.0 0.6 0.5 2.6 2.2 3.0 353 0]*112,500
where 112,500 is the gas flow rate in scfm and the values of E are taken from Table 3 for RTO.
Using equation (3) and the EICs from equations (4,5,6), the Life Cycle Emission Impact (EI) is as follows:
EI = 51.94*112,500 = 5.84 MMlbs of Emissions/year. The corresponding total cost assuming straight line depreciation for 20 years is $13.5 million/20 years + $421,676 = $1,096,676

Case 2: MultiPhase Biofilter
Using the same gas flow rate, the total cost of the MultiPhase Biofilter, Blower, duct work, controls, engineering and installation is estimated to be $10.6 million. This system consumes no natural gas. The yearly cost of nutrients is estimated to be $12,700. The inlet blower is designed for a total system pressure drop of 9 in water column within the vessel and 5 in water column in the duct work to give a total pressure drop of 14 in water column. The MultiPhase Biofilter's vessel diameter is 40 feet and the vessel total height is also 40 ft. A schematic of the

MultiPhase Biofilter is shown in Figure 1. Total electricity for inlet gas blowers is estimated to be 317 KWh for an annual cost of $142,183. The total annual operating cost is $154,883 and the total yearly cost using a 20 year equipment lifespan and linear depreciation is $672,183. Using equation (1) and the values from Table 3 corresponding to the MultiPhase Biofilter, we get:

E = [0.50 8 0.6 0.4 0 0 0 0.7 60 5]*112,500

where 112,500 is the gas flow rate in scfm and the median values are taken from Table 3 for MB.

Using equation (3) and the EIC from equations (4,5,6), the Life Cycle Emission Impact (EI) is as follows:

Environmental Impact, EI = 13.45*112,500 = 1.51 MMlbs of Emissions/year and the total yearly cost is $684,883.

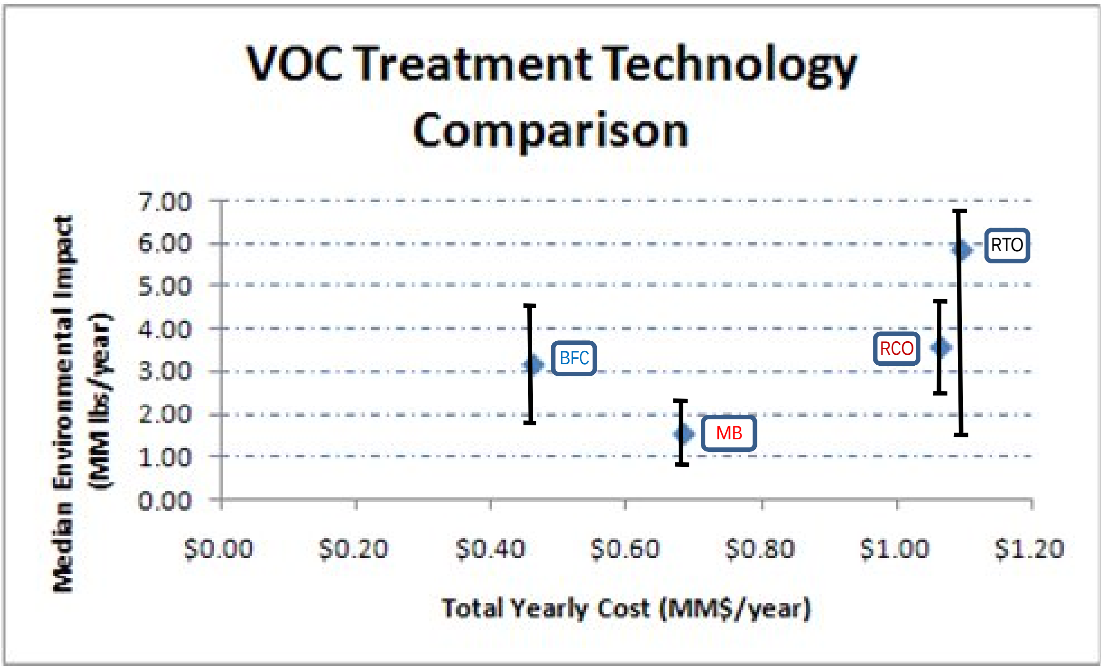
TECHNOLOGY COMPARISON

Using the above analysis, the four VOC treatment technologies for the wood dryer application were compared on the basis of total yearly cost and Environmental Impact. For purposes of this example, it was assumed that all emissions have equal importance, and hence equal weights were assigned to each emission. For an actual application, different weights (adding up to a total of 1.0) can be assigned to different emissions considered in this analysis, depending on the local importance of each emission. The important point is that in this analysis, different treatment technologies can be compared not only on the basis of total yearly cost, but also on their total environmental impact. Table 4 summarizes the results of these calculations and Figure 3 graphically shows the position of each treatment technology with total yearly cost plotted versus the environmental impact using only the median values from Table 3.

The plot shows that the MultiPhase Biofilter (MB) has the lowest Environmental Impact and its total yearly cost is higher than the Compost Biofilter (BFC). In actual practice it has been seen that compost biofilters are very often unable to successfully treat volatile organics mainly due to the following reasons: (1) Due to limited oxygen transfer within the compost material, the volatile compounds are not completely biotreated to carbon dioxide, but rather form intermediate products, such as acetic acid, etc., which have a sour odor; (2) Compost begins to clog due to biomass growth from the conversion of the organics, eventually requiring compost replacement; and (3) the used compost material, when spent, has to be landfilled, since it contains adsorbed organics, and this solid waste is not represented in the solid waste emission number used in this analysis. The MultiPhase Biofilter (MB) uses a ceramic media that never has to be discarded or changed, thereby reducing its generation of solid waste. Thermal Oxidizers have a significantly higher total cost and Environmental Impact due to their usage of natural gas.

Furthermore, compost biofilters (BFC) are unable to treat hot sources because they lack the sophistication to control and dissipate excess heat that would kill the bacteria. The MultiPhase can be utilized in a much wider range of industrial applications.

Figure 3. Plot showing the Comparison of the Four Treatment Technologies on the basis of Total Cost and Environmental Impact



CONCLUSIONS

A systematic methodology has been presented which is based on quantifying the environmental impact of treatment options (Compost Biofilter, MultiPhase Biofilter, Regenerative Thermal Oxidizer, Regenerative Catalytic Oxidizer) for treating the volatile organic emissions. The methodology uses ten source (treatment technology) and non-source (related to production, generation and delivery of electricity, natural gas, etc.) emissions to quantify the environmental impact, namely total energy usage, emissions of VOCs, HAPs, Particulates, NOx, SOx, CO, Greenhouse gases, waterborne emissions and solid waste generation. Data generated by a life cycle inventory analysis conducted by Sauer et al[5] for the American Forest and Paper Association regarding the treatment technologies used by the wood products industry, were used to obtain the Life Cycle Emissions (LCE) coefficients for compost biofilter and thermal oxidizer systems, while values for the MultiPhase Biofilter were estimated by the author.

These ten emissions (median, minimum and maximum) for each of the four treatment technologies were used to calculate an Environmental Impact, using weights for each of the emissions assigned by the user based on local and other considerations. The four treatment technologies are compared using both the total yearly cost (depreciated investment cost and yearly operating cost) and their Environmental Impact. Results of an analysis conducted for an exhaust gas flow showed that the MultiPhase Biosystem had higher total costs than a compost biofilter, but lower environmental impact. Both the Regenerative Oxidizers had significantly higher total yearly costs and environmental impacts than the two biofilters. This analysis indicates that selecting a treatment technology should be based on both the total yearly cost plus their environmental impacts rather than on immediate and narrow cost considerations alone.

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KEYWORDS

Life Cycle Analysis, Wood Products, Biofilter, VOC Treatment

Table 4. Summary of the Environmental Impact and Yearly Cost Calculations for the four treatment technologies

Economic and Life Cycle Analysis for Odor/VOC Treatment Technologies							
for the Wood Products Industry							
Gas Flow Rate				112,500	scfm		
Treatment Systems Considered:							
Compost Biofilter (BFC)							
MultiPhase Biofilter (MB)							
Regenerative Thermal Oxidizer (RTO)							
Regenerative Catalytic Oxidizer (RCO)							
LCE Coefficients							
		BFC			MB		EIC Values
	Median	Min	Max	Median	Min	Max	All
	0.51	0.25	0.75	0.5	0.25	0.75	4.61
	17	12	23	8	6	10	0.1
	0.6	0.4	0.8	0.6	0.4	0.8	0.1
	0.4	0	0.7	0.4	0	0.7	0.1
	0	0	0	0	0	0	0.1
	0	0	0	0	0	0	0.1
	0	0	0	0	0	0	0.1
	0.7	0.5	0.8	0.7	0.5	0.8	0.1
	71	60	100	60	40	80	0.1
	20	10	30	5	3	8	0.834
		RTO			RCO		EIC Values
	Median	Min	Max	Median	Min	Max	All
	2.7	0.5	3.25	1.6	1	2.25	4.61
	32	11	47	23	20	27	0.1
	1	0.8	1.1	1.3	1	1.8	0.1
	0.6	0.1	1	0.4	0.2	0.6	0.1
	0.5	0.4	0.6	0.8	0.6	1	0.1
	2.6	1.1	3.5	0.6	0.4	0.8	0.1
	2.2	0.38	3.21	1	0.8	1.2	0.1
	3	1	4.75	2.2	1.3	3.3	0.1
	353	100	400	213	150	270	0.1
	0	0	0	0	0	0	0.834
Economic Analysis							
				BFC	MB	RTO	RCO
Total Cost ($)				$6,400,000	$10,600,000	$13,500,000	$14,800,000
Yearly Operating Cost				$142,183	$154,883	$421,676	$325,810
Yearly Total Cost				$462,183	$684,883	$1,096,676	$1,065,810
Environmental Impact (EI) (MM lbs/year)							
		BFC	MB	RTO	RCO		
	Median	3.15	1.51	5.84	3.56		
	Min	1.89	0.94	1.55	2.48		
	Max	4.61	2.18	6.87	4.61		
Technology Comparison							
				Total Cost		Median Environmental Impact	
				(MM$/year)		(MM lbs Emissions/year)	
Compost Biofilter (BFC)				$0.46		3.15	
MultiPhase Biofilter (MB)				$0.68		1.51	
Regenerative Thermal Oxidizer (RTO)				$1.10		5.84	
Regenerative Catalytic Oxidizer (RCO)				$1.07		3.56	