Assessment of Styrene Emission Controls for FRP/C and Boat Building Industries

FINAL REPORT

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Abstract

Styrene emissions from open molding processes in fiberglass-reinforced plastics/composites (FRP/C) and fiberglass boat building facilities are typically diluted by general ventilation to ensure that worker exposures do not exceed Occupational Safety and Health Administration (OSHA) standards. This practice tends to increase the potential cost to the facility of add-on controls. Furthermore, add-on styrene emission controls are currently not generally mandated by regulations. Therefore, emission controls are infrequently used in these industries at present.

To provide technical and cost information to companies that might choose emission controls to reduce styrene emissions, several conventional and novel emission control technologies that have been used to treat styrene emissions in the United States and abroad and a few emerging technologies were examined. Control costs for these conventional and novel technologies were developed and compared for three hypothetical plant sizes.

The results of this cost analysis indicate that increasing styrene concentration (i.e., lowering flow rate) of the exhaust streams can significantly reduce cost per ton of styrene removed for all technologies examined, because capital and operating costs increase with increasing flow rate. Therefore, a company should evaluate methods to increase concentrations (i.e., lower flow rates) of the exhaust stream before considering any add-on control devices. This report also presents air flow management practices and enclosure concepts that could be used to create a concentrated exhaust stream while maintaining a safe working environment.

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Acronyms and Abbreviations

BACT	Best Available Control Technology
BCA	beaded carbonaceous adsorbent
Btu	British thermal unit
CE	capital equipment (cost)
CEFIC	Unsaturated Polyesters Sector Group of European Chemical Industry Council
CFC	chlorofluorocarbon
cfm	cubic feet per minute
EC	equipment cost
EC&C	Environmental C&C, Inc.
EPA	Environmental Protection Agency
FID	flame ionization detector
FRP/C	fiber-reinforced plastics/composites
ft	feet
ft/min	feet per minute
GPRMC	European Organization of Reinforced Plastics/Composite Materials
HAPs	Hazardous air pollutants
H.R.	heat recovery
kW	kilowatt
kWh	kilowatt-hour
lb	pound
lb/h	pounds per hour
LEL	Lower Explosive Limit
MACT	Maximum Achievable Control Technology
MEK	methyl ethyl ketone
MIAB	Molnbacka Industri, AB
MTR	Membrane Technology and Research, Inc.
NFPA	National Fire Protection Association
OAQPS	Office of Air Quality Planning and Standards
OMC	Outboard Marine Corp.
OSHA	Occupational Safety and Health Administration
PADRE	Polymer Adsorption and Removal
PCE	perchloroethylene
PEC	purchased equipment cost
PEL	permissible exposure limits
PIC	Pultrusion Industry Council
ppm	parts per million (by volume)
psig	pounds per square inch, gage
PVC	polyvinyl chloride
RBWAE	resin-bath-and-wet-out-area enclosure
REECO	Regenerative Environmental Equipment Co., Inc.
RPC	reinforced plastic composites

RTI	Research Triangle Institute
scfm	standard cubic feet per minute
SIC	Standard Industrial Classification
SMC	Sheet Molding Compound
SP	site preparation
SPI	Society of the Plastics Industry
TCE	trichloroethylene
TCI	total capital investment
TCP	1,1,3-trichloropropene
TDC	Total Direct Cost
tpy	tons per year
TRI	Toxics Release Inventory
TWA	time-weighted allowable
UV/AO	ultraviolet light/activated oxygen
VLA	vapor-laden airstream
VOC	volatile organic compound
yr	year
°C	degrees Celsius
°F	degrees Fahrenheit

Chapter 1

Introduction

The fiberglass-reinforced plastics/composites (FRP/C) and fiberglass boat building industries have many alternatives for reducing styrene emissions. Styrene emissions can be reduced by (1) using resin materials and application equipment that generate less styrene emissions, (2) improving operator techniques to reduce overspray, (3) changing open-molding processes to closed-molding processes, and (4) using add-on emission control devices. The amount of reduction achieved by these alternatives, taken separately or in various combinations, can vary widely.

Lacking the regulatory mandates, add-on pollution control systems are not often used to reduce styrene emissions in the FRP/C and boat building industries. Low concentrations and high air flow rates also have made conventional emission controls very expensive and, in some cases, less efficient in destroying the emissions. The FRP/C and boat building industries need information on the applicabilities and costs of conventional and emerging add-on pollution control technologies so they can make informed decisions about the use of controls to reduce their emissions. To meet this need, the cost and performance of several conventional and emerging add-on pollution control technologies and air flow management practices potentially applicable to these industries have been evaluated.

This report summarizes the results of literature reviews and control cost analyses. Background information about the industries and the characteristics of their emissions is provided in Chapter 2. Conclusions and recommendations of this study are presented in Chapter 3. Various pollution control technologies are described in Chapter 4, and their costs are compared in Chapter 5. Air flow management practices that may reduce worker exposure and control costs are described and evaluated in Chapter 6. Costing procedures for various pollution control technologies are presented in Appendix A, and instructions for using a computer spreadsheet cost model for add-on emission controls are presented in Appendix B.

This report provides preliminary technical and cost information to FRP/C and boat building companies for their use in selecting emission control technologies. Companies should identify those technologies that fit their production processes and contact the vendors of those technologies for more accurate information on equipment costs.

Chapter 2

Background

The FRP industry (excluding boat building) is large and diverse. More than 680 facilities nationally in the United States reported to the Toxic Release Inventory (TRI) in 1992. These facilities represent as many as 33 different Standard Industrial Classification (SIC) codes ranging from transportation to electronics and consumer products (Pacific Environmental Services, 1995). The FRP industry manufactures products such as bathtubs, shower stalls, spas, truck caps, vehicle parts, tanks, pipes, appliances, ladders, and railings. The FRP industry employs a variety of manufacturing processes. As shown in Table 2-1, the main manufacturing process is open molding. Open molding (including gel coat and resin spraying) is responsible for an estimated 75 percent of the 15,419 metric tons (17,000 tons) per year of styrene emissions from the FRP industry. This estimate is based on 1992 TRI reports (TRI 1995), and knowledge of FRP processes and their emission characteristics.

Table 2-1. Manufacturing Processes Employed by FRP/C Industry

Manufacturing Process	Estimated Facilities Employing Process (%)[a]
Open molding[b] (including hand layup, gel coat spraying, and/or resin spraying)	60
Compression molding	17
Filament winding	12
Pultrusion	8
Cultured marble casting	6
Continuous lamination	5

[a] Column total exceeds 100% because many facilities employ more than one type of manufacturing process.

[b] It is conventional to include filament winding in the open molding classification; however, for this study open molding was considered to be hand layup, gel coat spraying, and/or resin spraying.

Source: Pacific Environmental Services, 1995

The fiberglass boat building industry represents a segment of SIC code 3732, Boat Building and Repairing. The 1993 TRI report contains data from 144 boat manufacturers. The open molding process is the most common production method used in fiberglass boat building. Estimated styrene emissions from the these facilities was about 6,300 metric tons (6,900 tons) (Radian, 1995).

The open-molding process usually consists of applying a liquid gel coat or resin to a mold with a spray gun in an open environment. Styrene is emitted both during the application stage when gel coat or resin material is atomized and sprayed onto a mold and during the post-application period when the material cures. Most FRP/C production and boat building facilities use high ventilation rates to ensure that styrene levels are below the 100-ppm worker exposure limit established by the Occupational Safety and Health Administration (OSHA). Dilution increases the volume of contaminated air and, because the cost of an add-on emission control system is a strong function of the total air flow, these diluted air streams are more costly to control. Some facilities designate certain areas for gel coat or resin spraying to reduce the contamination of plant air. In these cases, a spray booth equipped with a dry filter medium may be used to reduce particulate emissions, but diluted styrene emissions are typically vented directly to the atmosphere.

Some FRP/C processes, such as pultrusion, continuous lamination, sheet molding compound (SMC) production, and resin mixing, have localized and concentrated emissions that can be enclosed and vented to a control device. Emissions from these processes can be captured with lower exhaust flow rates (i.e., at higher concentrations) than emissions from the open-molding process; therefore, it is more feasible or less costly to treat these streams. Most of the existing emission control devices installed in the FRP/C facilities are used to treat emissions from these processes.

References

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Radian Corporation; Minutes of the Boat Manufacturing P-MACT Teleconference on October 31, 1995. Memorandum from Brian Palmer, Radian Corporation, to Madeleine Strum, EPA-OAQPS, November 28, 1995.

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Chapter 3

Conclusions and Recommendations

Exhaust streams from open-molding processes in the FRP/C and boat building facilities are generally at low styrene concentrations and high air flow rates. General (dilution) ventilation is usually used to ensure that worker exposure is lower than that allowed by OSHA standards. Treating this low-concentration, high-air-flow stream is more expensive than treating a low-flow rate at higher concentration. Due to the general practice of dilution ventilation and the current lack of specific regulations, add-on control devices are not commonly used in the FRP/C and boat building industries.

Of the limited number of add-on control devices used in the FRP/C facilities in the United States, thermal and catalytic oxidation are the most common. The costs of novel technologies, including biofiltration and preconcentration followed by recovery or oxidation, by thermal or catalytic oxidation were compared. Preconcentration techniques appear to reduce the cost of styrene control, particularly at the lower styrene concentrations (less than 100 ppm) typically found at FRP/C and boat building facilities. However, this apparent reduction in cost is significantly affected by the equipment cost assumptions used in this analysis. Therefore, FRP/C companies should compare the costs of competing technologies on a case-by-case basis.

The capital and operating costs of all emission control devices are strongly related to the flow rate of the incoming stream. Cost analyses indicate, for all control devices examined, that cost per unit of styrene removed decreases as styrene inlet concentration increases (i.e., as the air flow rate decreases). Therefore, it is probably economical to concentrate the exhaust air stream, using improved air flow management practices or enclosures, before application of add-on emission control devices.

Improved air flow management techniques, which capture emissions at the source, or enclosures, which prevent styrene emissions from contaminating the plant air, can reduce the exhaust air flow rate and increase styrene concentrations in the exhaust streams from FRP/C facilities. These approaches can maintain a safe working environment and produce a high-concentration exhaust stream, which can be controlled with less expensive add-on control devices.

Chapter 4

Pollution Control Technologies

This chapter presents process description and discussions of conventional, novel, and emerging technologies that are or may be used to reduce styrene emissions from FRP/C and boat building facilities. Section 4.1 presents conventional technologies that are proven or have been traditionally used for VOC emission control. Section 4.2 presents novel technologies that have been applied in the last decade to treat low-concentration emissions and Section 4.3 presents emerging technologies that are still under investigation in laboratory or pilot plants, or are currently used to control VOC emissions from other industry sources.

4. 1 Conventional Technologies

Conventional technologies include combustion (i.e., thermal and catalytic oxidation), adsorption, and condensation, which have traditionally been used to treat VOC emissions. The process description, applicability to FRP/C processes, typical operating conditions and control efficiencies, and the advantage/disadvantage of its application are presented for each conventional technology.

4.1.1 *Combustion Technology*

Combustion is a process by which an exhaust stream containing VOCs is brought to adequate temperature and held for a sufficient residence time to allow for oxidation of the VOCs into the combustion byproducts of carbon dioxide (CO_2) and water vapor (H_2O). Theoretically, any hydrocarbon would be oxidized according to the following equation:

$$C_aH_b + (a + 0.25b)\, O_2 \Rightarrow a\, CO_2 + 0.5\, b\, H_2O. \qquad (4\text{-}1)$$

Combustion devices are classified according to how oxidation of the VOC occurs and how heat energy from the exhaust stream is recovered. The first classification differentiates between two oxidation methods -- thermal or catalytic -- and the second category classifies the method of heat recovery according to whether it is recuperative or regenerative (Haberlein and Boyd, 1995).

4.1.1.1 Thermal Oxidation

Thermal oxidizers, also called incinerators or afterburners, use high temperatures (typically between 538° and 1,093 °C [1,000° and 2,000° F]) to destroy VOC vapors.

Process Description. A typical thermal oxidizer includes a burner, an insulated expansion zone (to allow sufficient high-temperature residence time for complete combustion), and an induced-draft exhaust fan (to pull VOC-laden gases through the afterburner). The burner typically uses auxiliary fuel such as natural gas if inlet pollutant concentrations are not high enough to self-sustain the oxidation reaction, once operating temperature is reached.

Thermal Recovery. Thermal recovery is frequently employed to lower the operating fuel costs of thermal oxidizers. One method to recover heat from the exhaust of a thermal oxidizer is to install a heat exchanger. The heat exchanger may be used to preheat incoming combustion air. In this case, the heat exchanger is called a recuperator. In recuperators, energy recoveries of 40 to 60 percent are common, and recoveries of 80 percent are often practical (Cooper and Alley, 1986).

Regenerative thermal oxidizers cycle heat energy between an exhaust and an intake stream using an arrangement of thermal masses. The thermal oxidizer's hot exhaust gas heats a storage mass, usually a heat-resistant ceramic material. Once this storage mass has reached a preset temperature, the exhaust gas is redirected and the VOC-laden inlet gas flows through the now-heated mass. In this manner, the thermal energy of the incinerator's exhaust is recovered. Regenerative heat exchangers typically achieve higher heat recoveries than recuperative heat exchangers; heat recoveries of up to 95 percent are practical.

One effect of thermal recovery is to lower the inlet pollutant concentration required to achieve autothermal operation (i.e., using the inlet pollutant as the sole fuel source to sustain the oxidation reaction). Figure 4-1 depicts calculated styrene inlet concentrations required to achieve autothermal operation, for thermal and catalytic oxidizers, with varying levels of heat recovery. The calculated values are based on a thermal oxidizer temperature of 788 °C (1,450 °F), a catalytic oxidizer temperature of 329 °C (625 °F), and an assumed heating value of 40,900 kJ/kg (17,600 Btu/lb) for styrene.

Applicability to FRP/C Processes. Applications of thermal and catalytic oxidizers to FRP/C processes in the United States are listed in Table 4-1. As of October 1995, thermal or catalytic oxidizers were being employed to control emissions from five facilities performing gel coating and/or resin sprayup processes, three facilities performing pultrusion, two facilities performing continuous lamination, and one facility performing SMC production (LaFlam, 1995b).

Standard operating conditions. The performance of an incinerator is commonly characterized by three important parameters known as the "Three T's:"

- Temperature - The oxidation reaction rate is accelerated at elevated temperatures. Higher temperatures cause faster oxidation rates and higher destruction efficiencies.

Figure 4-1

Table 4-1. Thermal and Catalytic Oxidizer Applications on Gel Coating, Resin Spray-up, Pultrusion, Continuous Lamination, and SMC Production Processes (Source: LaFlam, 1995b).

Facility name	City	State	Install Date	Thermal or catalytic	Flow rate (cfm)	Process(es) vented to oxidizer
Gel coating and resin spray-up processes						
Cor Tec Company	Washington Court House	OH	1992	Catalytic	5,000	Automated gel coating on flat panels and resin mixing tanks
Tomkins - Lasco Bathware	Lancaster	TX	1985	Thermal	18,000	Gel coat and some resin spraying
Tomkins - Lasco Bathware	Elizabethtown	PA	1985	Thermal	24,000	Gel coat and some resin spraying
Tomkins - Lasco Bathware	South Boston	VA	1986	Thermal	18,000	Gel coat and some resin spraying
A.R.E., Inc.	Massillon	OH	1995	Thermal	100,000	Gel coat spraying, resin spraying, resin storage tanks, and painting
Pultrusion and continuous lamination processes						
Crane Kemlite (formerly BP Chemicals, Inc.)	Jonesboro	AR	11/90	Thermal	26,000	Continuous lamination and curing ovens
Enduro Composites System	Fort Worth	TX	1/91	Thermal	15,000	Continuous lamination and resin mixing
Owens Corning	Hazleton	PA	9/90	Thermal	Unknown	Pultrusion
Tecton Products	Fargo	ND	5/92	Thermal	Unknown	Pultrusion
BMC/SMC production processes						
Fibercast	Sand Springs	OK	1992	Catalytic	2,750	BMC mixing and centrifugal casting
Navistar Intl. Transportation	Columbus	OH	1/93	Thermal	14,000	SMC production and painting

BMC = bulk molding compound, SMC = sheet molding compound.

Time - For the oxidation reaction to occur, the exhaust must remain at the reaction temperature for a minimum amount of time, called the "residence" or "retention" time. Greater destruction efficiencies result from longer residence times. Note that the temperature and time are inversely proportional (although nonlinear) to each other in determining destruction efficiency.

- Turbulence - Turbulence is required to ensure that the exhaust is well-mixed throughout the incineration chamber. Otherwise, a packet of exhaust could pass through the chamber without adequate oxidation. Note that turbulence is not directly related to either temperature or time but is a necessary condition for high destruction efficiency.

A review of the literature indicates a range of recommended temperature and residence times for thermal oxidizers. Thermal oxidizers generally operate at a temperature ranging from 650° to 870° C (1,200° to 1,600° F) and require a minimum residence time of 0.3 second in the combustion zone (Bethea, 1978). The thermal oxidizer at the Lasco-South Boston facility operates at approximately 788° C (1,450° F). Most thermal oxidizers are designed to provide no more than 1 second of residence time to the flue gas in the combustion chambers (National Academy Press, 1983).

The VOC concentration of waste streams controlled by thermal oxidation can vary from the parts-per-million (ppm) range to 25 percent of the lower explosive limit (LEL). For styrene, this corresponds to a concentration of approximately 2,500 ppm. VOC concentrations typically cannot exceed 25 percent of the LEL for safety and insurance reasons. Thermal incinerators can be designed to control flow rates in excess of 2,832 m^3/min (100,000 cfm).

Control Efficiency. Studies indicate that a well-designed and -operated thermal oxidizer can achieve at least a 98 percent destruction efficiency. This corresponds to thermal oxidizers that are operated at 871° C (1,600° F), with a nominal residence time of 0.75 second (Farmer, 1980).

Advantages/Disadvantages. The principal advantages of thermal oxidizers purchased as air pollution control devices are their demonstrated use within the FRP/C source category and their potential for very high destruction efficiency. The principal disadvantages of thermal oxidizers purchased as air pollution control devices are their high energy requirements (for dilute VOC streams, particularly if heat recovery is below 70 percent) and the formation of additional air pollutants (carbon dioxide and nitrogen oxides) from the combustion of auxiliary fuel. Energy requirements and formation of carbon dioxide and nitrogen oxides are inversely related to the level of heat recovery employed (i.e., increasing heat recovery decreases energy requirements and formation of other air pollutants). A regenerative thermal oxidizer operating at 816° C (1,500° F) produces 2 to 12 ppm of nitrogen oxides (Gribbon, 1996). An EPA study (Sanderford, 1993) indicates that NO_x formation is dependent on such factors as O_2 content, residence time, and combustion temperature, and even a two-second residence time at 1,065° C (1,950° F) will result in formation of less than 10 ppm of NO_x.

Costs. Capital and operating cost data are presented in Appendix A and the spreadsheet cost model is presented in Appendix B.

In-plant Boilers and Heaters as Thermal Oxidizers. Theoretically, any in-plant natural-gas or oil-fired boiler or heater could also be used to destroy styrene. However, in-plant boilers have limited air flow rates, and their seasonal usage limits the amount of emission reduction that could be achieved. Also, temperatures and residence times for in-plant boilers are lower than for thermal oxidizers designed for air pollution control and would therefore result in lower destruction efficiency. The principal advantages of in-plant boilers as thermal oxidizers are that no additional combustion equipment is required and energy costs are reduced. The principal disadvantages of in-plant boilers as thermal oxidizers are their uncertain destruction efficiencies and their limited combustion air needs (boilers only require approximately 5 m^3/min (180 cfm) of combustion air per million Btu/hour).

4.1.1.2 Catalytic Oxidation

Catalytic oxidation systems pass VOC-laden exhaust through special catalytic beds to facilitate the oxidation of styrene at lower temperatures. These beds usually consist of precious metals. Catalytic oxidizers can reduce the required temperature for a given destruction efficiency by several hundred degrees Fahrenheit compared to thermal oxidizers.

Process Description. In most cases, inlet gases to the oxidizer are heated by a small natural-gas-fired burner (as with a thermal oxidizer, but to a much lower temperature). The heated gases are then passed directly through the catalyst bed, which is in the same unit as the burner. The catalyst is usually a noble metal such as palladium and platinum (other metals are used, including chromium, manganese, copper, cobalt, and nickel) deposited on an alumina support configuration. The support configuration is frequently a honeycomb arrangement to minimize pressure drop (relative to a packed bed of pellets) (Cooper and Alley, 1986).

Thermal Recovery. As with thermal oxidizers, thermal recovery can be used to lower the fuel costs of catalytic oxidizers. Thermal recovery can be performed in a recuperator (energy recoveries are typically 40 to 60 percent, with 80 percent often practical) or in a regenerator (energy recoveries up to 95 percent are practical).

Catalytic oxidizers have inherently lower fuel costs than thermal oxidizers (due to the lower combustion temperature in catalytic oxidizers). Therefore, catalytic oxidizers require a smaller amount of heat recovery to achieve autothermal operation (operation in which the inlet pollutant is the sole fuel source). Calculated styrene inlet concentrations required to achieve autothermal operation for catalytic and thermal oxidizers are depicted in Figure 4-1. The required inlet concentrations were calculated by RTI, based on a thermal oxidizer temperature of

788 °C (1,450 °F), a catalytic oxidizer temperature of 329 °C (625 °F), and a styrene heating value of 40,900 J/g (17,600 Btu/lb).

Applicability to FRP/C Processes. The Cor Tec facility (Washington Court House, Ohio) employs a catalytic oxidizer (see Table 4-1) designed to operate at 316° to 371° C (600 ° to 700° F), with a recuperative heat exchanger that recovers heat from the exhaust and uses it to preheat inlet air. The design flow rate is 142 m^3/min (5,000 cfm). The oxidizer treats exhaust gas streams from an automated gel coat spraying on flat panels at a rate of 102 m^3/min (3,600 cfm) and a resin mixing operations at a rate of 40 m^3/min (1,400 cfm). Testing of the oxidizer in 1994 indicated an average inlet styrene concentration (i.e., from both processes) of 240 ppm and an average destruction efficiency of approximately 98 percent (Patkar et al., 1994).

The Cor Tec facility and Fibercast (Sand Springs, Oklahoma) are the only two FRP/C facilities in the United States known to have a catalytic oxidizer.

Standard Operating Conditions. The catalyst bed in catalytic oxidizers generally operates at temperatures ranging between 149° and 482°C (300° and 900°F), with temperatures rarely exceeding 538° C (1,000° F). The required contact time between the contaminant and the catalyst for complete oxidation to occur is normally 0.3 second (Radian Corporation, 1985).

Control Efficiency. A well-operated and maintained catalytic oxidation unit can achieve destruction efficiencies of 98 percent, comparable to thermal oxidation units. Destruction efficiency would decrease in the presence of catalyst poisons and particulate matter (U.S. EPA, 1995).

Advantages/Disadvantages. Catalytic oxidizers have lower energy usage and resultant operating costs than thermal oxidizers (with equal levels of heat recovery). This operating cost advantage may be offset by the increased capital cost of catalytic oxidizers. The smaller size of catalytic oxidizers also typically results in lower installation costs than thermal oxidizers with an equivalent flow rate. The generation of nitrogen oxides is virtually eliminated with catalytic oxidizers (due to the low combustion temperatures). Testing of a regenerative catalytic oxidizer demonstrated nitrogen oxide production of less than 1 ppm (Gribbon, 1996).

Catalytic oxidizers may suffer from catalyst fouling or poisoning. Some materials that are considered catalyst poisons include heavy metals (mercury, lead, iron, etc.), silicon, sulfur, and halogens. Organic solids or inert particulate matter may also poison or foul catalyst beds (Farmer, 1980).

Costs. Capital and operating cost data are presented in Appendix A and the spreadsheet cost model is presented in Appendix B.

4.1.2 *Adsorption Technology*

Adsorption technology utilizes a mass transfer process involving interactions between gaseous and solid-phase components. The gas phase is captured on the solid phase by physical or chemical adsorption mechanisms. Most VOC adsorption systems use activated carbon as the solid phase, although a few systems use silica gels, diatomaceous earth, alumina, synthetic zeolites, special polymer materials, or other proprietary substances.

In carbon adsorption, gaseous VOC molecules are captured on the extensive surface area present in the gross and molecular pore spaces in the activated carbon adsorbent. The used carbon adsorbent is then either discarded or regenerated. Carbon adsorption units are commercially available as packaged units up to 1,700 m^3/min (60,000 scfm) (Purcell and Shareef, 1986).

Activated carbon is best for adsorbing high-molecular weight and nonpolar chemical substances. Compounds with a molecular weight of 40 or less do not adsorb well on activated carbon. Compounds with a boiling point greater than 150° C (300° F) do not desorb well. A high relative humidity may interfere with the adsorption efficiency (Haberlein and Boyd, 1995).

The following sections discuss three carbon adsorption systems: (1) fixed-bed carbon adsorption (steam regeneration), (2) fluidized-bed carbon adsorption (hot air regeneration), and (3) activated-carbon filter panels (disposal, no regeneration). Hybrid systems using carbon or polymeric adsorption and subsequent desorption for recovery or oxidation are presented in the novel technologies section (Section 4.2).

4.1.2.1 Fixed-Bed Carbon Adsorption

Process Description. A typical fixed-bed carbon adsorption system consists of two large chambers, called "beds," that contain a large quantity of activated carbon. The VOC-laden exhaust is first passed through one of the chambers, which slowly adsorbs the VOC vapor onto the carbon in the bed. When the bed approaches either saturation (full capacity) or breakthrough (rapid reduction in capture efficiency), the exhaust is switched to the second chamber. Steam is then used to regenerate the first carbon bed. The VOC-laden steam is allowed to condense and the VOC is either decanted from the condensate or chemically treated. The two chambers alternate between adsorption and regeneration, maintaining a fairly constant emission control rate.

Applicability to FRP/C Processes. There are no known fixed-bed carbon adsorption systems installed on FRP/C processes in the United States.

Standard Operating Conditions**.** Cameron-Yakima, an activated carbon vendor, reports an average adsorption capacity of 20 percent to 50 percent, with an average of 33 percent for compounds such as styrene (Haberlein and Boyd, 1995). In other words, 680 kg (1,500 lb) of activated carbon could adsorb 227 kg (500 lb) of styrene before requiring regeneration. Typical superficial gas velocities through a fixed-bed system are 18 to 49 m/min (60 to140 ft/min), and resulting pressure drops are from 1,244 to 3,732 N/m^2 (5 to 15 inches of water) (Cooper and Alley, 1986).

Control Efficiency**.** Control efficiency for an activated carbon system is largely dependent on the degree to which the VOC is allowed to "break through" the carbon bed (i.e., the carbon is completely or nearly completely deactivated). If the outlet of the carbon bed(s) is monitored continuously, breakthrough can be avoided by switching beds or replacing carbon. In this case, adsorption efficiencies above 95 percent can be maintained.

Advantages/Disadvantages**.** For high-volume low-concentration VOC streams, carbon adsorption has lower energy costs than incineration. Carbon adsorption can be used to preconcentrate styrene prior to incineration or recovery (see Section 4.2.1). Reclamation of styrene from carbon adsorption may not be feasible or cost-effective, depending on chemical purity requirements for the reclaimed styrene. If reclaimed styrene cannot be used, it might require disposal as a hazardous liquid waste. The most likely disposal method would be destruction in a thermal incinerator designed for liquid waste or in a permited industrial kiln operation. The additional cost of transportation and destruction of a hazardous liquid waste would need to be considered in any economic analysis of carbon adsorption and recovery.

4.1.2.2 Fluidized-Bed Carbon Adsorption

Process Description**.** A fluidized-bed carbon adsorption system uses styrene-containing exhaust gases to entrain or "fluidize" activated-carbon particles. The activated carbon particles are fluidized by a recirculation fan. The rate of recirculation of the activated carbon particles can be adjusted to handle a wide variation in VOC inlet loadings.

MIAB (Molnbacka Industri, AB, of Sweden) has developed a continuous duty fluidized-bed carbon adsorption system, the MIAB C-D, in which VOCs are adsorbed then desorbed to a thermal oxidizer. The desorbed VOCs are concentrated, therefore the thermal oxidizer has a lower flow rate than would otherwise be necessary. The MIAB system is presented in the novel technologies section (Section 4.2.1.1) of this report.

Applicability to FRP/C Processes**.** No facilities in the United States currently use fluidized-bed carbon adsorption to control emissions from FRP/C processes. MIAB built a 28-m^3/min (1,000 cfm) fluidized-bed carbon adsorption pilot unit, which was operated for 3 months in 1994 at an OMC boat manufacturing plant in Ryd, Sweden, in 1994. The inlet and outlet styrene concentrations of the pilot study were 70 and 1.4 ppm, respectively, and a control efficiency of 98 percent was achieved.

4.1.2.3 Activated Carbon Filter Panels

Process Description. A carbon filter panel system uses an activated carbon filter panel consisting of a standard pleated-fabric dust filter that contains an inner layer of activated carbon granules. Normally, an activated carbon filter panel is placed within the return duct of a comfort air conditioning system, where it gradually adsorbs odors from the recirculating conditioned air. In this application, the conditioned air makes several passes through the filter each hour. This explains why the carbon filter panels are fashioned in the shape and size of standard air conditioning dust filters (Haberlein and Boyd, 1995).

The Glastic Corporation (South Euclid, Ohio) installed a system consisting of 20 passive filter housings mounted on the roof of a building where compression molding, pultrusion, laminate production, resin mixing, and bulk molding compound production were conducted. Five of the housings (in place since February 1993) each contain 48 panels, 0.30 m x 0.61 m (1 ft x 2 ft) in area, and 0.15 m (6 inches) deep. Each panel contains approximately 14 kg (30 lb) of activated carbon. The filters are weighed weekly and, upon a 3-kg (7-lb) weight gain, are sent out for regeneration. The rest of the housings, which have been in place for a longer time, are situated directly above the several 567 m^3/min (20,000 cfm) plant exhaust fans. Each of these housings contains 48 panels that are either 5 or 10 cm (2 or 4 inches) deep. These filters are disposed of after use. Glastic estimated that the cost is about $110/kg ($50/lb or $100,000/ton) of VOC controlled. The company emphasized that the system is still under development, and that they would not configure the system this way if they were to begin again (plans are to change out the throwaway filters and collect from specific point source operations) (LaFlam, 1993).

Applicability to FRP/C Processes. The Glastic facility (Euclid, Ohio) and the U.S. Fiberglass Product, Inc. (Middlebranch, Ohio) are the only two FRP/C facility in the United States using activated carbon filter panels to control plant emissions. Carbon filters could be applied for low-concentration, low-mass-flow applications.

Standard Operating Conditions. Carbon filter panels are typically used only for low-mass-emission-rate processes, because the capacity of the filters does not allow prolonged operation at high-mass-emission rates. Glastic Corporation uses panels containing 14 kg (30 lb) of activated carbon, and the panels are replaced after weekly weighing indicates a weight gain of more than 3 kg (7 lb).

Control Efficiency. The VOC control efficiency of an activated carbon filter panel system depends primarily on: (1) the degree to which breakthrough of styrene through the filter panels is allowed to occur, and (2) the amount of “sneakage,” or air that does not go through the filter panels.

Advantages/Disadvantages. Carbon filter panels can be used in low-concentration applications, with emissions spread over a wide area. Similar to the fixed-bed carbon adsorption system, carbon filter panels have disadvantages, such as potential for styrene polymerization and unlikelihood of styrene recovery. Additionally, carbon filter panels, because of their limited adsorption capacity before replacement, are not applicable to high-emission-rate processes. Costs per unit of styrene removed can be very high.

Costs**.** Glastic Corporation reports a cost per unit of styrene removed of approximately \$110/kg (\$50/lb or \$100,000/ton) for throwaway carbon filter panels and approximately \$20/kg (\$9/lb or \$18,000/ton) for regenerable filters. These cost estimates do not include capital and labor costs. Annual filter costs for the facility are on the order of \$250,000 (LaFlam, 1993).

4.1.3 *Condensation*

Condensation (refrigeration) involves lowering the temperature of a VOC-laden exhaust stream below the dewpoint (saturation temperature) of the VOC to be condensed. Figure 4-2 shows RTI-calculated low-temperature saturation concentrations for styrene in air at atmospheric pressure. The values in the figure are based on styrene saturation data from two sources (CRC Press, 1972, and Cooper and Alley, 1986). This figure indicates that the saturation concentration for styrene is 357 ppm at -23° C (-10° F), and 84 ppm at -40° C (-40° F).

Process Description. There are two types of refrigeration units: single-stage and multi-stage units. Both types typically consist of a skid-mounted unit on steel beams, including a walk-in weatherproof enclosure, air-cooled low-temperature-refrigeration machinery with dual pump design, storage reservoir, control panel and instrumentation, vapor condenser, and piping. Each unit has a system pump, plus a bypass pump to short-circuit the vapor condenser during no-load conditions.

Applicability to FRP/C Processes. Condensation is not commonly used to treat styrene emissions. However, an FRP/C facility (Premix, Inc., Ashtabula, Ohio) recently installed a liquid-nitrogen condenser to recover styrene. Premix has several pultrusion lines and resin storage and mixing tanks. The facility originally applied enclosure and nitrogen blanketing on their resin tanks and process openings to confine styrene emissions. Recently, they decided to vent the styrene-laden nitrogen to a condenser, which uses liquid nitrogen to remove styrene. This FRP/C facility is currently conducting a study to examine the styrene reuse issue. Since the facility already has a nitrogen source on site, the additional cost for the condenser is less than that for other emission control systems (Bonner, 1995).

For condensation to be a viable control technology for open molding processes, concentrations in exhaust streams at FRP/C facilities would need to be raised considerably from their current typical values of below 100 ppm.

Standard Operating Conditions. Single-stage refrigeration units typically achieve temperatures between 4° and -29° C (40° and -20° F), although some of them can reach -51° C (-60° F). Multistage units typically operate between -23° and -73° C (-10° and -100° F)

Figure 4-2

(Vatavuk, 1995). For the purposes of this evaluation, it will be assumed that single-stage units operate at -23° C (-10° F) and multistage units operate at -40° C (-40° F).

Control Efficiency. Condensation control efficiency is dependent on the operating temperature of the condensation system, the vapor-saturation curve for styrene, and the inlet styrene concentration to the refrigeration system.

Figure 4-3 depicts RTI-calculated styrene-removal efficiencies for various styrene inlet concentrations, for a single-stage unit operating at -23° C (-10° F) (saturation concentration of 357 ppm) and a multistage unit operating at -40° C (-40° F) (saturation concentration of 84 ppm). Styrene removal efficiencies are calculated relative to the saturation concentrations at -23° C (-10° F) and -40° C (-40° F), respectively. For example, the calculated removal efficiency for a single-stage condenser operating with an inlet concentration of 500 ppm would be [(500-357)/500]x100 = 28.6 percent.

Advantages/Disadvantages. Condensation has an advantage relative to oxidation in that no additional air pollutants (e.g., carbon dioxide and nitrogen oxides) are generated. The styrene recovered from a styrene condenser may not be reusable. Condensation is not an economically feasible alternative at styrene exhaust concentrations currently found at most FRP/C facilities (i.e., below approximately 100 ppm).

Costs. Capital and operating cost data are presented in Appendix A and the spreadsheet cost model is presented in Appendix B.

4.2 Novel Technologies

Novel technologies are technologies that have been applied in the last decade to treat low-concentration emissions. These technologies have been installed in European and Japanese FRP/C or boat building facilities to treat styrene emissions or in the United States to treat paint booth emissions or organic vapor from soil remediation. One of the novel technologies incorporates adsorption and desorption for subsequent recovery or oxidation in a hybrid design. In this case, the adsorption unit acts as a preconcentration stage, which creates a smaller exhaust flow at a higher concentration for subsequent recovery or oxidation. This hybrid technology is described in Section 4.2.1. Section 4.2.2 addresses biofiltration technology, and Section 4.2.3 presents an ultraviolet light/activated oxygen (UV/AO) technology.

4.2.1 *Preconcentration/Recovery/Oxidation Hybrid Systems*

Technical information collected from various vendors for four hybrid systems is presented in this section. These systems are MIAB, Thermatrix PADRE, Polyad, rotary concentrator, and fluidized-bed preconcentration systems.

Figure 4-3

4.2.1.1 MIAB System

MIAB (Molnbacka Industri, AB, of Sweden) manufactures fixed-bed (MIAB F-D) and continuous duty fluidized-bed (MIAB C-D) carbon adsorption systems to preconcentrate VOC emissions and the VOCs are desorbed for recovery or oxidation. The manufacturer's representative for MIAB, Setco, Inc. (Minneapolis, MN), lists two European applications for MIAB fixed-bed carbon adsorption systems on styrene. The first application was at the Ursvik AB facility (a hand layup operation) in Kinna, Sweden, installed in 1991. The second application was at the Borealis Industrier AB facility (an SMC production), installed in 1992, also in Sweden. Characteristics of these two fixed-bed applications are summarized in Table 4-2.

Table 4-2. MIAB Fixed-Bed Carbon Adsorption Applications in Sweden for Styrene Removal (Source: Sundberg, 1995)

	Borealis Industrier AB, Sweden	Ursvik AB, Kinna, Sweden
Type of MIAB Unit	MIAB F-D (Fixed carbon bed, catalytic oxidizer destruction)	MIAB F-R (Fixed carbon bed, desorbed styrene condensed for recovery)
Date installed	1992	1991
Reported Operational Parameters		
Flow rate (m^3/min [cfm])	651 (23,000)	510 (18,000)
Daily operation (hours)	Continuous	9
Inlet relative humidity (%)	50 - 90	50 - 90
Inlet styrene concentration (ppm)	26	30
Control efficiency, guaranteed (%)	90	90
Control efficiency, measured (%)	96	93
Carbon life	2 years	Original carbon
Reported Equipment Cost and Power Requirements		
Capital cost, U.S. dollars	248,000	193,000
Main fan, kW	38	24
Strip air fan, kW	1	1
Startup heater, kW	40	40
Total electric costs, kWh/8 hours	480	320

Figure 4-4 shows the diagrams of MIAB F-D (fixed-bed) and MIAB C-D (continuous duty fluidized-bed) carbon adsorption systems.

Standard Operating Conditions. The MIAB fluidized-bed carbon adsorption system is designed so that the catalytic oxidizer operates autothermally when used with catalytic oxidation. The concentration ratio (ratio between the adsorbed and desorbed streams) is typically approximately 1 to 10.

Control Efficiency. MIAB of Sweden fabricated and operated a MIAB C-D pilot-scale unit (approximately 28 m^3/min [1,000 cfm]) for approximately 3 months. Tests were conducted on the MIAB C-D pilot-scale unit at the OMC-Sweden facility in Ryd, Sweden, in late 1994 and early 1995. Flow rate and inlet and outlet concentration measurements were made after 5 days, 35 days, and 65 days of operation. Concentration measurements were made with a photoionization detector. The average flow rate was 1,690 m^3/h (994 cfm). The average inlet and outlet styrene concentrations were 69 ppm and 0.9 ppm, respectively, yielding a calculated average collection efficiency of 98.7 percent (MIAB, 1995).

Advantages/Disadvantages. A stated advantage of the MIAB-C-D system is that the use of a fluidized-bed adsorber accommodates a wide range of inlet styrene concentrations compared to fixed-bed systems. The MIAB preconcentration systems can be expected to have many of the same advantages and disadvantages of other carbon adsorption systems, except that after 3 to 4 years of operation in Sweden, the MIAB systems have not experienced styrene polymerization problems.

Costs. Capital and operating cost data are presented in Appendix A and the spreadsheet cost model is presented in Appendix B.

4.2.1.2 Thermatrix PADRE® System

Thermatrix, Inc. manufactures an on-site, self-regenerable adsorbent system called PADRE that removes and recovers solvents from air streams. Purus Inc. (in San Jose, California) first introduced the technology, but the technology is currently marketed by Thermatrix, Inc. (Mechanicsburg, PA).

Process Description. The PADRE system is based on adsorption. The system is small relative to typical exhaust flows in the FRP/C industry, with the largest current installation handling around 198 m^3/min (7,000 cfm). The technology uses fixed beds, with one adsorber on-line while the other is either desorbing or on standby. Vacuum, nitrogen, and temperature (180° C [356° F]) are used to achieve the desorption. The exact "recipe" depends on the compounds being treated. The PADRE system can use four different types of adsorbents provided by Rohm & Haas and Dow Chemical Company. A two-stage condenser is used to recover the desorbed VOC as a liquid. In a few cases, PADRE customers are routing the offgas to an oxidizer. Figure 4-5 is a diagram of the Thermatrix adsorption system.

Figure 4-4

Figure 4-5

Standard Operating Conditions. The PADRE system is most commonly applied to processes involving low flows (less than 198 m^3/min [7,000 cfm]) and low concentrations. The system is typically used for control of chlorinated hydrocarbons.

Control Efficiency. Thermatrix's predecessor Purus has performed two pilot tests evaluating styrene removal for the PADRE system. The first test was for a composite manufacturing facility on a slipstream of 4.2 m^3/min (150 cfm), with concentrations of 10 ppm to 100 ppm (spikes). Another test was performed on the air stream containing 15 to 20 ppm of a mixture of volatiles and water vapor from a stripper operating on styrene-containing wastewater. (LaFlam, 1995a).

Applicability to FRP/C Processes. There are no commercial installations of the PADRE system for control of styrene from FRP/C processes, but there are approximately 50 U.S. installations on non-FRP/C processes. Most of these installations are for remediation technologies/processes (e.g., chlorinated solvents) at Superfund sites, but PADRE systems are also beginning to have other industrial applications.

The pilot study conducted for a composite manufacturing facility showed no drop in adsorption capacity over an unspecified desroption cycles. However, the recovered product was slightly off-color (due to water). A second recovery step is likely to be needed before the recovered styrene can be reused. The ability to reuse the recovered styrene is still in question. The applicability of the PADRE system will be determined by the usefulness and cost effectiveness of recovered styrene. In the second pilot study, the adsorbent in the PADRE system lost capacity after one or two desorption cycles (LaFlam, 1995a). Therefore, an adsorbent must be tested specifically for styrene, when the PADRE system is to be considered for styrene removal.

Advantages/Disadvantages. The Thermatrix system may provide lower annualized costs at low concentrations than thermal or catalytic incineration. However, the system has not been used for FRP/C operations in the United States, and typical Thermatrix PADRE installations are at much lower flow rates than typical FRP/C facility exhausts.

Costs. Capital and operating cost data are presented in Appendix A and the spreadsheet cost model is presented in Appendix B.

4.2.1.3 Polyad™ System

The Polyad system is manufactured by Chematur Engineering AB/Weatherly Inc. (Atlanta, Georgia).

Process Description. There are two types of systems: Polyad preconcentration system followed by oxidation, and Polyad-solvent recovery system. Both systems pull VOC-laden air through a fluidized-bed adsorber. The adsorber consists of four to six fluidized beds with polymeric adsorbents (i.e., Bonopore^{TM} 1120, Dowex Optipore® 493). Regenerated adsorbent is continuously fed to the top bed. The VOC-laden air passes countercurrently through the adsorber. The polymeric adsorbent adsorbs the VOCs (styrene). Polymeric adsorbent (loaded with VOCs) is transferred from the bottom of the adsorber to the desorption unit. Treated air, free of VOCs, passes through the adsorber fan and is released to the atmosphere via the stack.

The VOC laden polymeric adsorbent is continuously regenerated in either a fluidized-bed desorber or a moving-bed desorber. Desorption occurs at elevated temperatures (up to 149° C [300° F]). In the preconcentration system, fresh air is heated by the oxidizer flue gases before the desorption air enters the fluidized-bed desorber; steam is used as the heating medium in the moving-bed desorber. The small air stream, containing high concentrations of VOCs (styrene), leaves the fluidized-bed desorber and enters an oxidizer. For a preconcentration system treating 345 m^3/min (12,500 cfm) of incoming stream, the flow rate to the oxidizer is around 14 m^3/min (500 cfm) (LaFlam, 1995a). A concentration factor of 25 is achieved in the Polyad system. In the catalytic oxidizer, the VOCs are converted (oxidized) to carbon dioxide and water. The VOCs are used as the major fuel source for oxidation (minimizing the total energy consumption). The moving-bed desorber is integrated with a condenser system to be able to condense and recover the VOCs.

A diagram of the Polyad system with an oxidition unit is shown in Figure 4-6. The Polyad recovery system is similar to the system shown, except that a recovery condensor is substituted for the oxidation unit.

Applicability to FRP/C Processes**.** A Polyad preconcentration/oxidation system was installed at an American Standard facility in Salem, Ohio, in February 1996. The American Standard facility makes several products, including FRP bathtubs. The Polyad system at American Standard has a total inlet flow rate of approximately 963 m^3/min (34,000 cfm), and treats several exhaust streams from the FRP operations, as shown in Table 4-3 (Ross-Bain, 1996). In May 1995, Weatherly, Inc., provided a list of Polyad system applications in Europe that included five systems for styrene removal. These systems are listed in Table 4-4.

Standard Operating Conditions. The ratio of flow rate (i.e., concentration) between inlet and outlet of the fluidized-bed preconcentration system is designed on a case-by-case basis. However, for the American Standard (Salem, Ohio) plant, the inlet flow rate is approximately 991 m^3/min (35,000 scfm) and the (desorbed) flow rate to the oxidizer is approximately 48 m^3/min (1,700 acfm), at a temperature of 93° C (200° F) (Ross-Bain, 1996).

Control Efficiency. Control efficiency of a Polyad solvent recovery system was measured by the EPA during a pilot test conducted on the exhaust (approximately 5.6 m^3/min [200 cfm]) of a gel coat spray booth at the Eljer fiberglass bath fixture facility in Wilson, North Carolina, during November 1992. At that time, only the solvent recovery system was available for the pilot test. Results of 3 days of testing indicated an average VOC capture efficiency of

94.18 percent, with collection efficiency increasing during each day of testing (average collection

Figure 4-6

Table 4-3. Processes Treated by the Polyad Control System at the American Standard Facility in Salem, Ohio (Source: Ross-Bain, 1996)

Process	Location	Approximate flow rate, m^3/min (cfm)
Gel coat and resin sprayup	Spray booth #1 (new)	680 (24,000)
Accelerated curing	Drying (cure) booth	57 (2,000)
Resin mixing	Mixing tank	28 (1,000)
Chop spray	Spray booth #2 (existing)	198 (7,000)
Total	All	963 (34,000)

Table 4-4. Polyad Applications in Europe for Styrene Removal (Source: Danielsson, 1995)

Facility name and location	Air flow (m^3/min, [acfm])	Styrene recovery or preconcentration	Inlet concentration (ppm)	Reported efficiency (%)	Start-up date
IFÖ Sanitär AB Bromölla, Sweden	354 [12,500]	Recovery / Preconcentration[a]	92	90 / 97	1989/ 1993[a]
Beton und Kunstoff Industrie Schlinsog GmbH & Co., KGLauterbach/ Allmenrod, Germany	416 [14,700]	Recovery	46 - 92	98	1990
Hoesch, Metall + Kunstoffwerke GmbH & Co. Düren, Germany	1,000 [35,300]	Recovery	Not reported	> 90	1992
Norfrig A/S Hvam/Kjellerup, Denmark	912 [32,400]	Recovery / Preconcentration[a]	Not reported	> 90 / Not reported[a]	1992/ 1995[a]
Isola Werke AG Duren, Germany	198 [7,000]	Recovery	Not reported	> 90	1993

[a] = Unit initially installed to recover styrene (by condensation). Now modified for preconcentration followed by oxidation destruction.

efficiency was 92.63 percent the first day, 94.41 percent the second day, and 95.42 percent the third day). Collection efficiency was highest during periods of gel coat spraying (when inlet concentration was above 63 ppm) (Felix et al., 1993). Weatherly Incorporated indicated that a preconcentration system is now available for pilot studies, and its collection efficiency is higher than that of the solvent recovery system (Ross-Bain, 1996).

Advantages/Disadvantages. The Polyad system, as with other preconcentration systems, reduces the flow rate requirement for the oxidizer or VOC recovery device. This can reduce total annualized costs per unit of styrene removed, as compared to straight thermal or catalytic oxidation. The Polyad system is most economically attractive for flow rates above 283 to 340 m^3/min (10,000 to 12,000 cfm) (Ross-Bain, 1996). Weatherly Incorporated recommends preconcentration system over solvent recovery system for styrene removal.

Costs. Capital and operating cost data are presented in Appendix A and the spreadsheet cost model is presented in Appendix B.

4.2.1.4 Rotary Concentrator System

Process Description**.** In a rotary concentrator system, styrene-containing exhaust gases are filtered first to remove particulate matter (for long-term protection of adsorbent), then pulled through a large, rotating honeycomb wheel. The honeycomb is impregnated with either activated carbon or a specialized zeolite adsorbent. The wheel turns slowly while styrene in the exhaust gas is adsorbed. A small sector of the wheel is isolated from the exhaust stream, then a low volume of hot air is passed through this sector, desorbing the styrene to a higher concentration. This small, concentrated stream is normally conducted to an incinerator for destruction. Figure 4-7 shows a rotating-wheel design and Figure 4-8 shows a cylinder-type design of the rotary concentrator systems. Figure 4-9 shows the process diagram of a combined rotary concentrator and oxidation system.

Applicability to FRP/C Processes**.** There are no known applications of rotary concentrator systems on FRP/C processes in the United States. However, Daikin of Japan supplies carbon-based honeycomb rotary concentrators, which are used to control emissions from plants manufacturing hot tubs, shower stalls, etc. in Japan. There are nine applications installed in Japan. The first installation was in 1984. The concentrated vapor streams from these rotary concentrators are sent to catalytic oxidizers for on-site destruction (Sekiguchi, 1996). There are at least two zeolite concentrating rotor installations for styrene emissions control at styrene-butadiene synthetic rubber plants in Europe (Haberlein and Boyd, 1995).

Standard Operating Conditions. Styrene-laden air at ambient temperature first passes through a filter to remove particulate matter then enters the honeycomb rotary concentrator. The honeycomb rotor travels 2 to 6 revolutions per hour. Styrene adsorbed on the rotary concentrator is desorbed by heated air at 5 to 25 percent of the original flow rate. The temperature of the desorbing gas ranges from 66° to 120° C (150° to 250° F) for activated carbon and could be as high as 177° C (350° F) for zeolite. The styrene-concentrated gas stream is then subject to thermal or catalytic oxidation. The Durr pilot study at Navistar International Transportation did not observe progressive polymerization of styrene on the surface of either carbon or zeolite adsorbents over the month-long studies (Gupta, 1996).

Control Efficiency. The styrene removal efficiencies for three Daikin rotary concentrators in Japan range from 96.9 to 99.4 percent. For example, the inlet and outlet styrene concentrations of a rotary concentrator were 238 and 2.1 ppm, respectively. The styrene

Figure 4-7

Figure 4-8

Figure 4-9

concentration in the desorbed stream to the catalytic oxidizer was 1,160 ppm. At that concentration, the catalytic oxidizer was self-sustaining. This implies that the concentration increased or the exhaust flow rate was reduced by a factor of 5 (Sekiguchi, 1996).

Durr Industries, Inc. (Plymouth, Michigan) conducted two 1-month pilot studies at Navistar International Transportation (Columbus, Ohio) in October 1995 to determine the feasibility of activated carbon and zeolite rotary concentrators for reducing styrene emissions from SMC production. A split stream of 5.7 m^3/min (200 cfm) was taken from the SMC exhaust for the pilot study. The Durr pilot study showed that the styrene removal efficiency for the zeolite rotor was 97 percent over a month-long study. The average inlet and outlet styrene concentrations of the zeolite rotor were 137 and 4.3 ppm, respectively. The styrene removal efficiency for the activated carbon rotary concentrator was 98 percent with an average inlet styrene concentration of 136 ppm and outlet concentration of 2.4 ppm (Gupta, 1996). A concentration factor of 10 was used in the Durr pilot study, which implies that the desorbing flow rate is 10 percent of the incoming flow rate.

Advantages/Disadvantages. Rotary concentrators can reduce the exhaust stream and increase its concentration for subsequent destruction. The concentration factor is determined from the inlet and desorbing concentrations. For safety reason, the desorbing concentration is limited to 25 percent of the LEL, that is, 2,500 ppm. Typically, a rotary concentrator can reduce the exhaust flow rate to 5 to 25 percent of the original exhaust flow (i.e., a concentration factor of 4 to 20). Consequently, capital and operating costs for an add-on emission control device can be reduced significantly. A concentrated stream reduces or eliminates the auxiliary fuel required to operate an incinerator, resulting in a decrease in operating cost and related emissions of carbon and nitrogen oxides. Regenerative and recuperative thermal oxidation and catalytic oxidation units are typically used for final destruction. Selection of a destruction unit is based on the expected life of operation, required destruction efficiency, and operating cost.

Costs. Capital and operating cost data are presented in Appendix A and the spreadsheet cost model is presented in Appendix B.

4.2.1.5 Fluidized-Bed Preconcentration System

Process Description. The fluidized-bed preconcentration system applies newly developed spherical adsorption materials in a fluidized-bed adsorption unit and followed by either a fluidized-bed or moving-bed desorption unit. This system is particularly useful in large air flow and low VOC concentration applications. Theoretically, a high concentration factor or volume reduction ratio, as high as 800-1,000 to 1, can be achieved for odor control application when the inlet loading is in the few-ppm range.

The basic fluidized-bed preconcentration system consists of the following general sections: adsorber, desorber, condenser or oxidizer, process fan, media transfer blower, and plumbing for VOCs recovered from condenser. Figure 4-10 shows a flow diagram of the

Figure 4-10

REECO/EC&C fluidized-bed preconcentrator system with an oxidizer (Biedell and Cowles, 1996). The adsorber vessel consists of a series of perforated trays. Process gas enters the vessel in the bottom section and is directed upward through the trays. The VOCs in the process gas are adsorbed by a beaded carbonaceous adsorbent (BCA) medium. The regenerated BCA medium constantly enters the top of the adsorber, providing countercurrent VOC removal. The spent BCA medium is transferred to the desorber by an airlift blower.

The desorber section could be a smaller fluidized-bed similar to the adsorber. The ratio of adsorber and desorber sizes can be designed to achieve the desired concentration factor of the desorbate. The flow diagram incorporates a small oxidizer for final treatment. The flue gas provides the energy for desorption. As the BCA medium is heated, a very small volume of inert carrier gas flows through the desorber and carries the desorbate out of the desorber. Auxiliary air is added in sufficient quantity to oxidize the VOC in inert gas stream. The design allows for very small desorbate volume and makes the subsequent oxidation very economical.

The system has both condensation and oxidation options. The high-concentratio/low-volume offgas can be directed to either posttreatment device. For the condensation option, the unit has a separater/decanter to separate VOCs and water. The VOC is then pumped to the storage vessel. If an oxidation unit is used, the size of the oxidizer can be determined from the concentration and flow rate of the offgas.

Applicability to FRP/C Processes. There are no known applications of a fluidized-bed preconcentration system on FRP/C processes in the United States. The system can be used for any application that would normally use standard fixed-bed carbon adsorbers. The system has been used for odor control and demonstrated for halogenated solvents, methyl ethyl ketone (MEK), and other similar compounds.

Standard Operating Conditions. The system is suitable for treating diluted VOC emissions at ambient temperature and at 35 to 50 percent relative humidity. For the oxidation option, the desorbing gas, air, is heated to 177° C (350°F) to strip VOCs from the BCA medium in the desorber. For the condensation option, an electric heater is used to raise the temperature of the BCA medium in the desorber, then nitrogen is blown to remove VOCs from the BCA medium for subsequent condensation. According to the vendor, there is very little pressure drop in the adsorber and the BCA medium has good resistance to attrition (less than 2 percent per year). The vendor also claims that simplicity of design and few moving parts provide easy, low maintenance and high reliable operation.

Control Efficiency. EC&C's experience has shown that general efficiencies in the range of 90 to 95 percent can be expected for most VOCs (Merboth, 1996). However, control efficiency for styrene emissions has not been demonstrated.

Advantages/Disadvantages. The fluidized-bed preconcentration system offers a high concentration factor for diluted VOC emissions (e.g., odor control). The fluidized-bed adsorber design has a lower pressure drop and results in lower energy consumption than a fixed-bed adsorber. The fluidized-bed system uses less adsorbent than a fixed bed adsorber; therefore, it minimizes equipment size and weight. The concentration factor is determined by the inlet concentration and desorbing concentration. For safety reasons, the allowable concentration in the desorbing stream should not exceed 25 percent of the LEL. In the case of styrene emissions, 25 percent of the LEL is 2,500 ppm styrene. Therefore, the concentration factor will be 250 when a 10-ppm stream is concentrated to 2,500 ppm. However, the concentrator factor will be 10 when a 250-ppm stream is concentrated to 2,500 ppm. The concentration factor may be higher when the condensation option is used and the VOC is recovered as liquid.

Costs. Capital and operating cost data are presented in Appendix A and the spreadsheet cost model is presented in Appendix B.

4.2.2 *Biofiltration*

Biofiltration is a biologically based treatment technology. It uses microorganisms in a filter medium to control organic compound emissions in an air stream. Air emissions containing biodegradable constituents pass through a biologically active medium. The microorganisms degrade the organic constituents in the air stream to essentially carbon dioxide and water. Biofiltration has been used for many years in Europe, Japan, and the United States for odor control, but the use of biofiltration to degrade more complex air emissions from chemical plants has occurred only within the past few years. Descriptions for two types of biofilter systems are presented here.

4.2.2.1 Biofiltration System

Process Description. First, contaminated air enters a preconditioning unit, where the temperature, moisture level, and particulate matter of the gas are adjusted as needed. The air is then evenly distributed and passed once through a packed bed. The biofilter contains packing that houses microorganisms (Figure 4-11). A moist film of microorganisms is attached to a stationary synthetic or natural packing material such as peat, compost, leaves, wood bark, and/or soil. The biofilter can be optimized for moisture and nutrient levels, pH control, pressure drop, and adsorptivity. Within the packed bed, contaminates pass from the air into the biomass, where they are biologically destroyed. Instrumentation and process controls are provided as needed.

Standard Operating Conditions. Biofilter systems for VOC control are strongly affected by the choice of the attachment medium for microorganisms. Ideal attachment media are characterized by a high specific surface area, minimal backpressure, and a suitable surface for the attachment of microorganisms. Biofilter media are mainly of two types: (1) a natural organic medium composed of peat, compost leaves, wood bark, and/or soil, or (2) an inert synthetic medium. However, a combination of both types is sometimes used.

Figure 4-11

Flow rate, humidity, pH, pressure drop, temperature, growth of biomass, and bacteria count are critical operating parameters for biofiltration systems. Depending on design specifications, units may be equipped to continuously measure some of these parameters. For example, the AMT biofiltration system at Fiberform AB maintains a pH range of 5 to 7, and the pressure drop ranges from 1,000 to 2,000 Pa (0.145 to 0.29 psia).

Control Efficiency. Mr. Munters of AMT (Munters, 1995) describes biofiltration as "nature's own way of cleaning VOCs and odors" with obtainable control efficiency as high as 99 percent. According to Mr. Munters, some facilities do not measure removal efficiency; however, a Swedish company, Fiberform AB, has an integrated biofilter/heat exchange system designed to achieve 80 to 85 percent styrene reduction in a 284 m^3/min (10,000 cfm) stream. The system was installed in 1991, and the company has not experienced any problems with the system.

In facilities that do not measure removal efficiency, Mr. Munters said "one can smell the emitted VOC when the biofilter is not working properly". He also added that often flame ionization detectors (FID) are used to measure emissions, and, when moisture content, pH, and total microorganisms are monitored, additional monitoring is not necessary. He stated that controlling the humidity is important for preventing channeling. AMT's systems come equipped with a computer-operated moisture controller. Although styrene has low solubility in water, according to Mr. Munters, the biomass is porous and acts as a molecular sieve.

Applicability to FRP/C Processes. A Swedish company, Fiberform AB, that manufactures fiberglass hard tops for trucks and other parts, uses an AMT biofiltration system that was installed in 1991 to treat styrene emissions. The biofiltration system is an integrated prefabricated concrete structure with a filter bed area of 139 m^2 (1,500 ft^2). It treats an air flow of 283 m^3/min (10,000 cfm). Fiberform AB operates 8 hours per day and is closed for a 2-week vacation annually. The system is designed to achieve 80 to 85 percent styrene reductions. Moisture content and total microorganisums are monitored periodically. Fiberform AB has not experienced any problems with this system.

Dr. P. Togna with Envirogen told RTI (Togna, 1995) that information on the European biofiltration systems for styrene treatment has been shared mainly through conversation and not through published information. Although biofiltration is a proven technology that is widely used in Europe, Dr. Togna said that he had not read or seen many published papers or articles discussing styrene treatment. By personal communication, he has learned that several European biofiltration systems have observed decreased removal efficiency after 4 to 5 months when treating styrene. Researchers hypothesize that the decreased efficiency is attributed to buildup of an acid byproduct (Togna, 1995).

A Dutch research group, TNO, has developed a biofilter system to alleviate this problem. TNO is investigating the longevity of the system through a long-term bench- and pilot-scale styrene study. Envirogen and a Dutch company have a joint venture called CVT America.

CVT America has potential access to license TNO's technology through a sister company called CVT Bioway. (CVT Bioway is a separate company from CVT America.) TNO is performing their field-pilot styrene project with CVT Bioway in the Netherlands. The TNO system has been in operation for about 9 to 12 months, and styrene removal of 90 percent and greater has been maintained (Togna, 1995).

4.2.2.2 Biotrickling Filter System

Process Description. Contaminated air enters the biotrickling filter (Figure 4-12) and flows concurrently with recirculating water downward through a column filled with packing material. Microorganisms grow as a biofilm on the packing material and destroy the contaminants as they pass through the system. Biotrickling filters that employ synthetic, inorganic media (e.g., a monolithic channelized medium and a pelletized ceramic medium) yield more uniform gas distribution and biological contact than those that do not. These characteristics result in more consistent operation due to better overall pressure drop control and better nutrient and pH control. Superior performance was obtained with effluent recycle, which controlled pH and provided microbe reseeding. The recirculation water allows for optimal control of pH, nutrient levels, and biofilm thickness. Biotrickling filter systems can be supplied in standard or semi-custom sizes, with instrumentation and control packages provided as needed.

Control Efficiency. Envirogen has developed a biotrickling system for treatment of styrene to overcome the acid buildup problem. Envirogen's biotrickling filter system has not been proven in the field. However, a system has been designed to treat an air stream at a chemical manufacturing facility that emits styrene. The styrene-contaminated air comes from sequencing batch reactors at the facility's wastewater treatment system. The flow rate of the air stream is approximately 40 m^3/min (1,400 cfm) with a styrene concentration of about 150 ppmv. Because of customer constraints, Envirogen was not required to guarantee the removal efficiency of the system. However, the operating conditions of the system, such as pH and biomass growth control, are guaranteed. A removal efficiency of 50 percent is sufficient to meet the goals of the customer, but a removal efficiency of 90 percent is expected (Togna, 1995).

Advantages/Disadvantages. Biofiltration and biotrickling systems have several differences. Biotrickling systems typically contain packing that is a structured or randomly packed synthetic material designed not to plug. Liquid is constantly recirculated over packing material in a biotrickling filter system, and fresh makeup water and nutrients are added as needed. Acid intermediates are washed away continuously. Packing in a biofiltration system is typically organic matter, such as compost and/or wood chips, that may swell and/or compact over time. Biofiltration systems typically operate at a moisture content of 50 percent (slightly more or less depending upon the application), without a liquid recirculation loop. Overall, biotrickling filter systems can handle higher concentration loadings than biofilter systems (Togna, 1992).

Although styrene has low solubility in water, Dr. Togna said that a driving force for styrene transfer into the water/biofilm phase is always present due to microbial degradation of styrene. The biological matter on the packing material adsorbs and degrades the styrene.

Figure 4-12

Polymerization should not be a problem, even if some carbon is added to the packing material as a load buffer. Styrene concentration should be low enough, and microbial activity fast enough, for degradation effects to take place before polymerization is likely to begin. However, Dr. Togna has not seen any reports confirming his hypothesis (Togna, 1995).

When asked to explain why biofiltration was popular in Europe, Dr. Togna stated that people live closer together in Europe and that odor control is an issue. Biofiltration was first designed to eliminate that problem. Because energy -- natural gas and oil -- is more expensive in Europe compared to the United States, biofiltration was accepted over incineration as the most viable odor treatment option. Europeans then found that biofiltration could also be used for VOC applications in response to Europe's strict environmental laws. Dr. Togna and others in the biofiltration community believe that biofiltration systems that were not initially designed to handle VOC applications are now experiencing decreased removal efficiency when used for VOC applications. No studies were done initially to evaluate the longevity of these systems for VOC applications. Envirogen and its partner have since done research to address these issues (Togna, 1995).

4.2.3 *Ultraviolet/Oxidation Technology*

VM Technologies, Inc. (Lake Forest, CA) and Terr-Aqua Enviro Systems, Inc., (Fontana, CA) both provide integrated ultraviolet/oxidation technologies to destroy VOC emissions. The VM system has been used for air, water, and wastewater treatment. Its modular design allows the system to handle exhaust flow rates from 1,400 to 6,400 m^3/min (50,000 to 225,000 cfm). The Terr-Aqua system has been installed in several metal parts surface coating operations to treat a variety of VOCs. It was designed to handle exhaust stream flow rates ranging from 57 to 3,400 m^3/min (2,000 to 120,000 cfm).

Process Description. A basic schematic of the ultraviolet/oxidation system is shown in Figure 4-13. The system treats VOC emissions from exhaust streams from paint spray booths, curing ovens, paint mixing rooms, solvent cleaning, paint stripping facilities. The air treatment process follows these steps:

1. Contaminated air is filtered to remove any particulate matter.
2. Once particulate matter are removed, the VOCs are exposed to ultraviolet light and ozone. This preoxidation step breaks down the VOCs.
3. The air stream is sprayed with a mist in a contact chamber or through a packed-bed scrubber, and the VOCs are absorbed into the water. This contaminated water is subjected to more ozone in an aqua reactor and is filtered to remove particulate matter.
4. The exhaust air passes through carbon beds to remove any remaining VOCs.
5. The carbon is regenerated with ozone to destroy any VOCs adsorbed.

Standard Operating Conditions. Acceptable operating conditions for exhaust air streams treated with the ultraviolet/oxidation system are as follows (Shugarman, 1996):

Figure 4-13. Schematic of the Terr-Aqua's ultraviolet/oxidation system.

Temperature range: -1° to 66° C (30° to 150° F)
Relative humidity range: 0 to 100 %
Flow rate: 28 to 28,320 m^3/min (1,000 to 1,000,000+ cfm) (modular)

Control Efficiency. Terr-Aqua claims their system works well with mixtures of various VOCs/HAPs, including chlorinated/fluorinated compounds and its system is typically guaranteed to perform at a minimum of 95 percent control efficiency for many organic compounds (Shugarman, 1996). The VM system destroys and removes over 98 percent of VOCs (Viszolay, 1996). Photosensitive compounds, like those with benzene rings, begin to break down quickly in the preoxidation ultraviolet phase while other compounds are simply excited. Soluble or miscible VOCs are captured and neutralized very readily in the water phase aqua reactor. However, styrene does not have a high degree of solubility in water (Stitt, 1996).

Application to FRP/C Processes. Both the VM and Terr-Aqua's ultraviolet/oxidation systems have been commercial for more than 10 years; however, both companies do not have any working unit for FRP/C applications. Terr-Aqua has a joint research and development agreement with the Applied Research Laboratory of Penn State University for the investigation, development, and implementation of technology improvements for ultraviolet/oxidation systems. A fully instrumental pilot-scale ultraviolet/oxidation system has been installed at Penn State. The ultraviolet/oxidation system has been tested at Penn State on several compounds, including ethyl benzene. (Styrene, or vinyl benzene, is chemically similar to ethylbenzene.) Testing of the ultraviolet/oxidation system's performance on ethylbenzene indicated virtually no alteration or removal of ethyl benzene in the ultraviolet light or activated oxygen scrubber portions of the ultraviolet/oxidation system. All ethylbenzene removal achieved by the system occurred in the carbon adsorption portion of the system (Schneider, 1996).

Advantages/Disadvantages. An advantage of heterogeneous photocatalysis is its potential to purify air at ambient temperature and pressure in the presence of O_3 and H_2O. The technology also produces benign products, CO_2 and water, from the complete photocatalytic oxidation of hydrocarbons. The disadvantages of ultraviolet/activated oxygen technology are that it is more complex than other add-on emission control technologies evaluated, the UV light and ozone generator require routine maintenance, and the ultraviolet light and activated oxygen scrubbing portions of the Terr-Aqua system have not been demonstrated to be effective in the destruction/removal of styrene.

Costs. Cost data were not collected from the vendors.

4.3 Emerging Technologies

For many years, incineration, adsorption, absorption, and condensation have been the control technologies available for in-process recovery and end-of-pipe control of organic vapor emissions. Innovative options have been slow to show commercial viability and to gain industry acceptance (Simmons et al., 1994). Some emerging technologies have proven applications on air streams of specific manufacturing processes. Other emerging technologies are just beginning to be explored via field applications and pilot testing, after undergoing several years of laboratory evaluations. Information on several of the available emerging technologies is provided here. One of these new technologies is based on membranes that selectively allow permeation of organic compounds in preference to air. Another is photocatalytic oxidation, which takes place at ambient temperatures in the presence of ultraviolet light.

4.3.1 *Membrane Technology*

Membrane vapor recovery technology is based on membranes that selectively permeate organic compounds in preference to air. The transformation of membrane separation from a laboratory study to an industrial process was the development, in the early 1960s, of the Loeb-Sourirajan process for making defect-free, high-flux, ultrathin membranes for reverse osmosis (Baker and Wijmans, 1994). Membrane separation, developed over the past 10 years, is beginning to prove its commercial viability and is emerging as an alternative or complementary recovery technology for several industrial applications (see Table 4-5), such as vent gas control and recovery, gasoline vapor recovery, and other applications under development (Baker and Wijmans, 1994). Membrane separation systems are proving effective at recovering organic vapors from concentrated gas streams before the final vent. In addition, they can be combined with other air pollution control technologies to offer compelling advantages (Simmons et al., 1994).

Table 4-5. Selected Commercial Applications for Membrane Separation (Source: Baker and Wijmans, 1994).

CFCs from storage tank filling	Sterilizer vent gas recovery
Industrial chiller refrigerant recovery	Vinyl chloride from PVC manufacture
HCFC-123 from coating operation	Solvents from pharmaceutical process
Aerosol inhaler propellant process	Perfluorocarbon recovery

CFC = Chlorofluorocarbon, PVC = Polyvinyl chloride.

Process Description. Many types of modules are used for membrane separations. The diagram shown in Figure 4-14 represents a simplistic arrangement of only one of these options. A selective barrier layer, the membrane, separates a feed and a retentate stream from a downstream permeate stream (Koros, 1995).

Three membrane separation modules have been developed by several companies. Membrane Technology and Research, Inc. (MTR), in Menlo Park, California, and Nitto Denki in Japan use spiral-wound modules; GKSS Forshungszentrum Geesthacht GmbH (GKSS) in Geesthacht-Terperhude, Germany, and its licensees use plate-and-frame modules (Baker and Wijmans, 1994); Hoechst-Celanese Corporation has developed a hollow-fiber membrane contactor (Freeman, 1995; Prasad, 1995). Schematics of a spiral-wound, a plate-and-frame,

Figure 4-14. Diagram of a simple membrane module.

and a hollow-fiber contactor are illustrated in Figure 4-15. Spiral-wound modules are compact. Plate-and-frame systems are thought to offer advantages in flow distribution and reduce permeate-side pressure drops. The hollow-fiber contactor design has a high-membrane surface area (Prasad, 1995).

A basic membrane system for organic emissions control consists of two steps: a compression-condensation step followed by a membrane separation step. The compression-condensation step is conventional. The membrane separation step is based on high-performance composite membranes that are 10 to 100 times more permeable to organic compounds than to air (Jacobs et al., 1993).

A vapor-air mixture is compressed to 3.1×10^5 to 1.4×10^6 N/m^2 (45 to 200 psig). The compressed mixture is sent to a condenser where it is cooled. Part of the organic vapor condenses and is then directed to a solvent storage tank for recycling or reuse. The noncondensed portion of the organic mixture enters the membrane modules and passes across the surface of an organophilic membrane. The organophilic membrane separates the gas into two streams, consisting of a permeate stream and a solvent-depleted stream. The permeate stream contains most of the remaining solvent vapor for the condenser. The solvent-depleted stream, or vent, is essentially stripped of the organic vapor. Permeate is drawn back into the inlet of the compressor, and the solvent-depleted air stream is vented from the system. This two-step process is illustrated in Figure 4-16 (Jacobs et al., 1993).

Transport through the membranes is induced by maintaining the proper pressure difference. Vapor pressure on the permeate side of the membrane must be lower than on the feed side to provide the driving force for permeation. The pressure difference is obtained by compressing the feed stream of the membrane modules, as in Figure 4-16, or by using a vacuum

Figure 4-15

Figure 4-16

on the permeate side. Occasionally, a combination of both techniques is used (Jacobs et al., 1993).

The key element in the process is a composite membrane that selectively allows permeation of organic compounds over air. Air and organic vapors permeate the membrane at rates dependent upon their relative permeabilities and the pressure difference across the membrane. To achieve effective and economical separation, the described membrane system illustrated in Figure 4-16 must meet three requirements:

1. The membrane materials must have adequate selectivity to remove organic vapors from air.
2. These materials must be formed into high-flux, defect-free membranes.
3. These membranes must be formed into space-efficient, low-cost membrane modules (Jacobs et al., 1993).

<u>Standard Operating Conditions</u>. A key consideration in achieving separation with a membrane system is the selectivity of the membrane used. The composite membrane must selectively allow permeation of organic compounds over air. However, operating conditions also affect system performance. One of the most important operating parameters is the pressure ratio across the membrane. The pressure ratio is the feed pressure divided by the permeate pressure. To provide the driving force for permeation, partial vapor pressure on the permeate side of the membrane must be lower than on the feed side.

The second operating condition that affects membrane system design is the degree of separation required. The usual goal is to produce a residue stream essentially stripped of organic vapor, while simultaneously producing a small, concentrated permeate stream from which organic recovery is straightforward. These two requirements cannot be fully met simultaneously; therefore, a tradeoff must be made between vapor removal from the feed gas and permeate enrichment for the membrane system. The design term used to deal with this tradeoff is *stage cut*. Stage cut is the fraction of the total flow that permeates the membrane. It is equal to the permeate flow rate divided by the feed flow rate, expressed as a percentage.

Because of limitations of membrane selectivity and achievable pressure ratio, it is often impossible to separate two components adequately in one pass through a membrane system. However, better separation can be achieved using a multistage system, a multistep system, or a single membrane unit with a recycle system. In a multistage system, the permeate travels from the first membrane separation unit to one or more additional membrane separation steps. In a multistep system, the residue from the first membrane separation unit travels to one or more additional membrane separation steps. In a single membrane unit with a recycle system, the permeate is combined with the feed stream.

<u>Control Efficiency</u>. Air and organic vapors permeate the membrane at rates determined by their relative permeabilities and the pressure difference across the membrane. Because the

membrane is 10 to 100 times more permeable to organic vapor than air, a significant enrichment of organic vapor on the permeate side of the membrane is achieved. Depending on the system design, between 90 and 99.99 percent of the organic vapor is removed from the feed stream by the MTR process (Jacobs et al., 1993).

Using a vacuum and blower system instead of the compressor-condenser system, the hollow-tube modular system used in the Hoechst-Celanese process can achieve 50 to 90 percent recovery for organic streams containing 1.5 to 3 percent organic by volume. The outlet stream from the modules continues to another polishing step. This entire process may produce a 99+ percent recovery dependent upon the membrane surface area, the flow rate of the inlet stream, the pressure drop across the membrane, and the polishing steps (Prasad, 1995).

Applicability to FRP/C Processes. Based on current information, direct application of membrane technology as a viable emission control approach is best suited for treating concentrated streams (greater than 1,000 ppm) (Simmons et al., 1994; McInnes, 1995). For FRP/C processes, membrane technology could possibly be used following a preconcentration stage where the VOC concentration is maximized and the total air flow is minimized. The usefulness of membrane technology as a control technology will be judged by its cost, effectiveness, operations, and reuse of recovered styrene. Applications for membrane vapor recovery technology for FRP/C processes have not been identified.

Advantages/Disadvantages. The membrane separation process requires no desorption step, unlike carbon adsorption, and produces no secondary waste stream that needs further treatment or disposal. The membrane vapor recovery process, which combines compression-condensation with a membrane separation step, allows for recovery at higher temperatures and provides a constant recovery efficiency despite fluctuation in the feed stream conditions. This combination of two individual recovery methods exploits the advantage of each method, resulting in an optimized process that achieves better results, at higher efficiency, than can be obtained from either method alone. However, the membrane vapor recovery process is not efficient at high air flow rates and low inlet concentrations typically found in the FRP/C processes. Even when styrene emissions from the FRP/C process are preconcentrated, the process may not be cost-effective to recover styrene. Also, the quality of recovered styrene has not been evaluated for reuse in resin formulation.

Costs. Membrane system costs increase in proportion to the flow rate of the inlet stream to be treated but are relatively independent of the organic vapor concentration in the stream (Simmons et al., 1994; Baker and Wijmans, 1994). In addition, costs vary from system to system and are primarily determined by compression, vacuum, and piping requirements (Pinnau, 1995). Because of the current stage of development, cost data were not requested from the vendors.

4.3.2 *Photocatalytic Oxidation*

Heterogeneous photocatalysis is an emerging technology that can be used to treat VOCs in air. It is an ambient temperature process in which the surface of an illuminated semiconductor acts as a chemical reaction catalyst. Peral and Ollis at North Carolina State University presented research on the use of near-ultraviolet light to decompose VOC on a continuously activated semiconductor oxide, TiO_2 (Peral and Ollis, 1991, 1992). Their studies suggest that gas-solid photocatalysis may have broad potential for the destruction of a range of air contaminants at room temperature. They present a brief overview of previous work and more recent experimental results for the heterogeneous photocatalytic oxidation of trace level contaminant oxygenates: acetone, 1-butanol, butyraldehyde, and formaldehyde in humidified air. Styrene was not analyzed in this study. However, their studies show that the degradation of those organics takes place over illuminated TiO_2, presumably to CO_2. A schematic of the heterogeneous photocatalysis system is shown in Figure 4-17.

Process Description. The oxidation reaction takes place at ambient temperature in the presence of ultraviolet light on the illuminated surface of some metal oxides, such as TiO_2, or sulfides that have semiconductive properties. Upon total oxidation in the presence of ultraviolet light, the reaction converts VOCs into carbon dioxide and water. The semiconductor surface acts as a catalyst for the oxidation of VOC in air (Peral and Ollis, 1991, 1992).

Standard Operating Conditions. Heterogeneous photocatalytic oxidation offers the possibility of operation at ambient temperature. Using photocatalytic oxidation to treat dilute mixtures of toluene, Sauer et al. (1995) observed an increase of toluene conversion to 100 percent with the addition of chlorinated compounds, 1,1,3-trichloropropene (TCP) or perchloroethylene (PCE). Enhanced photocatalytic reaction rates have also been observed when trichloroethylene (TCE) was added to air lightly contaminated with iso-octane, methylene chloride, or chloroform (Berman and Dong, 1993).

Apparent quantum yields exceeding 100 percent have often been measured for photocatalytic oxidation of TCE. (Quantum yield is the measurement of the number of molecules converted per photon adsorbed on a reactive surface.) These high photon efficiencies indicate that chain reactions occur on the TiO_2 surface (Sauer et al., 1995). Moisture also has varying effects on the conversion rates of organic compounds. For example, trace water addition enhanced the conversion of *m*-xylene, but conversion was inhibited when higher water levels were added (Peral and Ollis, 1992).

Control Efficiency. The possibility of using photocatalytic purification to treat VOC-laden air streams depends primarily on identifying conditions in which the apparent quantum yield for contaminant disappearance is near or above 100 percent. With feed stream levels of 10 to 20 percent toluene, Sauer et al. (1995) observed increased photocatalytic reaction rates for treatment of dilute (10 to 750 $mg \cdot m^{-3}$) mixtures of toluene and TCP.

Figure 4-17

Applicability to FRP/C Processes. Documented information on the use of heterogeneous catalysis technology for styrene control has not been published. However several studies have been demonstrated to prove photocatalytic conversion of aromatic compounds including toluene, *m*-xylene, and ethyl benzene (Ibusuki and Takeuchi, 1986; Peral and Ollis, 1992; Sauer et al., 1995; d'Hennezel and Ollis, 1995).

Advantages/Disadvantages. According to process cost estimates by Miller and Fox (1993), photocatalytic treatment of lightly contaminated air is commercially viable only for conversions of high-quantum-yield reactants such as trichloroethylene or methanol/ethanol. In addition, gas-solid photocatalytic oxidation of air contaminants has been proven for a broad range of contaminant classes -- aromatics, ketones, aldehydes, alcohols, etc. However, quantum yields for such conversion are often mediocre and may require the addition of chlorinated compounds to improve quantum efficiency. All branched aromatic photocatalyzed degradation rates are enhanced by TCE addition (d'Hennezel and Ollis, 1995). The final products observed during photocatalytic oxidation of TCE were CO_2 and HCl. However, no gas phase intermediates were detected after photochemical degradation of aromatic compounds mixed with TCE in the study done by d'Hennezel and Ollis (1995).

Costs. Miller and Fox discussed the commercialization prospects for photocatalytic air treatment of several contaminated air streams (Miller and Fox, 1993; Sauer et al., 1995). The operating and capital costs for treatment of four contaminated air streams were estimated. The four contaminated air streams were: (1) soil vapor extract (100 ppm TCE), (2) air stripper vent (50 ppm benzene, 250 ppm other VOC), (3) product dryer vent (including 25 ppm methanol, 25 ppm ethanol), and (4) a paint drying vent (10 ppm xylene, odors, plasticizers, surfactants). Economic estimates of these processes suggest that photocatalytic treatment of TCE or methanol/ethanol is cost-competitive for these two high-quantum-yield reactants (d'Hennezel and Ollis, 1995; Sauer et al, 1995; Miller and Fox, 1993). However, cost estimates for treatment for styrene-contaminated air streams were not included.

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Chapter 5

Control Cost Analyses

The costs per unit of styrene removed were calculated for various control technologies described in this report. Calculating the cost per unit of styrene removed is a two-step process:

1. Calculate total annualized cost of a control technology
2. Calculate amount of styrene removed by the control technology.

The amount of styrene removed by a control device is simply the product of the amount of styrene entering the control device and the control device removal efficiency. For the cost analyses described in this report, the control efficiency of thermal oxidation was assumed to be 98 percent, the control efficiency of VOC condensers was calculated as described in Section 4.1.3, and the control efficiencies of all other control devices were assumed to be 95 percent.

Total annualized costs of all control technologies were calculated using the general procedures outlined in the EPA Office of Air Quality Planning and Standards (OAQPS) Control Cost Manual (Vatavuk, 1990). Specific equations and values used in the calculations are listed in Tables 5-1 and 5-2. Equipment costs acquired from various sources were used to develop cost functions for the control technologies evaluated in this study. The original cost information is included in Appendix A. A computer spreadsheet cost model (STY_COST.XLS for Excel and STY_COST.WK3 for Lotus 1-2-3) and general instructions for using the cost model are presented in Appendix B.

Control cost calculations were performed in the order listed below:

1. Equipment cost (EC), in dollars at the date of the quote or literature source
2. Equipment cost, escalated or deescalated to July 1995 dollars.
3. Total direct cost (TDC)
4. Total capital investment (TCI)
5. Direct operating costs (excluding fuel and electricity costs)
6. Fuel cost (natural gas cost, if appropriate to the control technology)
7. Electricity cost
8. Indirect operating costs (overhead, property tax, insurance, administration)
9. Capital recovery cost (assuming 7.5 percent interest, with 10-year depreciation)
10. Styrene recovery cost (styrene recovery credit [i.e., negative cost], if appropriate to the control technology)
11. Total annualized cost (July 1995 dollars)
12. Cost per unit of pollutant removed (July 1995 dollars per U.S. ton removed).

Table 5-1. Equations for Equipment Cost (EC)

Item	Condition / Value (July 1995 dollars)	Source
Catalytic oxidizer (regenerative, heat recovery of 95%)	IF $Q < 150{,}000$ cfm, $\$[200{,}000 + 15Q]$ IF $Q > 150{,}000$ cfm, $\$[450{,}000 + 13Q]$	Developed from quotes from three vendors.[a]
Catalytic oxidizer (recuperative, heat recoveries of 70% or less)	Equations in the OAQPS Cost Manual	OAQPS Cost Manual[b]
Thermal oxidizer	Equations in the OAQPS Cost Manual	OAQPS Cost Manual[b]
MIAB	$\$[68{,}181 + 16.8Q - 2.19E^{-5}Q^{2}]$	Based on MIAB equipment cost quotes.[c]
Thermatrix PADRE	IF $Q < 3{,}000$ cfm, $\$[106{,}000N + 80{,}000]$ IF $Q > 3{,}000$ cfm, $\$[106{,}000N + 25Q]$	Based on Purus equipment cost sheet, dated 12/2/94.[d]
Polyad	IF $Q < 56{,}000$ cfm, $\$[214{,}815 + 16.8148Q - 3.8E^{-4}Q^{2} + 5.15E^{-9}Q^{3}]$ IF $Q > 56{,}000$ cfm, $\$[363{,}158 + 6.538Q + 2.05E^{-5}Q^{2} - 7E^{-11}Q^{3}]$	Developed from Polyad equipment cost curves, dated July 1995.[e]
Biofiltration	$\$[119{,}136 + 15.47Q]$	Developed from Boat Manufacturing MACT analysis, dated 8/1/95.[f]
VOC condenser	Single-stage > 10 tons, $\$[0.95\exp(9.26 - 0.007Tcon + 0.627\ln R)]$ Multistage, $\$[0.95\exp(9.73 - 0.012Tcon + 0.584\ln R)]$	*Chemical Engineering*, August 1995.[g]
Rotary concentator	$\$[97{,}113 + 8.34\,Q + 1.38E^{-5}\,Q^{2} - 4.87E^{-11}\,Q^{3}]$	Based on Durr equipment cost quotes[h]
EC&C fluidized-bed preconcentrator	If $Q < 45{,}000$ cfm $\$[108{,}906 + 41.7Q - 1.53\,E^{-3}\,Q^{2} + 2.12E^{-8}Q^{3}]$ If $Q > 45{,}000$ cfm $\$[18.29Q]$	Based on Environmental C&C equipment cost quotes[i]
Equipment price escalation (to July 1995)	As appropriate	*Chemical Engineering*[j] Equipment Cost Index

$Q =$ Air flow rate, in scfm (1 scfm $= 0.0283$ m^{3}/min).

Table 5-1. Equations for Equipment Cost (EC) (continued)

N = Number of adsorption/desorption units (1 unit for every 12.5 kg/h [27.5 lb/h] of styrene).
Tcon = Condenser operating temperature (-23°C [-10°F] for single-stage, -40°C [-40°F] for multistage).

R = Refrigeration capacity, tons.

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[a] Mack, 1996, Josephs, 1996, and Sundberg, 1996
[b] Vatavuk, 1990
[c] Sundberg, 1996
[d] Irvin, 1995
[e] LaFlam, 1995
[f] Haberlein and Boyd, 1995
[g] Vatavuk, 1995
[h] Klobucar, 1996
[i] Merboth, 1996
[j] *Chemical Engineering*, 1995

A significant fraction of the total annualized cost for each of the control technologies is the capital recovery cost. The capital recovery cost is, in turn, significantly affected by the equipment cost of a control technology. Figure 5-1 presents the equipment cost values (in July 1995 dollars) used for each of the analyzed control technologies. For all of the technologies presented, equipment cost is related to flow rate through the device (i.e., higher flow rates require larger control devices, which cost more).

In some cases, Figure 5-1 presents equipment costs for two versions of the same control technology. For example, equipment costs are given for catalytic and thermal oxidizers with 70 and 95 percent heat recovery. The equipment costs for 95 percent heat recovery are significantly higher than for 70 percent heat recovery. However, equipment costs are listed for 95 percent heat recovery because, in some cases, particularly at low inlet concentrations, oxidation with 95 percent heat recovery produces a lower total annualized cost. In other cases, particularly at higher inlet concentrations, oxidation with 70 percent heat recovery produces a lower total annualized cost. The cost curve for the MIAB system represents a composite least-expensive cost function for a fixed-bed or a fluidized-bed adsorber.

The costs per unit of styrene removed were calculated for three different plant sizes: a large plant (363 metric tons [400 tons] per year of styrene at the control device inlet), a medium-size plant (91 metric tons [100 tons] per year at the control device inlet), and a small plant (18 metric tons [20 tons] per year at the control device inlet). These sizes were chosen, based on RTI's informal analysis of the FRP/C source category's emissions. (The analysis was confined to the approximately 290 facilities that RTI estimated emitted more than 9.1 metric tons [10 tons] per year of styrene, and the total emissions from these facilities were estimated at approximately 14,331 metric tons [15,800 tons] per year.) The results of this analysis indicate that approximately 11 large facilities, with average emissions of approximately 363 metric tons (400 tons) per year, emitted one-third of the source category's emissions. Similarly, approximately 50

Table 5-2. Other Cost Analysis Inputs and Significant Assumptions

Item	Value (July 1995 dollars)	Source
Purchased equipment cost (PEC)	1.2 X EC (includes instrumentation, sales tax, freight)	OAQPS Cost Manual (except sales tax = 5%, not 3%)
Direct installation costs	0.30 X PEC (includes foundations and supports, handling and erection, electrical, piping, insulation for ductwork, painting)	OAQPS Cost Manual
Site preparation (SP)	$[5,000 + 2.3Q]	Average of vendor quotes
Buildings (Bldg.)	Not required.	RTI assumption
Indirect costs for installation	0.31 X PEC (includes engineering, construction and field expenses, contractor fees, startup, performance test, and contingencies)	OAQPS Cost Manual
Total capital investment (TCI)	(1.61 X PEC) + SP + Bldg.	OAQPS Cost Manual
Direct operating costs, excluding electricity and fuel costs (DOC)	$0.598Q + 4,840 + Miscellaneous costs (includes operating, maintenance, and supervision labor; annual maintenance contract; miscellaneous costs)	Average of vendor quotes and OAQPS Cost Manual
Miscellaneous costs	As appropriate (includes catalyst and/or adsorbent replacement costs, startup fuel cost)	Based on vendor information
Indirect operating costs	0.6(DOC) + 0.04(TCI) (includes overhead, administration, property taxes, and insurance)	OAQPS Cost Manual
Plant operating schedule	4,000 h/yr	RTI assumption
Electricity cost	$0.06/kWh	Average of vendor quotes
Fuel cost	$4.27/billion joules ($4.50/million Btu)	Average of vendor quotes
Capital recovery factor	0.14569	7.5% interest, 10-year depreciation

Q = Air flow rate, in scfm (1 scfm = 0.0283 m^3/min).

Figure 5-1

medium-size facilities, with average emissions of approximately 91 metric tons (100 tons) per year, were estimated to emit one-third of the source category's emissions. Approximately 230 small facilities, with average emissions of 18 metric tons (20 tons) per year, were estimated to emit the final third of the source category's emissions.

Figure 5-2 presents cost curves for a catalytic oxidizer, for each of the three plant sizes, assuming 4,000 hours per year of operation. Figure 5-2 illustrates that costs per unit of styrene removed decrease with increasing plant size (i.e., the cost curve for the large plant is below the cost curve for the small plant). This is due to the economy of scale. Figure 5-2 also indicates that, for a given annual styrene input, costs decrease with increasing inlet concentration (i.e., decreasing flow rate). For example, for a catalytic oxidizer treating 363 metric tons (400 tons) per year, the cost decreases from \$5,200 to \$1,600 per ton of styrene removed, if inlet concentration increases from 50 to 200 ppm. This represents an annual savings of approximately \$1.4 million.

For a given annual styrene mass input to the control device, increasing inlet concentration represents decreasing flow rate, because mass input is the product of concentration and flow rate. For example in Figure 5-3, for a plant with 18 metric tons (20 tons) per year of styrene input, an inlet concentration of 50 ppm represents a flow rate of 351 m^3/min (12,400 cfm), but an inlet concentration of 100 ppm represents a flow rate of 176 m^3/min (6,200 cfm). The flow rates represented by various inlet concentrations are depicted in the upper axes on Figures 5-3 through 5-5.

Figure 5-3 compares costs of various technologies, for a small plant (18 metric tons [20 tons] per year at inlet). These cost curves are based on 4,000 hours per year of operation. For higher capacity factor (i.e., more hours of operation per year) the cost per unit of styrene removed would decrease. The cost curves for several preconcentration technologies (MIAB, Thermatrix PADRE, rotary concentrator, and EC&C fluidized-bed preconcentrator) can be compared with the cost for straight catalytic oxidation. Figure 5-3 illustrates that the costs per ton of styrene removed are lower for the preconcentration technologies than for straight catalytic (or thermal) oxidation at an inlet concentration of 50 ppm. However, as inlet concentration increases, straight oxidation becomes more competitive with the preconcentration technologies. In fact, Figure 5-3 indicates that straight catalytic oxidation is less expensive than the Thermatrix PADRE system at inlet concentrations above approximately 250 ppm, and catalytic oxidation is less expensive than the MIAB system at inlet concentrations above approximately 500 ppm. As inlet concentrations increase, preconcentration becomes less necessary to reduce annual cost; in fact, preconcentration becomes unnecessary if inlet concentrations are high enough.

Figures 5-4 and 5-5 illustrate costs for medium-size (91 metric tons [100 tons] per year inlet) and large plants (363 metric tons [400 tons] per year inlet), respectively. In both these figures, several preconcentration technologies are shown to be less expensive than straight catalytic or thermal oxidation, particularly at the inlet concentrations (below 300 ppm) typically found in FRP/C and boat building facilities.

Figure 5-2

Figure 5-3

Figure 5-4

Figure 5-5

Figures 5-4 and 5-5 show that as inlet concentration increases, the differences in cost per unit of styrene removed among various control technologies converge. It is because the differences in equipment costs for various control technologies are smaller at low flow rate and larger at high flow rate (as shown in Figure 5-1). This cost analysis also shows that condensation is not a cost-effective control technology due to the low styrene removal efficiency at low inlet concentration (as shown in Figure 4-3).

Figures 5-3 through 5-5 show that, for all plant sizes and all control technologies, the cost of an add-on control system can be reduced, if flow rate can be reduced (i.e., for a given plant size, inlet concentrations can be increased). Therefore, a company should evaluate methods of reducing flow rates to control devices before considering any add-on emission controls.

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Chapter 6

Ventilation and Emission Capture Systems in the FRP/C Facilities

One of the most important considerations in determining the cost of any emission control system is the volumetric flow rate of the exhaust stream to be treated. Ventilation systems in FRP/C facilities are currently solely designed to provide an environment that is safe for workers and that produces good product quality. General ventilation, also called dilution ventilation, is a common practice. This practice supplies an ample amount of makeup air to dilute the contaminants to an acceptable air quality level in the workplace. However, this dilution ventilation practice produces high-volume, low-concentration exhaust streams. Flow rates of 566 to 2,382 m^3/min (20,000 to 100,000 cfm) are common, and exhaust concentrations are rarely above 100 ppm. These high-volume, low-concentration exhaust streams make emission control systems very expensive. Proper air flow management would prevent mixing contaminated air with clean air and capture emissions at the point of generation. Thus, proper air flow management can maintain a safe environment for the operators, while significantly decreasing exhaust flow rates. These reduced exhaust flow rates (increased concentrations) can significantly reduce control costs.

The following sections present the regulations governing ventilation practices (Section 6.1) and several air flow management practices and concepts that could be applied to minimize air flow volumes. These practices and concepts include: local air flow management (Section 6.2), spray booth modifications (Section 6.3), and enclosures (Section 6.4). Each of the sections includes a process description and discussion of process applicability, performance, and costs.

6.1 Regulations Governing General Ventilation Practices

There are several OSHA regulations that govern the ventilation system design in the FRP/C industry:

1. 29 CFR 1910.1000 (OSHA, 1993a): This regulation establishes permissible exposure limits (PELs) for breathable occupational exposure. In areas that would result in unprotected worker exposures exceeding these levels, workers must wear sufficient respiratory protection (such as respirators) to bring worker breathable exposures within the allowable levels.

   The current OSHA 8-hour Time-Weighted-Average (TWA) for employee exposure to styrene is 100 ppm. A 50-ppm allowable was proposed by OSHA, but withdrawn later. However, many facilities are voluntarily conforming to the 50-ppm limit. In “dilution ventilation,” enough makeup air is supplied to lower the average exhaust concentration to the OSHA allowable limit. For the same amount of styrene emission to be removed, the exhaust flow rate will be inversely related to the desired concentration in the workplace.

For example, the volumetric flow rate for an exhaust concentration of 50 ppm is twice as large as for 100 ppm.

2. 29 CFR 1910.134 (OSHA, 1993b): This regulation concerns the conditions under which respiratory protection (respirators) should be used. Part (a) of this regulation states that: "In the control of those occupational diseases caused by breathing air contaminated with harmful...gases...the primary objective shall be to prevent atmospheric contamination. This shall be accomplished as far as feasible by accepted engineering control measures (for example, enclosure or confinement of the operation, general and local ventilation, and substitution of less toxic materials). When effective engineering controls are not feasible, or while they are being instituted, appropriate respirators shall be used..."

3. Regulation 29 CFR 1910.94, Table G-10 (OSHA, 1993c): This table lists minimum airflow velocities that must be designed or maintained at the entrance to spray booths under various operating conditions in order to meet health and safety requirements.

Operating conditions	Airflow velocity
Manual spray gun, up to 15 m/min (50 fpm) crossdraft	30.5 m/min (100 fpm)
Manual spray gun, up to 30.5 m/min (100 fpm) crossdraft	45.7 m/min (150 fpm)
Small spray booth	61 m/min (200 fpm)

4. Regulation 29 CFR 1910.107 (d) (9) (OSHA, 1993d): This regulation prohibits the recirculation of exhaust air from spray finishing operations from the standpoint of preventing fire and explosion hazards.

The regulation was adopted by OSHA from National Fire Protection Association (NFPA) 33 (NFPA, 1995), "Standard for Spray Application Using Flammable and Combustible Materials." The purpose of NFPA 33 was to prevent fire and explosion hazards during spray finishing operations. A letter regarding the issue of recirculation was sent by OSHA to EPA on January 19, 1990 (Hughes et. al., 1994). The letter stated that: "Employers who fully comply with the specifications and requirements of NFPA 33, concerning recirculation of exhaust air to an occupied spray booth, would not be cited under 29 CFR 1910.107 (d) (9), under the policy for de minimis violations." The letter further stated: "However, the quality of the respirable air in the booth must comply, at a minimum, with the requirements set forth by 29 CFR 1910.1000, which establishes permissible exposure limits (PELs)."

A review of the above OSHA regulations indicates that the design of an air flow management system should provide respirable air to the operators that meets permissible exposure limits and prevents fire and explosion hazards. When a spray booth is used, it should meet the minimum airflow velocity. Any modifications to the spray booth should not violate the above requirements.

6.2 Local Air Flow Management

Process Description. General ventilation usually involves moving a lot of air through the workplace; however, it is not effective when there are many emission points (e.g., open molding productions) in an open space. It is also expensive to move air and to heat the makeup air. Local air flow management involves moving air pollutants from the emission source directly; therefore, the amount of air to be ventilated or heated is minimized. In an open space, this can be done by directing makeup air toward the emission source and capturing the emission with an exhaust hood in the other end (a push-pull ventilation system). If a push-pull system is not used, the exhaust hood just picks up the emissions and the surrounding air. The capture efficiency is generally better for a push-pull system than for an exhaust hood by itself. This section presents several schematics of local exhaust ventilation that originally appeared in the *UP-Resin Handling Guide* (GPRMC/CEFIC, 1994). This section also discusses "displacement ventilation." Modifications to spray booths are another category of local air flow management; these modifications are discussed in Section 6.3.

The European Organization of Reinforced Plastic/Composite Materials (GPRMC) and the Unsaturated Polyesters Sector Group of European Chemical Industry Council (CEFIC) jointly produced *UP-Resin Handling Guide* (GPRMC/CEFIC, 1994). This guide describes many methods for improving local air flow management, including use of local extraction, in-mold push-(movable) pull ventilation, and out-of-mold (induction) push-pull ventilation. Figure 6-1 shows these three methods of local air flow management. Local extraction is effective when styrene emissions are extracted as close to the mold as possible, because the effectiveness of the extractor decreases by a factor of four when the distance from the mold is doubled (GPRMC/CEFIC, 1994). In-mold push-(movable) pull ventilation is best-suited for use with large, female molds (such as in boat manufacturing). The vertical induction push-pull ventilation requires a downdraft to pull emissions away from the workplace. Out-of-mold (induction) push-pull ventilation can be arranged horizontally, in the form of a (push) supply air and a local (pull) capture device (e.g., a spray booth).

In Europe, "displacement ventilation" has gained acceptance as a method of reducing worker exposure to contaminants. Displacement ventilation relies on the concept that there is a temperature gradient between air near the ceiling and air near the floor, at a typical industrial facility. Cool, "fresh" air is supplied, at a low velocity, to the work zone. If the source of the work zone emissions is at a higher temperature than the supply air, the supply air is heated and picks up contaminants as it rises out of the work zone. The important concepts/assumptions behind displacement ventilation are:

> Air is supplied at below-ambient temperature (so the "fresh" air arrives at breathing-zone level).
> Air is supplied at low velocity (so turbulent mixing of "fresh" and contaminated air does not occur).

Figure 6-1

The source of the contaminants is at higher-than-ambient temperatures (so contaminated air rises out of the breathing zone).

Applicability to FRP/C Processes**.** RTI has no knowledge of in-mold push-(movable) pull ventilation systems in the United States. However, such systems may exist. Vertical out-of-mold (induction) push-pull ventilation systems are used to a limited extent in the U.S. Horizontal push-pull ventilation systems are being used in FRP/C and other industries.

There are no known applications of displacement ventilation to FRP/C processes in the United States. AirSon AB (Sweden) provides Air Shower air supply systems to industrial facilities in Europe, including FRP/C facilities. A study of the displacement ventilation for FRP/C fabrication was performed by AirSon and the Swedish National Institute of Occupational Health (Andersson, et al., 1993). The intent of the study was to determine whether the AirSon Air Shower device was able to protect workers from exposure when they roll out a wet laminate in a spray booth. Four air supply outlets, each supplying approximately 10 m^3/min (375 cfm) of "fresh" (styrene-free) air, were placed in a spray booth, approximately 36 cm (14 inches) above the workers' heads. Personnel exposure to styrene was monitored with charcoal tubes and with a photoionization detector (providing real-time measurements of styrene concentrations). The study indicated that Air Shower air supply systems could reduce worker exposures by a factor of approximately 5 to 9 (i.e., from approximately 28 ppm to between 6 and 3 ppm, respectively). However, this exposure reduction occurred only when the supply air was approximately 1.8° to 2.5° C (3.2° to 4.5° F) cooler than the ambient air within the booth and when the operators remained in the protection zone created by the air supply system. Low-speed ventilation is required to evacuate styrene emissions in the work area so that the protection zone will not be disturbed.

The previous discussion indicates that use of displacement ventilation has been applied to FRP/C manufacturing situations to reduce worker exposure. However, the worker has to stay in the protection zone created by the air supply system. Another important concept in the use of displacement ventilation is that the process producing the contamination is at a higher temperature than the ambient air or the displacement air has to be cooler than the ambient air. However, emissions from open-mold FRP/C processes occur at nearly ambient temperature, because a vast majority of the emissions from sprayup occur during spraying and prior to the beginning of exotherm.

6.3 Spray Booth and Modifications

Spray booths are commonly used in the FRP/C industry, especially for gel coat and resin sprayup operations, and when part sizes are small enough to fit into a spray booth. Use of a spray booth prevents the cross-contamination created by general ventilation, because styrene emissions are captured and exhausted directly. Open-faced spray booths are typically used when molds are manually transferred in and out of the spray booth on wheels. Spray booths with openings on the side walls are typically used when molds are mechanically transferred in and out of the spray booth on a conveyor. The latter type of spray booth is common in high-production facilities.

In a typical spray booth, a mold is placed in the center of the booth. Air is drawn into the front opening of the booth, travels past the mold, and exits through a filter bank at the rear of the booth. A dry filter medium is used to capture overspray, and the medium is replaced frequently to protect the duct work and exhaust system. The captured emissions are vented to the atmosphere or to an emission control device.

A typical styrene concentration-versus-time profile for a sprayup operation in a constant-flow rate spray booth is shown in Figure 6-2. The profile includes three peaks, with average concentrations over 200 ppm. These peaks correspond to the spraying of three parts. The profile also includes four “valleys,” with concentrations of approximately 50 ppm. These valleys correspond to the time required to remove sprayed parts and to position a new mold for spraying. This profile shows that high styrene emissions result from the period of spraying. Previous RTI testing (Kong et al., 1995) indicated that approximately 39 percent of total gel coating emissions and approximately 50 percent of total resin application emissions occur during spraying and the remainder is emitted during the post application stage during rolling and curing. When the part is removed from the spray booth, curing emissions are not captured by the spray booth and have to be removed by the general ventilation system.

The following sections present the modifications to a spray booth design that could increase the pollutant concentration and decrease the exhaust flow, thus making the downstream emission controls more cost-effective.

6.3.1 *Recirculation*

Process Description. The concept of recirculation had its origin in the spray painting industry, as a means of lowering the flow rates (and therefore treatment costs) in paint spray booths. Recirculation involves redirecting a portion of the spray booth exhaust stream back into the spray booth. This concept is shown in Figure 6-3. The recirculation stream may be re-introduced at any location in the spray booth (e.g, near the inlet face or at the center of the booth).

Mobile Zone Associates (Knoxville, Tennessee) developed a recirculating spray booth in which a portion of the exhaust stream was recirculated back to the center of the spray booth. Another feature of the Mobile Zone Associates design is that the majority of the spray booth face is closed off, and the operator stands in a mobile cab that traverses across the face of the booth. The design is illustrated in Figure 6-4.

A spray booth developed by EPA and Acurex Environmental Corporation (Darvin and Ayer, 1993) incorporates recirculation of a portion of the spray booth exhaust stream to the vicinity

Figure 6-2

Figure 6-3.

Figure 6-4.

of the inlet face of the spray booth. The design also includes “split-flow” ventilation (see Section 6.3.2).

Applicability to FRP/C Processes**.** There are no known applications of recirculating spray booth designs on FRP/C processes in the United States.

Performance**.** For a spray booth with recirculation alone, the increase in control-device inlet concentration achieved by recirculation is directly related to the amount of recirculation. For example, if 50 percent of the exhaust air is recirculated, the control-device inlet concentration is doubled. Similarly, if 90 percent of the exhaust air is recirculated, the control-device inlet concentration is increased by a factor of 10.

Advantages/Disadvantages. The advantage of recirculating spray booth exhaust is that it increases control device inlet concentration. The primary disadvantage of recirculation is the potential for increased worker exposure. Another disadvantage of recirculation is the cost to modify a spray booth.

The Mobile Zone Associates design increases control device inlet concentration, while lowering worker exposure (because fresh makeup air is provided to the operator through the opening behind the operator). One disadvantage of the Mobile Zone Associates design is that spraying the sides of molds is more difficult than when the worker is standing within the spray booth. Another disadvantage of the Mobile Zone Associates design is that the mechanization associated with the mobile cab may result in comparatively high cost, relative to the other means of increasing control device inlet concentrations.

Costs. The capital cost for the EPA/Acurex split-flow recirculation design was estimated to be $60,000 for modifying an 850-m^3/min (30,000 cfm) (before recirculation) spray booth. Capital cost estimates for the Mobile Zone Associates design are not available at this time.

6.3.2 *Split-Flow Spray Booths*

Process Description**.** In a typical (horizontal-flow) spray booth, the part being sprayed does not extend to the full height of the spray booth. Therefore, most of the spraying and post-spraying emissions occur near the bottom of the booth. An EPA/Acurex split-flow painting spray booth design (Darvin and Ayer, 1993) takes advantage of this fact. In the EPA/Acurex design, higher-concentration exhaust air from the bottom of the booth is directed to an emission control device, while lower-concentration air from the top of the booth is recirculated. This is illustrated in Figure 6-5.

It is possible to have a split-flow spray booth without recirculation, in which case air in the top portion of the booth is exhausted directly to the atmosphere. In this case, the capture efficiency for VOCs emitted within the booth to an emission control device is less than 100 percent.

Figure 6-5.

Applicability to FRP/C Processes. There are no known applications of split-flow spray booths in the FRP/C industry.

Performance**.** Testing was conducted at a 4.27- m (14-ft) tall paint spray booth at Tyndall Air Force Base in Florida (Hughes et al., 1994). Measurements of VOCs and other pollutants were made at six different heights on the booth exhaust face: 0.46, 1.4, 2.0, 2.3, 3.2 and 4.0 meters (1.5, 4.5, 6.5, 7.5, 10.5, and 13 feet). The results of the VOC measurements are presented in Figure 6-6. This figure illustrates that the majority of the VOCs were exhausted from the bottom half of the 4.27-m (14-ft) booth. Approximately 93 percent of the total VOCs exited below the 2.14-m (7-ft) midpoint of the spray booth. In other words, if recirculation were not used, and the spray booth exhaust were to be split at the midpoint of the booth, 93 percent of the VOCs would be captured for delivery to the control device, assuming that VOCs do not escape somewhere else in the spray booth.

The results in Figure 6-6 can be interpreted in terms of a concentration factor. For example, if 93 percent of the emissions exit below the midpoint, but only 50 percent of the flow exits below the midpoint, the "concentration factor" for a split-flow design at the midpoint would be 1.86 (i.e., 93%/50%). A split-flow design, without recirculation, at the midpoint of the booth, would therefore increase the concentration to a control device by a factor of 1.86. Hence, splitting the flow at the midpoint of the booth therefore nearly doubles the concentration to the control device.

Advantages/Disadvantages. The main advantage of a split-flow design is that it produces an increase in concentration of VOCs going to a control device (if spraying and postspraying emissions are predominantly located near the bottom of the spray booth). The main disadvantage of a split-flow design is the capital cost to modify an existing spray booth. The area to be split also needs to be determined at the specific spray booth.

Costs. The capital cost for the EPA/Acurex split-flow design with recirculation was estimated to be \$60,000 for modifying an 850-m^3/min (30,000-cfm) (before recirculation) spray booth.

6.3.3 *Other Spray Booth Design Modifications*

Process Description. Other spray booth design modifications can alter air flow and contaminant (styrene) pickup within the spray booth to lower emission control costs. In a typical spray booth, a part is placed in the center of the booth. Air is drawn into the "face" (front opening) of the hood, travels past the part, and exits through a filter bank at the rear of the hood. The arrangement of the part within the booth is such that higher concentrations are drawn through the center of the filter bank than through the top or sides of the filter bank. This phenomenon is evidenced by the fact that the center of the rear filter can be nearly coated with gel coat or resin while the edges of the filter bank are nearly clean.

Figure 6-6.

A spray booth can be modified to enhance this spatial difference in concentrations. This could involve construction of a smaller, centrally located exhaust device. The higher-concentration exhaust collected by this device would be directed to an add-on emission control. The lower-concentration exhaust could be vented to atmosphere, or recirculated in the spray booth. The concept of a smaller, centrally located exhaust directed to end-of-pipe controls is shown in Figure 6-7.

Note: The following discussion pertaining to centrally located exhaust device is an idea or concept that has not yet been evaluated. RTI is evaluating this idea in an FRP facility under an EPA funded program in the Summer of 1996.

In addition to spatial differences in emissions within spray booths, there are temporal (time-related) variations in emissions that can be used to increase concentrations to add-on controls. For example, each "peak" in the styrene concentration profile of Figure 6-2 is approximately 4 minutes in duration; therefore, approximately 12 minutes, or 30 percent, of the 40-minute measurement period was at "high" concentration. The centrally located exhaust device could be activated to capture high-concentration exhaust during the spraying period. The main exhaust of the spray booth could be vented to atmosphere during the nonspraying or low-concentration period. Determination of periods of high emissions could be made either by concentration measurements or by assuming high emissions occur during any period of spraying (i.e., the small exhaust unit is activated by the spray-gun trigger). An improvement on this ventilation arrangement is to have fresh supply-air blown to the locations where the operator is standing (as shown in Figure 6-7).

Applicability to FRP/C Processes**.** There are no known applications of a smaller, centrally located exhaust device directed to emission controls at any spray booth in an FRP/C facility in the United States.

Several FRP/C facilities have fresh supply air directed to wherever the operator is standing in the spray booth. Among these facilities are the Lasco Bathware facilities (such as the facility in South Boston, Virginia) and the Viking Formed Products facility in Middlebury, Indiana.

Performance**.** No measurements of the increase in concentration achieved by a smaller, centrally located, variable-flow-rate exhaust device have been performed to date. However, it would be expected that such a device could achieve emission concentration factors above that achieved by a constant-flow-rate split-flow booth (without recirculation). Measurements of the increase in concentration achievable by a smaller, centrally located, variable-flow-rate exhaust device are being conducted by RTI under an EPA funded program at an FRP facility in the summer of 1996.

Advantages/Disadvantages**.** The main advantage of the centrally located exhaust device discussed in this section is that it could produce an increase in concentration of VOCs going to a control device; however the main disadvantages of this modification are (1) an add-on emission

Figure 6-7

control device capable of handling surge of emissions has to be installed and (2) the feasibility and cost of this modification has not been evaluated.

Costs. It would be expected that the cost to modify a spray booth to include a centrally located variable-flow-rate exhaust and a directed fresh-air supply would be under $20,000 per booth (for a 425-m^3/min [15,000-cfm] booth).

6.4 Enclosures and Total Enclosures

Process Description. Enclosures provide a physical barrier between the emissions and the surrounding environment and can be used to reduce or eliminate the dispersion of styrene vapors from an FRP/C process. Enclosures are currently being applied to certain emission sources in FRP/C facilities, such as covers on resin mixing tanks and enclosed resin baths. If an enclosure is not ventilated, the styrene concentration in the enclosure builds up to a point of equilibrium, after which further emissions are suppressed. If an enclosure is ventilated, the exhaust concentration is inversely related to the exhaust flow rate. Therefore, an enclosure can prevent emissions or can be used to create a low-flow-rate, high-concentration exhaust. This section describes how the enclosure concept can be applied to the FRP/C processes.

If an enclosure is designed to meet certain guidelines (described in EPA Method 204 [U.S. EPA, 1995]), it is considered by EPA to be a “total enclosure,” and capture efficiency is assumed to be 100 percent (i.e., it is assumed that no fugitive emissions escape from the enclosure). There are several criteria that must be met before an enclosure is considered to be a total enclosure:

The total area of all natural draft openings into the enclosure must be less than 5 percent of the total surface area of the enclosure.

- The air flow for all of the natural draft openings must be into the enclosure.
- The air velocity through the openings must be at least 61 m/min (200 ft/min).
- Exhaust points must be at least four equivalent exhaust-duct diameters from natural draft openings.

Applicability to FRP/C Processes. Although many buildings within the FRP/C industry can be considered total enclosure, there is limited use of enclosures **within** buildings in the FRP/C industry. Two examples of the use of enclosures within buildings in the FRP/C industry are described below. These examples show that total enclosures would be feasible when concentrated emission sources can be isolated and enclosed without interferring the production operation.

The first example is the Cor Tec facility (Washington Court House, Ohio) which manufactures side-wall panels for trailers and recreational vehicles. Automated gel coat spraying operations are conducted within a total enclosure. The enclosure is 3.6 m (12 feet) wide and 18.3 m (60 feet) long and consists of a spraying enclosure and three curing enclosures.

Mylar film is fed along a table that forms the bottom of the enclosure, and the gel coat is applied by automated spray guns located within the spraying enclosure. The only natural draft opening is a 7.6-cm (3-inch) -high by 3.6-m (12-foot) -long gap at the entrance to the spraying enclosure. This represents less than 5 percent of the total surface area of the enclosure, and the air velocity through the opening is greater than 61 m/min (200 ft) per minute, so a total enclosure is formed.

The spraying enclosure and each of the three curing enclosures are ventilated at a rate of 25.5 m^3/min (900 cfm), for a total flow rate of 102 m^3/min (3,600 cfm). The styrene mass flow rate (to a catalytic oxidizer) from the automated gel coat spraying operation is 8.2 kg/h (18.1 lb/h) (i.e., 32.8 metric ton/yr [36.2 tpy], operating 4,000 hours per year). This means that the average concentration in the gel coating enclosure exhaust is approximately 310 ppm (Patkar et al., 1994).

To avoid limiting production, the gel-coated panels are removed from the enclosure before curing emissions have completely stopped. Testing indicated that approximately 7 percent of the total emissions from the gel coating operation occur outside the enclosure (Patkar et al., 1994).

A second example is an emission study conducted by the Society for the Plastics Industry (SPI)/Composites Institute, in cooperation with the Pultrusion Industry Council (PIC) and the EPA Office of Research and Development. In that study enclosures were evaluated for a pultrusion process to determine their effects on styrene emissions in September 1995. Several conditions were evaluated, including partial and complete enclosure of the resin bath and wet-out area, with a combined wet-out area and resin bath exhaust. The exhaust from the resin bath and wet-out area was at a very low flow rate (58 cfm compared to 198 cfm from the overall temporary enclosure).

Performance**.** The SPI/PIC/EPA testing of enclosures for the pultrusion process yielded the following results (Schweitzer, 1996):

- Without an enclosure on the resin bath or wet-out area (Run A1) , the concentration and flow rate in the 8-inch duct from the temporary total enclosure constructed for testing were 293 ppm and 5.6 m^3/min (198 cfm), respectively. This represents an emission rate of 0.42 kg/h (0.93 lb/h).

- With ventilated enclosures on the resin bath and wet-out area (Run G1), the concentration and flow rate in the 8-inch duct from the temporary total enclosure were 12 ppm and 5.6 m^3/min (198 cfm), respectively, representing a styrene emission rate of 0.02 kg/h (0.04 lb/h). The concentration and velocity in the 6-inch duct from the resin bath and wet out area were 719 ppm and 1.6 m^3/min (58 cfm), respectively, representing a styrene emission rate of 0.30 kg/h (0.67 lb/h). This represents a total emission rate of 0.32 kg/h (0.71 lb/h).

Based on these results, the following performance for a ventilated resin-bath-and-wet-out-area enclosure (RBWAE) is calculated:

- The ventilated RBWAE produced an approximately 24 percent (from 0.93 lb/h to 0.71 lb/h) reduction in total emissions.

- Without the RBWAE, the concentration in the total temporary enclosure exhaust was 293 ppm, which is well above the OSHA allowable level of 100 ppm. If dilution ventilation was used to bring the total temporary enclosure exhaust down to 100 ppm, the flow rate would have to be increased from 5.6 to 16.3 m^3/min (198 cfm to 576 cfm). But if the ventilation system were redesigned with pick up points in the right places, it is likely that concentrations in the exhaust from the TTE would be lower. If dilution ventilation was used to bring the total temporary enclosure exhaust down to the 12 ppm achieved with the RBWAE in place, the total temporary enclosure exhaust would have to be increased from 5.6 to 136 m^3/min (198 cfm to 4,801 cfm).

- With the ventilated RBWAE, 94 percent of the total emissions (i.e., 0.67 lb/h out of 0.71 lb/h) are captured and prevented from entering the work area.

- The enclosure was used to capture emissions from the major emission points of the pultrusion process (resin bath and wet-out area), and to create a small exhaust flow (1.6 m^3/min [58 cfm]) at high concentration (719 ppm) that is suitable for emission controls.

Advantages/Disadvantages. There are potential advantages of the enclosure concept for FRP/C processes:

- Enclosures can dramatically reduce average operator breathing-zone styrene exposures by providing a physical barrier between the operator and the styrene emission source.

- Enclosures can significantly reduce flow rates to emission controls and therefore significantly reduce control costs.

The potential disadvantages of the enclosure concept are:

- Use of enclosures may slow production.

- While enclosures can dramatically reduce **average** operator breathing-zone styrene exposures, there is a potential for higher **peak** exposures (if the operator is exposed to concentrations within the enclosure or when the enclosure is opened for changing setup or for any other reasons).

- The higher concentrations within an enclosure may increase fire hazards within the facility, if the concentration in the enclosure exceeds LEL.

Costs**.** Costs are examined here for the pultrusion wet-out-area and resin-bath enclosure investigated by SPI in September 1995, based on a hypothetical plant having 10 pultrusion machines and operating 4,000 hours per year.

Without the RBWAEs, the flow rate and concentration for each pultrusion machine would either be 16.3 m^3/min (576 cfm) at 100 ppm (if worker exposure is at the OSHA limit), or 136 m^3/min (4,801 cfm) at 12 ppm (if worker exposure is equal to what is achieved with the RBWAE). Therefore, for 10 machines, the total flow rate would either be 163 m^3/min (5,760 cfm) at 100 ppm, or 1,360 m^3/min (48,010 cfm) at 12 ppm. Both these scenarios represent total uncontrolled emissions of 16.7 metric tons per year (18.4 tpy). The calculated control costs per unit of styrene removed for a catalytic oxidizer under these two scenarios would be $6,371/ton and $27,515/ton, respectively. It should be noted that these figures cited are from pilot test conditions, and not optimized.

The ventilated RBWAEs alone produce a 23 percent, or 3.8-metric-ton/yr (4.2-tpy), reduction in emissions. If the total capital investment to install the 10 RBWAEs (with ventilation system) is **assumed** to be $100,000, and a capital recovery factor of 0.1459 is used, the total annual cost of the enclosures is $14,590. The cost per unit of emissions reduced (avoided) is $3,474/ton ($14,590 / 4.2 tons). The total exhaust flow for the 10 RBWAEs would be 580 cfm, with a concentration of 719 ppm. The calculated control cost for a catalytic oxidizer under this scenario is $2,226/ton of styrene. Assuming a 95 percent control efficiency, the catalytic oxidizer will remove 13.5 tpy of styrene. The average annual cost per ton of styrene avoided using the enclosures and removed using a 95 percent efficiency catalytic oxidizer is $2,522/ton ($3,474/ton x 4.2 ton +$2,226/ton x 13.5 ton)/(4.2 ton +13.5 ton). **Note: The cost per unit of styrene emissions eleminated by this analysis is directly proportional to the assumed capital investment.**

This cost analysis indicates that enclosures have the ability to significantly reduce control costs per unit of pollution removed (or avoided) in the pultrusion process or similar processes, such as SMC production and continuous lamination, when concentrated emission sources can be isolated and enclosed without interfering with the operation.

Note: The following discussion pertaining to enclosures for open molding processes is an idea or concept that has not yet been evaluated. RTI is evaluating this concept in an FRP facility under an EPA funded program in the Summer of 1996.

It may be possible to use enclosures to contain spraying emissions in open molding processes. Enclosures may be particularly suited to facilities that spray parts of nearly uniform size and shape and conduct spraying in well-defined locations, for example, the gel coating of sinks and vanities in the cultured marble industry and gel coating and chop sprayup in the tub and shower industry. The concept of an enclosure for a sink/vanity gel coating operation is illustrated in Figure 6-8.

Figure 6-8.

The enclosure would be a “box,” with a limited natural-draft opening for inserting the spray gun and viewing the spraying operation. If possible, the area of the opening would be less than 5 percent of the total enclosure surface area. The operator would stand outside the enclosure, extending only his hand or arm inside the enclosure. The enclosure would have an exhaust flow rate sufficient only to maintain flow into the enclosure. If possible, the flow would be sufficient to maintain a velocity of 61 m/min (200 ft/min) through any natural draft opening in the enclosure. The enclosure would have no structural function (i.e., the enclosure would only need to support itself). Therefore, the enclosure could consist of nonrigid sides on a rigid frame, which would lower its cost. The most important aspects of the enclosure concept are:

- The operator stands outside the enclosure, placing only the spray gun inside the enclosure.
- Openings to the enclosure are as limited as possible, with a goal of less than 5 percent of the total enclosure surface area.
- Exhaust from the enclosure is as low as possible, maintaining only enough flow to keep emissions from escaping from the opening (s).

One important consideration in the design of an enclosure are the physical considerations of moving the part into and out of the enclosure, and the timing for removal of the part from the enclosure. The enclosure design needs to incorporate a method by which the part can be moved into the enclosure and removed from the enclosure. As the enclosure is opened to remove the part, styrene emissions in the enclosure may escape. RTI testing (Kong et al., 1995) has indicated that approximately 39 percent of total gel coating emissions occur during the spraying process, and approximately 50 percent of resin application emissions occur during spraying. Therefore, even though capture may be 100 percent while the part is **within** the enclosure, uncaptured emissions may occur when the part is outside the enclosure. The feasibility of the enclosure concept for open molding process is being evaluated in an EPA funded program in the summer of 1996.

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APPENDIX A

Development of Cost Functions for Styrene Emission Control Technologies

This Appendix presents the original cost data collected from various vendors. Other references, including the OAQPS Control Cost Manual (Vatavuk, 1990), a report, and a paper in the *Chemical Engineering* magazine are listed. The original equipment cost data were fitted with linear regression to develop cost functions for equipment costs. The equipment cost functions for various styrene emission control technologies are presented in Table 5-1.

Equipment cost curves for thermal oxidizers (at all heat recovery levels) were taken from equipment cost equations 3.24 through 3.27 in the OAQPS Control Cost Manual. Fuel requirements were calculated based on the principles of thermodynamics, and an assumed 10 percent insulation losses. Electricity requirements were based on equations presented in the OAQPS Control Cost Manual, except that the electricity requirement for thermal oxidation with 95 percent heat recovery was based on quotations by an equipment vendor.

Equipment cost curves for catalytic oxidizers with recuperative heat recovery (i.e., with heat recoveries of 0, 35, 50 and 70 percent) were taken from equipment cost equations 3.29 through 3.32 in the OAQPS Control Cost Manual. Fuel requirements were calculated based on the principles of thermodynamics, and 10 percent insulation losses. Electricity requirements were based on equations in the OAQPS Control Cost Manual.

The equipment cost curve for catalytic oxidizers with regenerative heat recovery (i.e., with heat recovery of 95 percent) was based on equipment cost quotations from three vendors (Anguil Environmental Systems, Engelhard Corporation, and Setco, Inc.). The equipment cost curve and the cost quotations are depicted in Figure A-1.

The equipment cost curves for VOC condensers were based on equations presented in a paper by Vatavuk (Vatavuk, 1995).

The equipment cost curve for the MIAB system was based on quotations from the MIAB's U.S. representative, Setco, Incorporated (Sundberg, Facsimiles dated December 22, 1995 and January 26, 1996). The equipment cost curve and cost quotations are depicted in Figure A-2.

The equipment cost curve for the Thermatrix PADRE system was based on budgetary quotation from Purus (Irvin, Facsimile dated November 8, 1995).

The equipment cost curve for the Polyad system were based on the midpoint (center) of upper and lower cost curves provided by Polyad's representative, Weatherly Inc. (Danielsson, Facsimile dated April 26, 1995).

The equipment cost curve for the rotary concentrator system was based on equipment cost quotations from Durr, Industries (Klobucar, Facsimile dated March 14, 1996). The equipment cost curve and cost quotations from Durr are depicted in Figure A-3. Quotes of rotary concentrator equipment cost from Munters Corporation (Drohan, Facsimile dated January 3, 1996) are also shown in Figure A-3. However, Munters Corporation does not have industrial systems in place, while Durr Industries has several operating systems in Japan; therefore, the Durr estimates, only, were used to develop cost functions.

The equipment cost curve for the fluidized-bed preconcentrator system was based on cost data provided by Environmental C&C, Inc. (Merboth, Letter dated March 28, 1996).

The equipment cost curve for biofiltration was developed based on budgetary quotes for an exhaust flow rate of 52,000 scfm by several vendors in a report (Haberlein and Boyd, 1995). The equipment cost curve and cost quotations are depicted in Figure A-4.

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APPENDIX B

Cost Model for Styrene Emission Control Technologies

A discussion of the computer spreadsheet cost model (STY_COST.XLS for Excel and STY_COST.WK3 for Lotus 1-2-3) developed for this project is included in this Appendix. This cost model includes a separate spreadsheet for each of the control technologies evaluated. These spreadsheets are listed by the order of appearance in the cost model:

A) EC&C - EC&C fluidized-bed preconcentrator system
B) Rotary - rotary concentrator system
C) Catalytic - catalytic oxidation process
D) Condenser - condensation process
E) MIAB - MIAB system
F) Polyad - Polyad system
G) Thermal - thermal oxidation process
H) PADRE - Thermatrix PADRE system
I) Biofiltration - biofiltration process

General instructions for using the spreadsheets in the cost model:

1) Under "Inputs" in Column B, enter two of the following three items:
   a) Flow rate (cfm),
   b) Control device input mass (tons per year), or
   c) Concentration (at control device inlet) (ppm).

   Do <u>not</u> enter values for all three items; the program will calculate (in Column C) the value for the item that you left blank.

2) Enter input values in Column B for items such as Facility Operating Schedule (hours per year), electricity cost ($/kilowatt-hour), and fuel cost ($/million Btu). All inputs must be in the correct units.

3) If you have received a plant-specific quote for the cost of a particular control device, enter that cost in the first row having the title "Equipment Cost (EC)". Note that the costs for other control devices in these spreadsheets are in July 1995 dollars. Therefore, you must de-escalate the cost in the second row titled "Equipment Cost (EC)" into July 1995 dollars, if you will be comparing your site-specific equipment cost with other non-site-specific costs listed in these spreadsheets.

4) Read about how the calculations were developed for items such as:

a) "Total Direct Costs (TDC)" - based on capital cost factors shown in Table B-1,
b) "Total Capital Investment (TCI)" - based on capital cost factors shown in Table B-1,
c) "Direct Operating Costs, excluding fuel and electricity costs",
d) "Overhead, Property Taxes, Insurance, Administration", and
e) "Capital Recovery Cost".

Adjust these calculations as needed. For example:

a) The lines titled "Total Direct Costs (TDC)" contain an assumed site preparation cost of \$(5,000 + 2.3[flow rate]). This non-site-specific site preparation cost is the average of vendor quotes and it is assumed for every control technology. If you have site-specific site preparation costs, insert these in place of the calculated site-preparation costs.

b) The lines titled "Total Direct Costs (TDC)" contain an assumed building cost of zero (i.e., it is assumed that the control device is not located inside a building. If a building must be built to house the control device at your plant, add this cost to the "Total Direct Costs".

c) The "Capital Recovery Cost" calculation assumes a capital recovery factor of 0.14569, which represents a 10-year depreciation at a 7.5% annual interest rate. This capital recovery factor can be changed to represent a specific situation (for example, the capital recovery factor for 10-year depreciation at 10 percent interest is 0.16275).

Table B-1. Capital Cost Factors for Emission Control Devices[a]

Cost Item	Factor
Direct Costs	
Purchased equipment costs	
Emission control device (EC) + auxiliary equipment	As estimated, A
Instrumentation	0.10 A
Sales taxes	0.05 A
Freight	0.05 A
Purchased equipment cost, PEC	B = 1.20 A
Direct installation costs	
Foundations & supports	0.08 B
Handling & erection	0.14 B
Electrical	0.04 B
Piping	0.02 B
Insulation for ductwork	0.01 B
Painting	0.01 B
Direct installation cost	0.30 B
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Cost, DC	1.30 B + SP + Bldg.
Indirect Costs (installation)	
Engineering	0.10 B
Construction and field expenses	0.05 B
Contractor fees	0.10 B
Start-up	0.02 B
Performance test	0.01 B
Contingencies	0.03 B
Total Indirect Cost, IC	0.31 B
Total Capital Investment = DC + IC	1.61 B + SP + Bldg.

[a] Source: Vatavuk, 1990 (Table 3-8, except sales tax taken as 5%, instead of 3%, for a more realistic situation)

Explanation of spreadsheet equations

Row/Cell	Explanation
Flow rate (cfm)/C3	If flow rate input in cell B3 is "zero" (i.e., if flow rate in cell B3 is left blank), this equation will calculate the flow rate in cfm, based on the control device input in tons per year, the facility operation in hours per year, and the control device inlet concentration in ppm. Conversion factors: 2000 lb/ton; 454,000 mg/lb; 60 min/hr; 4.326 mg/m^3 per ppm of styrene; 35.3 ft^3/m^3.
Control device input mass (tons/year)/C4	If control device input mass in cell B4 is "zero" (i.e., if input mass in cell B4 is left blank), this equation will calculate the input mass in tons per year, based on the flow rate, the facility operation in hours per year, and the control device inlet concentration in ppm. Conversion factors: 2000 lb/ton; 454,000 mg/lb; 60 min/hr; 4.326 mg/m^3 per ppm of styrene; 35.3 ft^3/m^3.
Concentration (ppm)/C5	If control device inlet concentration in cell B5 is "zero" (i.e., if the control device inlet concentration in cell B5 is left blank), this equation will calculate the control device inlet concentration, based on the flow rate, the facility operating schedule in hours per year, and control device input mass in tons per year. Conversion factors: 2000 lb/ton; 454,000 mg/lb; 60 min/hr; 4.326 mg/m^3 per ppm of styrene; 35.3 ft^3/m^3.
Electrical power (kW)	This equation calculates the electrical power consumption of the control device at any flow rate. Electrical power consumption for most of the control devices was based on vendor quotes, except where power consumption was based on equations in the OAQPS Cost Manual. In most cases, the vendor supplied electrical power consumptions for one or two flow rates. In these cases, electrical power was assumed to be linear with flow rate.

Row/Cell	Explanation
Fuel usage (Btu/hr)	Fuel usage was either calculated from first principles (such as for catalytic and thermal oxidation), or was based on vendor quotes (such as for the rotary concentrator). Fuel usage is dependent on flow rate in cfm, heat recovery percentage, oxidizer design temperature, and styrene inlet concentration. Conversion factors/constants: 60 min/hr; air density of 0.0751 ft^3/lb at 68°F; air specific heat of 0.241 or 0.245 Btu/lb_m-°F (for catalytic or thermal oxidation, respectively); divide the calcuated heat recovery value by 100 to get percentage heat recovery; 1.1 represents 10 percent insulation heat loss; 0.00475 Btu/ppm of styrene.
Equipment Cost (EC), (Vendor quotes)	This equation calculates the equipment cost as a function of flow rate. The equations were typically based on polynomial- or straight-line curve fitting of vendor quotes.
Equipment Cost (EC), (July 1995 dollars)	All equipment costs were escalated (or de-escalated, if appropriate) to July 1995 dollars, using the Chemical Engineering magazine equipment cost index. The value of this index in July 1995 was 428.1 (referenced to 1957-1959 at 100).
Total Capital Investment ($)	Based on the OAQPS Cost Manual (except sales tax taken as 5%, instead of 3%, for a more realistic situation), this equation calculates total direct cost, based on equipment cost, site preparation cost, and cost of buildings to house the control device. Site preparation cost is assumed to be $(5,000 +2.3[flow rate, cfm]), for all control devices. Cost of buildings to house control devices is assumed to be zero (all control devices assumed to be outdoors).
Direct Operating Costs, excluding fuel and electricity costs ($).	Includes maintenance costs. Maintenance costs are based on 4 hours per week, 52 weeks per year, at a labor rate of $25/hour, for a 10,000 cfm control system. Costs for other control sizes are assumed to be linearly related to flowrate. An additional 15 percent is added for supervisory cost. An annual maintenance contract of $4,840 is assumed for each control device. Where appropriate, additional costs, such as media replacement costs, are included in Direct Operating Cost. Fuel and electricity costs are separately calculated based on vendor quotes.

Row/Cell	Explanation
Fuel costs ($/year), calculated separately from Direct Operating Cost	If Fuel Usage (Btu/hr) is calculated to be positive, annual fuel cost is the product of the Fuel Usage (Btu/hr) times Facility Operating Schedule (hours/year) times the fuel cost ($/Btu). If Fuel Usage was calculated to be negative (i.e., autothermal operation), fuel cost was assumed to be represented by 5 percent (0.05) of the heating value of the styrene in the incoming stream. This factor of 5 percent is based on discussion in the OAQPS Cost Manual about maintaining a stable flame within the oxidizer.
Electricity cost ($/year), calculated separately from Direct Operating Cost	Electricity cost ($/year) is the product of Electrical Power required (kW) times facility operating schedule (hours/year) times electricity cost ($/kWhr).
Overhead, property tax, insurance, administration ($/year)	Overhead cost was calculated based on 60 percent of Direct Operating Costs ($/year) and other costs were calculated based on 4 percent of Total Capital Investment ($/year), as outlined in the OAQPS Cost Manual.
Capital Recovery Cost ($/year)	Capital Recovery Cost ($/year) was obtained by multiplying the Total Capital Investment by a capital recovery factor. The capital recovery factor (CRF) can be calculated by the following equation: $CRF = i(1+i)^n/([1+i]^n-1)$, where i = annual interest rate (%), and n = number of years of depreciation. The capital recovery factor assumed in these spreadsheets was 0.14569 (7.5%, 10-year depreciation).
Total Annualized Cost ($/year)	Total annualized cost is the sum of all annualized costs, including direct operating costs, fuel costs, electricity costs, overhead, property tax, insurance, administration, and capital recovery cost.

Row/Cell	Explanation
Cost per unit of pollutant removed ($/ton)	This is obtained by dividing the total annualized cost ($/year) by the amount of pollutant removed (tons per year). The amount of pollutant removed is the product of the Control Device Input Mass (tons/year) times the control device efficiency (expressed as a fraction). In these spreadsheets, thermal oxidation was assumed to have a control device efficiency of 98% (i.e., 0.98). All other control devices were assumed to have 95% control efficiency, except for VOC condensers. The efficiencies of VOC condensers were calculated based on the saturation curve for styrene gas and a specified operating temperature for the VOC condenser.

References

Vatavuk, W.M.; OAQPS Control Cost Manual, 4th Ed. EPA-450/3-90-006 (NTIS PB90-169954); U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, January 1990.

Figure 4-13. Schematic of the Terr-Aqua’s ultraviolet/oxidation system.