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An Assessment of Styrene Emission Control Technologies for the FRP and Boat Building Industries

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ABSTRACT

Styrene emissions from open molding processes in fiber-reinforced plastics (FRP) and 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 costs of add-on controls, since costs are strongly dependent on air flow rate through the control system. Also, add-on styrene emission controls are currently not generally mandated by regulations. Therefore, emission controls are infrequently used in these industries at present. In order to provide technical and cost information to companies that might choose emission controls to reduce styrene emissions, Research Triangle Institute (RTI), working with the U.S. Environmental Protection Agency (EPA), examined several emission control technologies that have been used to treat styrene emissions in the U.S. and abroad. Control costs for these technologies were developed and compared for three hypothetical plant sizes. The results of this cost analysis indicate that increasing styrene concentration in the exhaust streams can significantly reduce cost per ton of styrene removed for all technologies examined. Therefore, a company should evaluate methods to increase concentrations in the exhaust stream before considering any add-on control devices. This paper 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.

INTRODUCTION

The fiber-reinforced plastics (FRP) and 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. For example, the overall efficiency of an add-on emission control system is a product of the emission capture efficiency and the control system efficiency and thus is less than either efficiency.

Conventional pollution control technologies are not often used to reduce styrene emissions in the FRP and boat building industries; low concentrations and high air flow rates have made conventional emission controls very expensive, and in some cases, less efficient. The FRP and boat building industries need information regarding the applicabilities and costs of conventional and emerging control technologies, so they can make informed decisions about the use of controls to reduce their emissions. To meet this need, Research Triangle Institute (RTI), working with the U.S. Environmental Protection Agency's (EPA's) Air Pollution Prevention and Control Division, evaluated air flow management practices, and the cost and performance of several conventional and emerging pollution control technologies potentially applicable to these industries.

This paper summarizes the results of literature reviews and control cost analyses. Background information about the industries and the characteristics of their emissions are provided. The various pollution control technologies are described, and their costs compared. Air flow management practices that may reduce control costs are described and evaluated, and conclusions of the evaluation are presented.

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

BACKGROUND

The FRP industry (excluding boat building) includes over 680 facilities nationally in as many as 33 different Standard Industrial Classification (SIC) categories ranging from transportation to electronics and consumer products.[1] 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 1, the main manufacturing process is open molding. RTI estimates that open molding (including gel coat and resin spraying) is responsible for approximately 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 Toxic Release Inventory (TRI) reports,[2] and RTI's knowledge of FRP processes and their emission characteristics.

The FRP boat building industry represents a segment of SIC code 3732, Boat Building and Repairing. A 1990 EPA report[3] indicated that 1,822 facilities made up the boat building and repair industry; however, only 214 of these facilities employed 50 or more people. The open molding process is the most common production method used in FRP boat building. Estimated VOC emissions from the boat building operations in the U.S. were 19,954 metric tons (22,000 tons) in 1990.[3]

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 production and boat building facilities use high ventilation rates to ensure that styrene levels are below the 100-ppm worker exposure limit established by 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, dilute 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 to the atmosphere directly.

Some FRP processes, such as pultrusion, continuous lamination, sheet molding compound (SMC) and prepreg production, and resin mixing, have localized and stationary 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, they are more feasible or less costly to treat. Most of the existing emission control devices installed in the FRP facilities are used to treat emissions from these processes.

POLLUTION CONTROL TECHNOLOGIES AND CONTROL COST ANALYSES

This section describes pollution control technologies that have been used in the U.S. and abroad to treat styrene emissions and presents cost analyses of these technologies for three hypothetical plant sizes.

Pollution Control Technologies

Pollution control technologies include (1) conventional pollution control technologies, such as thermal and catalytic oxidation and condensation; (2) preconcentration by an adsorption unit, followed by a recovery or destruction device; and (3) emerging technologies, such as ultraviolet (UV) oxidation, that are not currently used in the U.S., but have potential to treat styrene emissions.

Conventional Technologies. Four conventional technologies are currently used in U.S. FRP facilities to treat styrene emissions: thermal oxidation, catalytic oxidation, adsorption, and condensation. Process descriptions and their applications in the FRP industry are presented.

In thermal oxidation (also called "incineration"), the styrene-containing stream is heated in a combustion chamber to a predetermined temperature for a sufficient time to convert styrene to carbon dioxide (CO_2) and water (H_2O). Commercial thermal oxidizers operating at 907°C (1,600°F) with a nominal residence time of 0.75 seconds can achieve 98 percent destruction of non-halogenated organics.[4] Auxiliary fuel is used to maintain the high combustion temperature. Thermal recovery, using recuperative or regenerative heat exchangers, is frequently used to lower the fuel costs of thermal oxidizers. If a shell-and-tube heat exchanger is used to preheat incoming combustion air, the heat exchanger is called a "recuperator." Recuperators typically have energy recoveries of 40 to 60 percent, although recoveries of 80 percent or more are possible. Regenerative thermal incinerators cycle thermal energy between an exhaust and an intake stream using an arrangement of thermal masses. The hot flue gas from the incinerator heats a storage mass, usually a heat-resistant ceramic material. Once this storage mass reaches a preset temperature, the flue gas is redirected and the styrene-laden inlet gas flows through the now heated mass. In this manner, up to 98 percent of the thermal energy in the incinerator's exhaust can be recovered. Due to the higher thermal efficiency, a regenerative thermal oxidizer is typically better suited for low-concentration streams than a recuperative thermal incinerator. Thermal oxidizers are currently used in facilities manufacturing sheet- and bulk-molding compounds and prepreg materials, in facilities using continuous lamination and pultrusion processes, and in some open molding processes.[5]

Catalytic incinerators modify the thermal incinerator concept by adding a fixed- or fluidized-bed catalyst to promote the oxidation reaction, allowing faster reaction and/or reduced reaction temperature. Typical temperatures range from 260 to 650°C (500 to 1,200 °F). A lower reaction temperature generally reduces auxiliary fuel requirements, thus reducing operating costs. Both recuperative and regenerative heat exchangers can be applied to catalytic incinerators. Catalytic oxidizers are used in an FRP facility (Fibercast, Sand Springs, Oklahoma) to treat styrene emissions from bulk-molding-compound preparation and centrifugal casting and in another facility (CorTec, Washington Court House, Ohio) to treat emissions from gel coating.[5]

Adsorption units using activated carbon or polymeric adsorbent have been installed in several European FRP facilities to preconcentrate styrene emissions for subsequent recovery or destruction. Preconcentration technologies are discussed later. At least two FRP facilities in the U.S. (U.S. Fiberglass, in Middlebranch, Ohio, and Glastic Corporation, in South Euclid, Ohio) use activated carbon filter panels to treat styrene emissions from their production buildings, which house compression molding presses, pultrusion lines, and bulk molding compound production. These carbon filter panels are disposed of after use or sent out for reactivation.[5]

Condensation is not commonly used to treat styrene emissions. However, an FRP facility (Premix, Incorporated, Ashtabula, Ohio) recently installed a liquid-nitrogen condenser to recover styrene.[6] The facility originally applied enclosure and nitrogen blanketing on their resin-mixing tank and sheet-molding-compound manufacturing process 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 facility is currently conducting a study to examine the styrene reuse issue. Since the facility already has a nitrogen source on site, the annual cost for the condenser is less than that for other emission control systems.

Preconcentration Technologies. A low-concentration, high-air-flow-rate exhaust stream can be concentrated into a smaller stream at higher styrene concentration for more economical destruction. Typically, a preconcentration device can reduce the exhaust flow rate to 10 percent of the original exhaust flow rate. Consequently, capital and operating costs for a downstream emission control device can be reduced significantly. A concentrated stream reduces or eliminates the auxiliary fuel required in a downstream incinerator, resulting in a decrease in operating cost and related emissions of carbon and nitrogen oxides.

Preconcentration technologies use the adsorption-and-desorption principle to convert a low-concentration/high-flow-rate exhaust stream into a high-concentration/low-flow-rate stream. Three preconcentration technologies have been developed by U.S. and European engineering firms. The Polyad system preconcentrates styrene emissions by adsorption on polymer beads, then destroys desorbed styrene by catalytic oxidation. The Purus PADRE system uses a polymeric adsorbent to preconcentrate styrene emissions, then recovers styrene after desorption. Alternatively, the desorbed styrene might be reused if the recovered styrene meets material purity standards. The MIAB concentrators use activated carbon in fixed- or fluidized-bed designs; both are followed by catalytic oxidation.

Biofiltration. Biofiltration is a relatively recent air pollution control technology in which an exhaust gas containing biodegradable organics is vented, under controlled temperature and humidity, through a medium inoculated with cultured microorganisms. The microorganisms contained in the compost-like medium digest the organic and produce CO_2 and H_2O. This technology has been applied in Germany and the Netherlands in many full-scale applications to control odors, volatile organic compounds, and air toxic emissions from a wide range of industrial sources. A biofiltration unit has been installed in an FRP boat building facility in Sweden to treat styrene emissions. The unit was designed for a 283 m^3/minute (10,000 cfm) flow rate and an 85 percent removal efficiency.[7] The pH, temperature, moisture, growth of biomass, and pressure drop of the biofiltration unit need to be monitored carefully to maintain an optimum condition.[8]

Ultraviolet Oxidation. Ultraviolet/activated oxygen (UV/AO) oxidation is an emerging technology that combines UV light oxidation, absorption, and carbon adsorption into a system to treat volatile organic emissions. The system uses filters to remove particulates from the air stream. The organic-laden air then enters a photolytic reactor, where it is exposed to UV light and mixed with activated oxygen/ozone. Partial destruction of the organic vapor takes place in the reactor. The air then enters a scrubber where organic vapor in the gas phase is transferred to the liquid phase. The water is heavily oxidized in the scrubber's recycling tank to convert organics into CO_2 and H_2O. The air stream from the scrubber is treated by activated carbon adsorbers to remove any remaining organic vapor that did not dissolve in water. Activated carbon adsorbers are alternately regenerated on-site using oxidant, and the adsorbed organic is converted to CO_2 and H_2O. This system involves many unit operations that require careful operation and maintenance. A UV/AO system was installed in an FRP job shop in California to treat styrene emissions from a sprayup operation; however, it is no longer in operation because the plant was shut down.

Control Cost Analyses

RTI collected capital and operating cost data from several sources in order to calculate annualized costs for various conventional and emerging control technologies for three hypothetical plant sizes. Annualized costs were calculated using procedures outlined in the EPA Office of Air Quality Planning and Standards' *OAQPS Control Cost Manual*.[4] Table 2 summarizes the equations for equipment costs that were used to calculate annual costs. Other cost analysis inputs and major assumptions are presented in Table 3. All costs were calculated in July 1995 dollars using *Chemical Engineering* equipment cost indices.

Based on the quantity of styrene emitted and the control efficiencies of the technologies, the costs per ton of styrene removed were calculated from annualized costs. Cost curves are presented in Figure 1 for catalytic oxidation for three hypothetical plants, treating 18, 91, and 363 metric tons (20, 100, and 400 tons) per year of styrene. For each hypothetical plant, a cost curve was developed for different inlet concentrations (which are inversely related to air flow rates). The cost curves show that cost-per-ton of styrene removed decreases as the inlet concentration increases (i.e., exhaust air flow rate decreases). For example, Figure 1 indicates that, for a large plant treating 363 metric tons (400 tons) per year of styrene, the cost-per-ton of styrene removed decreases from $5,200 to $1,600, if inlet concentration increases from 50 to 200 ppm. This represents an annual saving of approximately $1.4 million. This figure also shows that costs-per-ton of styrene removed are higher for small plants than for large plants, because of the economy of scale.

Figures 2, 3, and 4 compare cost curves for various control technologies for three hypothetical plant sizes, under the assumptions presented in Tables 2 and 3. These figures indicate that concentrating technologies appear to reduce the cost of styrene control, particularly at lower styrene inlet concentrations. However, this reduction in cost is significantly affected by the equipment cost assumptions used in this analysis. Therefore, FRP companies should compare costs of different technologies on a case-by-case basis. These figures also show that, for all control technologies, control costs can be significantly reduced by increasing styrene inlet concentration (i.e., lowering exhaust flow rates). Containing or capturing styrene emissions at the source, thus reducing inlet flow rates to control devices, are good approaches to making any control technology more economically feasible.

AIR FLOW MANAGEMENT PRACTICES

Current ventilation systems in FRP and boat building facilities are primarily designed to provide an environment that is safe for workers and produces good product quality. General ventilation, also called dilution ventilation, supplies an ample amount of makeup air to dilute the contaminants to an acceptable air quality level in the workplace. This common practice produces high-volume, low-concentration exhaust streams. Flow rates of 566 to 2,830 m^3/min (20,000 to 100,000 cfm) are common in FRP and boat building facilities, and styrene concentrations are rarely above 100 ppm. As shown in the previous cost analysis, these high-volume, low-concentration exhaust streams make emission control systems more expensive. It is also more expensive to heat or cool large volumes of makeup air.

Proper air flow management would capture emissions at the point of generation and prevent mixing contaminated air with clean air. 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 reduce control costs.

The following sections present several air flow management practices and concepts that could be applied to minimize air flow volumes at FRP and boat building facilities. These practices and concepts are: local air flow management, spray booth modifications, and enclosures. RTI and EPA may collaborate to test the effects of enclosures and spray booth modifications on styrene emissions, in 1996, if suitable arrangements can be made.

Local Air Flow Management

Local air flow management involves capturing air pollutants at the emission source directly; therefore, the amount of air to be ventilated is minimized. In an open space, this can be done by blowing makeup air toward the emission source and capturing the emission with an exhaust hood at the other end (a push-pull ventilation system). The capture efficiency is generally better for a push-pull system than for an exhaust hood alone. Figure 5 shows three schematics of local exhaust ventilation that originally appeared in the *UP-Resin Handling Guide.*[9] These practices are local extraction, in-mold push-pull ventilation, and out-of-mold push-pull ventilation.

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.[9] "In-mold push-pull ventilation" is a technique in which a small amount of air is blown from one side of the mold, over the wet mold surface, and immediately captured by an exhaust hood at the other side of the mold. This technique is best-suited for large, female molds (such as boat hulls). "Vertical push-pull ventilation" directs makeup air from the ceiling toward the mold and pulls emissions away from the workplace through a down-draft exhaust. When the push-pull ventilation is arranged horizontally, it is like a spray booth with air pushed at the mold from one direction, and exhaust air pulled from the other side of the mold. The advantages of these push-pull systems are that less air flow is required to sweep the high-concentration emissions from the mold surface and that emissions are captured at the source directly, thus avoiding contamination of the surrounding air.

In-mold push-pull ventilation systems are not common in the U.S., and vertical out-of-mold push-pull ventilation systems are used only to a limited extent. Horizontal push-pull ventilation systems (e.g., spray booths with forced supply air) are more commonly used in FRP and boat building facilities in the U.S.

Spray Booth Modifications

Spray booths are commonly used in the FRP and boat building industries, especially for gel coat and resin sprayup operations, and for parts that can fit into a spray booth. Using a spray booth can prevent 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 transferred mechanically 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. Dry filter media are used to capture overspray, and the media are replaced frequently to protect the duct work and exhaust system. The captured emissions are vented to the atmosphere or to an emission control device.

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

Recirculation. The concept of recirculation had its origin in the spray painting industry, as a means of lowering the exhaust 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. The recirculation stream may be reintroduced at any location in the spray booth (e.g., near the inlet face, or at the center of the booth). For a spray booth with recirculation alone, the increase in inlet concentration to a control device is directly related to the amount of recirculation. The disadvantage of recirculation is the potential for increased worker exposure, unless fresh makeup air is provided to the operator through a duct, or the operator wears a respirator.

Split-Flow. 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. A split-flow painting spray booth design that takes advantage of this fact was developed by EPA and Acurex Environmental, Inc.[10] 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 split-flow design is illustrated in Figure 7. 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. The main advantage of a split-flow design is that it produces an increase in VOC concentrations going to a control device; however, the area to be split must be specific to each spray booth, based on the actual spraying pattern and concentrations at various locations.

Other Design Modifications. In a typical spray booth in an FRP facility, a mold is placed in the center of the booth. The arrangement of the mold within the booth is such that higher concentrations are drawn through the center of the filter bank, rather than through the top or sides of the filter bank. A spray booth can be modified to take advantage of this spatial difference in concentrations. Modification would involve constructing a smaller, centrally located exhaust device as shown in Figure 8. The higher-concentration exhaust collected by this device would be directed to an emission control device. The lower-concentration exhaust could be vented to atmosphere or recirculated in the spray booth.

In addition to spatial differences in emissions within spray booths, temporal (time-related) variations in emissions can be used to increase concentrations to the emission control device. The centrally located exhaust device could be activated to capture high-concentration exhaust during the spraying period. The main exhaust of the spray booth will be continuously operating during the nonspraying or low-concentration period. Periods of high emissions could be determined by concentration measurements, or high emissions could be assumed to occur during any period of spraying (i.e., the small exhaust unit is activated by the spray-gun trigger). Fresh makeup air can be supplied to the locations where the operator is standing.

Enclosures

Enclosures provide a physical barrier between the emissions and the surrounding environment, and they can reduce or eliminate the dispersion of styrene vapors from a production process. However, the styrene concentration within the enclosure must be kept below 2,500 ppm (25 percent of the lower explosive limit) by some ventilation. If an enclosure is ventilated, the exhaust concentration is inversely related to the exhaust flow rate. Therefore, an enclosure can be used to confine emissions or to create a low-flow-rate, high-concentration exhaust stream for destruction.

Enclosures are currently being applied to certain emission sources in FRP facilities, such as covers on resin storage and mixing tanks. The CorTec Company (Washington Court House, Ohio) uses an enclosed chamber for robotic gel coat spraying; emissions in the enclosure are vented to a catalytic oxidation unit. The exhaust flow rate is 102 m^3/min (3,600 cfm) with an average styrene concentration of 310 ppm.[11] Enclosures can also be applied to resin bath or wetout area in continuous lamination, pultrusion, and SMC production processes. Styrene emissions from these processes are fixed in location and high in concentration. With proper enclosures, styrene emissions at low flow rates and high concentrations can be vented to an emission control device and treated economically.

CONCLUSIONS

Exhaust streams from open molding processes in the FRP 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 and boat building industries.

Of the limited number of add-on control devices used in the FRP facilities in the U.S., thermal and catalytic oxidation are the most common. RTI compared the costs of alternative technologies, including biofiltration and preconcentration followed by recovery or oxidation, with straight thermal and catalytic oxidation. Preconcentration technologies appear to reduce the cost of styrene control, particularly at the lower styrene concentrations (less than 100 ppm) typically found at FRP and boat building facilities. However, this apparent reduction in cost is significantly affected by the equipment cost assumptions used in this analysis. Therefore, FRP 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 ton 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 proper air flow management practices or enclosures, before application of add-on emission control devices.

Proper 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 concentration in the exhaust streams from FRP facilities. These approaches can maintain a safe working environment and produce a high-concentration exhaust stream that makes add-on emission control devices less expensive.

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Table 1: Manufacturing processes employed by the FRP industry.

Manufacturing Process	Estimated % of Facilities Employing Process[a]
Open molding (gel coat and 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. Data are from Reference 1.

Table 2. Equations for equipment cost (EC).

Item	Condition / Value (July 1995 dollars)		Source
Catalytic oxidizer (regenerative, heat recovery of 95%)	IF $Q^{a}<150{,}000$ cfm,	$\$[200{,}000+15Q]$	Developed from quotes from three vendors.[12, 13, 14]
	IF $Q>150{,}000$ cfm,	$\$[450{,}000+13Q]$	
Catalytic oxidizer (recuperative, heat recoveries of 70% or less)	Equations in the OAQPS Cost Manual		OAQPS Cost Manual
Thermal oxidizer	Equations in the OAQPS Cost Manual		OAQPS Cost Manual
MIAB	$\$[68{,}181+16.8Q-2.19E^{-5}Q^{2}]$		Based on MIAB equipment cost quotes.[14]
Purus PADRE	IF $Q<3{,}000$ cfm,	$\$[106{,}000N^{b} + 80{,}000]$	Based on Purus equipment cost sheet, dated 12/2/94.[15]
	IF $Q>3{,}000$ cfm,	$\$[106{,}000N + 25Q]$	
Polyad	IF $Q<56{,}000$ cfm,	$\$[214{,}815 + 16.8148Q -3.8E^{-4}Q^{2} + 5.15E^{-9}Q^{3}]$	Developed from Polyad equipment cost curves, dated July 1995.[16]
	IF $Q>56{,}000$ cfm,	$\$[284{,}286 + 10.0316Q -2.9E^{-5}Q^{2} + 1.5E^{-10}Q^{3}]$	
Biofiltration	$\$[119{,}136 + 15.7Q]$		Developed from Boat Manufacturing MACT analysis, dated 8/1/95.[17]
VOC condenser	Single-stage >10 tons,	$\$[0.95\exp(9.26-0.007Tcon^{c} + 0.627\ln R^{d})]$	*Chemical Engineering*, August 1995.[18]
	Multistage,	$\$[0.95\exp(9.73-0.012Tcon + 0.584\ln R)]$	
Equipment price escalation (to July 1995)	As appropriate		*Chemical Engineering*[19] Equipment Cost Index

[a] Q= Air flow rate, in scfm (1 scfm = 0.0283 m^3/minute). [b] N=Number of adsorption/desorption units (1 unit for every 12.5 kg/hr [27.5 lb/hr] of styrene). [c] Tcon=Condenser operating temperature (-23°C [-10°F] for single-stage, -40°C [-40°F] for multistage). [d] R=Refrigeration capacity, tons.

Table 3. 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[a]]	RTI assumption
Buildings (Bldg.)	Not required.	RTI assumption
Indirect costs for installation	0.31 X PEC (Includes engineering, construction and field expenses, contractor fees, start-up, performance test, and contingencies.)	OAQPS Cost Manual
Total Capital Investment (TCI)	(1.61 X PEC) + SP + Bldg.	OAQPS Cost Manual
Direct operating costs, minus utilities (DOCMU)	$0.598Q + 4,840 + Miscellaneous costs (Includes operating, maintenance, and supervision labor; annual maintenance contract, miscellaneous costs).	RTI assumption
Miscellaneous costs	As appropriate. (Includes catalyst and/or adsorbent replacement costs, start-up fuel cost, etc.)	Based on vendor information.
Overhead, administration, property taxes, insurance	0.6(DOCMU) + 0.04(TCI)	OAQPS Cost Manual
Plant operating schedule	4,000 hours per year	RTI assumption
Electrical cost	$0.06/kWh	RTI assumption
Fuel cost	$4.27/billion joule ($4.50/million Btu)	RTI assumption
Capital Recovery Factor	0.14569	7.5% interest, 10-year depreciation

[a] Q= Air flow rate, in scfm (1 scfm = 0.0283 m^3/minute).

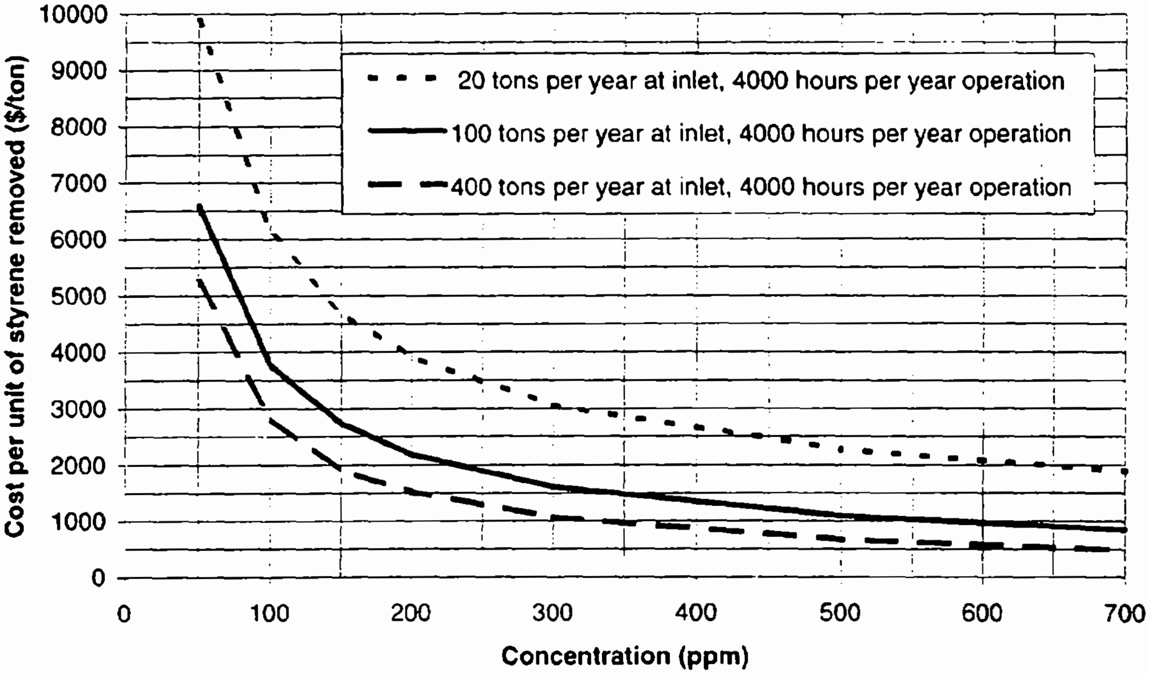


Figure 1. Cost curves for a catalytic oxidizer with 70% heat recovery (H.R.).

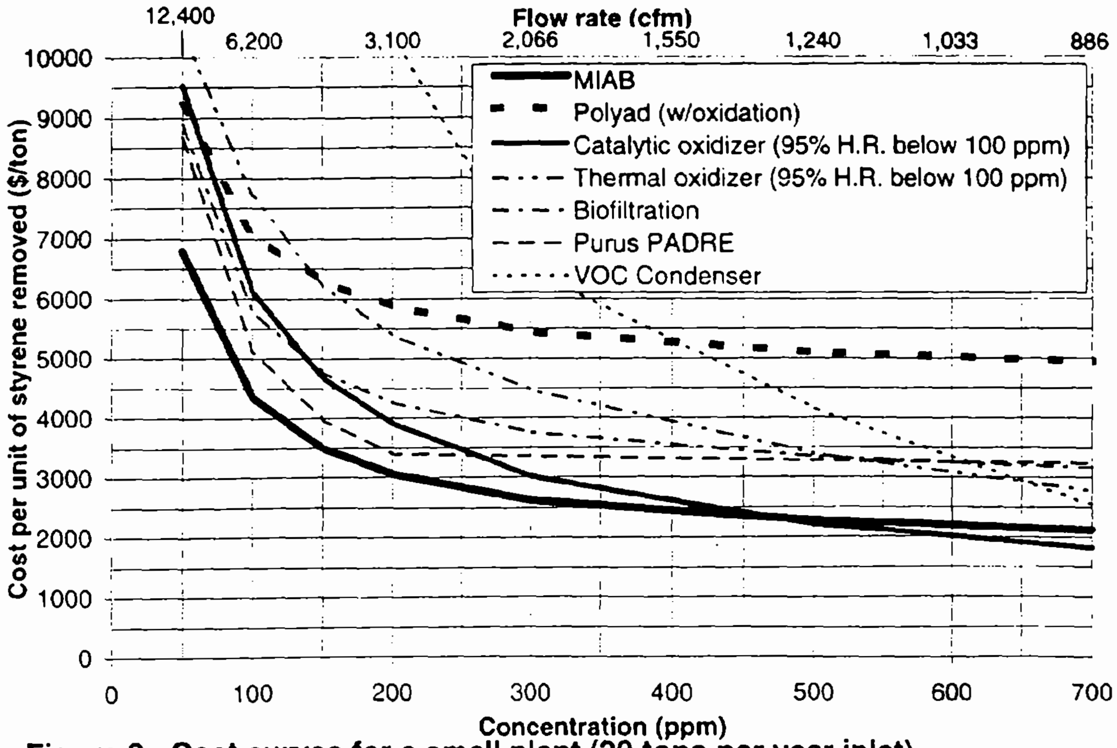


Figure 2. Cost curves for a small plant (20 tons per year inlet).

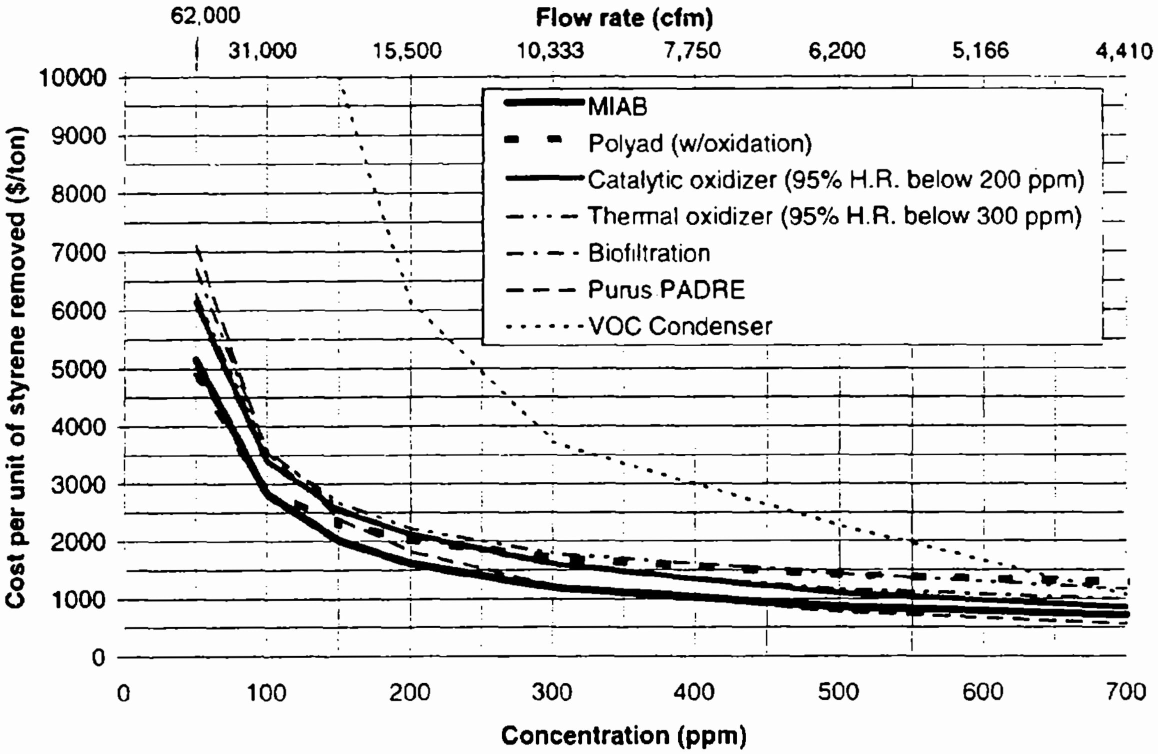


Figure 3. Cost curves for a medium-size plant (100 tons per year inlet).

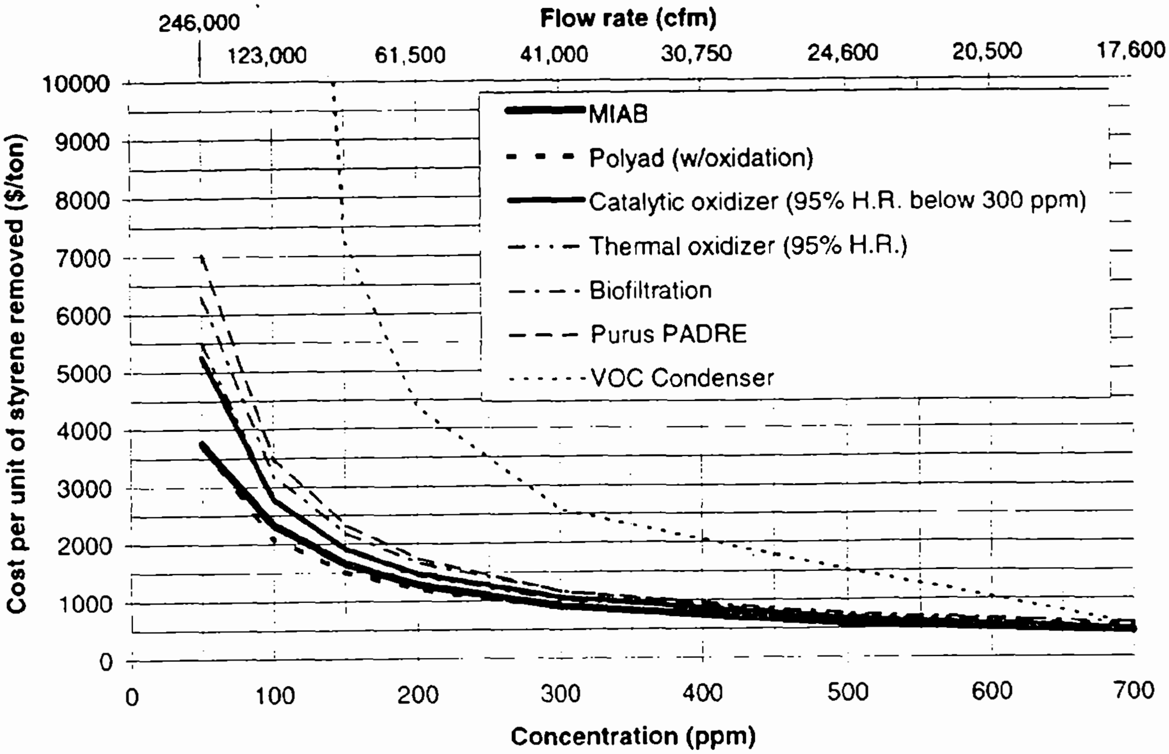
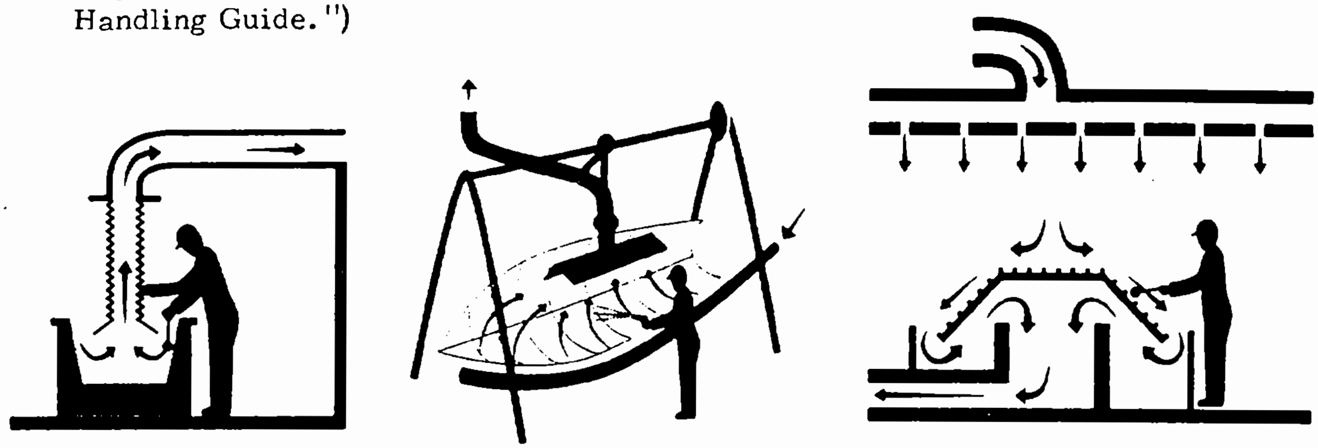


Figure 4. Cost curves for a large plant (400 tons per year inlet).

(Reproduced with permission from "UP-Resin Handling Guide.")



Local extraction In-mold push-pull ventilation Out-of-mold push-pull ventilation

Figure 5. Three methods of local extraction ventilation.

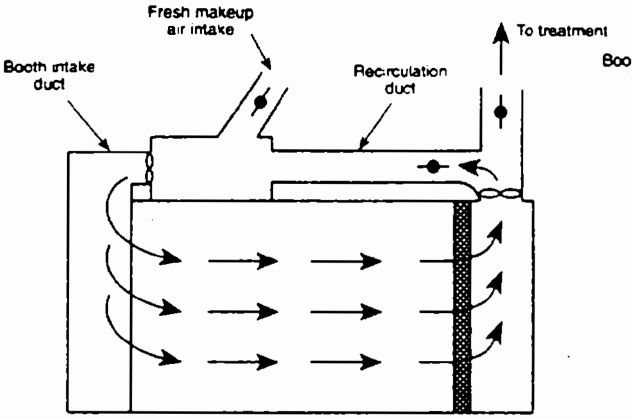


Figure 6. A spray booth with recirculation.

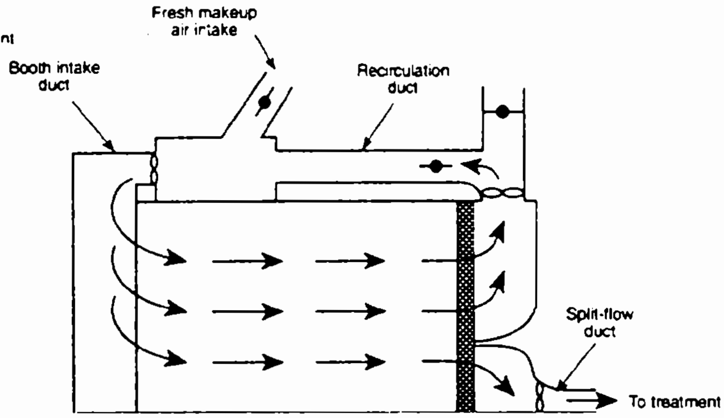


Figure 7. A spray booth with split-flow and recirculation.

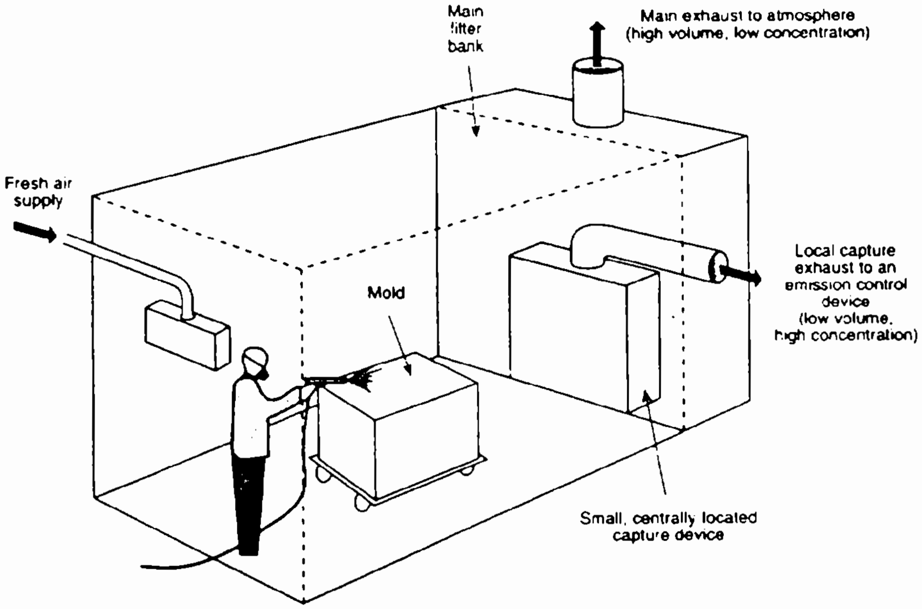


Figure 8. A spray booth with a centrally located exhaust device.

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before complet.

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16. ABSTRACT

The paper gives results of an assessment of styrene emission control technologies for the fiber-reinforced plastics (FRP) and boat building industries. (NOTE: Styrene emissions from open molding processes in FRP and boat building facilities are typically diluted by general ventilation to ensure that worker exposures do not exceed Occupational Safety and Health Administration standards. This practice tends to increase the costs of add-on controls, since costs are strongly dependent on air flow rate through the control system. Also, 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, Research Triangle Institute, working with the U.S. Environmental Protection Agency, examined several emission control technologies that have been used to treat styrene emissions in the U.S. and abroad.) Control costs for these technologies were developed and compared for three hypothetical plant sizes. Results of this cost analysis indicate that increasing styrene concentration in the exhaust streams can significantly reduce cost per ton of styrene removed for all technologies examined.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Moldings	Pollution Control	13B	11G
Emission	Molding Techniques	Stationary Sources	14G	13H
Styrene		Boat Building	07C	
Fiberglass-Reinforced Plastics			11D, 11I	
Boats			13J	

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