American Journal of Industrial Medicine 8:219-232 (1985)

Styrene Vapor Control Systems in FRP Yacht Plants

William F. Todd, PE

The production of large (greater than 25-ft) fiber-reinforced plastic (FRP) yachts has presented problems of styrene exposure in excess of the Occupational Safety and Health Administration permissible exposure level (OSHA PEL) of 100 ppm. Also, the National Institute for Occupational Safety and Health (NIOSH) is currently recommending a 10-hour workshift, 40-hour workweek time weighted average (TWA) of 50 ppm for styrene. Meeting this challenge will require a system of engineering, work practice, personal protective equipment, and monitoring control measures.

NIOSH has performed a study of the engineering controls in three FRP yacht plants. Work practices and the use of personal protective equipment (PPE) were also considered in the evaluation. The three systems evaluated included a dilution system, a local ventilation system, and a push-pull ventilation system. The cost of constructing and operating these systems was not evaluated in this study. Study results indicated that each type of ventilation system can meet the present PEL of 100 ppm styrene; however, it is not certain that these systems can meet a lower PEL of 50 ppm styrene.

Key words: **boat building, engineering controls, fiber reinforced plastics, FRP yachts, gel coat, lamination, personal protective equipment, polyester/styrene resin, styrene, ventilation, work practice**

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) has the responsibility for conducting research and developing criteria for the advancement of health and safety in the workplace. To meet the need for attaining lower control levels of toxic materials in the workplace, NIOSH has sponsored a series of industry-wide control technology evaluations. The goal of these evaluations is to provide industry with documented successful control systems. In carrying out these evaluations, NIOSH seeks to identify the best available control techniques practiced by selected companies, encourage the distribution of this knowledge within the industrial community, and outline control technology research needs. This is provided as a service to those companies wishing to improve the quality of the workplace environment and to an industry needing to meet more stringent controls levels in the workplace.

The production of fiber-reinforced plastic (FRP) boats involves the use of a polyester resin containing 40% to 60% styrene monomer. A review of the health

Engineering Control Technology Branch, National Institute for Occupational Safety and Health, Centers for Disease Control, Cincinnati, OH.

Address reprint requests to W.F. Todd, National Institute for Occupational Safety and Health, Centers for Disease Control, Engineering Control Technology Branch, 4676 Columbia Parkway, Cincinnati, OH, 45226.

Accepted for publication May 6, 1985.

literature for this and other FRP industries indicates that the major health problems include irritation to the mucous membranes and solvent narcosis from exposure to styrene vapor and contact dermatitis from skin contact with solvents, fibrous glass, and the uncured polyester resin [International Labour Office, 1972; Bourne and Milner, 1963]. Changes in psychomotor test results were noted among subjects in styrene-exposed workers at both high and low concentrations [Brooks, 1979].

Industrial hygiene surveys conducted by NIOSH in seven FRP boat-building plants indicated that of 464 personal air samples collected, 96 were in excess of the OSHA eight-hour time-weighted average standard of 100 ppm [Crandall, 1982]. There is clearly a need to train workers in how to avoid unnecessary styrene exposure and to design and install engineering controls that will reduce the workplace concentration to a level below the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL).

Meeting the above objectives is best carried out through a systems approach to control, which will bring the best combination of methods and resources together to provide a safe working environment. The methods of control that can be brought to bear on the problem consist of (1) engineering controls, (2) work practices, (3) personal protective equipment, and (4) control monitoring.

Controls applied at the source of the hazard are material substitution, process/equipment modification, isolation, local ventilation, work practices, or any combination of these [Peterson, 1973]. Controls most applicable to the general workplace environment include general dilution ventilation and housekeeping. Control measures applied near or by individual workers include the use of remote-control rooms, isolation booths, supplied-air cabs, good work practices, and personal protective equipment.

These principles apply to all situations, although the best combination of the principles varies from case to case. Existing processes can be roughly categorized by degree of automation or labor intensity. In general, processes that are continuous and automated involve fewer employees with less potential for uncontrolled exposures. The boat-building industry is labor intensive and therefore has a high potential for uncontrolled exposure.

APPLICABILITY OF ENGINEERING CONTROLS TO THE BOAT-BUILDING INDUSTRY

Engineering controls are those devices and systems installed in plants to remove or isolate toxic materials at the source or to control the concentration to a point well below the PEL.

Ventilation

Ventilation is the preferred method for meeting occupational standards for styrene in the workplace. General ventilation is widely used in warm climates where the air is not conditioned. Local ventilation is appropriate in cold climates where energy conservation is desired or when difficult ventilation problems make general ventilation ineffective.

Material Substitution

This method of control involves substitution of a less hazardous material than styrene in the resin. There are some alternate monomers for styrene, but they are either just as toxic or too high-priced to be economical.

Process Modification

Process modification will not alter the basic materials or operations of a process but will alter the design of the process from batch to continuous or from open to closed. There is no process modification for the production of large boats.

Equipment Modification

Equipment modification or substitution is a common means of control. This is a less drastic means of control than altering the process. An example of this principle in the boat industry would be the selection of spray equipment that produces the least amount of fine droplets. Most up-to-date lamination plants use airless spray equipment that minimizes droplet formation.

Isolation of Process

Isolation of stored materials, of equipment, and of the process involves the use of a barrier between a hazard source and those who might be affected by the hazard. Limiting employee access to certain areas during hazardous operations may also be a means of isolation. Physical enclosure of an area normally requires ventilation to prevent the build-up of toxic and/or explosive materials. The preparation and mixing of resins is frequently done in isolated areas but more for compliance with fire codes than for health reasons.

APPLICATION OF WORK PRACTICES TO THE BOAT-BUILDING INDUSTRY

A work practice is an action taken by a worker in the performance of his job and is described in terms of the worker's behavior.

A good industrial-hygiene work practice is a manner of performing job-related tasks so as to prevent exposure to toxic materials. Work-practice categories germane to styrene lamination processes were listed and evaluated by Hopkins [Hopkins, 1981] of The University of Kansas. These are (1) performance of job task requirements, (2) practice of personal hygiene, (3) use of personal protective equipment, (4) recognition of health hazards, (5) cooperation with medical and biological monitoring, (6) adherence to emergency procedures, (7) observance of safety procedures.

Each category contains from two to eight general work practices and a number of specific work procedures for each work practice.

APPLICATION OF PERSONAL PROTECTIVE EQUIPMENT TO THE BOAT-BUILDING INDUSTRY

Personal protective equipment is defined as clothing and hardware that isolate the worker from toxic agents and physical trauma. Personal protective equipment can be divided into three categories: (1) safety equipment (eg, hard hats, shoes, safety glasses); (2) protective clothing (eg, impermeable gloves, fireproof clothing); and (3) respiratory devices.

MONITORING CONTROL MEASURES

Monitoring control measures are defined as provisions for monitoring process parameters or workplace conditions that will forewarn of imminent toxic levels of contaminants by taking direct, real-time measurements. The need for this type of system is obvious with highly toxic chemicals that can cause short-term, irreversible health effects. The value of such a system in the control of styrene vapor is not so obvious, but it could be important in terms of assuring compliance with OSHA regulations.

SURVEY SAMPLING METHODOLOGY

The field studies involved the taking of many personal and area samples for styrene and acetone, the collection of substantial air-velocity data on the ventilation system, and the observation of work practices and types of protective equipment used by the employees.

The personal samples were collected simultaneously for 30-minute (nominal) periods to determine the styrene and acetone exposures. Notes were made of the tasks performed by the workers so exposure levels could be correlated to specific worker tasks. An example of a typical worker-exposure profile is shown in Figure 1. The styrene and acetone were collected in 150 mg charcoal tubes using MDA Accuhaler pumps operating at 100 cc/min. For analysis, each tube was separated into a front (A) and back (B) portion and desorbed in 1 ml of carbon disulfide. Analyses were performed by the Utah Biomedical Testing Laboratories (UBTL) in accordance with NIOSH Method P&CM 127 using gas chromatography and a flame ionization detector.

Ventilation measurements were made with either a Kurz or TSI hot wire velometer, and in one case with a pitot tube. The reason for the preference for the hot wire velometer was that most air flow encountered was turbulent or of very low velocity. The hot wire velometer is generally better suited for these situations when quick measurements are necessary and the highest accuracy is not required.

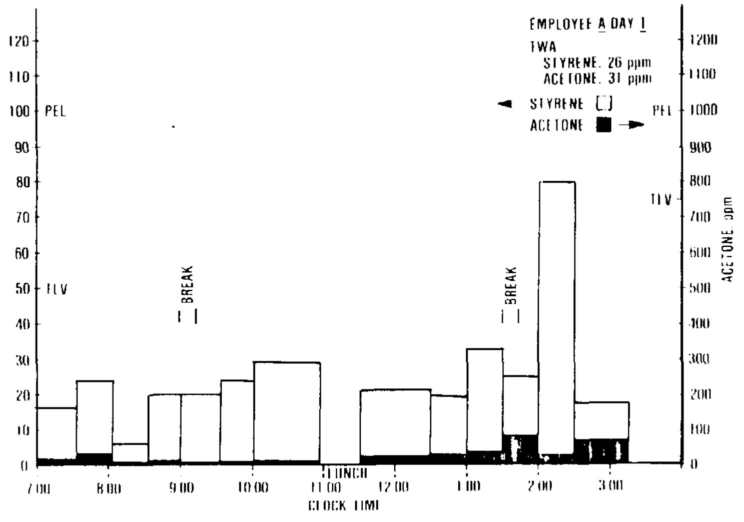


Fig. 1. Plant A—styrene exposure profile for lamination worker (1/2 hour samples).

CONTROL SYSTEMS FOR PLANTS A, B, AND C

Plant A

Plant A is located in Marysville, Washington. It is privately owned. This plant was surveyed in December 1981. Marysville is located near Puget Sound and experiences mild winters. The layout of the plant is shown in Figure 2. The plant has a dilution ventilation system having two rows of ceiling air supply vents located toward the center of the building and exhaust vents located along the walls parallel to the rows of inlet vents. The six inlet blowers are located on the roof and are matched by six exhaust blowers located at ground level outside the building. The layout of the ventilation system is shown in Figure 3. The design of a dilution ventilation system must take into account the maximum rate of styrene emission and provide a volume

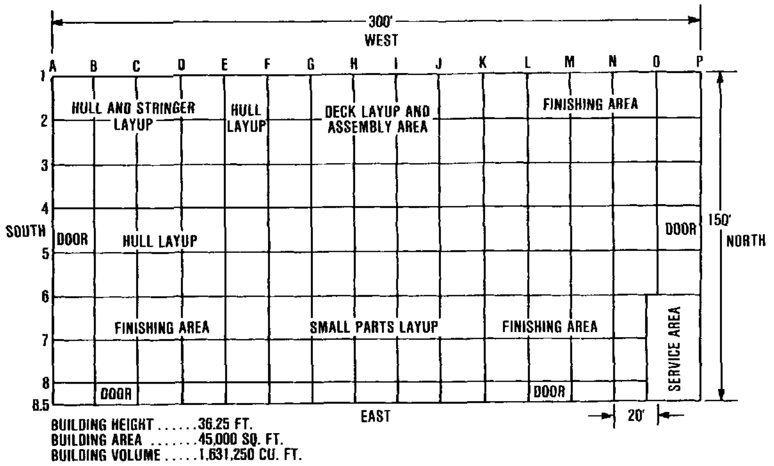


Fig. 2. Plant A—lamination building layout.

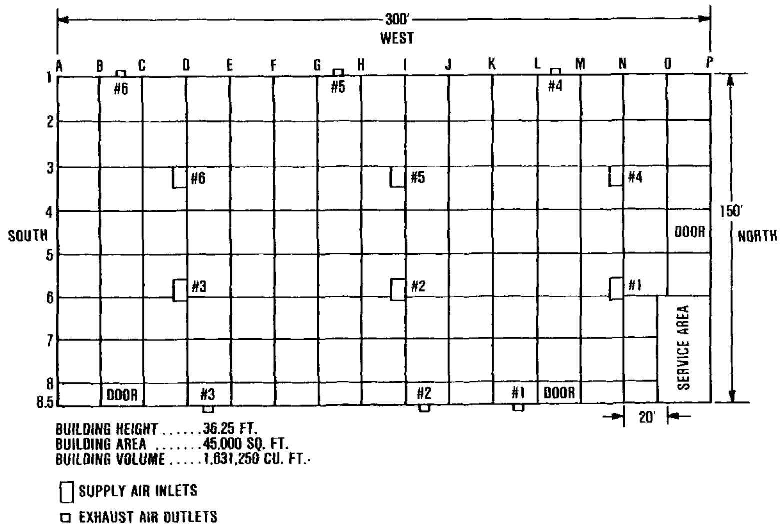


Fig. 3. Plant A—location of roof vents and intakes.

flow of air that will maintain the styrene concentration below the target level. To allow for incomplete mixing, irregular styrene release rates, and the fact that mixing requires a period of time, it is recommended that a safety factor, K, with a value between 3 and 10 be applied to the flow rate to insure adequate dilution in all parts of the plant [Industrial Ventilation, 1972]. This value is applied during the design of the system, but the effective value of K can be estimated from the styrene area sample data. The best estimate of the ventilation system air flow is 130,000 cubic feet per minute (CFM), which was determined by a six-point traverse of each of the six 37 × 29-in exhaust stacks that vent at the roof edge flush with the roof line. This flow rate results in about five air changes per hour in the plant, which has a volume of 1,631,250 cubic feet.

The air-flow pattern in this plant was determined by measuring air velocity with an anemometer and the air direction with a smoke tube. The observations were taken at a height of 6 ft above the floor in a grid pattern formed by the support structures of the building that divide it into bays. Each bay has an overhead air-supply diffuser located along the two rows of internal building support columns. The results of 252 data points indicated that the inlet air diffusers created large eddy currents, as shown in Figure 4.

Plant B

Plant B is located in New Gretna, New Jersey. It is privately owned. This plant was surveyed in July 1982. The company constructed a new building in 1981 with a novel ventilation system. The new building measures 630 × 150 ft and has an Applications Building module on the east end of the facility that measures 230 × 150 ft, as shown in Figure 5. This plant has five boat production lines, with each tiltable hull mold located over an air slot located in the floor. The air slots are 35 × 1 ft with a 1-ft divider and lead to exhaust air fans located outside the east wall of the building, as shown in Figure 6. Decks are molded in front of the hulls, and the boat assembly begins when the hull is removed from the mold and is fitted with the hull bracings and deck. The building is also fitted with eight ceiling fans that exhaust (nominally) 12,000 CFM each. All of the ceiling fans operate in the summer for comfort ventilation and three operate in cold weather. In cold weather the makeup or supply air is provided by three large blower/heaters located at the east end of the building and by four smaller blower/heaters located toward the west end of the building. The three larger blowers direct air toward the boat hulls to help purge styrene vapor into the air slots. In hot weather, makeup air is supplied by opening the large doors on the north and south sides of the building.

A velocity traverse was made on air slot 1 to determine the exhaust flow. Three traverse readings were made at 1 ft intervals for a total of 105 data points. The

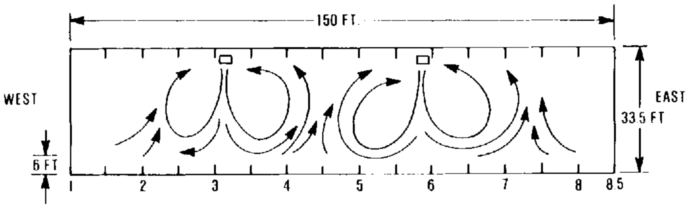


Fig. 4. Plant A—apparent air circulation pattern.

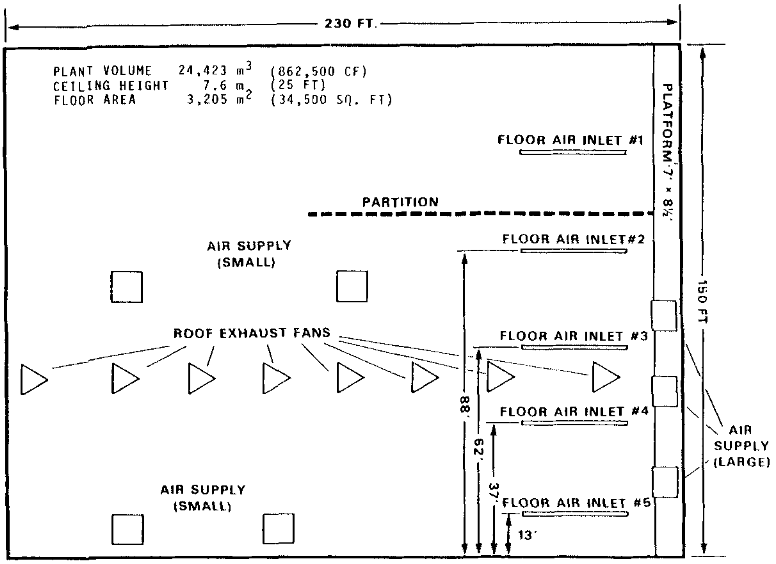


Fig. 5. Plant B—applications module.

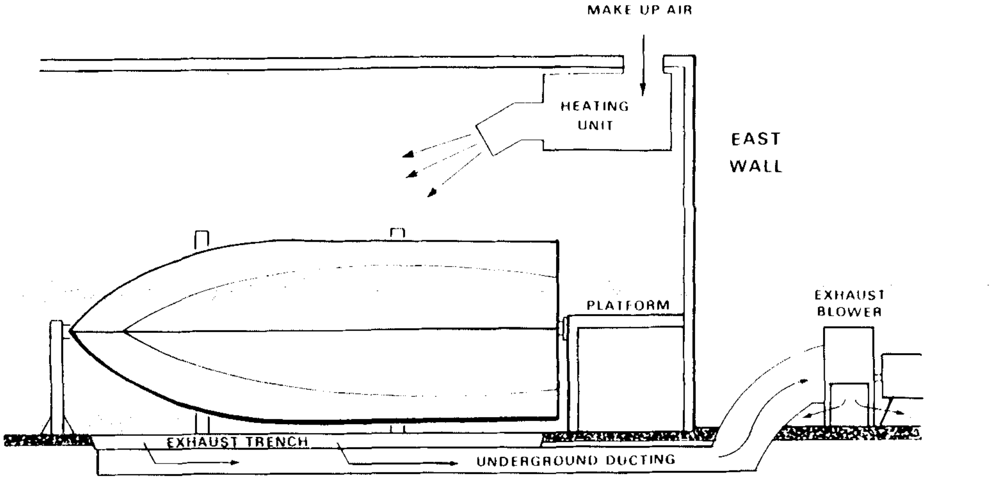


Fig. 6. Plant B—floor ventilation system.

average air velocity was 510 feet per minute (FPM), and the total flow rate was calculated to be 17,780 CFM. The five air slots will give a combined air flow of about 88,900 CFM. This plus the contribution of eight ceiling fans will produce a combined exhaust flow of about 184,900 CFM for hot weather operation. In cold weather, this will be reduced to about 124,900 CFM. These flows will result in 13 air changes per hour in hot weather and 9 air changes per hour for cold weather. Note that this is higher than that for plant A (5 air changes per hour), which was designed as a dilution system.

The air-flow patterns around the 41-and 46-ft hull molds were checked by measuring the air velocities at points located at 2-ft intervals along the hull and located

1- and 2-ft levels above the floor. The flow profiles in Figures 7 and 8 were averaged from velocity readings taken at the middle of the boat, where the hull shape did not change significantly. The back of the two hull molds were draped with 3-mil plastic sheeting to test whether such draping could improve the hull mold ventilation. The results were statistically suggestive that the draping lowered the worker exposure but were not proven to be statistically significant.

Plant C

Plant C is located in High Point, North Carolina. This plant had the most difficult control problem because the boat molds are immobile, sit in 9-ft-deep pits, and are difficult to ventilate. The plant layout is shown in Figure 9. A new retrofit ventilation system was designed in 1981, which provides push air into the bow of the hull mold and exhaust air intake hoods located at the stern of the hull mold. This is shown in Figure 10. The push air was provided by two 20-in-diameter propeller fans. The air flow provided by these fans was estimated with a 13-point traverse across the fan shroud. The fans were pushing about 4,250 CFM each.

The exhaust air from the stern hoods is removed through subfloor ductwork altered to connect to the existing above-floor system. Figure 11 shows the modified system. The alteration has several bends and cross-sectional transitions that added considerably to the system resistance. A velocity traverse was performed in the subfloor duct. The results of this traverse indicate a flow of about 6,500 CFM, which is well below the 15,000 CFM rated capacity of the exhaust fan situated on the roof. The static pressure near the fan was measured at 1.12 in of water.

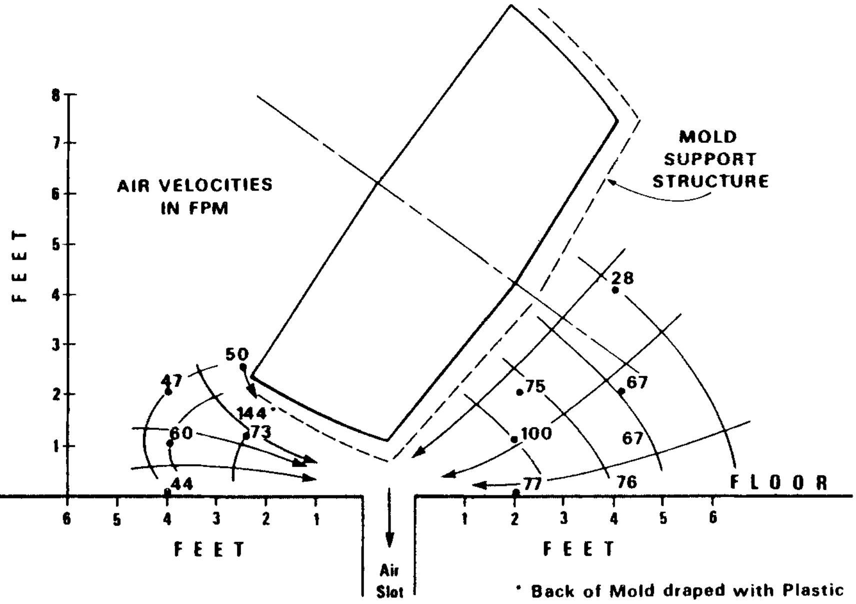
Subsequent to reviewing the survey report, plant C management stated that the exhaust hood fan had been speeded up, turning vanes had been added to 90° ells, and an obstruction was removed from the ductwork. These changes reportedly increased the total flow to 15,000 CFM at 1.0″ static pressure (SP), which should make a significant decrease in the air spill-over from the hood into the work area.

PERSONAL SAMPLING AND RESULTS

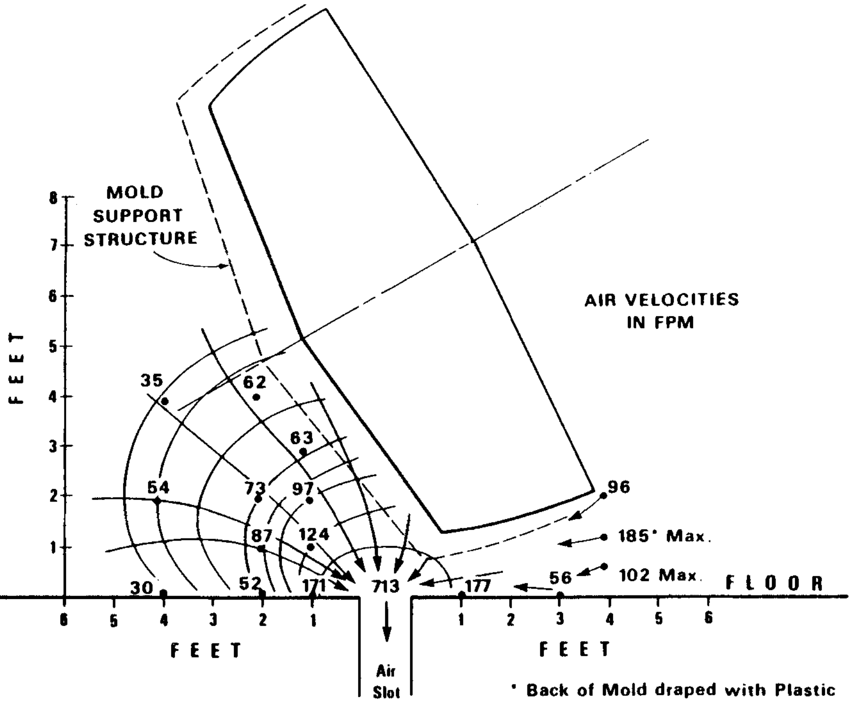
The results of the personal sampling of lamination workers for the plants is shown in Table I. A variety of tasks were performed by the laminators in plant A. It is interesting to note in this plant that the deck lamination produced higher exposure levels than the hull lamination. There was nothing of note in the manner of performing those two tasks to indicate the reason for this. Note also the average exposure of laminators at plant A is considerably higher than for workers in plants B and C.

Statistical Analysis for Special Interactions

The study for plants B and C included the test for differences in some factors that involve worker exposure to styrene. For example, in plant B, it was desired to test the difference in exposure of the lamination workers when a hull is tilted to the right or to the left and the effect on worker exposure when the back of a hull is draped with plastic film to encourage hull ventilation. The worker-exposure data obtained from the personal samplers has a skewed distribution because the data has a low mean value and a large standard deviation or wide range. Since statistical inference must be made on a normal distribution, the sampling data is normalized by performing a log transform of the data. The statistical analysis of variance was carried out on the SAS



7



8

Fig. 7. Plant B—air flow pattern around 41 foot hull.
Fig. 8. Plant B—air flow pattern around 46 foot hull.

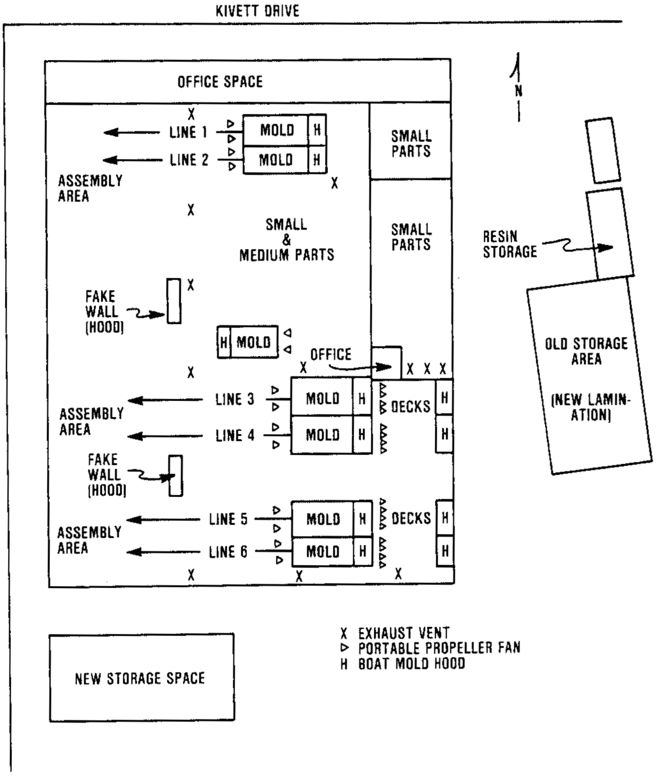


Fig. 9. Plant C—lamination building layout, High Point, North Carolina.

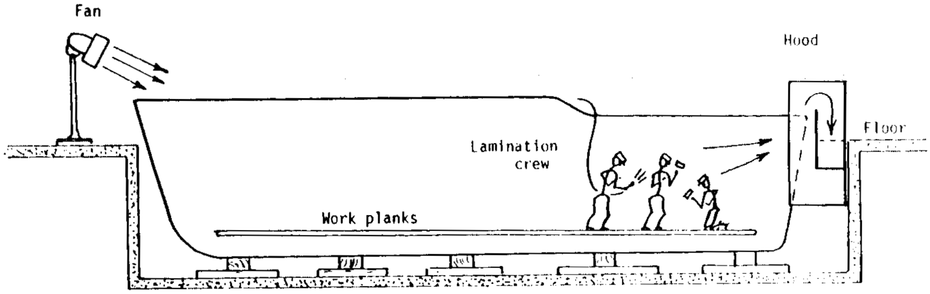


Fig. 10. Work arrangement for 46 foot hull mold.

Multivariate Analysis Computer program by Mr. Stanley Shulman, Statistician, Division of Physical Sciences and Engineering, National Institute for Occupational Safety and Health.

In plant B, the only factor having statistical significance was the right and left tilt position of the 46-ft hull mold. This was found to be significant at the 90% confidence level. This is apparently because, in the right-tilt position, the hull work surface faces a partition that inhibits ventilation of the hull.

In plant C, the worker exposure was higher when the workers were laminating toward the stern on the port side as opposed to laminating toward the bow on the

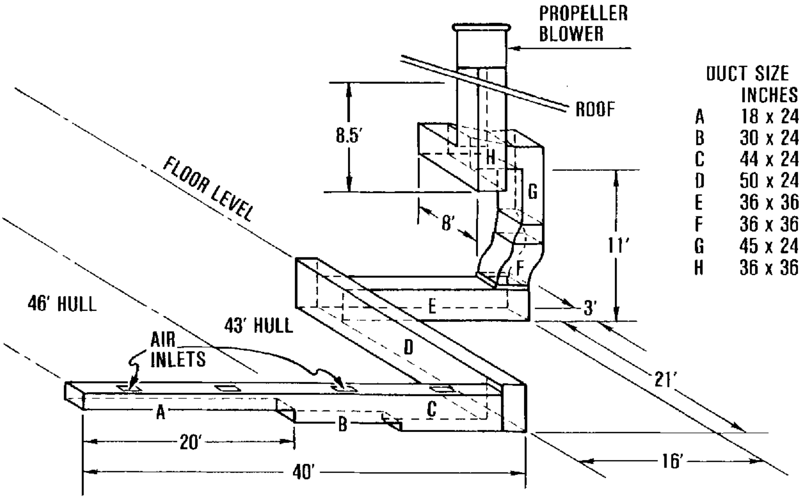


Fig. 11. Plant C—hull mold ventilation system.

starboard side. This was significant at the 96.5% confidence level. The reason for this is apparently that on the port side, the evaporating styrene from the curing resin is blown past the workers. The difference in exposure is 37% for working on one side as compared to working on the other. This difference was anticipated by plant C management and was confirmed by our data analysis.

Area Sampling

Except for duration (240 minutes) and sampling rate (10 ml/min), sampling and analyses were identical with the personal samples. Area samples were collected at various locations in each plant to determine the average background level of styrene and to indicate styrene straying from lamination operations. The sample data for different plants cannot be meaningfully compared because different criteria were used in each plant to locate the sample sites. The eight area sample sites for plant A were located in the lamination area to test the pervasiveness of styrene vapor. In plant B, sample sites were selected in the west end of the plant to determine how much styrene found its way to that end of the building. The area sample sites in plant C were selected to indicate the concentration of styrene in air leaving the hull mold. The results of area sampling are shown in Table II.

DISCUSSION OF RESULTS

The control strategies for large boat-manufacturing plants include dilution ventilation, local exhaust ventilation, and push-pull ventilation. The plants surveyed in this study each represent one of the above approaches to control.

Plant A

The area samples in Plant A have a small standard deviation of 7.2, which indicates a high degree of mixing in the building, a result of the high-velocity air from the overhead inlet diffusers. This system achieves the design objective by air dilution to maintain the mean styrene concentration below the PEL. It has the

TABLE I. Worker Exposure to Styrene in the Plants

Worker	Day	Styrene (ppm 8-hr TWA)	Task description	Average exposure styrene (ppm)
Plant A				44
A	1	26	Varied	
B	1	24	Stringers in hull	
C	1	21	Stringers in hull	
A	2	37	Varied	
B	2	45	Hull lamination	
C	2	34	Deck lamination	
D	3	65	Deck lamination	
E	3	66	Deck lamination	
F	3	72	Deck lamination	
G	3	51	Small parts	
Plant B				21
A	1	17	Hull lamination	
B	1	17	Hull lamination	
C	1	15	Hull lamination	
D	1	16	Hull lamination	
A	2	26	Hull lamination	
B	2	23	Hull lamination	
C	2	28	Hull lamination	
D	2	29	Hull lamination	
A	3	—	Did not work	
B	3	13	Hull lamination	
C	3	31	Hull lamination	
D	3	19	Hull lamination	
Plant C				28
A	1	34	Hull lamination	
B	1	30	Hull lamination	
C	1	33	Hull lamination	
A	2	26	Hull lamination	
B	2	25	Hull lamination	
C	2	31	Hull lamination	
A	3	24	Hull lamination	
B	3	33	Hull lamination	
C	3	16	Hull lamination	

TABLE II. Results of Area Sampling for Styrene

Plant	Mean value (ppm styrene)	Standard deviation	Range of values (ppm styrene)	No. of samples
A	20	7.2	9–31	14
B	2	0.86	0.5–3	10
C	7[a]	3.45	3–12	11[b]

[a] Samples taken inside the hood are not included.

[b] 42 ppm, morning sample, day 3, not included because push fans were off.

disadvantage of exposing all workers in the building to a moderate concentration of styrene.

Plant A is in an area having a moderate to mild climate. Dilution ventilation is the most common approach to styrene control in boat plants located in mild climates but has the disadvantage of exposing all workers to a low level of styrene. Plant A was studied in December. In warmer weather, when convective or ambient ventilation could augment the system the plant styrene level would probably be lower. When dilution ventilation is used in colder climates, the heating costs rise and economic pressure exists to invest money in more efficient systems.

Plant B

Plant B has a higher volume flow than plant A, which changes the air about nine times per hour, but it does not have the turbulent mixing feature of plant A. Plant B features local ventilation exhaust air slots under the hull molds, which remove styrene vapors. The high volume of air exhausted by the five air slots pulls air toward the east end of the building and keeps the background levels low in other areas. In the summer, when the heated air supply is shut off, this air drift averages 23 FPM. Two sites sampled were in the small-parts production area. The results were very low, which indicate that very little styrene back-mixes into the west end of the building. In the winter when the heated air supply located above the boat hull molds is turned on, the air movement from the west to the east end of the building is reduced, and the styrene background level in the west side of the building would be expected to rise somewhat. The only data on this is the two area samples obtained at plant B during a preliminary survey in February 1982. These values are 1.8 ppm styrene near the resin transfer molding (RTM) area and 13.4 ppm near the hull lamination area. Comparable values in the in-depth survey (summer) were 1.2 ppm styrene for the RTM area and 2.4 ppm near the deck lamination area. The limited data for this comparison make it inconclusive, but it appears that the closed building and reduced air changes result in higher plant styrene levels. Acetone concentrations, on the other hand, rose slightly in the summer, probably as a result of the higher temperature in the plant.

The data suggest that this plant may have difficulty meeting the NIOSH recommendation for a styrene TWA of 50 ppm. It was recommended that some provision be made to move air through the hull of the 46-ft mold when it is facing the partition or to remove the partition. Although the data suggest that the draping of the back of the hull molds lowers exposure, it is questionable whether the time required would be worth the cost. The venting of the hull is thought to be more productive in lowering exposure.

Plant C

The push-pull ventilation system of plant C represents the most sophisticated approach to hull mold ventilation; it is a first attempt at such a design in boat plants and could possibly be improved in future designs. In this plant, the molds do not tilt, so styrene-laden air tends to lay in the mold. This push-pull system was designed to push room air into the hull then to be exhausted at the other end into a hood bracketing the stern of the mold. These tests were performed in the late summer, when bay doors were open, so no data are available for comparison to a closed building mode. The data indicated an acceptable level of personal exposure to the lamination crew but the exhaust hood flow was about 50% of the design specification. This resulted in much spill-over of air from the hull into the room.

The sample sites in plant C were confined to the area of the hull mold because there was no other lamination activity on the first two days of the survey. The area samples were obtained at the bow near the push fans and at the stern above the exhaust hood. Samples so located will indicate if styrene is being pushed from the hull mold by the push fans. The area samples have low values except for one morning sample of 42 ppm on the third day, obtained at the bow near the push fans. It has been omitted from the calculation of the mean. Those fans had been turned off for a period of time while lamination was being carried out in the bow. This is apparently necessary to prevent the draft from the push fans from dispersing the resin spray. The mean value of 7 ppm styrene indicates that most of the styrene is contained in the hull mold and drawn into the exhaust hood. The personal sampling data obtained for the three workers indicates good control in terms of the average exposure. However, the peak values of 80, 62, and 97 ppm styrene for workers A, B, and C, respectively, indicate that there are some problems, even though these values are below the current PEL of 100 ppm styrene.

The exhaust duct system leading from the hood is not well designed because it is retrofitted to the previous ductwork. It was recommended that the ductwork be straightened and that the fan be replaced with another type that works better against a high resistance. It was also suggested that the workers be encouraged to work in an upstream direction from the resin spray to avoid exposure to the styrene evaporating from the curing styrene surface.

CONCLUSIONS

This study has evaluated three ventilation systems used in large-boat manufacture that successfully control lamination worker exposure to styrene below the existing TWA PEL of 100 ppm. It also appears certain that these plants will be very close to meeting the proposed NIOSH 50 ppm ten-hour workshift, 40-hour workweek TWA for styrene and can probably do so with some modification of their existing facilities.

Each of these ventilation systems may be retrofitted in an existing plant. Systems similar to those in plants A and C would need roof supports or trussing adequate to carry the weight of blowers and ducting. Systems similar to those in plants B and C would require trenched ducting. Location of the hull molds near the outside walls can allow ducting to supply outdoor fans on grade and eliminate roof blowers.

REFERENCES

Bourne LB, Milner FJM (1963): Polyester resin hazards. Br J Indust Med 20:100–109.

Brooks S (1979): "Investigation of Workers Exposed to Styrene in the Reinforced Plastic Industry." Kettering Laboratory, University of Cincinnati. (This report was performed for the Society of Plastics Industries.)

Crandall MS (1982): "Extent of Exposure to Styrene in the Reinforced Plastic Boat Making Industry." DHHS (NIOSH) 82-110 March, 1982.

Hopkins B (1981): "Behavioral Procedures for Reducing Work Exposures to Carcinogens." University of Kansas, Final Report, NIOSH Contract 210-77-0040.

International Labour Office (1972): "Encyclopedia of Occupational Health and Safety, Vol II." New York: McGraw-Hill Book Company.

"Industrial Ventilation, A Manual of Recommended Practice." 12th Ed. ACGIH, section 2, page 1, 1972.

Peterson JE (1973): Principles for controlling the occupational environment. In: "The Industrial Environment—Its Evaluation and Control." USDHEW, PHS, CDC, NIOSH, 1973.