

# Occupational Exposures to Styrene Vapor in a Manufacturing Plant for Fiber-Reinforced Composite Wind Turbine Blades

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**Objectives:** A utility-scale wind turbine blade manufacturing plant requested assistance from the National Institute for Occupational Safety and Health (NIOSH) in controlling worker exposures to styrene at a plant that produced 37 and 42 m long fiber-reinforced wind turbine blades. The plant requested NIOSH assistance because previous air sampling conducted by the company indicated concerns about peak styrene concentrations when workers entered the confined space inside of the wind turbine blade. NIOSH researchers conducted two site visits and collected personal breathing zone and area air samples while workers performed the wind turbine blade manufacturing tasks of vacuum-assisted resin transfer molding (VARTM), gelcoating, glue wiping, and installing the safety platform.

**Methods:** All samples were collected during the course of normal employee work activities and analyzed for styrene using NIOSH Method 1501. All sampling was task based since full-shift sampling from a prior Occupational Safety and Health Administration (OSHA) compliance inspection did not show any exposures to styrene above the OSHA permissible exposure limit. During the initial NIOSH site visit, 67 personal breathing zone and 18 area air samples were collected while workers performed tasks of VARTM, gelcoating, glue wipe, and installation of a safety platform. After the initial site visit, the company made changes to the glue wipe task that eliminated the need for workers to enter the confined space inside of the wind turbine blade. During the follow-up site visit, 12 personal breathing zone and 8 area air samples were collected from workers performing the modified glue wipe task.

**Results:** During the initial site visit, the geometric means of the personal breathing zone styrene air samples were 1.8 p.p.m. ( $n = 21$ ) for workers performing the VARTM task, 68 p.p.m. ( $n = 5$ ) for workers installing a safety platform, and 340 p.p.m. ( $n = 14$ ) for workers performing the glue wipe task, where  $n$  is the number of workers sampled for a given mean result. Gelcoating workers included job categories of millers, gelcoat machine operators, and gelcoaters. Geometric mean personal breathing zone styrene air samples were 150 p.p.m. ( $n = 6$ ) for millers, 87 p.p.m. ( $n = 2$ ) for the gelcoat machine operators, and 66 p.p.m. ( $n = 19$ ) for gelcoaters. The geometric mean of the personal breathing zone styrene air samples from the glue wipe task measured during the follow-up site visit was 31 p.p.m. ( $n = 12$ ).

**Conclusions:** The closed molding VARTM process was very effective at controlling worker exposures to styrene. Personal breathing zone styrene air samples were reduced by an order of magnitude after changes were made to the glue wipe task. The company used chemical substitution to eliminate styrene exposure during the installation of the safety platform. Recommendations were provided to reduce styrene concentrations during gelcoating.

*Keywords:* alternative energy; styrene; task-based sampling; wind blade; wind turbine

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## INTRODUCTION

A utility-scale wind turbine blade manufacturing plant in the USA requested assistance from the National Institute for Occupational Safety and Health (NIOSH) in controlling worker exposures to styrene at a plant that produces 37 and 42 m long fiber-reinforced wind turbine blades. Prior to the first NIOSH evaluation at the wind turbine blade manufacturing plant, two separate evaluations of styrene exposures had already been conducted at the same plant by other organizations. One evaluation was an Occupational Safety and Health Administration (OSHA) compliance inspection and the other evaluation was performed internally by site personnel at the wind turbine blade manufacturing plant. The OSHA compliance inspection did not find any exposures to styrene above the OSHA permissible exposure limit (PEL) of 100 p.p.m. as an 8-h time-weighted average (TWA). Full-shift sampling conducted internally by site personnel at the wind turbine blade manufacturing plant also did not find any exposures to styrene above the OSHA PEL. However, air monitoring using MultRAE Plus direct reading instrumentation performed by site personnel during a separate evaluation indicated that peak styrene concentrations were above short-term exposure limits (STELs) during several tasks. Following the OSHA and company evaluations, NIOSH researchers conducted a walk-through evaluation and observed several tasks with high potential for short-term styrene exposure while also noting that the same workers also spent a considerable amount of time working with dry materials with minimal exposure to styrene. Based on this information, NIOSH researchers decided to conduct task-based sampling and look for opportunities to recommend engineering controls to reduce concentrations of styrene in the air for four tasks.

During the initial in-depth site visit, NIOSH researchers collected 67 personal breathing zone and 18 area air samples while workers performed the wind turbine blade manufacturing tasks of vacuum-assisted resin transfer molding (VARTM), gelcoating, glue wiping, and installing the safety platform. After the initial site visit, the company made changes to the design of the molds that eliminated the need for workers to enter the wind turbine blade to wipe off excess glue. NIOSH researchers conducted a follow-up site visit 3 months later and collected 12 personal breathing zone and 8 area air samples from workers performing the modified glue wipe task.

Styrene is a fugitive emission when it evaporates from resins, gelcoats, solvents, and surface coatings

commonly used in the manufacturing process for fiber-reinforced plastics (FRP) and can present an inhalation hazard to workers handling these materials. The polyester resins used at the studied wind turbine blade manufacturing plant contained between 36 and 42% styrene.

The following exposure criteria include both full-shift and short-term criteria even though all sampling during the present evaluation was task based. The NIOSH recommended exposure limit for styrene is 50 p.p.m. as a 10-h TWA, with a 15-min STEL of 100 p.p.m. (NIOSH, 2004). These recommendations are based upon reported central nervous system effects, eye irritation, and respiratory irritation effects. The NIOSH immediately dangerous to life or health (IDLH) value for styrene of 700 p.p.m. is based on acute inhalation toxicity in humans. The OSHA PEL for styrene is 100 p.p.m. as a TWA. The OSHA ceiling limit for styrene is 200 p.p.m. with a 600 p.p.m. 5-min maximum peak in any 3 h. The American Conference of Governmental Industrial Hygienists (ACGIH®) revised its threshold limit value (TLV®) in 1997 and recommends styrene be controlled to 20 p.p.m. TWA with a 40 p.p.m. STEL (ACGIH®, 2009). The TLV® is based on a number of health effects of low styrene exposure such as ototoxicity, central and peripheral neurologic, optic, and irritant actions in humans (ACGIH®, 2001). The Swedish Work Environment Authority (SWEA) has an occupational exposure level limit value for styrene of 20 p.p.m. and a short-term value of 50 p.p.m. (SWEA, 2005).

In February 1996, the Styrene Information and Research Center (SIRC) and three other styrene industry trade associations—American Composites Manufacturers Association, National Marine Manufacturers Association, and the International Cast Polymer Association—entered into an arrangement with OSHA to voluntarily adhere to the 50-p.p.m. level set by the 1989 update of the OSHA PEL that was later vacated by court order (OSHA, 1989). OSHA announced the voluntary agreement in a 1996 newsletter (OSHA, 1996). The SIRC encouraged its members to continue to comply with the 50-p.p.m. standard as an appropriate exposure level for styrene, regardless of its regulatory status (SIRC, 1996).

### *Facility description*

At the time of the evaluation, the facility was operating multiple 10- and 12-h overlapping shifts to manufacture wind turbine blades 24 h day<sup>-1</sup>, 365 days per year. Workers performing the glue wipe task were working 12-h shifts and workers

performing gelcoating, VARTM, and installation of the safety platform worked 10-h shifts. Approximately 600 of the plant's 940 employees worked in areas where there was potential for exposure to styrene vapor. At the time of the evaluation, approximately eight wind turbine blades were produced per day using 16 mold tools with a cycle time near 24 h. The manufacturing operations took place in two buildings on the ~50 000 m<sup>2</sup> (12.4 acre) property. Each building contained ~9000 m<sup>2</sup> (96 900 ft<sup>2</sup>) of manufacturing floor space. The VARTM, gelcoating, and glue wiping tasks were performed in Building 1 and installation of the safety platform was performed in Building 2.

The supply air flow rates from the four air handling units in each of the buildings were provided by facility representatives and were ~87 m<sup>3</sup> s<sup>-1</sup> in Building 1 and ~94 m<sup>3</sup> s<sup>-1</sup> in Building 2. The plant used direct reading MultiRAE Plus monitors near each task to measure for potential buildup of styrene vapor. The MultiRAE Plus monitors were calibrated to styrene and generally located between the process and the building general exhaust ventilation.

The dilution ventilation supply system for the manufacturing space in both buildings consisted of fabric sock air distribution systems located near the ceiling. Exhaust locations for each dilution ventilation system were generally located along the walls in both buildings. Additional exhaust vents were located in the floor in Building 1. The exhaust vents in the floor were originally located to be at the ends of the wind turbine blades; however, as product demands required longer wind turbine blades, the ends of the blades extend beyond the location of the vents. According to plant management, the supply air flow rate for each system was greater than that of the exhaust air to keep the plant under positive pressure. The supply air system delivered 100% outside air, heated or cooled, as needed, so there was no recirculation.

### *Process description*

FRP wind turbine blades at this plant were manufactured using a closed molding technology referred to as VARTM. VARTM is a form of resin transfer molding that uses vacuum to offset some of the injection pressure. Compared to open molding, closed molding technology should significantly reduce environmental emissions and worker exposure to styrene. However, the gelcoating portion of most closed molding operations is still performed in an open mold and represents a potential source of exposure (Hammond *et al.*, 2007).

FRP wind turbine blades were manufactured at this plant starting from the outside of the blade to the

center. Molds were prepared with the application of a release agent that allowed the part to separate from the mold when it was finished. After the release agent was applied, the part was ready for gelcoating. The gelcoat was a pigmented polyester resin that contained styrene. The gelcoat was sprayed on the mold where it hardened to produce a smooth outer surface. The sample duration for the gelcoating task was ~45 min and the equipment consisted of a hand spray tool with hoses connected to a gelcoating machine on wheels that was pushed along manually. Each half mold tool required three workers for the spray application of gelcoat. The gelcoater walked backwards along the concave side of the mold while spraying the gelcoat. Two other workers walked along the ground next to the sprayer to operate the gelcoat machine. Workers performing the gelcoating tasks at the evaluated plant wore powered air purifying respirators with organic vapor cartridges. After gelcoating, the workers took a break and waited for the concentration of styrene in the air to drop <20 p.p.m. as measured by direct reading monitors. After the concentrations dropped <20 p.p.m., the same workers that applied the gelcoat removed their respirators and began preparing core materials next to the mold. After gelcoating, the lamination task began with the placement of the glass fibers and core material. The mold was then covered and sealed with a vacuum film. Vacuum lines were attached to the mold to assist the flow of resin to saturate and bond the fiber and core material. Workers performing the VARTM task monitored various flow, temperature, and other parameters and did not come in contact with the resin. The vacuum film over the mold also prevented the release of styrene vapor. The sample duration for the VARTM task was ~2 h. This closed molding VARTM method was used instead of traditional open molding methods of manufacturing fiberglass parts. The VARTM process is shown in Fig. 1.

Using the VARTM method, the wind turbine blades were laminated in two shells before the sandwich web was installed. The sandwich web ran almost the entire length of the wind turbine blade and provided structural reinforcement. Glue containing 34% styrene by weight was applied to the edges of the shell and web, and one shell was lifted and fixed to the other half to assemble the wind turbine blade. After the two shells were pressed together, workers entered the confined space inside of the wind turbine blade to wipe any excess glue that was pressed out. Workers crawled around inside of the three sections of the wind turbine blade and wiped excess glue using a plastic tool and placed the glue into a bucket. The excess glue was located

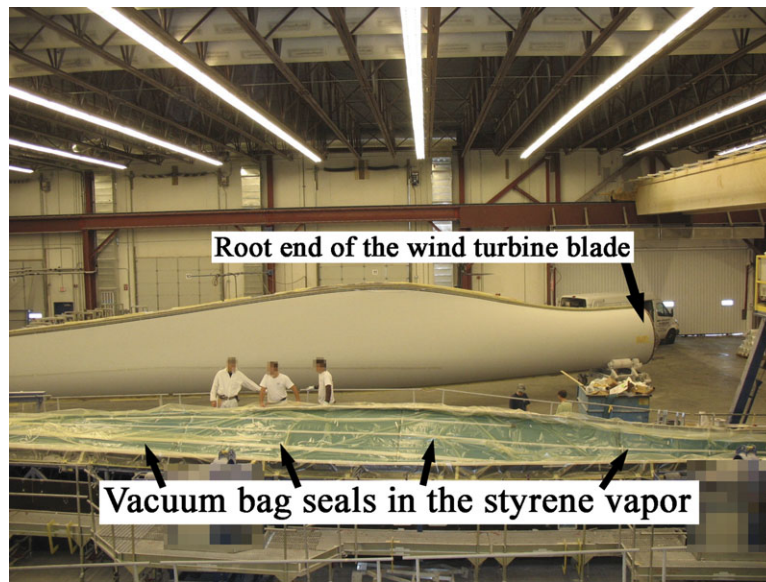


Fig. 1. The vacuum film over the mold for the VARTM process.

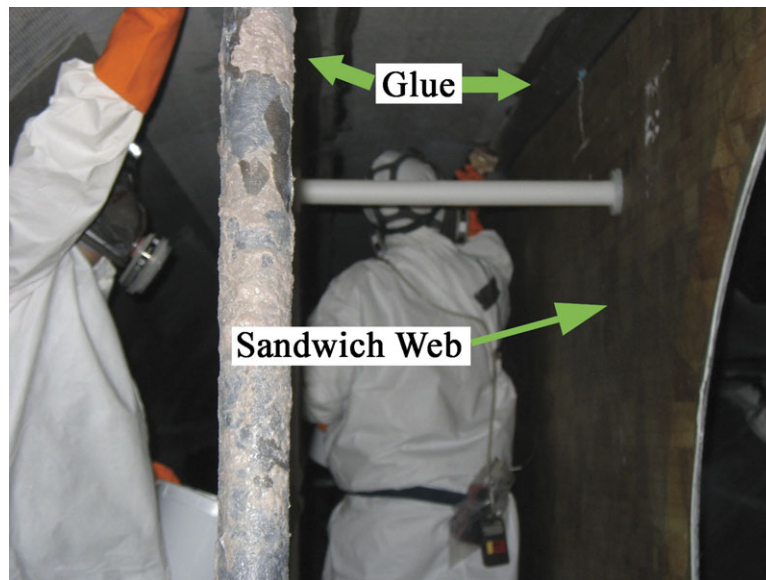
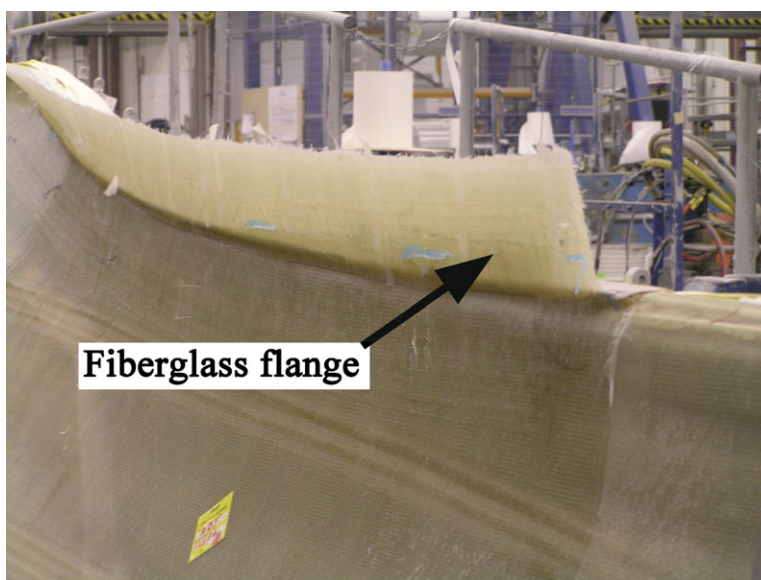


Fig. 2. Workers wiping glue inside of the wind turbine blade.

mostly in areas where the two half shells were placed together and along the edges next to the surface where the sandwich web contacted the shell. The workers were wearing sampling equipment [and respirators] to measure personal breathing zone concentrations of styrene. The glue wipe task took 15 min but the sampling duration was ~40 min to allow time for the workers to complete tasks outside of the wind turbine blade before and after wiping glue. Figure 2 shows workers inside of the wind turbine

blade wiping the glue with a plastic tool and putting the glue into a bucket.

After the initial NIOSH site visit, the company made changes to the mold design that eliminated the need for workers to enter the wind turbine blade during the glue wipe task. Design changes tightened dimensional tolerances of the mold so that less glue was pressed out when the two half wind turbine blades were joined together. Another change included a fiberglass flange on the inside of the wind



**Fig. 3.** Fiberglass flange to catch glue after the two half wind turbine blades are joined together.



**Fig. 4.** Safety Platform glassed in as a disk shaped fiberglass part near the root of the wind turbine blade.

turbine blade to catch glue that was pressed out and hold it against the surface where the two parts joined. The fiberglass flange is shown in Fig. 3. These changes eliminated the need for workers to enter the wind turbine blade during the glue wipe task. Instead, workers stood outside of the wind turbine blade and used a long handled tool to wipe the excess glue near the open end of the blade.

After the two shells or half wind turbine blades were joined together, the wind turbine blade was removed from the mold for cutting, grinding, and sanding of

the outside edge to provide a smooth finish. After all grinding and sanding tasks were completed, a safety platform was installed near the root of the wind turbine blade. The safety platform was installed using styrene resin and glassed in by hand using plastic tools and a bucket of resin. The platform was installed as two half disks with some workers applying resin from the inside of the blade while other workers applied resin from the outside. The sample duration for the installation of the safety platform was ~1 h. An installed safety platform is shown in Fig. 4.

## METHODS

### *Air sampling for styrene*

All personal breathing zone and area air styrene samples were collected for the duration of each individual task where styrene was used. Since workers performed some tasks with styrene and some without styrene during their shift, the decision was made to conduct task-based personal breathing zone and area sampling instead of full-shift sampling. Also, air sampling data from a prior OSHA compliance inspection did not find any exposures above the OSHA PEL of 100 p.p.m. for styrene. Additional air sampling data collected by the company raised concerns about peak exposures during several tasks.

Personal breathing zone and general area air samples for styrene were collected and analyzed in accordance with NIOSH Method 1501 (NIOSH, 1994). Samples were collected on SKC sorbent tubes (Model number 226-01, Anasorb CSC, Coconut Charcoal, Lot #2000). After breaking the sealed ends, each tube was connected to a low flow SKC Pocket Pump (SKC Inc.) set at a flow rate depending on the sample time of the task. The nominal flow rate was set to 100 ml min<sup>-1</sup> during sampling of tasks for the gelcoaters, millers, gelcoat machine operators, and workers performing the glue wiping tasks. The nominal flow rate was set to 60 ml min<sup>-1</sup> for the tasks of VARTM and the installation of the safety platform. The pumps' actual flow rates were calibrated before and after sampling using a DryCal® primary calibration standard (BIOS, Butler, NJ, USA). For personal breathing zone air samples, the air inlet of the sampling apparatus was secured in each worker's breathing zone with a lapel clip, and the battery-powered pump clipped to the worker's belt. In addition, field blank samples were collected to ensure that the sample media was not contaminated and to account for any variance in sample preparation. The analyses of the charcoal tube samples for styrene were performed by Bureau Veritas North America, Inc., in Novi, Michigan. The limit of detection and limit of quantification for styrene for this sample set was 8 µg per sample and 180 µg per sample, respectively.

General area air samples were collected using the same type of sampling apparatus and flow rates as used for the personal air sampling. These samples were placed in stationary locations near each evaluated task.

Once the sample results were received from the analytical laboratory, the styrene breathing zone concentrations and general area concentrations were calculated using equation (1).

$$C = \frac{m}{V \times 4.26}, \quad (1)$$

Where  $C$  = styrene concentration, parts per million;  $m$  = mass of styrene per sample, micrograms;  $V$  = volume of air sample, liter; and 4.26 = conversion constant micrograms per liter to parts per million (NIOSH, 1994)

## RESULTS

The distribution of all samples was checked for normality using the normal plot, frequency histogram, and Shapiro–Wilk's test and the results indicated that the data were log-normally distributed. Subsequently, all data were log transformed for statistical analysis. Geometric mean, geometric standard deviation, 95% confidence limits, and sample size for comparison of personal breathing zone and general area air styrene samples are included in Table 1 for the initial and follow-up site visits.

The personal breathing zone samples for styrene from workers performing the glue wipe task inside the wind turbine blade were higher than any other evaluated task with a geometric mean concentration of 340 p.p.m. The geometric mean air styrene concentration from area samples collected outside of the wind turbine blade during the glue wipe task was 18 p.p.m. The geometric mean of personal breathing zone task-based air sampling from the glue wipe task collected during the follow-up evaluation after the design change was 31 p.p.m. This is approximately an order of magnitude lower than the task-based sampling results from the glue wipe task collected during the initial evaluation. This reduction in personal breathing zone styrene concentrations was a result of the design change that eliminated the need for workers to enter the space inside of the wind turbine blade during the glue wipe task. The workers that were sampled for the follow-up survey included the same workers that would have otherwise been working inside of the wind turbine blade. Instead, these workers were performing some glue wiping while standing outside of the wind turbine blade and reaching inside of the blade with a long handled tool.

The lowest personal breathing zone sampling results for styrene were measured among the 21 workers performing the VARTM task. All personal breathing zone and general area styrene air samples measured during the VARTM task were <5 p.p.m. for the ~2-h task time sampled.

Table 1. Personal and area sample statistical results for styrene vapor

Job description	Sample type	Geometric mean (p.p.m.)	Geometric standard deviation	Geometric upper 95% confidence limit	Geometric lower 95% confidence limit	<i>n</i>
Infuser (VARTM)	Personal	1.8	1.5	2.2	1.5	21
Infusion (VARTM)	Area	1.5	1.1	1.9	1.2	3
Safety platform	Personal	68	4.3	410	11	5
Safety platform	Area	4.2	1.5	11	1.6	3
Gelcoat machine	Personal	87	2.0	<sup>a</sup>	<sup>a</sup>	2
Gelcoat	Personal	66	2.6	100	42	19
Miller	Personal	150	1.4	220	100	6
Gelcoat	Area	47	2.4	91	24	9
Glue wipe (first site visit)	Personal	340	2.0	510	230	14
Glue wipe (second site visit)	Personal	31	3.2	65	14	12
Glue wipe area outside of the blade (first site visit)	Area	18	1.3	37	8.6	3
Glue wipe area outside of the blade (second site visit)	Area	11	1.6	17	9.1	8

<sup>a</sup>No meaningful confidence limit due to small sample size and high variation

The geometric mean of the personal breathing zone task-based air sampling for styrene from the gelcoaters, gelcoat machine operators, and millers were 66, 87, and 150 p.p.m., respectively, for the ~45-min task time sampled. The highest two individual personal breathing zone styrene air samples collected from gelcoating workers were 250 p.p.m. for a 42-min sampling time and 230 p.p.m. for a 45-min sampling time. Actual worker exposures were likely lower than measured concentrations since at the time of the survey, all gelcoaters, millers, and gelcoat machine operators wore either half-mask or powered air purifying respirators with organic vapor cartridges that were changed out daily. Under the 'NIOSH Respirator Decision Logic', any air purifying half-mask respirator equipped with appropriate gas/vapor cartridges has an assigned protection factor of 10 (NIOSH, 1987). Any powered air purifying respirator with a loose-fitting hood or helmet equipped with appropriate gas/vapor cartridges has an assigned protection factor of 25.

Five personal breathing zone samples for styrene were measured from workers installing the safety platform. Three of the five air samples were measured from workers who were standing inside of the wind turbine blade while applying resin to the safety platform and two from workers outside the wind turbine blade while applying resin to the other side of the safety platform. For the 1-h task time

sampled, the three personal breathing zone samples measured from workers standing inside the wind turbine blade from the safety platform were 92, 156, and 316 p.p.m., while personal air styrene samples measured from workers who were outside the wind turbine blade from the safety platform were 46 and 7 p.p.m. Actual exposures were much lower since workers wore full-face piece respirators with organic vapor cartridges that were changed out daily. Any air purifying full-face piece respirator equipped with appropriate gas/vapor cartridges has an assigned protection factor of 50.

The personal breathing zone results were highly variable for air samples collected from workers performing tasks near the opening to the wind turbine blade for the glue wipe and safety platform tasks. The gradient of styrene concentrations changed more than an order of magnitude in the short distance between the low concentrations outside of the wind turbine blade and the much higher concentrations inside of the wind turbine blade. Therefore, it is expected that workers performing tasks at locations within this gradient might have highly variable personal breathing zone results. It is possible that the distance between the breathing zone and resin, proximity to the opening of the wind turbine blade, or other factors contributed to the variability. There is some evidence in the public literature to suggest that high variability in styrene

air sampling data can be expected. A study of styrene exposures at a boat manufacturing plant found significant differences in styrene exposures when four monitors were placed at different locations around the breathing zone of each worker (Malek et al., 1999).

## DISCUSSION

The task-based sampling performed in this study provided information on which tasks could benefit most from introducing controls. But even sampling the glue wipe task presented some difficulties in attempting to measure concentrations only during the task time. The glue wipe task inside of the wind turbine blade took 15 min. However, it was not possible to start and stop samples immediately when workers entered and exited the wind turbine blades due to the need for workers to put on or take off personal protective equipment or perform additional tasks outside the wind turbine blade while sample pumps were still operating. The results for the glue wipe personal breathing zone samples collected during the initial site visit as presented in Table 1 include the 15 min each worker spent inside the wind turbine blade along with the time spent outside the wind turbine blade during the glue wipe task. For discussion purposes, it is possible to calculate an adjusted value for each of the 14 glue wipe personal breathing zone air samples that subtracts the time each worker spent outside of the wind turbine blade during the glue wipe task. This calculation of an adjusted value is being made in this particular case to estimate the 15-min breathing zone concentration using the available sample result as if it had been possible to obtain the 15-min sample inside the confined space of the wind turbine blade. The adjusted values are calculated by assuming worker exposures during the glue wipe task were 18 p.p.m. for the portion of the sample time that exceeded 15 min. The value of 18 p.p.m. is used since the three area samples collected outside of the wind turbine blade had a geometric mean of 18 p.p.m. The adjusted values were calculated using equation (2):

$$C_i = \frac{C_t \times t_t - C_o \times t_o}{t_i} \quad (2)$$

Where  $C_i$  = styrene concentration when the worker was inside of the wind turbine blade, parts per million;  $C_t$  = styrene concentration for the task time sampled, parts per million;  $C_o$  = styrene concentration for the time the worker spent outside of the wind turbine blade, parts per million;  $t_i$  = time the worker spent inside of the wind turbine blade, minutes;  $t_t$  =

task time sampled, minutes;  $t_o$  = time the worker spent outside of the wind turbine blade, minutes.

For example, the first glue wipe personal breathing zone styrene air sample collected from the glue wipe task was 603 p.p.m. for a 29-min sample. The following example calculation estimates the concentration during the 15 min the worker spent inside the wind turbine blade by subtracting out the 14 min spent outside of the wind turbine blade at 18 p.p.m.

$$C_i = \frac{(603 \text{ p.p.m.} \times 29 \text{ min}) - (18 \text{ p.p.m.} \times 14 \text{ min})}{15 \text{ min}} \quad (3)$$

$$= 1149 \text{ ppm.}$$

Based on this sample calculation, is it possible to estimate that the concentration for the first personal breathing zone air sample for styrene was 1149 p.p.m. (0.11%) for the 15 min that the worker spent inside of the wind turbine blade. After applying this calculation to each of the 14 styrene personal breathing zone air samples collected from the glue wipe task during the initial site visit, the geometric mean is calculated at 970 p.p.m. for the 15 min that the workers spent inside the wind turbine blade during the glue wipe task. Glue wipe personal breathing zone samples for styrene before adjustment indicated several samples were either approaching or higher than the established NIOSH IDLH exposure level for styrene of 700 p.p.m. The adjusted personal breathing zone calculations indicate that 12 of the 14 values were >700 p.p.m.

OSHA Compliance Assistance Guidelines for Confined and Enclosed Spaces and Other Dangerous Atmospheres [29 CFR 1915.12(b)(3)] considers that atmospheres with a 'concentration of flammable vapors  $\geq 10\%$  of the LEL are considered hazardous when located in confined spaces'. The LEL for styrene is 0.9% or 9000 p.p.m. Concentrations should be <900 p.p.m. in order to remain <10% of the LEL. When the data from the glue wipe task were adjusted for the time workers were inside of the wind turbine blade, 11 of the 14 adjusted values were >900 p.p.m.

### *NIOSH respirator decision logic for IDLH conditions*

The company had a respiratory protection program. However, during the initial site visit, workers performing glue wipe tasks wore powered air purifying respirators which is not consistent with NIOSH respirator decision logic for IDLH atmospheres. The current NIOSH definition for an IDLH condition, as given in the NIOSH Respirator Decision

Logic, is 'an exposure condition that poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment'. NIOSH has established an IDLH exposure level for styrene of 700 p.p.m. The IDLH is considered a maximum level above which only a highly reliable breathing apparatus providing maximum worker protection is permitted. Any appropriate approved respirator may be used to its maximum use concentration up to the IDLH concentration. Under the NIOSH Respirator Decision Logic, only 'highly reliable' respirators (i.e. the most protective respirators) would be selected for IDLH conditions (NIOSH, 1987). These highly reliable respirators include a pressure demand, full-face piece self-contained breathing apparatus (SCBA) or a pressure demand, full-face piece supplied air respirator (SAR) in combination with an auxiliary pressure demand, and full-face piece SCBA. The auxiliary SCBA must be of sufficient duration to permit escape to safety if the air supply is interrupted. An auxiliary unit means that the SAR unit includes a separate air bottle to provide a reserve source of air should the airline become damaged. The auxiliary unit shares the same mask and regulator and enables the SAR to function as an SCBA if needed. During the follow-up evaluation of the glue wipe task, workers wore powered air purifying respirators with organic vapor cartridges which was consistent with the NIOSH respirator decision logic since they were no longer entering the confined space or IDLH atmosphere due to the design change.

## CONCLUSIONS

### *Initial site visit*

The closed molding VARTM task was very effective at controlling worker exposures to styrene as demonstrated by the air samples collected during the initial site visit. Air sampling results from the gelcoating, glue wipe, and safety platform installation tasks indicated that control measures were needed to reduce styrene concentrations.

During the initial site visit, the plant was using respiratory protection combined with an administrative control to reduce average styrene exposures of workers during the gelcoating task. The administrative control required workers to leave the room and take a break after gelcoating was finished and return when area concentrations for styrene decreased <20 p.p.m. Recommendations were made that the administrative control effort should continue and

all workers in the gelcoating area should be required to leave the room to take advantage of the administrative control. Recommendations were also made to continue the use of organic vapor charcoal filter respirators during gelcoating. Recommendations were made to consider installing traveling or moving air systems to provide local exhaust ventilation during gelcoating. The moving air systems could be designed to supply fresh air near the breathing zone of the worker and exhaust air downstream of the source with air flows low enough not to interfere with the application of gelcoat. Worker exposures to styrene could be reduced further by implementing robotic gelcoating. In-mold gelcoating technology may also be applicable to VARTM and large components (Summerscales *et al.*, 2010).

### *Follow-up site visit*

At the time of the follow-up evaluation, the design changes to the molds eliminated the need for workers to enter the wind turbine blade during the glue wipe task. This change was very important since it dramatically reduced exposures to styrene for workers that were previously entering the wind turbine blade. Although the changes to the glue wipe task dramatically reduced worker exposures to styrene, some workers were observed standing outside of the wind turbine blade while leaning in with a pole to wipe glue near the opening. Other workers standing near the opening to the wind turbine blade for training or other purposes did not consistently wear respiratory protection. The pole used by the worker was flimsy which increased the likelihood that the worker would lean in and cross the plane of the confined space while wiping glue. Recommendations were made to the company that better tools should be provided to the glue wipe workers along with training to keep their breathing zone out of the confined space during the task. Recommendations were also made to continue using organic vapor charcoal filter respirators for workers performing the glue wipe task or standing near the opening to the wind turbine blade.

After the follow-up site visit, management along with plant engineers began investigating pneumatic conveying air systems that follow the gelcoater along the wind turbine blade. The traveling or moving air system could possibly be tied into existing conveying systems over each mold.

Since the time of the evaluation, the company initiated a chemical substitution to eliminate styrene exposures during the installation of the safety platform. A product called Sika Flex replaced the styrene resin used to secure the safety platform inside of the wind turbine blade. Although the new adhesive

did not contain styrene, the new Sika Flex product contained xylene. Recommendations were provided that sampling for xylene vapor should be conducted to make sure that it does not replace one hazard with another and present an exposure hazard for workers. The OSHA PEL for xylene is 100 p.p.m. The NIOSH recommended STEL for xylene is 150 p.p.m. Recommendations were made to consider the STEL in addition to the PEL when sampling for xylene.

The task-based sampling approach was effective in identifying tasks that could benefit from the introduction of engineering controls to reduce styrene concentrations during tasks such as glue wipe, gelcoating and the installation of the safety platform. The modifications to the glue wipe process dramatically reduced personal breathing zone concentrations of styrene vapor for the task time sampled. Chemical substitution was used to eliminate styrene exposure during the installation of the safety platform. Recommendations were provided to reduce styrene concentrations during the gelcoating process. The VARTM technology effectively reduced personal breathing zone styrene concentrations. Other companies who manufacture FRP parts should consider closed molding technologies such as VARTM to reduce occupational exposures.

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