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# A Field Comparison of Methods for Monitoring Ethylene Oxide Concentration

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**A variety of methods for monitoring ethylene oxide (ETO) in air have been developed and evaluated in the laboratory and in the field to provide the ability to monitor this compound at the increasingly lower levels required by current guidelines and regulations for exposure limits. The field evaluation described here compares results obtained using four techniques: two commercially manufactured passive monitors, the Crystal Diagnostics AirScan® and the 3M #3551 badge; the sorbent tube method currently being used by the Occupational Safety and Health Administration; and a portable gas chromatographic (GC) method published in the current edition of the *Manual of Analytical Methods* of the National Institute for Occupational Safety and Health. Samples were collected at two commercial sterilization facilities that use ETO for sterilization of a variety of materials. Concentrations ranged from approximately 0.7 to 32 ppm for samples of 15-minute duration, and from approximately 0.5 to 1.6 ppm for samples of 8-hour duration. The precision and relative response of the various monitoring techniques were compared with one another because the true concentration of ETO was not known and therefore no measure of accuracy could be determined. At the first sampling site the AirScan passive sampler gave significantly higher results than the sorbent tube method, but neither of those methods could be statistically distinguished from the 3M passive sampler or the GC method. Results at the second site indicated all sampling techniques were equivalent except for the subset of 3M badges that were analyzed by one of two laboratories that analyzed the 3M badges. Precision ranged from <2 percent mean relative standard deviation for on-site GC analysis by one instrument to approximately 15 percent for the AirScan sample results. In general, although the AirScan monitoring method was less precise than the other methods, all the methods provided statistically equivalent measures of workplace ETO concentrations for both short-term and full-shift exposures under the conditions of this evaluation.**

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## Introduction

A variety of both active and passive methods for monitoring ethylene oxide (ETO) concentration in air have been developed and evaluated in the laboratory, and in some cases also in the field.(1-9) Detector tubes and on-site analytical instruments also are available and some workplace exposure assessment studies have been published using data from these techniques when continuous monitoring or short-duration sampling was required.(10,11)

One of the major problems involved in collecting ETO for subsequent laboratory analysis has been its poor stability and high volatility. Air samples collected on conventional charcoal surfaces require special handling and storage procedures to control for sample loss.(1,2) Additionally, for passive monitors, effective collection requires that the adsorbent layer have high affinity for the substance being measured because weakly adsorbed chemicals will diffuse through the adsorbent layer, resulting in reduced net sampling rate with time.(12) This change in sampling rate with the amount of material collected renders a passive monitor useless for sampling unknown atmospheres of chemicals that have low affinity for the adsorbent surface.

The ability to measure ETO at lower concentrations has become necessary in recent years. In 1977, the National Institute for Occupational Safety and Health (NIOSH) recommended an exposure limit of 50 parts per million (ppm) by volume in air for an 8-hour time-weighted average (TWA) and 75 ppm for a 15-minute ceiling.(13) Currently, NIOSH recommends a TWA exposure limit of 0.1 ppm and a 10-minute ceiling of 5 ppm.(14) The Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) also has become increasingly stringent, changing from a 50-

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ppm TWA in 1984 to the current 1-ppm TWA and 5-ppm short-term exposure limit (STEL).(15)

The evaluation described herein was undertaken to compare results obtained for short (15-minute) and long (8-hour) duration samples using four techniques for monitoring ETO at concentrations near the current OSHA PELs. One of the limitations of a field study is the difficulty in establishing accuracy of a test method or methods relative to a reference method. Protocols for the evaluation of sampling and analytical methods,(16) and additional protocols for passive sampling methods(17,18) are available; however, these protocols are developed for laboratory evaluations, and adapting them to a field evaluation is difficult. In lieu of these limitations, the results of this study are comparative rather than definitive relative to a known value.

The techniques selected for evaluation included two commercially available passive monitors, a solid sorbent sampler, and on-site analysis by portable gas chromatographs (GC). Two specially designed portable sampling chambers were used to sample workplace atmospheres to enable simultaneous collection of multiple samples of all types.

One passive device tested was the Crystal Diagnostics AirScan® Ethylene Oxide (Crystal Diagnostics Corp., Woburn, Massachusetts) passive monitor. Exposure of this monitor to ETO results in reaction of the ETO via a proprietary process to form a nonvolatile product. Following exposure the reaction product is treated with a liquid reagent to form visible crystals. The length of crystal growth on the badge can be visually observed on site at the end of the sampling period and is proportional to the amount of ETO collected. Different model badges are required for monitoring 15-minute or 8-hour durations.

The second passive device was the 3M #3551 badge (3M, St. Paul, Minnesota), which uses a hydrobromic acid treated charcoal pad to collect ETO as 2-bromoethanol. The 2-bromoethanol product is much less volatile than ETO and is effectively trapped on the adsorbent surface of the monitor, thus avoiding the problem of weak adsorption of ETO on charcoal.(5) Subsequent to sampling, these monitors must be submitted for laboratory analysis. In this study two analytical laboratories were used, with each receiving half of the 3M badge samples. The 3M #3351 monitor can be used for either STEL or TWA monitoring.

The solid sorbent technique is described in OSHA Method #50, which uses a hydrobromic acid coated sorbent tube, through which air is drawn by a battery-powered personal sampling pump at a rate of 0.2 L/min for periods of 15 minutes for short-term exposure monitoring, or at 0.05 L/min for 8 hours for TWA monitoring.(7) The ETO is converted to 2-bromoethanol on the sorbent surface, and the sorbent tube is submitted to an analytical laboratory for quantitation by electron capture detector GC. All sorbent tube samples were analyzed by one laboratory.

On-site GC analysis is described in the NIOSH(9) *Manual of Analytical Methods.* Sample collection was in inert plastic bags with subsequent direct injection and quantitation by photoionization GC. No conversion was required for stabilization.

## Methodology

To compare results obtained from multiple samples, ambient workplace air was drawn into chambers and mixed to provide a homogeneous atmosphere for exposing the samples. Two identical portable sampling chambers were used at each site (Figure 1). One sampling chamber was used to monitor an 8-hour shift and the other chamber was used periodically throughout the day to collect STEL samples. Each chamber consisted of a rectangular box, 46 cm (18 inches) long × 11.6 cm (4.5 inches) wide × 15 cm (6 inches) deep, (7 L or 0.25 $ft^3$ volume) constructed of 0.6-cm (0.25-inch)-thick acrylic plastic. Through the center of each end of the box was positioned a 5.7-cm (2.25-inch) OD acrylic plastic cylinder. At the inlet end the cylinder extended 16.5 cm (6.5 inches) outside the box, and 3 cm (1.25 inches) inside the box. At the outlet end the cylinder extended 27 cm (10.5 inches) outside the chamber and 3 cm (1.25 inches) inside the chamber. Both the inlet and outlet cylinders were capped inside the sampling box with a diffusion plate to facilitate gas mixing. Eight 0.8-cm ($\frac{5}{16}$-inch)-diameter holes were drilled around the outer surface of the end of the tubes to allow air to enter and exit the chamber. A small battery powered fan was mounted inside the inlet of the sampling chamber and used to supply air at a velocity of approximately 30 m/min (100 ft/min). This high air exchange rate in the chamber (approximately 1 air change per second) was selected to allow the chamber concentration to follow any rapid changes in ETO concentration in the workplace. Preliminary tests of the sampling chambers indicated no differences in concentration with the position of the sample within the chambers, nor were there any observable differences in concentration related to location within the chamber from any of the samples collected at the two sites.

One of the major problems in evaluating passive monitors for a short-term exposure is being able to initiate and stop the sampling process precisely for all monitors for an identical period. This sampling error is generally negligible for long-term monitors because the variations in sampling

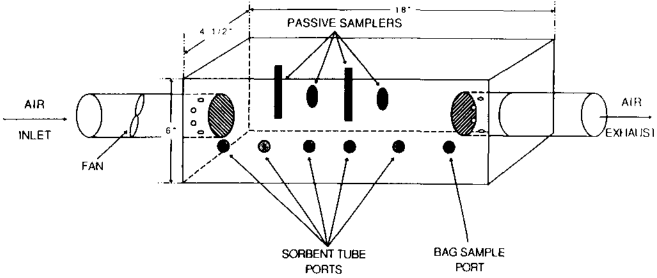

**FIGURE 1.** Diagram of portable sampling chambers for simultaneous collection of 10 sorbent tube, 20 passive monitor and 2 bag samples. (For clarity, some sample locations are not shown.)

are not significant over an 8-hour period. However, if STEL monitors are allowed to remain in an ETO atmosphere at the end of the sampling period the additional sampling time will result in significant errors. One approach used to solve this problem is to place the samples in the sampling chamber in an initially ETO-free atmosphere, and at the end of the sampling period to sweep the chamber with ETO-free air. A rather sophisticated sampling chamber and well-documented field validation protocol has been described for sampling short-term exposures to ETO using this method.(19) For the purposes of this study the monitors were positioned in the sampling chamber and removed and capped in an ETO-free atmosphere. Using this procedure, the additional exposure time was negligible because the exposure was zero during this time.

This evaluation was conducted at two commercial sterilization facilities that use ETO for the sterilization of medical supplies. Both facilities operated sterilization chambers at least 8 hours/day using either 100 percent ETO or a 12 percent w/w (27% v/v) mixture of ETO with dichlorodifluoromethane (Freon 12). The sterilization chambers at these facilities varied in size but were typically the size of a semi-tractor trailer. Both facilities employed approximately 10 workers.

The first evaluation was conducted in the late summer in southeastern United States, and the second was performed in the spring in southwestern United States. These sampling locations are referred to as Site 1 and Site 2, respectively. During the 2-day sampling period at Site 1, the temperature ranged from approximately 28° to 32°C (83° to 89°F) and the relative humidity from 66 to 83 percent. At Site 2, the temperature ranged from approximately 17° to 21°C (62° to 70°F), and the relative humidity was approximately 55 to 60 percent.

Each set of samples consisted of 10 AirScan monitors, 10 3M badges, 10 sorbent tubes, and 2 gas sampling bags. The passive devices were suspended from the top of the chamber and spaced throughout the chamber. Sorbent tube samples were collected from the chamber by inserting tubes into sampling ports equally spaced along both sides of the chamber. The sampling ports consisted of male 0.6-cm (¼-inch) black polypropylene elbows (United States Plastic Corp., Lima, Ohio) threaded into the side of the sampling chamber. Glass sampling tubes containing 120/60 mg HBr coated charcoal (SKC Inc., Eighty Four, Pennsylvania) were inserted into the fitting and held tightly in place by means of a rubber O-ring. Personal sampling pumps attached to precalibrated and postcalibrated sampling manifolds were used to draw air from the sampling chamber through the sampling tubes. To obtain an integrated air sample for on-site GC analysis, air was drawn from the chamber through Teflon® tubing by a constant flow sampling pump. To fill the gas bag, Teflon tubing was attached from the exit port of the sampling pump to the inlet of the gas bag. Gas bag samples were collected in duplicate from opposite ends of the sampling chamber for each set of samples. Previous studies have demonstrated that ETO is stable for more than 4 hours when stored in Tedlar gas bags.(19)

At both sites samples were placed in the sampling chamber in a rest area adjacent to the sterilization facility and tested for background ETO level. The unexposed badges were quickly placed in the sampling chamber prior to exposure, the lid was attached, and the chamber was carried quickly to the sampling site. At the sampling site the plastic end caps were removed from the sampling chamber and the sampling chamber fan and sampling pumps were turned on.

Approximately 30 seconds prior to completion of the sampling period, the sampling chamber fan was shut off and the chamber was either flushed with clean air supplied by a cylinder of zero grade compressed air and the end caps reattached, or the chamber was removed from the ETO atmosphere and capped at the end of the 15-minute period. The passive monitors and sorbent tubes were then removed and capped according to the prescribed procedure.

Long-term sample sets were collected in an area of the building found by GC analysis of grab samples to have an ETO concentration near the OSHA TWA PEL of 1 ppm when the sample was collected. Short-term sample sets were collected by moving the short-term sampling chamber between areas of lower and higher concentration (determined by GC measurements) for variable lengths of time to control the amount of sample collected. No personal breathing zone samples were collected, nor was any estimate made of workers' exposure to ETO.

All samples were handled as prescribed. The sorbent tube and 3M samples were stored at room temperature and shipped via first class mail to the analytical laboratories for analysis. The 3M monitors from each set of samples were split into two equal sized groups and analyzed by two laboratories. The 3M samples analyzed by Laboratory 1 were completed using OSHA Method #49, while Laboratory 2 analyzed samples according to the manufacturer's prescribed method.(20) The manufacturer's suggested sampling rate of 49.3 cm³/min, corrected for temperature and pressure, was used to calculate concentrations for all the 3M badges.

At Site 1, a Photovac Model 10S50 portable GC (Photovac, Inc., Huntington, New York) equipped with a photoionization detector was used for replicate analysis of the gas bag samples collected from the sampling chamber and for the determination of the concentration of ETO at various locations in the facility. A 1.2-m × 0.3-cm (4-ft × ⅛-inch) Carbopack BHT 60/80 mesh column operating at ambient temperature with ultra pure air as carrier gas and flow rates of 15–20 ml/min was used in the analysis. Gas samples and standards were directly injected by means of gastight syringes. Retention time for ETO was approximately 1 minute. This method is further described in the NIOSH *Manual of Analytical Methods*.(9)

At Site 2, both the Photovac GC and an HNU Model 311 (HNU Systems Inc., Newton, Massachusetts) photoionization detector GC were used to analyze air samples. The

HNU system was fitted with a 1.8-m × 0.3-cm (6-ft × ⅛-inch) stainless steel analytical column and a 15-cm (6-inch) precolumn, both packed with 80/100 mesh Gas Chrom 102. Nitrogen was used as the carrier gas at 20–30 ml/min. The oven temperature was 140°C, and the injector/detector temperature was 135°C. Injections from gas bag samples and gas bag standards were made with an internal gas sampling loop. A precolumn backflush began 15 seconds after injection. The retention time for ETO for this analysis was approximately 2.4 minutes. An external Hewlett-Packard Model 3390A integrator (Avondale, Pennsylvania) was used to determine the area under the chromatographic peaks because the internal integration software for this GC did not yield reproducible results for calibration injections.

At both sites the GC analyses were done in a rest area near the work site, and all instruments were operated from line power. A standard of ETO in nitrogen (Scott Specialty Gas, Troy, Michigan), certified by the supplier at 10 ppm ±5%, was used for calibration of both GCs. A certified mixture of 27 percent ETO and 73 percent Freon 12 (v/v) was available at Site 2, and it was used to prepare ETO standards by dilution in gas bags for comparison with the 10-ppm standard.

## Results and Discussion

At Site 1, a total of eight sets of samples was collected over a 2-day period during late summer. Three sets of 15-minute STEL samples and 1 set of 8-hour samples were collected each day. The long-term sampling chamber was placed near one of the large sterilization chambers and the 8-hour sampling was begun just prior to the removal of a sterilized load in the morning. Because comparatively low ETO concentrations were measured in the vicinity of this sampling chamber during the day, the chamber was moved into the aeration room, which contained ETO levels ranging from 10 to 100 ppm for a brief exposure during the last half hour of the 8-hour sampling period.

A second sampling chamber was used to collect STEL samples. A majority of the STEL sample sets were collected by placing this sampling chamber in the aeration room for variable lengths of time. To estimate the approximate exposure time, the concentration of ETO in the area was determined just prior to the sampling by obtaining a grab air sample for GC analysis.

Near the end of the valuation at Site 1, it was discovered that the background level for ETO averaged approximately 2 ppm in the area in which the badges were being prepared. Because of this high background all the 3M badge sample sets that were prepared in this atmosphere were corrected for a 5-minute exposure at 2 ppm. This corresponded to a 0.7-mg correction and was based on an estimate of the approximate time the badges remained uncapped in this atmosphere. Except for the first short-term sample set (1/ST-1 in Appendix A), this source of error was not significant for the samples collected at this site.

A similar procedure was followed the next spring at Site 2. Six sets of STEL samples and one full-shift set of samples were collected on the first day, and two sets of STEL samples and one set of full-shift samples were collected on the second day. Because GC analysis of air samples in the sample preparation area indicated that the background level of ETO was low at this site, no background correction was applied to any of the monitors.

The mean, relative standard deviation (RSD) and number of replicates for each analytical method for all 18 sets of samples are shown in Appendix A. Because the 3M badge samples were submitted to two laboratories, the location of analysis is indicated for this split. The bag samples analyzed on site by the Photovac portable GC are listed as "On-site GC–PV" for both sites, while those analyzed on site by the HNU portable GC at Site 2 are listed as "On-site GC–HNU." The number of replicate analyses by on-site GCs in all cases is the total number of replicates from the two gas sample bags collected from the sampling chamber because no difference in concentration was determined in the bags.

Two methods of statistical analysis were used in the evaluation of these data. Initially, sorbent tube results were compared with the other sampling methods using a paired *t*-test. Then, a two-way analysis of variance (ANOVA) of the log transformed data was performed. Prior to the ANOVA, a (natural) log transformation was performed on each data point due to an observed correlation between the mean and standard deviation of the samples. The data were blocked by analytical method, and a two-way ANOVA was conducted on the transformed data. Using the block-by-sampler interaction as the error term, the difference among sampler means averaged over blocks was evaluated. No significant difference at the 0.05 confidence level was observed in the paired *t*-test, but the ANOVA indicated some statistically significant sampler differences.

The least squares estimates of sampler means, standard errors, and significance levels for *t*-tests of all 10 pairwise differences between samplers are presented in Appendix B. The Bonferroni method for multiple comparisons was

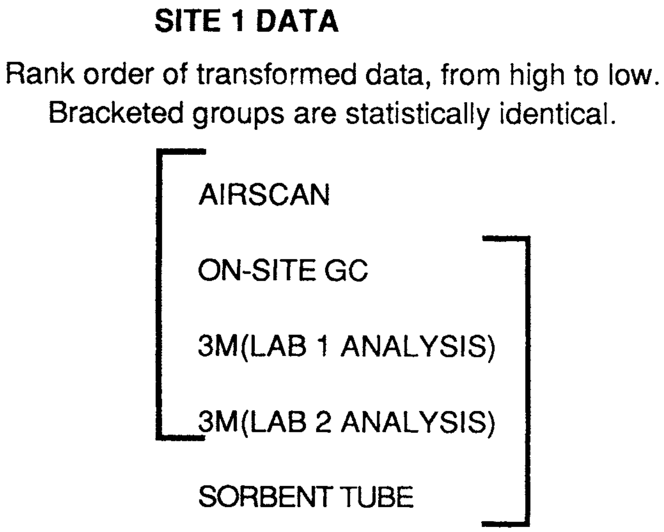

**FIGURE 2.** Comparison of monitoring techniques used at the first sampling site. Analytical lab indicated for split (3M) samples.

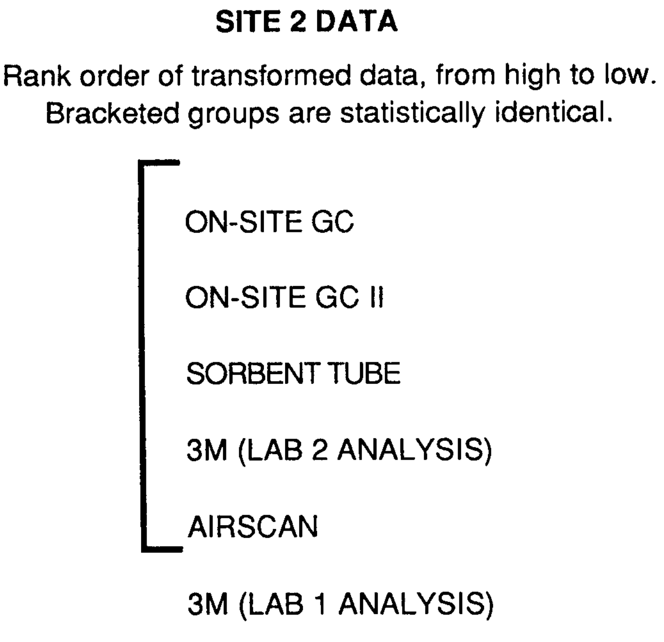

**FIGURE 3.** Comparison of monitoring techniques used at the second sampling site. Analytical lab indicated for split (3M) samples.

used to evaluate the 10 pairwise differences between samplers.(21) To achieve significance at the 0.05 level for this 5×5 comparison, a value of less than $0.05/10 = 0.005$ is needed. (These values are indicated in italics in Appendix B.) The data from Site 1 indicate that the AirScan method could be distinguished from the sorbent tube method ($p \leq 0.05$), but neither could be distinguished from the three other methods. That is to say, the four analytical techniques in either bracketed group in Figure 2 are indistinguishable.

The data from Site 2, based on the least squares estimates shown in Appendix B and Figure 3, indicate that the 3M sampler analyzed by Laboratory 1 is lower than the others, but that there is no significant difference ($p \leq 0.05$) among the other five methods. In this case statistical significance is achieved at a value $\leq 0.0033$ (noted with italics) because there were fifteen pairwise comparisons ($0.05/15 = 0.0033$).

Some differences in precision between the methods are noted; however, there is no difference in precision between the short-term samples and full-shift samples despite the difference in the total mass of ETO collected. Precision data are shown in Table I as the mean RSD for each technique, separated by short-term and full-shift samples, with the total number of replicate analyses also indicated. The average relative standard deviation for the sorbent tube method is 6.0 percent for the 14 sets of short-term samples collected and it is 6.8 percent for the four sets of full-shift samples collected. Similar precision is observed for the 3M monitor analyzed by Laboratory 2, with the average RSD = 6.3 percent for short-term samples and 6.1 percent for the full-shift samples. Poorer precision is observed for analysis by Laboratory 1 of the short-term 3M monitors; the RSD for the short-term samples is 11.5 percent, although better precision is observed for the full-shift 3M monitors analyzed by Laboratory 1. The RSD for these four sets of samples is 5.0 percent.

The Crystal Diagnostics AirScan ETO monitor results are less precise than either the sorbent tube or the 3M results. While the precision for the length of stain is good (4.6 percent for the short-term exposures and 4.9 percent for the long-term exposures), the average RSDs are 14 percent and 16 percent when these are converted to short-term and full-shift ETO concentrations. According to the manufacturer, this imprecision is caused by the difficulty with mathematically converting the nonlinear response to a concentration value. When the length of stain formation is converted to ETO concentration using the calibration curve supplied by the manufacturer, a significant error is introduced because the mathematical formula underlying the calibration chart does not precisely predict the actual concentration for every possible crystal line length. Despite these limitations this monitor does provide a useful, immediate measure of potential worker exposure to ETO, whereas both the sorbent tube and the 3M methods require laboratory analysis.

The on-site GC results proved to be the most precise. Average RSDs of 5.0 percent and 7.7 percent are obtained using the Photovac instrument for the short-term and full-shift samples, respectively. The HNu instrument, equipped with an autosampling loop, gives respective results of 1.9 percent and 0.7 percent, though for a smaller number of samples.

**TABLE I. Mean Relative Standard Deviation for Each Monitoring Technique (and Total Number of Analyses Performed by That Technique) Grouped by Short-Term and Full-Shift Measurements**

| | Short-Term Samples | | Full-Shift Samples | |
|---|---|---|---|---|
| Technique | Mean % RSD | Number | Mean % RSD | Number |
| 3M badge (Laboratory 2) | 6.3 | (69) | 6.1 | (20) |
| 3M badge (Laboratory 1) | 11.5 | (68) | 5.0 | (18) |
| Sorbent tube | 6.0 | (135) | 6.8 | (39) |
| AirScan monitor | 13.7[A] | (120)[A] | 16.0 | (40) |
| On-site GC—PV[B] | 5.0 | (75) | 7.7 | (16) |
| On-site GC—HNU[C] | 1.9 | (16) | 0.7 | (3) |

[A] Does not include sample results indicating concentrations of ETO above or below the range of the monitoring technique.
[B] PV = Photovac Model 10550 portable gas chromatograph.
[C] HNU = HNU Model 311 gas chromatograph.

## Conclusions

In this study four methods for measuring the concentration of ETO in air were compared. Two of the methods relied on passive devices for sampling workplace air. The AirScan passive sampler was field readable, whereas the 3M sampler required laboratory analysis. The other two methods employed sampling pumps and collected ETO on a solid sorbent for laboratory analysis as specified in an OSHA method, and in a bag for portable GC analysis according to a NIOSH method.

These methods were evaluated in the field, not the laboratory, and the many tests required for a complete laboratory evaluation could not be performed. The precision of the methods was compared, and the bias of the methods relative to one another was determined. The data were collected from two sites visited at different times of the year. The exact locations for sample collection at each site were selected by comparing preliminary concentration data to the desired levels based on current short-term and full-shift exposure limits. At both sites, three of the methods had a precision ≤7% RSD, while the field-readable AirScan passive sampler had a precision of 15 to 20 percent RSD. At one site, only two of the methods—the AirScan passive sampler and the OSHA sorbent tube method—gave results that differed by a statistically significant amount. The 3M badge and the portable GC method gave intermediate results that were not significantly different from those of any of the other three methods. At the other site, only the 3M passive samplers analyzed in one of two laboratories gave significantly lower results.

In general, although the AirScan monitoring method was less precise than the other methods, all the methods provided statistically equivalent measures of workplace ETO concentrations for both short-term and full-shift exposures under the conditions of this evaluation.

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## Disclaimer

Mention of company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

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**APPENDIX A. Summary of Data**

| Sample Site/I.D.[A] | Method | No. of Replicates | Mean ETO Conc. (ppm) | RSD (%) |
|---|---|---|---|---|
| 1/ST-1 | 3M badge (Lab 2 analysis) | 5 | 0.86 | 6.9 |
| | 3M badge (Lab 1 analysis) | 5 | 2.7 | 17.7 |
| | Sorbent tube | 10 | 0.73 | 4.7 |
| | AirScan monitor | 10 | <1.8 | — |
| | On-site GC-PV[B] | 3 | 1.7 | 3.3 |
| 1/ST-2 | 3M badge (Lab 2 analysis) | 5 | 24.7 | 6.3 |
| | 3M badge (Lab 1 analysis) | 5 | 25.3 | 7.0 |
| | Sorbent tube | 10 | 22.9 | 12.7 |
| | AirScan monitor | 10 | >20.9 | — |
| | On-site GC-PV | 4 | 32.1 | 6.0 |
| 1/ST-3 | 3M badge (Lab 2 analysis) | 5 | 11.8 | 3.8 |
| | 3M badge (Lab 1 analysis) | 5 | 13.7 | 5.6 |
| | Sorbent tube | 10 | 12.8 | 4.1 |
| | AirScan monitor | 10 | 17.4 | 16 |
| | On-site GC-PV | 0 | — | — |
| 1/ST-4 | 3M badge (Lab 2 analysis) | 5 | 4.6 | 12.1 |
| | 3M badge (Lab 1 analysis) | 5 | 6.7 | 12.1 |
| | Sorbent tube | 10 | 4.9 | 5.0 |
| | AirScan monitor | 10 | 5.7 | 21 |
| | On-site GC-PV | 7 | 5.1 | 8.2 |
| 1/ST-5 | 3M badge (Lab 2 analysis) | 5 | 4.6 | 4.3 |
| | 3M badge (Lab 1 analysis) | 5 | 5.2 | 28.4 |
| | Sorbent tube | 10 | 4.2 | 5.1 |
| | AirScan monitor | 10 | 7.7 | 19 |
| | On-site GC-PV | 4 | 6.1 | 3.4 |
| 1/ST-6 | 3M badge (Lab 2 analysis) | 5 | 8.9 | 6.0 |
| | 3M badge (Lab 1 analysis) | 5 | 8.5 | 14.7 |
| | Sorbent tube | 8 | 10.2 | 5.9 |
| | AirScan monitor | 10 | 16.3 | 15 |
| | On-site GC-PV | 4 | 11.8 | 9.8 |
| 1/LT-1 | 3M badge (Lab 2 analysis) | 5 | 0.78 | 3.2 |
| | 3M badge (Lab 1 analysis) | 5 | 0.81 | 4.0 |
| | Sorbent tube | 9 | 0.94 | 11.9 |
| | AirScan monitor | 10 | 1.35 | 18 |
| | On-site GC-PV | 0 | — | — |
| 1/LT-2 | 3M badge (Lab 2 analysis) | 5 | 0.67 | 5.8 |
| | 3M badge (Lab 1 analysis) | 5 | 0.76 | 8.1 |
| | Sorbent tube | 10 | 0.79 | 5.7 |
| | AirScan monitor | 10 | 1.07 | 31 |
| | On-site GC-PV | 4 | 1.30 | 15.6 |
| 2/ST-1 | 3M badge (Lab 2 analysis) | 5 | 5.65 | 7.2 |
| | 3M badge (Lab 1 analysis) | 5 | 4.49 | 5.0 |
| | Sorbent tube | 10 | 4.43 | 6.0 |
| | AirScan monitor | 10 | 5.33 | 10.7 |
| | On-site GC-PV | 9 | 5.4 | 6.0 |
| | On-site GC-HNU[C] | 2 | 5.65 | 1.9 |
| 2/ST-2 | 3M badge (Lab 2 analysis) | 4 | 5.73 | 5.1 |
| | 3M badge (Lab 1 analysis) | 4 | 4.72 | 5.3 |
| | Sorbent tube | 10 | 6.51 | 1.8 |
| | AirScan monitor | 10 | 3.51 | 13.2 |
| | On-site GC-PV | 4 | 5.50 | 5.4 |
| | On-site GC-HNU | 2 | 5.27 | 4.2 |

[A] ST = short-term (STEL) sample; LT = long-term (TWA) sample.
[B] PV = Photovac Model 10550 portable gas chromatograph.
[C] HNU = HNU Model 311 gas chromatograph.

**APPENDIX A. Summary of Data *(Continued)***

| Sample Site/I.D.[A] | Method | No. of Replicates | Mean ETO Conc. (ppm) | RSD (%) |
|---|---|---|---|---|
| 2/ST-3 | 3M badge (Lab 2 analysis) | 5 | 19.1 | 4.9 |
| | 3M badge (Lab 1 analysis) | 5 | 5.9 | 6.7 |
| | Sorbent tube | 10 | 19.7 | 4.9 |
| | AirScan monitor | 10 | 17.1 | 12.8 |
| | On-site GC-PV | 6 | 17.8 | 6.7 |
| | On-site GC-HNU | 2 | 19.0 | 0 |
| 2/ST-4 | 3M badge (Lab 2 analysis) | 5 | 5.5 | 8.4 |
| | 3M badge (Lab 1 analysis) | 5 | 1.4 | 13.5 |
| | Sorbent tube | 10 | 6.9 | 4.2 |
| | AirScan monitor | 10 | 5.7 | 13.7 |
| | On-site GC-PV | 6 | 5.8 | 3.8 |
| | On-site GC-HNU | 2 | 5.7 | 0 |
| 2/ST-5 | 3M badge (Lab 2 analysis) | 5 | 3.5 | 4.2 |
| | 3M badge (Lab 1 analysis) | 5 | 5.2 | 28.4 |
| | Sorbent tube | 10 | 3.6 | 1.8 |
| | AirScan monitor | 10 | 4.5 | 12.6 |
| | On-site GC-PV | 7 | 4.4 | 3.2 |
| | On-site GC-HNU | 2 | 4.2 | 2.7 |
| 2/ST-6 | 3M badge (Lab 2 analysis) | 5 | 3.8 | 5.6 |
| | 3M badge (Lab 1 analysis) | 5 | 3.0 | 12.3 |
| | Sorbent tube | 10 | 3.9 | 5.2 |
| | AirScan monitor | 10 | 3.3 | 11.7 |
| | On-site GC-PV | 7 | 3.9 | 3.8 |
| | On-site GC-HNU | 2 | 3.7 | 1.1 |
| 2/ST-7 | 3M badge (Lab 2 analysis) | 5 | 4.9 | 5.4 |
| | 3M badge (Lab 1 analysis) | 4 | 1.1 | 18.6 |
| | Sorbent tube | 7 | 4.9 | 17.6 |
| | AirScan monitor | 10 | 3.8 | 8.4 |
| | On-site GC-PV | 5 | 6.6 | 2.7 |
| | On-site GC-HNU | 2 | 5.0 | 3.1 |
| 2/ST-8 | 3M badge (Lab 2 analysis) | 5 | 4.1 | 6.6 |
| | 3M badge (Lab 1 analysis) | 5 | 3.6 | 9.9 |
| | Sorbent tube | 10 | 4.6 | 4.3 |
| | AirScan monitor | 10 | 3.6 | 10.1 |
| | On-site GC-PV | 9 | 5.7 | 3.1 |
| | On-site GC-HNU | 2 | 4.1 | 2.2 |
| 2/LT-1 | 3M badge (Lab 2 analysis) | 5 | 0.62 | 5.3 |
| | 3M badge (Lab 1 analysis) | 5 | 0.51 | 4.9 |
| | Sorbent tube | 10 | 0.60 | 2.0 |
| | AirScan monitor | 10 | 0.85 | 7.2 |
| | On-site GC-PV | 6 | 1.00 | 0 |
| | On-site GC-HNU | 1 | 0.93 | — |
| 2/LT-2 | 3M badge (Lab 2 analysis) | 5 | 1.1 | 10.1 |
| | 3M badge (Lab 1 analysis) | 3 | 0.92 | 2.8 |
| | Sorbent tube | 10 | 1.1 | 7.6 |
| | AirScan monitor | 10 | 1.3 | 7.9 |
| | On-site GC-PV | 6 | 1.6 | 7.4 |
| | On-site GC-HNU | 2 | 1.5 | 0.7 |

**APPENDIX B. Site 1 Data: Least Squares Estimates of Mean Level by Sampler with Estimated Standard Errors and Significance Levels for All Pairwise *t*-Tests of Sampler Differences Using Transformed Data**

| | | | | Significance Level for Pairwise *t*-Test of Difference Between Sampler i and Sampler j Mean* | | | | |
|---|---|---|---|---|---|---|---|---|
| Sampler | Mean (ln ppm) | Std Error (ln ppm) | i/j | 1 | 2 | 3 | 4 | 5 |
| 3M (Lab 2 analysis) | 1.4927 | 0.101426 | 1 | | 0.0779 | 0.0067 | 0.0304 | 0.9932 |
| 3M (Lab 1 analysis) | 1.7569 | 0.101426 | 2 | 0.0779 | | 0.4088 | 0.5469 | 0.0443 |
| AirScan | 1.8613 | 0.071719 | 3 | 0.0067 | 0.4088 | | 0.9494 | *0.0014* |
| On-site GC | 1.8524 | 0.118969 | 4 | 0.0304 | 0.5469 | 0.9494 | | 0.0162 |
| Sorbent tube | 1.4916 | 0.072988 | 5 | 0.9932 | 0.0443 | *0.0014* | 0.0162 | |

*Using the Bonferroni method for ten pairwise tests, a significance level of 0.005 (indicated by italics) is required to indicate a difference between members of the pair of samplers tested.

**APPENDIX B. Site 2 Data: Least Squares Estimates of Mean Level by Sampler with Estimated Standard Errors and Significance Levels for All Pairwise *t*-Tests of Sampler Differences Using Transformed Data**

| | | | | Significance Level for Pairwise *t*-Test of Difference Between Sampler i and Sampler j Mean* | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sampler | (ln ppm) | (ln ppm) | i/j | 1 | 2 | 3 | 4 | 5 | 6 |
| 3M (Lab 2 analysis) | 1.3363 | 0.092147 | 1 | | *0.0001* | 0.6676 | 0.1548 | 0.6669 | 0.8996 |
| 3M (Lab 1 analysis) | 0.7623 | 0.092147 | 2 | *0.0001* | | *0.0001* | *0.0001* | *0.0001* | *0.0001* |
| AirScan | 1.2875 | 0.065157 | 3 | 0.6676 | *0.0001* | | 0.0354 | 0.4518 | 0.4969 |
| On-site GC | 1.515 | 0.082193 | 4 | 0.1548 | *0.0001* | 0.0354 | | 0.5619 | 0.1241 |
| On-site GC II | 1.4136 | 0.152808 | 5 | 0.6669 | *0.0001* | 0.4518 | 0.5619 | | 0.7064 |
| Sorbent tube | 1.3506 | 0.065157 | 6 | 0.8996 | *0.0001* | 0.4969 | 0.1241 | 0.7064 | |

*Using the Bonferroni method for fifteen pairwise tests, a significance level of 0.0033 (indicated by italics) is required to indicate a difference between members of the pair of samplers tested.