

# Evaluating the Effects of Modified Windscreens on Organic Vapor Monitor Performance

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**ABSTRACT:** Passive sampling using diffusive samplers has become popular as a convenient means of occupational compliance sampling for volatile organic compounds (VOCs). However, diffusive samplers possess sensitivity limitations when sampling low concentrations and for short durations. To reduce these limitations, our research team has been developing a novel method of sample recovery called photothermal desorption (PTD), which uses high energy visible light pulses to desorb analytes from sampling media. Newly designed passive samplers that will use PTD will be equipped with windscreens in a similar design with the 3M OVM. In a preliminary design effort, the present work sought to find a suitable, windscreen for future use in a PTD-compatible diffusive sampler prototype that would be similar to those found in commercially available diffusive samplers. To do so, 2 stainless steel windscreens (wire diameters 0.015" and 0.0055" respectively) were compared to a standard windscreen by exposing modified (ie, steel mesh installed) and non-modified 3M OVM samplers to 3 analytes. To mimic in-field conditions, each sampler was exposed to analyte concentrations at their short-term and personal exposure limits (STELs and PELs). From these comparisons, it was determined that the 0.0055" mesh was most similar to the standard windscreen in contributing to sample collection based on the uptake and concentration determinations for each analyte and concentration.

**KEYWORDS:** Volatile organic compounds, exposure assessment, diffusive sampling, method development, gas chromatography, photothermal desorption

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## Introduction

Volatile organic compounds (VOCs) are chemicals which readily evaporate at room temperature and include aromatic hydrocarbons, aliphatics, aldehydes, ketones, ethers, acids, and alcohols, all with diverse functional groups.<sup>1</sup> VOCs are known to cause both acute and chronic effects including mucosal membrane irritation, headaches, liver and kidney damage, central nervous system effects, and even cancer.<sup>2–4</sup> Though the precise number of workers affected by VOC exposure is difficult to determine, a review of the 2019 data published by the U.S. Bureau of Labor Statistics shows that millions of workers are employed in occupations which are known to use VOC containing products.<sup>5</sup>

To prevent adverse health effects due to VOC overexposure, personal air sampling needs to be conducted for the purposes of compliance with occupational exposure regulations.<sup>6</sup> A common means to accomplish this is through the use of passive samplers placed in the worker's breathing zone during a sampling period. There are several advantages of using passive sampling techniques including their small size, light weight, independence from power supplies, and accuracy of results.<sup>7</sup>

\*These authors claim co-first authorship, based on equal contributions to the present work made by both authors.

However, due to their diffusion-driven sampling rate, only a small amount of VOC analyte can be collected. This occurs because the rate of diffusion may not be rapid enough to transport sufficient analyte mass to the sorbent before the ambient concentration changes.<sup>6</sup> This limitation is then compounded by the use of chemical desorption (CD) prior to analysis via gas chromatography (GC). The analytical methods published by occupational safety and health administration (OSHA) and National Institute of Occupational Safety and Health (NIOSH)<sup>8–11</sup> require analyte extraction with solvents such as carbon disulfide (CS<sub>2</sub>), thus diluting the sample, and specify the use of a minimum 1 µL aliquot of the solution be used for GC injection. This effectively reduces the sample mass used in analysis to 0.1% of the original collected mass. Due to these limitations, sampling of low concentrations or short time periods is non-ideal.

To remedy the pitfalls of passive sampling, our research group recently developed an emerging, pre-analytical technology called photothermal desorption (PTD).<sup>12,13</sup> This method increases sensitivity and reduces pre-analytical workups by directly desorbing sampled analytes from the sorbents with pulses of high-energy, visible light.<sup>12,13</sup> Previous studies using PTD as a means of analyte desorption from single-walled carbon nanotube (SWNT) sorbents resulted in 0.4% mass



recovery of toluene from a single flash, which is comparatively 4-times higher than a single injection from CD.<sup>14</sup> This was accomplished by using the adsorptive and thermal characteristics of SWNTs to collect and desorb analytes when flashed with light for instrumental analysis and quantification.<sup>12,13,15,16</sup> Additionally, PTD desorbs only a small fraction of the collected sample while maintaining the overall sample integrity, thus allowing for repeat analysis.<sup>12</sup>

Since PTD's introduction,<sup>12</sup> reliable fabrication techniques for SWNT sorbents (ie, buckypapers; BPs) have been developed,<sup>15</sup> and a process for maximizing the adsorption properties of BPs has been reported.<sup>16,17</sup> For PTD to fully be developed as a robust methodology, a diffusive sampler needs to be developed and tested with PTD. In this regard, 2 PTD-compatible diffusive sampler prototypes have been fabricated. However, a suitable windscreen has yet to be selected for use in these prototypes. Additionally, PTD will need to be tested with a variety of analytes, as previous studies focused primarily on toluene as a VOC analog. Considering the sampler prototypes have yet to be fully characterized, the present study sought to determine the most suitable windscreen by comparing the analyte concentrations measured by industry standard (3M 3500 OVM) samplers equipped with non-modified windscreen and modified windscreens of different mesh sizes (0.015" and 0.0055" respectively) when exposed to toluene, trichloroethylene (TCE), and n-hexane, as an analogous means of selecting an appropriate prototype windscreen. In doing so, the present work also sought to characterize the general windscreen performance for future studies using aromatic (toluene), halogenated (TCE), and aliphatic (n-hexane) VOCs.

## Methods

### *GC calibration*

GC (with flame-ionization detector; GC-FID; Model 6850, Agilent Technologies, Santa Clara, CA) analytical conditions were adopted from NIOSH Analytical Method 4000<sup>18</sup> and a 6-point calibration curve (ranging 10–10000 µg/mL) was generated for toluene (ACS grade), trichloroethylene (99.9%), and n-hexane (99+%), respectively, in CS<sub>2</sub> (ACS grade) spiked with a known amount of an internal standard, 4-chlorobenzotrifluoride (all solvents acquired from Fisher Scientific; Waltham, MA). For each analyte, a stock solution (10000 µg/mL) was prepared by spiking 116, 69, and 152 µL of toluene, trichloroethylene, and n-hexane, respectively, to a 10 mL volumetric flask. Each stock solution was diluted to concentrations of 10, 50, 250, 1000, and 5000 µg/mL with CS<sub>2</sub>. A calibration curve was created for each analyte and *r*<sup>2</sup> was .99977, .98842, and .99993 for toluene, trichloroethylene, and n-hexane, respectively. Per the manufacturer provided GC-FID technical data,<sup>19</sup> the detector used in the present work possessed a minimum detectable limit of <1.4 pgC/s (using tridecane) and a linear dynamic range >10<sup>7</sup> (±10%).

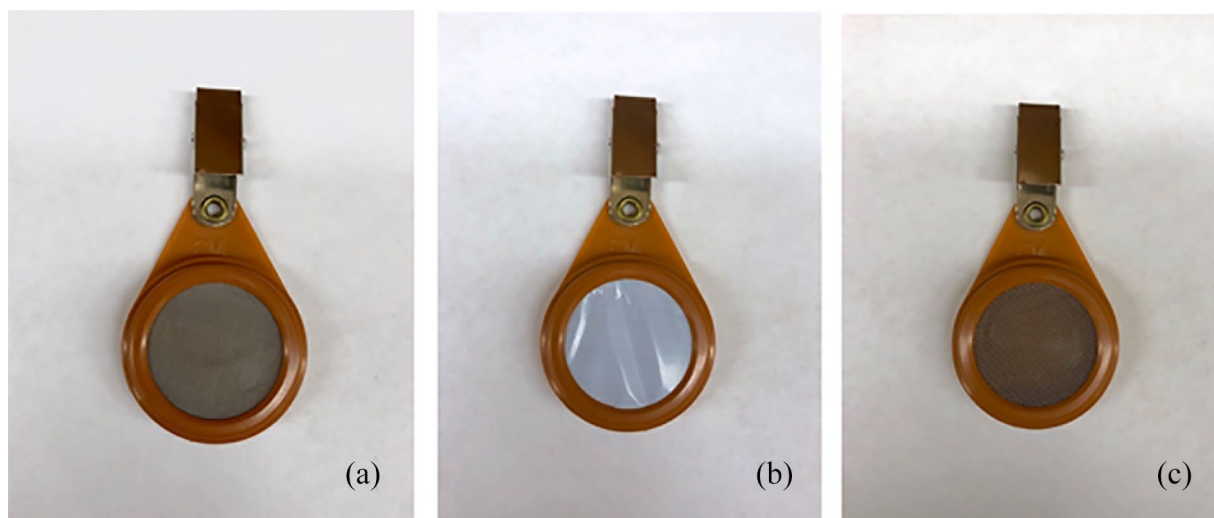
### *PID calibration*

Weekly 2-point calibrations were performed on a 10.6 eV photoionization detector (PID) obtained from Baseline-Mocon (VOC-Traq II; Lyons, CO), under standard ambient temperature and pressure (SATP) conditions, using dry, compressed N<sub>2</sub> (g) as a zero gas and a 100 ppm isobutylene in N<sub>2</sub> (g) mixture as a span gas. Calibration data was monitored and logged via manufacturer-provided VOC-Traq II software, and corrected from isobutylene equivalent concentration to analyte concentration using PID response factors provided by the manufacturer.

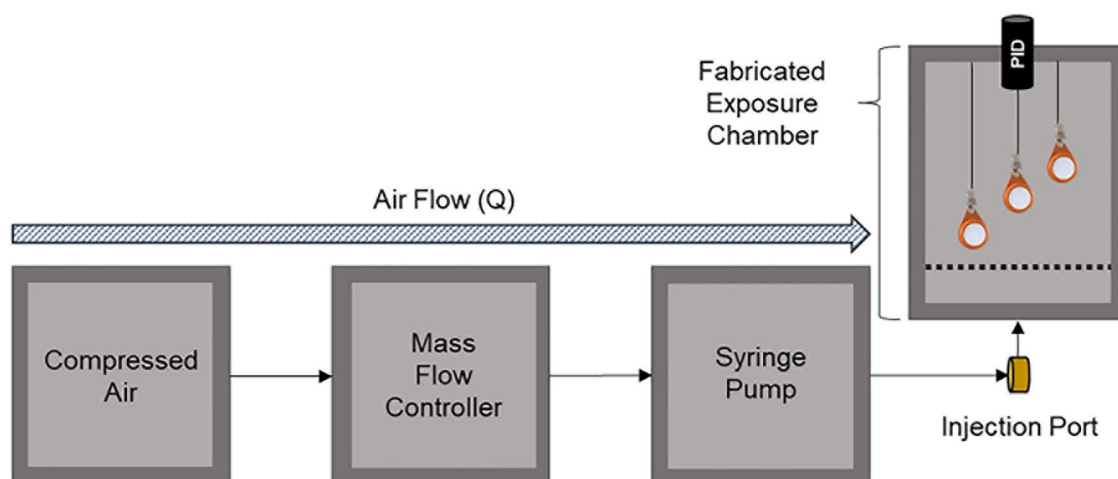
### *Short term exposure limits and 8-hours threshold limit values*

Toluene, TCE, n-hexane, and 3M OVM 3500 monitors were obtained from Fischer Scientific (Waltham, MA; detection limit: 2 µg<sup>20</sup>). Additionally, 2 types of 316 stainless steel windscreens, with mesh sizes of 0.0055" (open area 30%) and 0.015" (open area 36%) respectively, were obtained from McMaster-Carr (Elmhurst, IL). Using the 3M OVM samplers as housing for each windscreen, 2 samplers were modified replacing the original windscreen with the as received 0.0055" and 0.015" screens respectively, with one 3M OVM left intact as a control. The 3 samplers (Figure 1) were placed simultaneously into a stainless steel exposure chamber (V=1903.1 cm<sup>3</sup>; Figure 2) under SATP conditions and exposed to known concentrations of a given analyte over varying exposure periods. In addition, the position of each sampler type was changed with each respective experimental run, to ensure exposures were uniform throughout the chamber.

The sampling times correspond to each analyte's respective regulatory limits for 15 minute (short term exposure limit; STEL) and 8-hour exposures (OSHA PEL). Analyte concentrations near the PEL and STEL values (ie, ideal concentrations) were generated within the chamber via direct, in-line injection of liquid analyte by automatic syringe pump (Fusion 200, Chemyx, Stafford, TX) and quantified in real-time via a PID (ie, actual concentration). PID data monitoring and logging was conducted using VOC-TRAQ software (V. 1.0.0.32; Ametek Mocon—Baseline; Lyons, CO) provided by the PID manufacturer, with concentration data recorded once per second. The flowrate of air (Q= 50.15 L/min) through the chamber was selected based on the volumetric flowrate needed to generate a sampler face velocity greater than 25 fpm, as requested by the manufacturer. A constant flowrate was maintained throughout each experimental run using a mass-flow controller (Mesa-Labs; Lakewood, CO) upstream of the syringe pump, as seen in Figure 2. Analyte injection rates for each VOC of interest and exposure period were calculated by equation (1), and data for both STELs and PELs were collected for each analyte and sampler in triplicate.



**Figure 1.** (a) 3M OVM modified with 0.0055" McMaster Windscreen, (b) non-modified 3M OVM, and (c) 3M OVM modified with 0.015" McMaster Windscreen.



**Figure 2.** Diagram of fabricated exposure chamber with connected air flow.

$$Injection\ rate = \frac{C \cdot MW \cdot Q}{V_n \cdot \rho} \quad (1)$$

Where *injection rate* is the volume of analyte injected per unit time (mL/min), *C* is the desired concentration (ppm), *MW* is the analyte molecular weight (g/mol), *Q* is the volumetric flowrate of the carrier gas (L/min),  $V_n$  is the volume occupied by 1 mole of an ideal gas (24.45 L/mol at SATP),<sup>21</sup>  $\rho$  is the analyte density (g/mL).

### GC analysis

GC analysis was performed by adopting the NIOSH Analytical Method 4000.<sup>18</sup> Once dosed, samplers were removed from the chamber and analytes of interest were chemically desorbed with a respective 2 mL of CS<sub>2</sub>. Desorbed analytes were then transferred into GC vials (12 × 32 mm) and either analyzed immediately or wrapped in a wax film and placed in cold storage at 5°C prior to next-day analysis

(cold storage min/max residence time: 24 hours-2 weeks). After desorbing for 30 minutes, an approximate 150 μL aliquot of the sample was transferred into a GC autosampler vial (ThermoFischer Scientific, Co; Waltham, MA) and 1 μL was injected into GC for analysis. This procedure was performed in triplicate and averaged for each analyte (ie, toluene, TCE, and n-hexane) and windscreen. Because of the nature of separation techniques such as GC, we assumed a lack of sample contamination if no elution peaks were observed aside from those associated with analytes of interest during a given analytical cycle.

### Concentration calculation

Analyte mass obtained from GC analysis was converted to concentration in parts per million (ppm) using equation (2).

$$C_{Sampler} = \frac{m_{VOC} \cdot V_{Solv} \cdot V_n}{Q \cdot t \cdot MW} 10^6 \quad (2)$$

**Table 1.** STEL concentrations determined by individual samplers ( $C_{\text{Sampler}}$ ) compared to concentrations determined by in-chamber PID ( $C_{\text{Chamber}}$ ).

STEL			
VOC*	WINDSCREEN	$C_{\text{SAMPLER}}$ (PPM) <sup>c</sup>	$C_{\text{CHAMBER}}$ (PPM) <sup>d</sup>
Toluene <sup>a</sup>	0.0055"	151 ± 57	$P = .008$
	0.015"	330 ± 213	
	3M OVM	138 ± 51	
TCE <sup>b</sup>	0.0055"	259 ± 55	$P = .096$
	0.015"	338 ± 174	
	3M OVM	211 ± 39	

<sup>a</sup>n = 4 per screen.<sup>b</sup>n = 3 per screen.<sup>c</sup>Average ± SD.<sup>d</sup>Average ± standard error.\*VOC STELs: Toluene—150 ppm<sup>24</sup>; TCE—200 ppm.<sup>25</sup>

Where  $C_{\text{Sampler}}$  is the chamber concentration (ppm) calculated based on the sample mass collected by diffusive sampler;  $m_{\text{VOC}}$  is the mass (mg) of VOC as obtained by GC analysis;  $V_{\text{Solvent}}$  is the volume (mL) of CS<sub>2</sub> used for chemical desorption (2 mL in the present work);  $V_n$  is the volume occupied by 1 mole of an ideal gas (ie, 24.267 L/mol at lab temperature and average atmospheric pressure for Birmingham, AL, 24°C and 101 828 Pa, respectively);  $Q$  is the sampling rate (mL/min) of each analyte as described by the 3M OVM manufacturer ( $Q_{\text{toluene}} = 31.4$  mL/min;  $Q_{\text{trichloroethylene}} = 31.1$  mL/min;  $Q_{\text{n-hexane}} = 32$  mL/min)<sup>22</sup>;  $t$  is the sampling time (min);  $MW$  is the respective analyte's molecular weight (g/mol), and  $10^6$  is the conversion factor from mL to m<sup>3</sup>. The percent difference between the chamber and the measured concentration for each windscreen and analyte at STEL and PEL exposures were then determined using equation (3).

$$\%_{\text{uptake}} = \frac{C_{\text{Sampler}}}{C_{\text{Chamber}}} \times 100 \quad (3)$$

Where  $C_{\text{Chamber}}$  is the concentration (ppm) measured within the sampling chamber via PID.

### Statistics

A one-way analysis of variance (ANOVA) was used to determine the presence of significant differences between analyte concentration data collected by the modified and non-modified windscreens ( $\alpha = .05$ ). A post hoc pairwise comparison was then performed for each windscreen, grouped by the analyte used for data collection, via Tukey's HSD.<sup>23</sup> All statistical calculations were run using JMP Statistical Software (v14.0; SAS; Cary, NC).

## Results

### Comparison of sampler concentration with actual concentration

Concentration data collected by OVM samplers, as processed by GC-FID, ( $C_{\text{sampler}}$ ) and an in-chamber PID ( $C_{\text{Chamber}}$ ; actual concentration) have been compiled in Tables 1 and 2. Table 1 shows the comparative concentration data for toluene and TCE at near-STEL concentrations (150 and 200 ppm respectively) for each windscreens. The STEL concentrations for both analytes were most accurately (ie, most similar to the PID-determined concentration) measured by the 3M OVM windscreen (industry standard), with the 0.0055" mesh windscreen being the closest to the industry standard.

Table 2 displays the concentration data for toluene, TCE, and n-hexane at near-PEL concentrations (200, 100, and 350 ppm respectively). The 0.015" mesh windscreen was found to give the most PID-comparative toluene measurement by diffusive samplers exposed to PEL concentrations, with 0.0055" mesh windscreen being the closest to the 3M OVM windscreen. TCE concentrations were most accurately measured with the 3M OVM windscreen, with the 0.0055" mesh windscreen being the closest to the industry standard. PEL concentrations of n-hexane were most accurately determined by the 0.0055" mesh windscreen. This windscreen was also the most similar to the industry standard windscreen for n-hexane measurements.

### Percent uptake calculated from sampler and actual concentration

Using equation (3), the STEL and PEL percent difference between the chamber and measured concentration were

**Table 2.** PEL concentrations determined by individual samplers ( $C_{\text{Sampler}}$ ) compared to concentrations determined by in-chamber PID ( $C_{\text{Chamber}}$ ).

PEL				
VOC*	WINDSCREEN	$C_{\text{SAMPLER}}$ (PPM) <sup>A,B</sup>		$C_{\text{CHAMBER}}$ (PPM) <sup>C</sup>
Toluene	0.0055"	185 ± 27	$P < .001$	224 ± 9
	0.015"	243 ± 60		224 ± 9
	3M OVM	149.2 ± 0.7		224 ± 9
TCE	0.0055"	122 ± 24	$P = .005$	102 ± 19
	0.015"	142 ± 29		102 ± 19
	3M OVM	98 ± 4		102 ± 19
n-Hexane	0.0055"	440 ± 72	$P < .001$	411 ± 3
	0.015"	544 ± 92		411 ± 3
	3M OVM	357 ± 14		411 ± 3

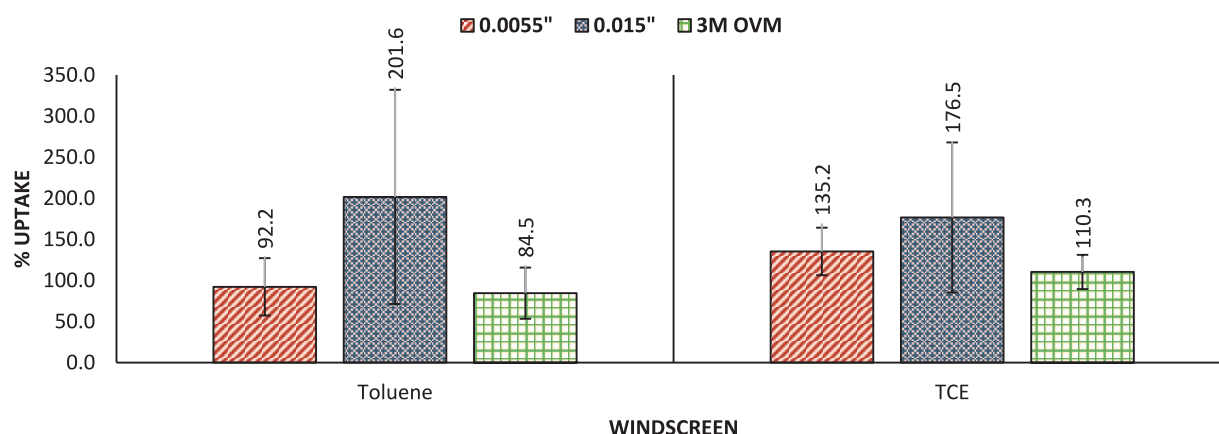
<sup>a</sup>n = 3 per screen.

<sup>b</sup>Average ± SD.

<sup>c</sup>Average ± standard error.

\*VOC PELs: Toluene—200 ppm,<sup>24</sup> TCE—100 ppm,<sup>26</sup> n-Hexane—500 ppm<sup>27</sup> (350 ppm used due to syringe pump volume limitations).

### PERCENT UPTAKE OF VOC STEL BY WINDSCREEN

**Figure 3.** Percent uptake of toluene (n=4) and TCE (n=3) at their respective STEL concentrations for samplers with varying windscreen pore sizes.

determined based on the data presented in Tables 1 and 2. The calculated percent uptakes were then compiled into Figures 3 and 4 and separated by the type of windscreen used for data collection.

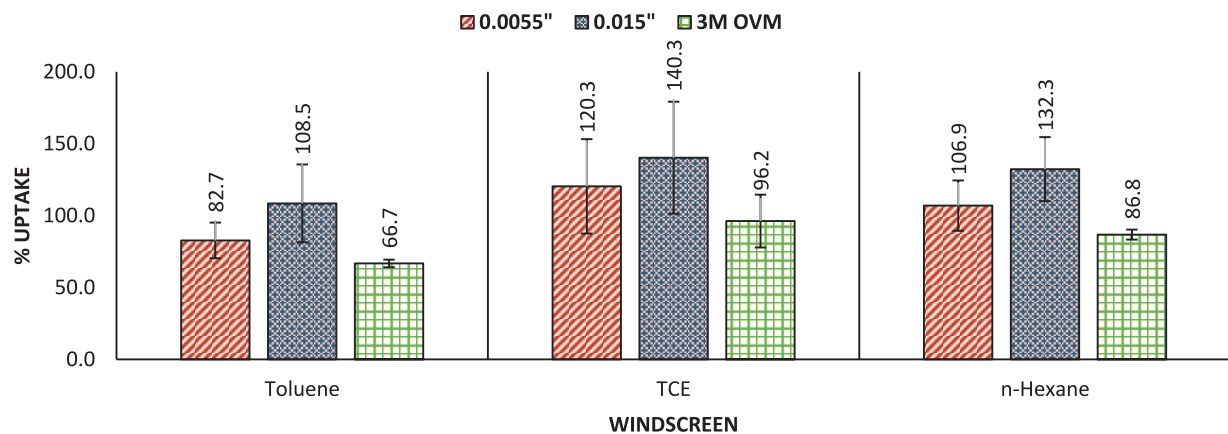
#### Statistics

A one-way ANOVA showed the mean sampler concentrations collected by each windscreen at respective STELs (Table 1) were significantly different for toluene ( $F(2,21)=6.178$ ,  $P=.0078$ ) but not for TCE ( $F(2,15)=2.7541$ ,  $P=.0958$ ). Tukey's HSD<sup>23</sup> was used to make post hoc pairwise comparisons between the windscreen pairs used at the toluene and

TCE STEL (Table 3). The post-hoc analyses for the toluene STEL data showed the 0.015" × 3M OVM pair was significantly different ( $P=.013$ ), as are the 0.015" × 0.0055" pair ( $P=.0208$ ), but the comparison of the 3M OVM × 0.0055" pair failed to show significant differences. Post-hoc analyses for all TCE STEL pairs failed to show any significant differences.

One-way ANOVA of the mean concentrations collected by each windscreen at respective PELs (Table 2) showed significant differences for all analytes (toluene ( $F(2,15)=11.2676$ ,  $P=.001$ ), TCE ( $F(2,15)=7.5847$ ,  $P=.0053$ ), and n-hexane ( $F(2,15)=13.1522$ ,  $P=.0005$ )). Post-hoc analysis with Tukey's HSD<sup>23</sup> was used to determine the differences in windscreen

## PERCENT UPTAKE OF VOC PEL BY WINDSCREEN



**Figure 4.** Percent uptake of toluene, TCE, and n-hexane (n=3, respectively) at their respective PEL concentrations for samplers with varying windscreen pore sizes.

**Table 3.** Tukey's HSD<sup>23</sup>—Pairwise comparisons of modified and non-modified windscreens.

VOC	STEL			PEL		
	PAIRS		<i>P</i> <sup>A</sup>	PAIRS		<i>P</i> <sup>A</sup>
Toluene	0.0055"	0.015"	.0208	0.0055"	0.015"	.0255
	0.015"	3M OVM	.013	0.015"	3M OVM	.0008
	3M OVM	0.0055"	.9762	3M OVM	0.0055"	.22
TCE	0.0055"	0.015"	.3372	0.0055"	0.015"	.2161
	0.015"	3M OVM	.0834	0.015"	3M OVM	.0039
	3M OVM	0.0055"	.6718	3M OVM	0.0055"	.1176
n-Hexane	-	-	-	0.0055"	0.015"	.0326
	-	-	-	0.015"	3M OVM	.0003
	-	-	-	3M OVM	0.0055"	.0869

<sup>A</sup> $\alpha = .05$ .

pairs for toluene, TCE, and n-hexane at PEL concentrations (Table 3). Post-hoc analyses of the toluene PEL showed significant differences in the 0.0055"  $\times$  0.015" ( $P = .0255$ ) and the 0.015"  $\times$  3M OVM ( $P = .0008$ ) pairs, but not between the 0.0055"  $\times$  3M OVM pair. Similarly, post-hoc analyses of the TCE PEL showed significant differences in the 0.015"  $\times$  3M OVM ( $P = .0039$ ) pair, but failed to show a significant difference in either the 0.0055"  $\times$  0.015" or 0.0055"  $\times$  3M OVM pairs. Post-hoc analyses for the n-hexane PEL showed significant differences in the 0.0055"  $\times$  0.015" ( $P = .0326$ ) and 0.015"  $\times$  3M OVM ( $P = .0003$ ) pairs, but failed to show significant differences in the 0.0055"  $\times$  3M OVM pair. These results indicate that the 0.0055" mesh windscreens are most similar to that used in the industry standard 3M OVM.

## Discussion

### *Modified and non-modified sampler performance*

The current work compared as-received 3M OVMs (non-modified) to modified 3M OVMs with aftermarket windscreens (pore diameters 0.0055" and 0.015") installed, to determine a suitable windscreens for use in designs of PTD-compatible diffusive sampler prototypes. This was performed by exposing each sampler to known, airborne concentrations of toluene, TCE, and n-hexane, respectively, and ascertaining which sampler produced the most accurate concentrations. Analyte concentrations at near-STEL and PEL concentrations of toluene, TCE, and n-hexane were obtained by modified and non-modified 3M OVMs, using the non-modified samplers as a standard for performance comparisons. The

samplers modified with a 0.0055" windscreens were noted to be the most similar in sample collection to the non-modified samplers and were the closest of all tested samplers in predicting the chamber concentration. In contrast, the 0.015" windscreens were seen to collect the highest sample masses of the tested samplers (Tables 2 and 3). The observed behaviors of the modified windscreens may be explained by advection affecting the mass collected by the 0.0055" and 0.015" windscreens. Because the 0.015" windscreen had comparably larger pores than the 0.0055" and non-modified 3M OVM windscreens, turbulence created by the sampler placement in the air stream, could have resulted in analyte molecules being transported through the pores and directly onto the sorbent pad by the bulk motion of turbulent air, rather than by diffusion alone, as is the understood mechanism of the 3M OVM. Though advection likely took place with the 0.0055" windscreen, the relatively small pore size limited the amount of mass collected outside of diffusion-driven uptake, making it more similar to the non-modified 3M OVM, as evidenced by the relatively smaller standard deviation in samples collected using the 0.0055" windscreen. Additionally, advection may also explain the considerable standard deviations seen in both modified windscreens. Sampler placement within the chamber was changed between collection runs with the intent of balancing out any effects of varying chamber turbulence on sample collection, however, doing so may have resulted in variations in the level of advection experienced due to changes in air flow, thus resulting in larger standard deviations. Based on this line of thinking, the proprietary, 3M OVM windscreen appears to provide more protection against advection than either modified windscreen, with the 0.0055" windscreen being the next most protective of the 3 windscreens observed.

### Statistics

A pairwise comparison of each windscreen at near-STEL and PEL concentrations of toluene, TCE, and n-hexane, using Tukey's HSD, failed to find significant differences between the sample concentrations obtained by these samplers equipped with the 3 windscreens, meaning the non-modified 3M OVM and 0.0055" windscreens are statistically similar. The only exception to these findings was seen in the collection of TCE samples at near-STEL concentrations. However, considering the sensitivity limitations of diffusive sampling for short sampling times,<sup>6</sup> combined with the diluted sample used for GC analysis,<sup>8-11</sup> the lack of statistical differences in collected TCE mass could be an effect of the limited mass-uptake by diffusion. Had the sample collection period been allowed to run beyond 15 minutes, it is likely that relevant statistical differences would have been observed, as evidenced by the findings observed in the TCE samples collected at PEL concentrations for 8 hours. Based on these results, we believe that a 0.0055" pore

windscreen is a suitable, non-proprietary choice for use in future development of diffusive samplers.

### Limitations

Though careful considerations were made to minimize systemic errors within the present work, some limitations should be noted. First, the present work was conducted without explicit environmental controls (ie, temperature, barometric pressure, relative humidity). Though temperature and barometric pressure remained consistently at or near SATP conditions, changes in the relative humidity within the lab may have occurred, leading to slight changes in the adsorption capacity of the 3M sorbent pads. Second, while injecting analytes into the chamber's airstream, air back-flowed into the syringe, causing analyte to be injected into the chamber at a faster rate than that programmed into the syringe pump, resulting in concentration spikes recorded by the in-line PID at the beginning of each experimental run. Though it may be possible to generate a correction factor to improve sampler measurement accuracy, there is no guarantee that the concentration spikes will be uniform for each analyte. Third, the air changes within the modified samplers were assumed to be similar to the non-modified sampler and not explicitly measured. If significantly different air change rates were to occur in the modified samplers, this could have affected their ability to uptake analyte mass. Fourth, 3M encourages OVM users to verify the recovery coefficient of each analyte of interest, as laboratory and analysis techniques may vary between analytical labs.<sup>22</sup> For the purposes of this study, we assumed the accuracy of the manufacturer provided recovery coefficients for toluene, TCE, and n-hexane (1, 1.01, and 1.07 respectively).<sup>22</sup> This may have contributed to slight, but non-negligible differences in  $C_{\text{sampler}}$  calculations. Finally, the present work used only 2 commercially available windscreens for comparison with the non-modified 3M OVM windscreen, however, the 2 utilized in this study were easily accessible and affordable, as well as the smallest pore size windscreens available commercially.

### Conclusion

The present work sought to quantify the effects on sample collection of toluene, trichloroethylene, and n-hexane caused by the use of 3 discrete windscreens with varying pore sizes. This was accomplished by exposing modified and non-modified 3M 3500 OVMs to each analyte at PEL concentrations for 8 hours and STEL concentrations for 15 minutes, and determining the resulting mass uptake. Based on the collected data, the 0.015" windscreen equipped sampler collected the highest amount of sample, with the 0.0055" and non-modified 3M OVM windscreens following in order of highest to lowest collected mass. In addition, this study sought to determine the most comparable, non-proprietary windscreen to the commercially available

3M 3500 OVM, for use in the development of a PTD-compatible diffusive sampler. By comparing the sampling performance of a non-modified 3M OVM with 3M OVM modified with either a 0.0055" or 0.015" pore size windscreen for collecting toluene, TCE, and n-hexane, this study has demonstrated that using a 0.0055" windscreen is statistically similar to the proprietary 3M OVM windscreen across all analytes and most exposure environments (ie, PEL and STEL exposures). The 0.0055" windscreen-modified sampler was also seen to more accurately predict the concentrations produced in the sampling chamber. Though the non-modified windscreen appeared to be more protective against sample collection via advection, we believe the use of 0.0055" windscreen is an overall sufficient choice as a non-proprietary windscreen for use in future developments of diffusive sampling technologies based on the data presented.

### Author Contributions

Savannah R. Jones: investigation, formal analysis, writing-original draft, writing-reviewing and editing. Jacob S. Shedd: conceptualization, methodology, visualization, supervision, writing-original draft, writing-reviewing and editing. Jonghwa Oh: supervision, writing-reviewing and editing. Claudiu Lungu: conceptualization, methodology, project administration, funding acquisition, supervision, resources, writing-reviewing and editing.

### Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article. Additional question concerning the data presented may be addressed to the corresponding author [C.T.L.].

### Patent Information

Provisional patent 63/251,286 was filed on 10/01/2021 to protect the intellectual property herein.

### ORCID iD

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### REFERENCES

- Montero-Montoya R, López-Vargas R, Arellano-Aguilar O. Volatile organic compounds in air: sources, distribution, exposure and associated illnesses in children. *Ann Global Health*. 2018;84:225-238.
- ASTDR. Interaction Profile for: Benzene, Toluene, Ethylbenzene, and Xylenes (BTEX). Department of Health and Human Services Public Health Service Agency for Toxic Substances and Disease Registry. May 2004. Accessed August 11, 2021. <https://www.atsdr.cdc.gov/interactionprofiles/IP-btex/ip05.pdf>
- United States Environmental Protection Agency. Volatile organic compounds' impact on indoor air quality. Published 2021. Accessed January 6, 2021. [www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality](https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality)
- WHO Working Group. Updating and revision of the quality guidelines for Europe: report on WHO Working Group on Volatile Organic Compounds, Brussels, Belgium, 2-6 October 1995. Published 1996. Accessed February 10, 2021. [http://apps.who.int/iris/bitstream/handle/10665/107551/EUR\\_ICP\\_EHAZ\\_94\\_05\\_MT\\_12.pdf?sequence=1&isAllowed=y](http://apps.who.int/iris/bitstream/handle/10665/107551/EUR_ICP_EHAZ_94_05_MT_12.pdf?sequence=1&isAllowed=y)
- US Bureau of Labor Statistics. Labor force statistics from the current population survey. Published 2021. <https://www.bls.gov/cps/lfcharacteristics.htm#occind>
- Anna DH.ed. *The Occupational Environment: Its Evaluation, Control, and Management*. 3rd ed. American Industrial Hygiene Association; 2011.
- United States Environmental Protection Agency. Passive samplers for investigations of air quality: method description, implementation, and comparison to alternative sampling methods. *Eng Issue*. Published online 2014:1-22. Accessed March 19, 2021. <https://clu-in.org/download/issues/vi/VI-passive-samplers-600-R-14-434.pdf>
- NIOSH. Hydrocarbons, BP 36°-216°C (NIOSH-1500). In: *NIOSH Manual of Analytical Methods*. 4th ed. National Institute for Occupational Safety & Health; 1994:8-11. <https://www.cdc.gov/niosh/docs/2003-154/pdfs/1500.pdf>
- NIOSH. Hydrocarbons, Aromatic (NIOSH-1501). In: *NIOSH Manual of Analytical Methods*. 4th ed. National Institute for Occupational Safety & Health; 2003:1-7. <https://www.cdc.gov/niosh/docs/2003-154/pdfs/1501.pdf>
- NIOSH. Hydrocarbons, halogenated (NIOSH-1003). In: *NIOSH Manual of Analytical Methods*. 4th ed. National Institute for Occupational Safety & Health; 2003:1-7.
- Elskamp CJ. OSHA sampling and analytical methods – Toluene (Organic Method #111). OSHA sampling and analytical methods. Published 1998. Accessed August 11, 2021. <https://www.osha.gov/dts/sltc/methods/organic/org111/org111.pdf>
- Floyd EL, Sapag K, Oh J, Lungu CT. Photothermal desorption of single-walled carbon nanotubes and coconut shell-activated carbons using a continuous light source for application in air sampling. *Ann Occup Hyg*. 2014;58:877-888.
- Shedd JS, Kuehster WW, Ranjit S, et al. Determining the thermal properties of buckypapers used in photothermal desorption. *ACS Omega*. 2021;6:5415-5422.
- Oh J. *Fabrication and Characterization of Buckypapers for Use in Air Sampling*. PhD dissertation. The University of Alabama at Birmingham; 2016.
- Oh J, Floyd EL, Watson TC, Lungu CT. Fabrication and adsorption characterization of single-walled carbon nanotube (SWNT) buckypaper (BP) for use in air samplers. *Anal Methods*. 2016;8:4197-4203.
- Oh J, Floyd EL, Parit M, Davis VA, Lungu CT. Heat treatment of buckypaper for use in volatile organic compounds sampling. *J Nanomat*. 2016;2016:1-6.
- Shedd JS, Floyd EL, Oh J, Lungu CT. FTIR determination of surfactant removal from arc discharge buckypapers for air sampling. *J Adv Nanomater*. 2019;4:11-16.
- Woeckenberg ML. Toluene (diffusive sampler) 4000. In: *NIOSH Manual of Analytical Methods*. 4th ed. National Institute for Occupational Safety & Health; 1994:6-9. Accessed August 12, 2021. <https://www.cdc.gov/niosh/docs/2003-154/pdfs/4000.pdf>
- Agilent Technologies. Agilent 7890B gas chromatograph: data sheet. Published 2013. <https://www.agilent.com/cs/library/datasheets/public/5991-1436EN.pdf>
- 3M Occupational Health and Environmental Safety Division. 3M Technical data bulletin: #119, September, 1996—Toluene. Published 2000. Accessed January 12, 2021. <https://multimedia.3m.com/mws/media/51010/3morganic-vapor-monitors-toluene-technical-bulletin.pdf>
- Caravanos J. *Quantitative Industrial Hygiene: A Formula Workbook*. American Conference of Industrial Hygienists (ACGIH); 1991.
- 3M OH&ESD. Organic vapor monitor sampling and analysis guide. Published 2019. Accessed August 11, 2021. <https://multimedia.3m.com/mws/media/1107310/organic-vapor-monitor-sampling-and-analysis->
- Tukey JW. Comparing individual means in the analysis of variance. *Biometrics*. 1949;5:99-114. <http://www.jstor.org/stable/3001913>
- NIOSH. NIOSH Pocket Guide to Chemical Hazards: Toluene. Published 2019. Accessed January 6, 2020. <https://www.cdc.gov/niosh/npg/npgd0619.html>
- NIOSH. *Immediately Dangerous to Life or Health (IDLH) Values: Trichloroethylene*. National Institute for Occupational Safety and Health. Published 1994.
- NIOSH. NIOSH Pocket Guide to Chemical Hazards: Trichloroethylene. Published 2019. Accessed January 6, 2020. <https://www.cdc.gov/niosh/npg/npgd0629.html>
- NIOSH. NIOSH Pocket Guide to Chemical Hazards: n-Hexane. Published 2019. Accessed January 6, 2020. <https://www.cdc.gov/niosh/npg/npgd0322.html>