Robots can reduce the exposure of people to volatile organic compounds (VOCs) during application of spray foam insulation

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Abstract

An experimental study was conducted to determine whether, and by how much, worker exposure to volatile organic compounds (VOCs) would be reduced when robots are used to apply spray foam insulation. The study was undertaken in a test room where the ventilation rates were controlled and temperature and relative humidity were recorded. Four independent spraying experiments were conducted where robots were used to spray foam onto a suspended timber floor. The environmental conditions were recorded and VOCs were actively sampled using thermal desorption tubes during the periods of spraying (15 min) and curing (10 min). The tubes were analysed using thermal desorption-gas chromatography- mass spectrometry (TD-GC-MS). Four VOCs were quantified in two locations- near the spraying surface and near the worker operating the robot (outside the room). Measurable concentrations of 1,2-dichloropropane, 1,4-dioxane, chlorobenzene and triethyl phosphate (TEP) were quantified inside the room, whilst the concentration near the worker were below the detection limits. The experiment indicates that if workers wear ineffective personal protection equipment, they could be exposed to multiple airborne pollutants due to their close proximity to the spraying surface. Our study is the first to quantify the reduction of workers exposure to four VOCs when robots are used compared to conventional manual spraying.

1 INTRODUCTION

Isocyanate based materials (polyurethane (PU) and polyisocyanurate (PIR)) are widely used across the world for retrofitting buildings. The two products use the same component liquids; however, mixed at different ratios where PU uses a balanced approach (A:B=1:1), whilst for PIR more isocyanate is used (A:B=2:1) (Gravit *et al.*, 2017). Sales of PU products in the U.S. construction industry alone generated $790 million in revenue in 2015 (ACC, 2018). These products offer high carbon savings potential, as embodied carbon of PIR is lower than EPS and mineral wool (Tingley, Hathway and Davison, 2015), and high energy savings potential as PU outperforms conventional insulation materials in thermal conductivity (Al-Ajlan, 2006). However the potential for worker exposure to volatile organic compounds (VOCs) when PU and PIR materials are sprayed on site is a subject of growing interest (ASTM International, 2017). Research on VOCs from spray foam insulation products (SPF) is still scarce taking into account the wide use of these products in the built environment. As Class 1 (1,2-DCP) and Class 2B (1,4-dioxane) carcinogens have been found to emit from spray foam (Sleasman et al., 2017), it is important to consider the potential of using robots for application of SPF. Recent evidence suggests insufficient personal protection equipment (PPE) kit is sometimes used by sprayers and helpers in the industry (Estill *et al.*, 2019). This study measures, and compares, concentration of four VOCs during spraying of SPF - near the spraying surface where a robot installs SPF and near the worker operating the robot from a distance. The objective of this paper is to provide experimental data comparing exposure to VOCs of workers between manual spraying (by hand) and automated spraying (with robot). The study aims to provide evidence of best practice for worker protection when applying isocyanate based sprayable insulation materials.

2 METHOD

To measure VOC concentration, active sampling using thermal desorption (TD) tubes was used. Four VOCs emitted from SPF were selected for the study: 1,2-dichloropropane (1,2-DCP), 1,4-dioxane, chlorobenzene and triethyl phosphate (TEP). Air samples were extracted near the worker and from a spraying room where the ventilation rate was controlled and temperature and relative humidity were monitored during the study period. The experiment was repeated four times in order to reduce uncertainty between different insulation batches. The tubes were analysed using gas chromatography-mass spectrometry (GC-MS).

Chemicals evaluated and criteria

The SPF used was a two component closed cell spray foam, which contained polymeric methylene diphenyl diisocyanate (pMDI) (side A) and a mixture of polyol and additives (side B). Side B contained a polyol, flame retardants, catalyst and blowing agent. During the application, the two components were heated and mixed using a Graco E-20 hydraulic foam equipment and sprayed through a nozzle attached on a robot. The chemicals chosen for this study and the emission criteria are listed in Table 1. The four VOCs were selected due to their carcinogenicity classification (1,2-DCP and 1,4-dioxane) and potential impact as irritants (chlorobenzene and triethyl phosphate).

Table 1. Recommended and legally permissible exposure values for chemicals evaluated in this study (all units are μg/m^3)

Chemical	Carcinogenicity (IARC)	CAS Number	EU-LCI	California OEHHA CREL	UK HSE STEL (15-min)	NIOSH REL (30-min)	New Zealand WES (8-hour)	EPA AEGL (10 min)
1,2-DCP	Class 1	78-87-5	n/a	n/a	n/a	n/a	23,100	n/a
1,4-dioxane	Class 2B	123-91-1	400	3000	n/a	3600	n/a	61,000*
Chlorobenzene	n/a	108-90-7	n/a	1000	14,000	n/a	n/a	46,000
Triethyl phosphate	n/a	78-40-0	n/a	n/a	n/a	n/a	n/a	n/a

Analytical method and sampling protocol

All sampling was undertaken using Tenax-TA thermal desorption tubes and low flow SKC 224-PCMTX8 pumps. The foam was applied to the underside of the timber floor structure at a thickness of 150 mm also covering the floor joists. The concentrations of VOCs during spraying (15 min) and curing (10 min) were determined using TD-GC-MS. The short sampling time as per Table 2 was selected due to the high amount of VOCs during spraying and to avoid saturation of the sampling tubes. The locations of the pumps were selected to quantify the difference in exposure of the sprayer during manual application compared to when using a robot. Following existing protocols (Tian *et al.*, 2018), a flow rate of 0.05 l/min was used to extract air from the box and 0.2 l/min was used to extract air near the worker exposure and for background samples. The pumps were calibrated using two clean desorption tubes before each sample was taken. The sampling parameters are shown in Table 2.

Table 2. Sampling and analytical chemistry procedure

Unit	Location	Sampling rate (l/min)	Sampling period (min)			Sampling media
			Background	Spraying	Curing	
Pump #1	Inside box	0.05	30	15	10	Tenax-TA tube
Pump #2	Inside box	0.05		15	10	
Pump #3	Near worker	0.20	30	30		

Background samples of the empty box and the working area of the sprayer were taken between each test. Blank tubes were used between each sample and all consumables were brand new. The pump and tubes near the worker were left running for 30 min during the spraying and curing of the SPF. The tubes in the box were replaced by new ones after spraying had finished to measure the concentration of VOCs during curing. After each sampling process, the tubes were closed with long-term storage brass caps (Perkin Elmer Part Number M0413624). All samples were analysed within 12 h using GC-MS. The analytical conditions (TD-GC-MS) of Naldzhiev et al. (2017) were used for all analytical runs. Between each set of sampling tubes (primary and backup), a blank tube was analysed to ensure no contaminants were transferred between samples and the column and TD lines were flushed. Each tube was conditioned at 350 °C at a 150 ml/min nitrogen flow for 15 min before each use. All brass storage caps were placed in an oven at 150 °C for 24 h between experiments. PTFE ferrules inside brass caps were submerged in methanol and cleaned with ultrasonic bath in 99% methanol for 15 min and placed inside oven at 150 °C for 5 min to dry between experiments. The analytical calibration parameters for each VOC are summarised in Table 3. Pearson's linear regression (r^2) calibration for each VOC was developed using OriginPro2017 software. Linear fit with x-error and Pearson's linear regression (r^2) was used for the calibration points as per Table 3 to calculate the concentration of each VOC in the samples. Two tubes were used for each test and no breakthrough occurred in any of the samples above the detection limits.

Table 3. Analytical calibration parameters for VOCs in TD-GC-MS process

Chemical	**1,2-DCP**	**1,4-dioxane**	**Chlorobenzene**	**TEP**
Desorption efficiency	99% ± 0.97%	99% ± 1.67%	99% ± 1.23%	100% ± 1.82%
Linear regression (r^2)	0.985	0.986	0.989	0.991
Calibration points	21	21	21	21
Calibration range (ng)	45-13800	49-9272	54-9720	44-8341
Limit of detection[1] (ng)	28	42	17	119

Testing facility information and insulation material used

A two component closed cell SPF was sprayed to the interior of a wooden box with a suspended timber floor (Figure 1). The dimensions of the box are 3 m (L) by 1 m (W) by 1.20 m (H) and the inside of it is covered with aluminium foil, apart from the floor (1 m x 1 m). Between each experiment both the floor and aluminium cover of the box was replaced to avoid cross-contamination between experiments. The box was placed

[1] Code of Federal Regulations, Definition and procedure for the determination of the method detection limit – Revision 1.11. In 2003; Vol. CFR 40, Ch. 1, Pt. 136

within a room with a total volume of 39.4 m^3 and dimensions of 4 m x 4 m and height of 2.2-2.4 m. The ventilation rate of the room was controlled through an extract fan located on top of the room that generated negative pressure. The ventilation rate used for the experiment was 550 m^3/h as per best practice procedures for spraying (Center for Polyurethane Industry, 2012; Poppendieck *et al.*, 2019) and was measured with a Testo 417 vane anemometer attached to a funnel. Between each experiment, the timber floor and aluminium foil from the box were replaced with new ones and the ventilation was left running for 48-168 h at a rate of 125 m^3/h to flush out all VOCs. During spraying the experimental setup simulates a best practice field study environment, where an extractor fan is attached to the air brick of an existing house during the spraying process onto a suspended timber floor as per Figure 1. Four surveys were undertaken over a two-month period between September and December 2018. Samples were collected from inside the box and near the sprayer operating the robot as per Figure 1.

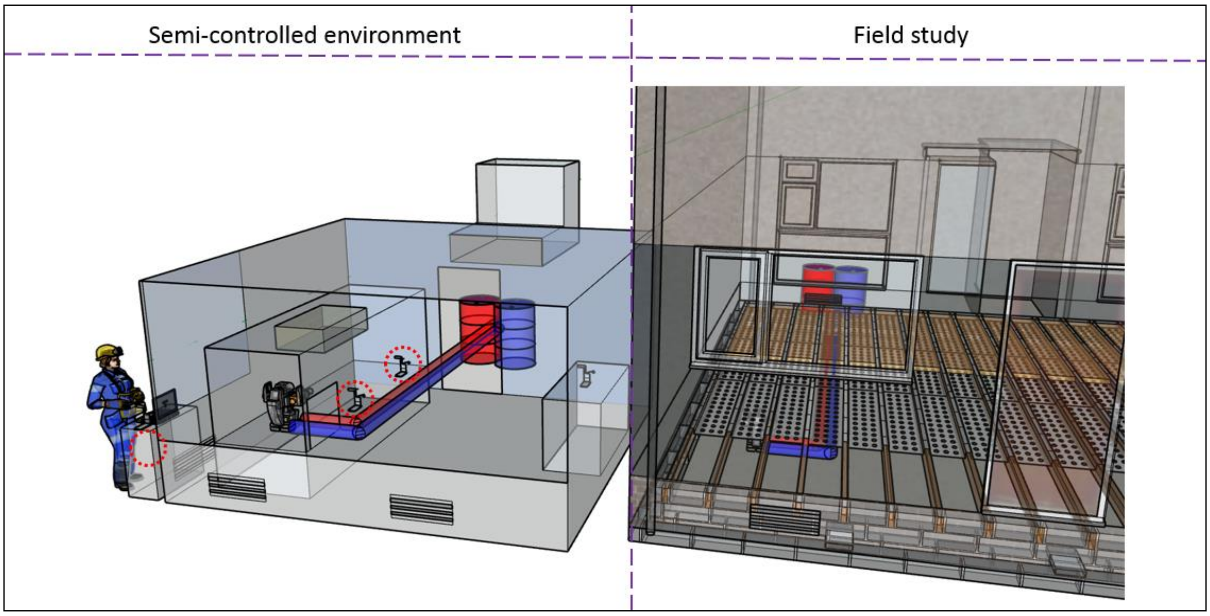

Figure 1. Visualisation of the semi-controlled environment and similarity with field studies. Dotted red lines represent where locations for samples collection.

Environmental conditions

The temperature and relative humidity in the testing room were recorded using a HOBO data logger with a recording interval of 1 min. The logger was calibrated by the manufacturer before use and had a declared accuracy of ±0.21 °C (temperature) and ±2.5% (RH). Figure 2 shows the ambient conditions during all experiments.

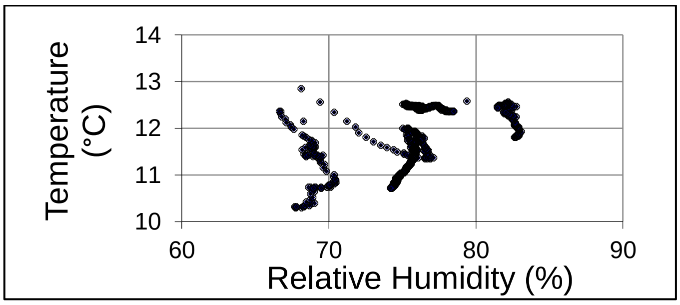

Figure 2. Ambient application conditions during sampling

3 RESULTS

For each individual VOC, the mass-spectrum was retrieved using single-ion-monitoring (SIM) and the peak area was retrieved. Regression analysis using the calibration curves was used to calculate the concentrations of each VOC in the samples. No breakthrough over the detection limits occurred during the sampling process making the results quantifiable. Figures 3-6 show the concentration of the four VOCs in the spray box during spraying and curing. The full dataset is present in Appendix A. All concentrations in the background samples (box and sprayer area) and the worker area were below the detection limits for all experiments.

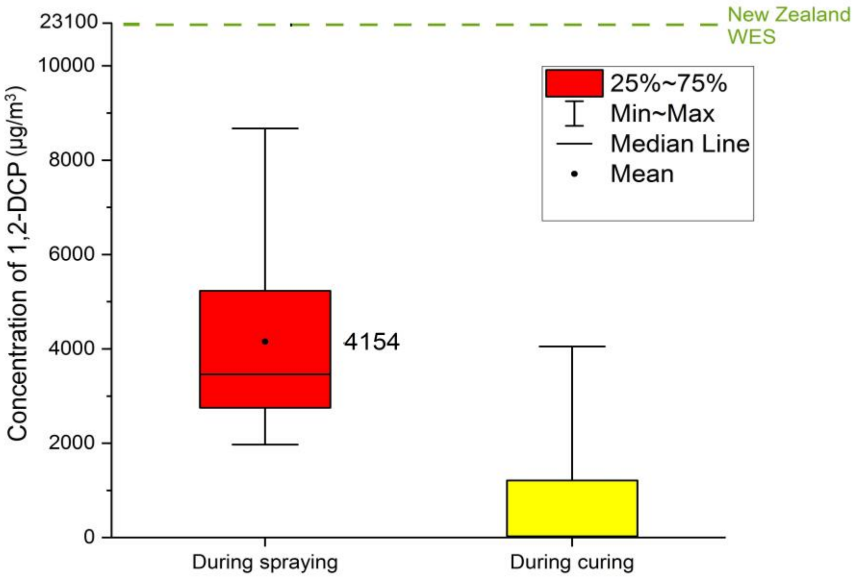

Figure 3. Concentration of 1,2-DCP (µg/m3) in air in the control box during spraying and curing. During curing 62.5% of the samples (n=5) were below detection limits therefore the mean was not calculated.

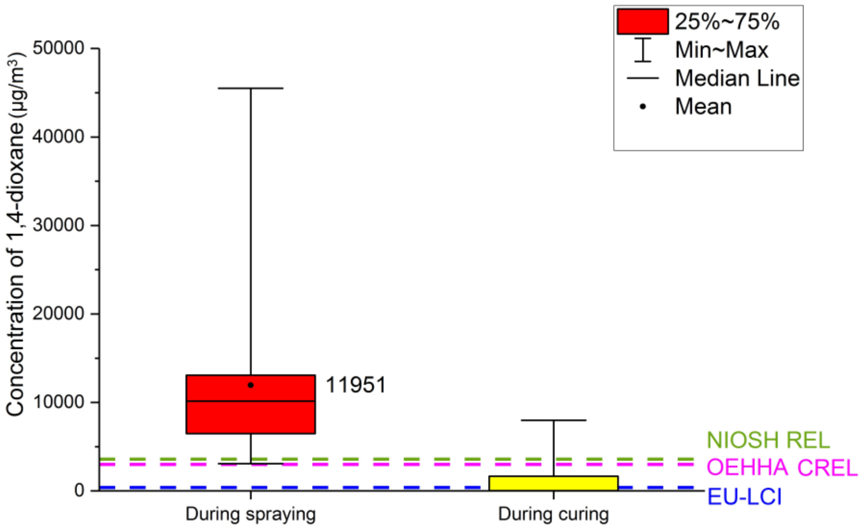

Figure 4. Concentration of 1,4-dioxane (µg/m3) in air in the control box during spray-ing and curing. During curing 75% of the samples (n=6) were below detection limits therefore the mean was not calculated.

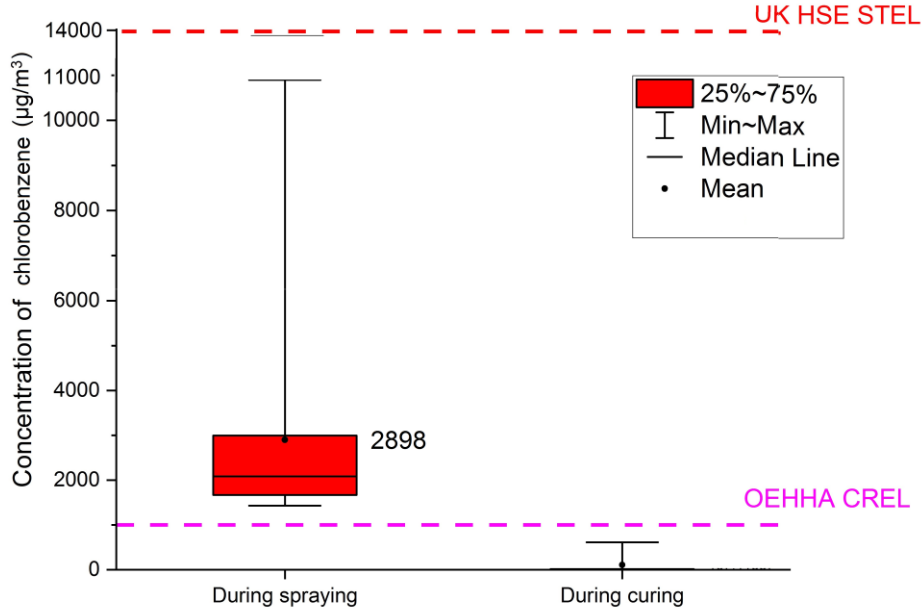

Figure 5. Concentration of chlorobenzene (µg/m3) in air in the control box during spraying and curing. During curing 75% of the samples (n=6) were below detection limits therefore the mean was not calculated.

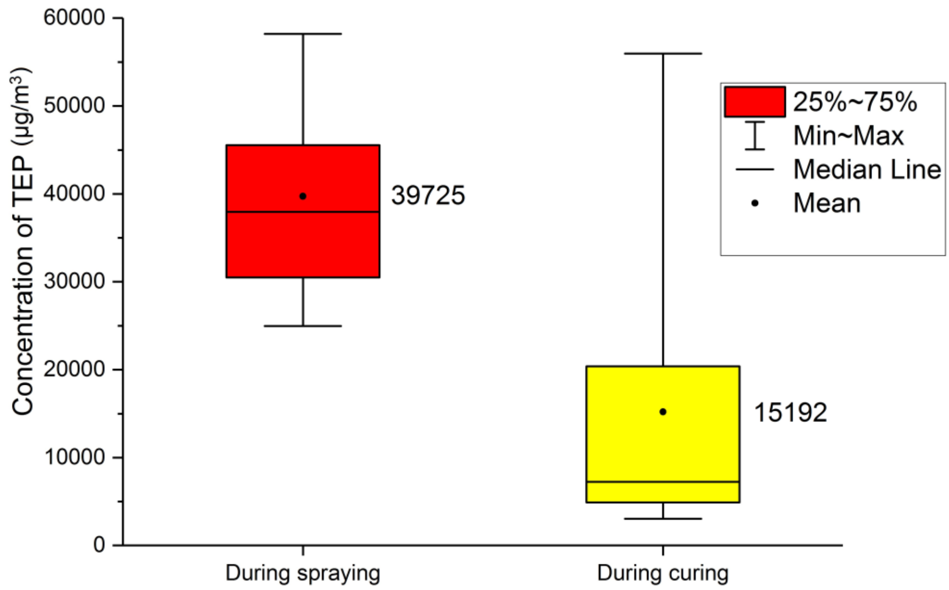

Figure 6. Concentration of TEP (µg/m3) in air in the control box during spraying and curing. All concentrations were above detection limits.

The concentration of the three compounds that were not present in the safety data sheets (1,2-DCP, 1,4-dioxane and chlorobenzene) decreased after spraying stopped in the spray box (Figures 3-6). The 1,2-dichloropropane concentration in the box did not exceed the New Zealand WES value during spraying (Figure 3). The 1,4-dioxane concentration exceeded the NIOSH REL, OEHHA CREL and EU-LCI values, whilst the chlorobenzene concentrations exceeded the OEHHA CREL values during spraying (Figure 4 and 5). The flame retardant (TEP) concentration decayed after spraying had finished; however, it was still present in measurable concentrations during the curing process as per Figure 6. All four VOCs within the spraying area were below the recommended exposure values during the curing process, apart from a single outlier for 1,4-dioxane as per Figure 4.

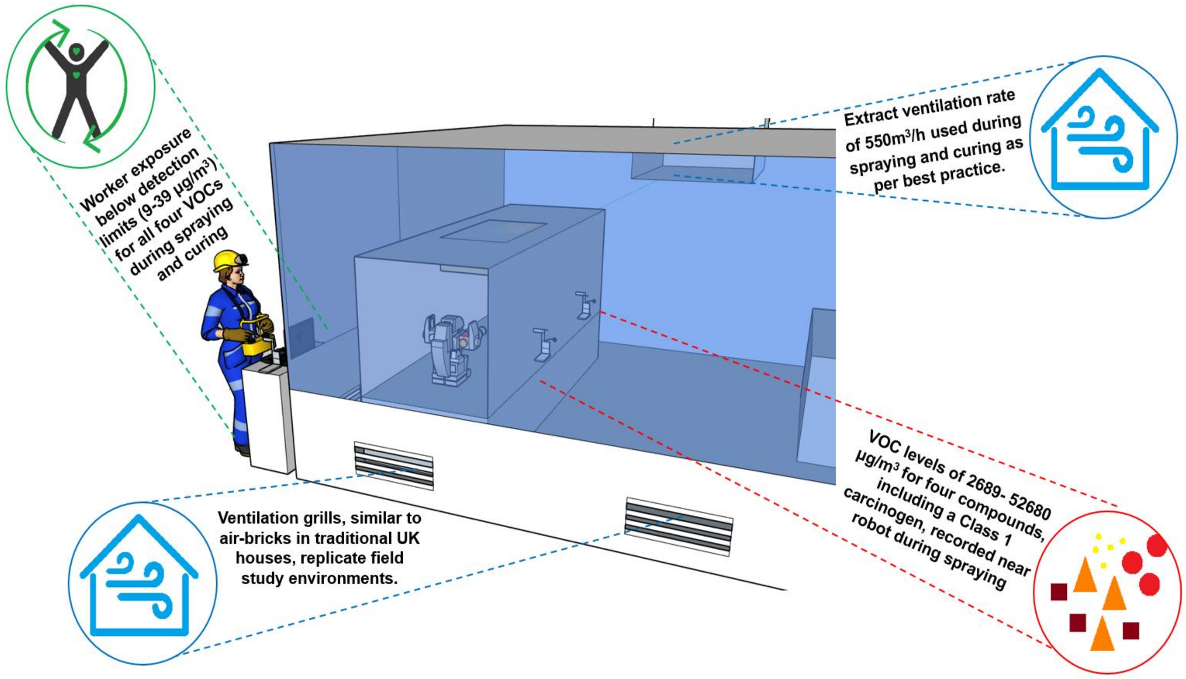

Figure 7. Summary of the experimental setup and results.

4 DISCUSSION

Figures 3-6 demonstrate that high concentrations of VOCs were recorded near the spraying surface (inside the containment). The mean 1,4-dioxane concentration exceeded NIOSH recommended exposure limits (REL) by a factor of 10 with the maximum level recorded exceeding NIOSH REL by a factor of 34. Our findings confirm that during manual application, even if best practice for extract ventilation is used, significant concentrations of VOCs will be released near the spraying surface and therefore using appropriate PPE equipment is paramount. Workers in the SPF industry were found to not always wear the full PPE kit, with helpers particularly vulnerable to exposure of chemical emissions (Estill *et al.*, 2019). Even when full PPE kit is used, including respirators, coveralls and gloves, workers in the SPF industry could still be exposed to measurable concentrations of flame retardants (Bello *et al.*, 2018). Our findings suggest that emissions of chemicals not listed in safety data sheets (1,2-DCP, 1,4-dioxane and chlorobenzene) decrease after spraying has stopped. These compounds have however been found emitting from cured, and up to 2 year old, SPF products (Poppendieck, Gong and Emmerich, 2016; ASTM International, 2017). Concentration in the vicinity of the worker were all below detection limits when using robots. Although this study was undertaken in semi-controlled conditions, it does demonstrate the potential of using robots to minimise exposure of workers to chemical emissions when applying SPF insulation.

Limitations and further research

The study demonstrated concentrations constituting exposure during spraying, however this does not translate to personal exposure when using appropriate PPE kit. Only one SPF product with several batches was tested, therefore the results might not be representative of all products available on the market. Different products will be used for further investigation. The experiments were undertaken in a semi-controlled environment with limited external air infiltration, therefore the ventilation of the room was driven by the extract fan. Although these conditions are very similar to a field study consisting of an existing UK house with an extractor fan attached to an air brick, further investigation will be undertaken to determine the exposure of workers in-situ. The study focused on four VOCs, which represent 1-5% of the raw materials weight of the SPF product. Further investigation will be undertaken measuring isocyanates (Ferreira *et al.*, 2014) and all B-side emissions following the principles of the ASTM 8142-17 method. These steps will allow for a more complete comparison of robots versus manual application during SPF insulation applications.

5 CONCLUSION

Four experiments were conducted in a room with a controlled ventilation rate where spray foam insulation was applied using robots. The SPF was sprayed in a box onto a suspended timber floor and four VOCs were collected using low flow pumps and Tenax-TA tubes during spraying and curing (for a total time of 30 min). The air near the worker operating the robots was also sampled for VOCs during these two periods. The four VOCs (1,2-dichloropropane, 1,4-dioxane, chlorobenzene and triethyl phosphate) were quantified using gas-chromatography mass-spectrometry (GC-MS).

The concentration of VOCs near the worker were below the detection limits, whilst significant concentrations of all four VOCs were measured inside the spray box. In particular, 1,4-dioxane exceeded recommended exposure limits and the maximum chlorobenzene levels were close to the maximum allowable UK workplace exposure limits reinforcing the case for wearing appropriate and correctly fitted PPE when spraying manually. The experiment indicates that if workers wear improper personal protection equipment, they could be exposed to multiple airborne pollutants due to their close proximity to the spraying surface. Our study is the first to demonstrate that if robots are used to apply SPF, workers' exposure to four VOCs can be significantly reduced compared to conventional manual spraying. The 1,2-DCP concentration did not exceed recommended guideline levels, but as it is a Class 1 carcinogen, our study highlights that it would be a more appropriate strategy to eliminate it at the source, alongside 1,4-dioxane (Class 2B carcinogen) and chlorobenzene.

Our future work will consist of quantification of all primary emissions from a number of SPF materials in-situ in order to assess the potential of using robots for worker protection in field studies.

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Appendix A- Complete dataset of study results.

Table A. Concentration of four VOCs in an experimental chamber during polyurethane spray foam spraying and curing study results. All recorded concentrations were measured using thermal desorption tubes and analysed with TD-GC-MS. Concentrations were calculated with calibration curves and measured in μg/m^3.

	Experiment number ↓	Worker area background	Spraying box background	Worker area	Spray box pump #1	Spray box pump #2	Spray box pump #1	Spray box pump #2
Period →		Before spraying	Before spraying	During spraying and curing	During spray-ing	During spray-ing	During curing	During curing
Compound ↓					(μg/m^3)	(μg/m^3)	(μg/m^3)	(μg/m^3)
1,2-DCP	1	<DL	<DL	<DL	2689 ± 569	4630 ± 708	<DL	<DL
	2	<DL	<DL	<DL	7526 ± 1416	6447 ± 1324	1579 ± 360	993 ± 301
	3	<DL	<DL	<DL	2527 ± 558	3531 ± 629	<DL	<DL
	4	<DL	<DL	<DL	3251 ± 609	2812 ± 578	3270 ± 799	<DL
1,4-Dioxane	1	<DL	<DL	<DL	5545 ± 1293	6125 ± 3039	<DL	<DL
	2	<DL	<DL	<DL	33638 ± 11858	12381 ± 2135	6282 ± 1714	3683 ± 397
	3	<DL	<DL	<DL	13791 ± 1650	10251 ±1948	<DL	<DL
	4	<DL	<DL	<DL	6930 ± 3202	6953 ± 3207	<DL	<DL
Chloroben-zene	1	<DL	<DL	<DL	1533 ± 104	1591 ± 106	<DL	<DL
	2	<DL	<DL	<DL	6969 ±3927	4233 ± 1290	614 ± 107	378 ±100
	3	<DL	<DL	<DL	1749 ± 111	2946 ± 279	<DL	<DL
	4	<DL	<DL	<DL	2056 ± 243	2107 ± 245	<DL	<DL
TEP	1	<DL	<DL	<DL	34840 ± 7139	37130 ± 7366	4910 ± 1300	6255 ± 1488
	2	<DL	<DL	<DL	52680 ± 5524	28951 ± 3990	47486 ± 8465	32164 ± 7567
	3	<DL	<DL	<DL	37776 ± 7429	50843 ± 5324	10818 ± 5359	4899 ± 1858
	4	<DL	<DL	<DL	38099 ±7461	37485 ± 7440	6684 ± 2111	8326 ± 4773