

Evaluation of the COSHH Essentials Model with a Mixture of Organic Chemicals at a Medium-Sized Paint Producer

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The Control of Substances Hazardous to Health (COSHH) Essentials model was evaluated using full-shift exposure measurements of five chemical components in a mixture [acetone, ethylbenzene, methyl ethyl ketone, toluene, and xylenes] at a medium-sized plant producing paint materials. Two tasks, batch-making and bucket-washing, were examined. Varying levels of control were already established in both tasks and the average exposures of individual chemicals were considerably lower than the regulatory and advisory 8-h standards. The average exposure fractions using the additive mixture formula were also less than unity (batch-making: 0.25, bucket-washing: 0.56) indicating the mixture of chemicals did not exceed the combined occupational exposure limit (OEL). The paper version of the COSHH Essentials model was used to calculate a predicted exposure range (PER) for each chemical according to different levels of control. The estimated PERs of the tested chemicals for both tasks did not show consistent agreement with exposure measurements when the comparison was made for each control method and this is believed to be because of the considerably different volatilities of the chemicals. Given the combination of health hazard and exposure potential components, the COSHH Essentials model recommended a control approach ‘special advice’ for both tasks, based on the potential reproductive hazard ascribed to toluene. This would not have been the same conclusion if some other chemical had been substituted (for example styrene, which has the same threshold limit value as toluene). Nevertheless, it was special advice, which had led to the combination of hygienic procedures in place at this plant. The probability of the combined exposure fractions exceeding unity was 0.0002 for the batch-making task indicating that the employees performing this task were most likely well protected below the OELs. Although the employees involved in the bucket-washing task had greater potential to exceed the threshold limit value of the mixture ($P > 1 = 0.2375$), the expected personal exposure after adjusting for the assigned protection factor for the respirators in use would be considerably lower ($P > 1 = 0.0161$). Thus, our findings suggested that the COSHH essentials model worked reasonably well for the volatile organic chemicals at the plant. However, it was difficult to override the reproductive hazard even though it was meant to be possible in principle. Further, it became apparent that an input of existing controls, which is not possible in the web-based model, may have allowed the model be more widely applicable. The experience of using the web-based COSHH Essentials model generated some suggestions to provide a more user-friendly tool to the model users who do not have expertise in occupational hygiene.

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INTRODUCTION

Control banding (CB) is a framework used to manage occupational risk (AIHA, 2007). CB follows a utilitarian philosophy that presumes it is possible to group agents of similar toxicity or similar toxic mechanisms, agents of like exposures and/or like risks, and to manage risks expediently and with limited resources. The first initiative to use the CB approach came from the pharmaceutical industries who divided pharmacological agents typically into five hazard categories based on their inherent toxicological and pharmacological properties (Naumann *et al.*, 1996). In the early 1990s, an effort to extend the CB approach into small- and medium-sized enterprises where employees' exposure assessment was unlikely to be performed was initiated by the Health and Safety Executive (HSE) in Great Britain and resulted in a development of a tool known as the Control of Substances Hazardous to Health (COSHH) Essentials (Brooke, 1998; Maidment, 1998; Russell *et al.*, 1998). The key components of the COSHH Essentials are health hazard bands using 'risk phrases' (R-phrases), exposure potential bands based on a dustiness or volatility of chemicals and quantity of chemicals used, and stratified control approaches to provide adequate control strategies. In the COSHH Essentials model, risk assessment is performed through combining a health hazard band and an exposure potential band, and risk management is achieved by applying an adequate control method recommended as a result of the risk assessment.

Employers or supervisors perform routine sampling to ensure that employees' exposures are below occupational exposure limits (OELs). However, exposure measurements are expensive and often require an expert (Balsat *et al.*, 2003), and an intensive schedule of routine exposure monitoring is only necessary when there is a likelihood that exposures may approach or exceed OELs. Many countries would support the use of fully validated CB tools as a screen for the purpose of prioritizing exposure measurements. Such a strategy would be valuable in assisting companies to comply with the Registration, Evaluation, Authorization, and Restriction of Chemicals regulation (REACH) (European Union, 2006; Tielemans *et al.*, 2007; Bracker *et al.*, 2009; Ogden, 2010).

The COSHH Essentials model is widely accepted already (Money, 2003). Prior to the dissemination of

this tool to the public, the potential users and professional groups were consulted regarding the model and it has been evaluated by several researchers (Tischer *et al.*, 2003; Jones and Nicas, 2006; Hashimoto *et al.*, 2007; Lee *et al.*, 2009). Tischer *et al.* (2003) evaluated the COSHH Essentials against exposure measurements from Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA) field studies and existing chemical exposure data. Overall, good agreements from the comparison of the measurements and the model predicted ranges were reported for the solid substances and for organic solvents of liter quantities, while the predicted ranges were above the measurements for some instances of small-scale use of solvents such as painting and applying adhesives in a dispersive process. Hashimoto *et al.* (2007) also reported a good agreement from the evaluation of the model with observed data at 12 workplaces of a petroleum company in Japan. In our previous study (Lee *et al.*, 2009), it was determined that the COSHH Essentials worked well for both short-term and full-shift evaluation in a small printing plant. On the other hand, Jones and Nicas (2006) tested the COSHH Essentials using data from the National Institute for Occupational Safety and Health (NIOSH) Health Hazard Evaluations (HHE) and Control Technology Assessments (CTA) by defining under-controlled errors and over-controlled errors. They defined under-controlled errors as 'instances in which the airborne concentration exceeded the upper limit of the chemical's exposure band in the presence of control technology' and over-controlled errors as 'instances in which the airborne concentration was within or below the chemical's exposure band in the absence of control technology.' It should be noted that the information on established controls and their efficacy was often incomplete. Nevertheless, Jones and Nicas (2006) were not in favor of the model and suggested systematic evaluation should be undertaken prior to using the model outside the UK. Money (2003) also emphasized systematic evaluation of control banding approaches. While several researchers (Evans and Garrod, 2006; Money *et al.*, 2006; Garrod *et al.*, 2007; Tischer *et al.*, 2009) have pointed out that the COSHH Essentials model is an integrated tool and cannot be evaluated solely on the basis of the exposure prediction band, there is still value in testing the individual components of any model.

Kromhout (2002) criticized CB models such as the Estimation and Assessment of Substance Exposure (EASE) and the COSHH Essentials model on the grounds that they should be evaluated properly prior to public use. He noted that EASE and COSHH Essentials could not replace traditional occupational hygiene practices but recommended these tools for initial screening. Tischer *et al.* (2009) evaluated a German CB tool, Einfaches Massnahmenkonzept Gefahrstoffe (EMKG) 'Easy-to-use workplace control scheme for hazardous substances,' by comparing OELs with measurement data and by using a probabilistic model. When the data basis was homogeneous, the probabilistic model was able to reproduce the same distributions as the measured data. However, when the data used to generate a probabilistic model were heterogeneous (i.e. pooled data from different workplaces), the simulated results were too generic and unspecific. The CB model did not promise compliance in either case. In the conclusion, they emphasized more measurement-based evaluations from a variety of workplaces are necessary to reduce uncertainty from the generic simulation. The need for validation of the COSHH Essentials and other CB models has been stressed by others (Oldershaw, 2003; Tischer *et al.*, 2003; Jones and Nicas, 2006; AIHA, 2007; Lee *et al.*, 2009; NIOSH, 2009; Tischer *et al.*, 2009).

The current study evaluated the COSHH Essentials at a medium-sized industry producing automotive coating materials and paint materials in the USA. Two work tasks, batch-making in a large paint plant and bucket-washing, were selected and the chemicals tested in each task were acetone, ethylbenzene, methyl ethyl ketone (MEK), toluene, and xylenes. The COSHH Essentials exposure predictions were compared against the range of actual exposure monitoring data, and the control recommendations of the COSHH Essentials model were then compared to recommendations that would have arisen from expert interpretation of the actual monitoring data using the lowest OEL from prevailing regulatory and advisory standards for each chemical component, alone and in combination.

METHODS

Job tasks

The facility, located in the mid-west region of the USA, had a total of 265 employees producing automotive coating materials and paints that were distributed to commercial stores. Of those, 120 were plant employees and 145 were office or laboratory employees. The facility operated three shifts per day

and sample collection for the purpose of our study was limited to the employees involved in two specific tasks, batch-making in the large paint plant and bucket-washing. Of the 120 plant employees, only 3 were involved in the bucket-washing task, but any of the others could be assigned at any time to the batch-making task. Figs 1 and 2 show examples of the batch-making task in the large paint plant and the bucket-washing task.

Three or four batches were run per shift. Typically, one employee worked on one batch per shift and the main operations included raw material charging, product mixing, and dispensing into containers. Approximately 75–85% of all raw materials were added directly to the vessel either through piping from the manifold or by using a pump in a closed system. The remaining 15% was added by the employee. Adding all of the raw materials typically took ~1–2 h per batch. Liquid solvents including acetone, ethylbenzene, MEK, toluene, and xylenes were used and Table 1 shows the mean and proportion of each solvent used per shift. Resins and solid raw materials (pigments or powders) were also occasionally added through the tank man-way. When solid materials were added to the tank, a collection vent was positioned near the man-way to capture fugitive dusts. The batches ranged in size from 570 to 16340 l. Each batch took about 5–6 h to mix. The facility was controlled by general ventilation (~10 air changes per hour) through the heating ventilation and air conditioning system. Only exposures to the five liquid solvents mentioned were tested in the present study. The likelihood of an employee's direct exposure to the chemicals from the raw material charging and product mixing would be very low because the mixing was done in a closed system. However, the employee is exposed to fugitive chemical vapors not only from the particular batch the employee was involved in but also from other batches adjacent to his/her work area. After the mixing was complete, the product was dispensed into containers without any additional control method, resulting in further fugitive emissions. Routine exposure monitoring of the workers confirmed that no additional control methods for chemical vapors were required to maintain compliance with regulatory exposure limits.

The bucket-washing task involved automated solvent cleaning followed by visual inspection of the interior of each bucket and manual finishing if required. Any remaining solvent was manually removed by draining and mopping. Buckets ranged in size from 122 to 1060 l. Smaller sized buckets (≤ 400 l) were arranged in a fully enclosed cleaning unit analogous to a dish washer. After the cycle was complete, the buckets were inspected, finished, and



Fig. 1. Batch-making.



Fig. 2. Bucket-washing task (left: preparation of automatic washing of a bucket, right: checking for any residual paint left on a bucket after automatic washing).

drained and mopped out by hand under general ventilation. Larger buckets (>400 l), which could not fit into the washer were cleaned by pressurized solvent applied through a top-loading cap system (Fig. 2 left). After the automated washing cycle was complete, the large buckets were transported a short distance to a walk-in hood (ventilation rate $>0.57 \text{ m}^3 \text{ s}^{-1}$) where they were turned on their side, inspected, finished, and mopped out by an employee wearing a half-mask respirator [NIOSH (1987) and ANSI (1992); Assigned Protection Factor: 10] with organic vapor cartridges in addition to protective clothing during the process (Fig. 2 right). Thus for this task, there are multiple levels of control: containment, local exhaust ventilation (LEV), general ventilation, and personal protective equipment (PPE). Chemicals used to clean the buckets in the washing chamber are listed in Table 1.

A single wash of a large bucket wash took ~ 30 min including the automatic wash cycle. The employee assigned to this task usually washed ~ 15 large buckets per shift.

PERSONAL SAMPLE COLLECTION

Personal exposures were collected over the entire work-shift using SKC 575-002 passive samplers (SKC Inc., Eighty four, PA, USA) as per the company's routine monitoring program. Although prior company-monitoring results were available, the samples were not taken with the purpose of accurately describing the range of exposures, as is the case with most data collected with compliance in mind, and so those results were not incorporated into this study.

Table 1. Chemicals involved in task-based activity

Task	Chemicals	Liters per shift [proportion, % (w/w)]	Quantity ^a	N ^b	Control method ^c
Batch-making	Acetone	391 (14.0)	Medium	24	Containment and General ventilation ^d
	Ethylbenzene	870 (34.3)	Medium	24	
	MEK	471 (17.3)	Medium	24	
	Toluene	15 (0.6)	Medium	24	
	Xylenes	859 (33.8)	Medium	24	
	Total	2607 (100)		120	
Bucket-washing	Acetone	7539 (77.5)	Large	18	Containment, General ventilation, LEV, and PPE ^c
	Ethylbenzene	186 (2.1)	Medium	18	
	MEK	1379 (14.5)	Large	18	
	Toluene	426 (4.8)	Medium	18	
	Xylenes	95 (1.1)	Medium	18	
	Total	9625 (100)		90	

^aQuantity: small <2.5 l; medium 2.5–1000 l; large >1 m³.

^bN, number of sample measurements.

^cControl method, control method at the time of sampling.

^dGeneral ventilation: raw material charging and product mixing was done in a closed system and no additional control method except for the general ventilation was applied when the mixed product was dispensed into containers.

^eMultiple levels of control were applied for this task and see the section of job tasks for the detailed information.

For this study, all workers normally assigned to the bucket-wash, i.e. three employees per day (one per shift) were sampled, and four of the batch-making employees were randomly selected for monitoring per day. If a designated batch-making employee was not present on the sampling day, then a different employee, randomly selected from the group of employees who were performing the batch-making task, was sampled instead; a total of 10 employees volunteered to participate and each employee was sampled at least two or three times during the study period. As shown in Table 1, a total of 24 samples for the batch-making task and 18 samples for the bucket-washing task were collected and the sampling time for each measurement was ~8 h. The collected samples were analyzed by the facility's contract analytical laboratory using an analytical method developed by the laboratory. The analytical method was proprietary to the laboratory but similar methodology has been validated by the US Occupational Safety and Health Administration (OSHA) (see OSHA method: 1002, 1004, and 1009). Sampling was done once each month for 6 months from April 2005 to September 2005.

COSHH ESSENTIALS MODEL

The volatility of each chemical was estimated from Fig. 2 in the published version of the model (Maidment, 1998) and classified as medium for all chemicals used in this facility as shown in Table 2,

based on the boiling point of each chemical component and operating temperature of the facility (about 25°C for all chemicals). The volatility of the acetone was very close to the borderline between medium and high volatility; medium volatility was selected in the present study. Using high volatility for the acetone would not change the predicted exposure range (PER) for the batch-making task but would change the PER for the bucket-washing task. However, the end product of the model (i.e. recommended control) would not be changed for the bucket-washing task. The quantities of each chemical component were defined according to Maidment (1998) and Garrod *et al.* (2007). The frequency and time duration of the tasks were assumed to be 1 and 480 min per shift, respectively, due to the major exposure being from the far-field build-up of solvent vapors. The generally low concentrations and the preference for long-term diffusive sampler measurements anyway precluded breaking the tasks down further. Given the information of the volatility and the volume of the chemicals used in the solution, the COSHH Essentials model predicted exposure prediction level (EPL) to be Level 3 for both tasks (Table 3). The published version of the COSHH Essentials model (Maidment, 1998) allows for combining the control strategy at the sampling time and the predicted EPL, to provide a PER. Several strategies for control were in use in this facility. It has been suggested that the least stringent control method be used to estimate the PER when multiple control methods are in use

(Tischer *et al.*, 2003). However, since the purpose of the present study is to validate the COSHH Essentials model, the estimated PER using each control method was compared with the exposure measurements. Table 3 shows the PER of each chemical component per each control method for both job tasks. The web version of the model does not allow

for the current control strategy to be input, but the PER is not an output of the web model. In the web model, the recommended control strategy is that which would bring the PER from general ventilation (i.e. 50–500 p.p.m. for both job tasks) to the same range as the target exposure band (TEB) for the appropriate hazard band (A–E) for the chemical or

Table 2. Physical characteristics, R-phrases, and ACGIH classification of chemicals

Chemicals (CAS number)	Volatility	BP ^a (°C)	R-phrases ^b	ACGIH classification/notation ^c
Acetone (67-64-1)	Medium	56	11-36-66-67	A4 (Not classifiable as a human carcinogen); upper respiratory tract (URT) and eye irritation; CNS impairment; hematologic effect
Ethylbenzene (100-41-4)	Medium	136	11-20	A3 (Confirmed animal carcinogen with unknown relevance to humans); URT and eye irritation; CNS impairment
MEK (78-93-3)	Medium	79	11-36-66-67	URT irritation; CNS and peripheral nervous system impairment
Toluene (108-88-3)	Medium	111	11-38-48/ 20-63-65-67	A4 (Not classifiable as a human carcinogen); visual impairment; female reproductive system; pregnancy loss; CNS impairment ^d
Xylenes (1330-20-7)	Medium	138	10-20/21-38	A4 (Not classifiable as a human carcinogen); URT and eye irritation; CNS impairment

^aBP, boiling point.

^bR10-flammable; R11-highly flammable; R20-harmful by inhalation; R20/21-harmful by inhalation and in contact with skin; R36-irritating to eyes; R38-irritating to skin; R48/20-harmful, danger of serious damage to health by prolonged exposure through inhalation; R63-possible risk of harm to the unborn child; R65-harmful, may cause lung damage if swallowed; R66-repeated exposure may cause skin dryness or cracking; R67-vapors may cause drowsiness and dizziness.

^cResource: ACGIH, 2009a.

^dCNS impairment was not listed in the ACGIH TLVs and BEIs (ACGIH, 2009a) for toluene but listed in the Documentation of the TLVs and BEIs (ACGIH, 2009b).

Table 3. COSHH essentials model predictions

Task	Chemicals	EPL ^a	PER ^b (p.p.m.)			Hazard band (TEB ^f , p.p.m.)	Recommended CS
			CS 1 ^c	CS 2 ^d	CS 3 ^e		
Batch-making	Acetone	3	50–500		0.5–5	A (50–500)	CS 1
	Ethylbenzene	3	50–500		0.5–5	B (5–50)	CS 2
	MEK	3	50–500		0.5–5	A (50–500)	CS 1
	Toluene	3	50–500		0.5–5	D (0.05–0.5)	Special advice ^g
	Xylenes	3	50–500		0.5–5	B (5–50)	CS 2
	Recommended CS from a mixture of chemicals						Special advice
Bucket-washing	Acetone	3	50–500	5–50	0.5–5	A (50–500)	CS 1
	Ethylbenzene	3	50–500	5–50	0.5–5	B (5–50)	CS 2
	MEK	3	50–500	5–50	0.5–5	A (50–500)	CS 1
	Toluene	3	50–500	5–50	0.5–5	D (0.05–0.5)	Special advice
	Xylenes	3	50–500	5–50	0.5–5	B (5–50)	CS 2
	Recommended CS from a mixture of chemicals						Special advice

^aEPL, exposure prediction level.

^bPER, predicted exposure range based on the published version of the model (Maidment, 1998).

^cCS 1, good standard of general ventilation.

^dCS 2, LEV or engineering containment control (partial enclosure).

^eCS 3, containment control.

^fTEB.

^gSpecial advice, seek for special advice from occupational professionals.

mixture of chemicals of interest. If the TEB is 5–50 p.p.m., then the control strategy (CS) recommended in this case would be 2: use of local exhaust ventilation.

The TEB is obtained from the toxicity of the chemical(s) in use, which is derived from the R (risk)-phrases (actually hazard notations) required to be on Safety Data Sheets under European regulations. Several researchers have noted inconsistency in the R-phrases assigned to chemicals by different sources (Rudén and Hansson, 2003; Zalk and Nelson, 2008; Lee *et al.*, 2009). For the current study, R-phrases were obtained from the European Commission Joint Research Centre Institute for Health and Consumer Protection (<http://ecb.jrc.ec.europa.eu/classification-labelling/search-classlab/>) and are listed in Table 2. The hazard band for each chemical and the TEBs were estimated as shown in Table 3. The hazard band was A (eye irritants, skin dryness, and drowsiness and dizziness; TEB = 50–500 p.p.m.) for acetone and MEK, B (harmful by inhalation and skin irritants; TEB = 5–50 p.p.m.) for ethylbenzene and xylenes, and D (lung damage if swallowed and possible risk of harm to the unborn child; TEB = 0.05–0.5 p.p.m.) for toluene. The American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV®) documentation also notes possible failures of female reproduction and pregnancy loss from exposure to toluene (Table 2) (ACGIH, 2009a), although the assigned TLV of 20 p.p.m. is the same as that for styrene, which is not considered to have these critical health effects. Styrene would be classified as hazard band B (TEB = 5–50 p.p.m.) on the basis of its R-phrase, R20 (harmful by inhalation). The TEBs for toluene, ethylbenzene (TLV = 100 p.p.m.), and xylenes (TLV = 100 p.p.m.) are stricter than the TLV, while the TLVs for acetone (500 p.p.m.) and MEK (200 p.p.m.) fall within their TEB.

Each chemical component was processed separately for each task, even though the chemicals were mixed during the process. The most stringent among the recommended controls was selected as the appropriate CS (Maidment, 1998; AIHA, 2007). The model recommended CS 1, good standard of general ventilation, for acetone and MEK, CS 2, LEV or engineering containment controls (partial enclosure), for ethylbenzene and xylenes, and Special Advice for toluene.

DATA ANALYSIS

The measured concentrations were task-based full-shift exposures of individual employees because

the employee worked on only one task for a full-shift. The values below the limit of quantitation (LOQ) were imputed with the $LOQ/\sqrt{2}$. A total of 24 measurements for each of the five chemicals in the batch-making task and 18 measurements for each of the five chemicals in the bucket-washing task were used in the data analysis.

The data analysis in the current study followed the same method used in our previous study (Lee *et al.*, 2009); a probability distribution was determined for each chemical and the probabilities of being above or below the range of PER were estimated. Also, the control method at the time of sampling was evaluated against the smallest OEL of regulatory and advisory standards such as the ACGIH TLV–time-weighted average (TWA), OSHA permissible exposure limits (PELs)–TWA, and British HSE workplace exposure limits (WEL)–TWA. Additional analysis using the additive mixture formula ($C_1/T_1 + C_2/T_2 + \dots + C_n/T_n \leq 1$, where C is the measured concentration from 1 to n chemicals and T is the corresponding TLV of each chemical) was performed to estimate whether the estimated exposure of a mixture of chemicals having similar health effects exceeded the TLV (ACGIH, 2009a). As shown in Table 2, acetone, ethylbenzene, MEK, and xylenes have similar health effects including upper respiratory tract and/or eye irritation and central nervous system (CNS) impairment. For the toxic effects of toluene, although CNS impairment was not listed in the annual ACGIH TLVs and biological exposure indices (BEIs) (ACGIH, 2009a), it was included in the documentation of the ACGIH TLVs and BEIs (ACGIH, 2009b). Thus, it might be reasonable to include toluene in the additive mixture formula due to possible contribution of the toluene to cause CNS impairment. For the corresponding TLV (T), the smallest OEL of each chemical from the ACGIH TLV–TWA, OSHA PEL–TWA, and HSE WEL–TWA was selected. After obtaining the sum of fractions of all chemicals per shift, a probability distribution and probability exceeding unity were estimated. To make a judgment, a probability of 5% was used that is based on the criterion used by the NIOSH for acceptability of exposures in US workplaces (Leidel *et al.*, 1977).

RESULTS

Comparison of exposure measurements and PER

For the batch-making task at the large paint plant, the geometric mean (GM) of employee exposure to acetone (35.1 p.p.m.) was considerably higher than for the other chemicals (<5 p.p.m.) used in the

Table 4. Probability estimation for full-shift exposures

Task	Chemicals	Geometric mean (p.p.m.) (GSD) ^a	Number of measurements (<LOQ/total) ^b	CS 1 ^c		CS 2 ^d		CS 3 ^e	
				$P < L_L$ of PER ^f	$P > L_U$ of PER ^g	$P < L_L$ of PER ^f	$P > L_U$ of PER ^g	$P < L_L$ of PER ^f	$P > L_U$ of PER ^g
Batch-making	Acetone	35.1 (1.89)	0/24	0.6844	<0.0001			<0.0001	0.9989
	Ethylbenzene	0.8 (1.89)	2/24	>0.9999	<0.0001			0.0847	0.0151
	MEK	4.9 (1.90)	0/24	0.9998	<0.0001			0.0003	0.4943
	Toluene	1.6 (2.17)	0/24	>0.9999	<0.0001			0.0757	0.0194
	Xylenes	0.6 (1.95)	7/24	>0.9999	<0.0001			0.0111	0.0607
Bucket-washing	Acetone	72.2 (7.51)	2/18	0.4267	0.1810	0.1001	0.5733	0.0087	0.8999
	Ethylbenzene	1.1 (3.46)	3/18	0.9984	<0.0001	0.8803	0.0016	0.2760	0.1197
	MEK	3.3 (4.31)	3/18	0.9647	0.0004	0.6076	0.0353	0.1035	0.3924
	Toluene	0.9 (2.31)	2/18	0.9999	<0.0001	0.9604	<0.0001	0.1782	0.0396
	Xylenes	1.2 (3.64)	5/18	0.9980	<0.0001	0.8642	0.0020	0.2509	0.1358

^aGSD, geometric standard deviation.

^bNumber of measurements below the LOQ over the total number of measurements.

^cCS 1, good standard of general ventilation.

^dCS 2, LEV or engineering containment controls (partial enclosure).

^eCS 3, containment control.

^fProbability of exposure measurements less than the lower limit of the PER.

^gProbability of exposure measurements higher than the upper limit of the PER.

mixture (Table 4). High variation was observed for each chemical component probably due to different batch formulations on different days. The COSHH Essentials model reasonably predicted the PER estimated using CS 1 for the acetone ($L_L < P < L_U = 0.3156$), while the probabilities of the other chemicals being within the PER range were either 0.0001 or 0.0002; none of the exposure measurements was above the upper limit of the PER ($P > L_U = <0.0001$) and exposure measurements for all chemical components except for the acetone were less than the lower limit of the PER ($P < L_L = >0.999$). The comparison of exposure measurements with the PER estimated using CS 3 (0.5–5 p.p.m.) showed that most exposure measurements for ethylbenzene, toluene, and xylenes were within the PER ($L_L < P < L_U = >0.9$). On the other hand, the probability of exposure measurements being within the PER was considerably lower for acetone ($P = 0.0011$) and moderate for MEK ($P = 0.5054$).

For the bucket-washing task, the GM exposure for the acetone was 72.2 p.p.m., while exposures to the other chemicals in the mixture were <4 p.p.m. (Table 4). The comparison of exposure measurements with the PER estimated using CS 1 (50–500 p.p.m.) results in 12 measurements of the acetone exposures (66.7%) being within the range of the PER and ~18% of the estimated distribution of likely acetone exposures would be above the COSHH Essentials predicted range ($P > L_U = 0.1810$). For

the other chemical components in the mixture, all measurements were below the lower limit of the PER estimated using CS 1 and the 95% probabilities of those chemicals being greater than the upper limit of the PER were <0.0004. When the exposure measurements were compared with the PER estimated using CS 2, the acetone and MEK showed moderate probability of observed exposures within the PER ($L_L < P < L_U = 0.3266$ for the acetone and 0.3571 for the MEK). More than half of the estimated distribution of the acetone exposures was above the COSHH Essentials predicted range ($P > L_U = 0.5733$). Most exposure measurements for the other chemical components were below the lower level of the PER. When the exposure measurements were compared with the PER estimated using CS 3, all chemical components except for the acetone showed high or moderate probabilities of exposures being within the PER, while most acetone exposures were greater than the upper limit of the PER ($P > L_U = 0.8999$). Fig. 3 shows examples of exposure measurements for the acetone and xylenes and PERs based on different control methods at the time of sample collection.

As a control level is reduced a step lower, the estimated PER is increased by a factor of 10, i.e. 0.5–5 p.p.m. (range 4.5), 5–50 p.p.m. (range 45), and 50–500 p.p.m. (range 450) for CS 3, CS 2, and CS 1, respectively. Therefore, most observed exposures for all chemicals in the present study were

considerably lower than the PER or within the PER of the corresponding chemical components as the control level was reduced from CS 3 to CS 1.

Recommended control method from the COSHH Essentials web model

The average exposure measures of all chemical components were less than the OELs of ACGIH TLV-TWA, OSHA PEL-TWA, and HSE WEL-TWA. As shown in Table 5, the probabilities of exposure exceeding the OELs for all chemicals were <0.05 except for the acetone used in the bucket-washing task. Acetone for the bucket-washing task

generated a higher probability than the other chemicals in the mixture for the same task due to higher volatility compared to the others. Generally, the bucket-washing task showed higher probabilities of exposure exceeding the OELs for individual chemicals than the batch-making task. For both tasks, the results of the additive mixture formula with exposure measurements also showed average exposure fractions less than unity (batch-making task: 0.25, bucket-washing task: 0.56) indicating that the mixture of chemicals did not exceed the additive TLV. As shown in Fig. 4, the probability of the exposure fraction exceeding unity indicates that the employees

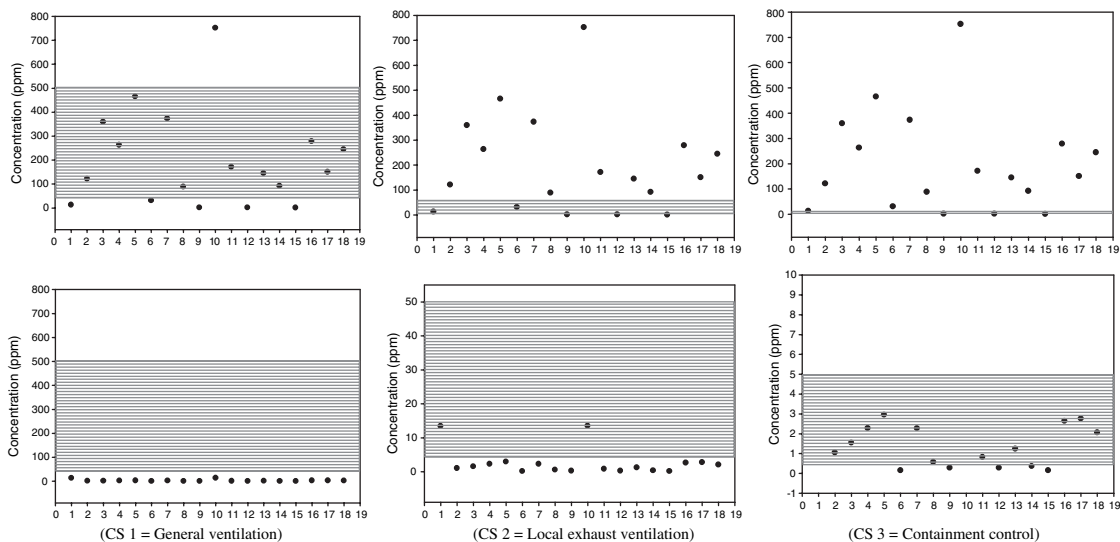


Fig. 3. PER and full-shift measurements of acetone (upper row) and xylenes (lower row) for the bucket-washing task (note: the shaded areas represent the PER estimated from each control method).

Table 5. Probability of exposure exceeding OELs for full-shift exposure

Task	Chemical	TWA ^a (p.p.m.)			$P > \text{OELs}^b$			$P > 1^c$ (TI ^d)
		ACGIH TLV	OSHA PEL	HSE WEL	ACGIH TLV	OSHA PEL	HSE WEL	
Batch-making	Acetone	500	1000	500	<0.0001	<0.0001	<0.0001	0.0002 (± 0.000032)
	Ethylbenzene	100	100	100	<0.0001	<0.0001	<0.0001	
	MEK	200	200	200	<0.0001	<0.0001	<0.0001	
	Toluene	20	200	50	0.0006	<0.0001	<0.0001	
	Xylenes	100	100	50	<0.0001	<0.0001	<0.0001	
Bucket-washing	Acetone	500	1000	500	0.1810	0.1072	0.1810	0.2375 (± 0.000494)
	Ethylbenzene	100	100	100	0.0002	0.0002	0.0002	
	MEK	200	200	200	0.0031	0.0031	0.0031	
	Toluene	20	200	50	0.0004	<0.0001	<0.0001	
	Xylenes	100	100	50	0.0003	0.0003	0.0020	

^aTWA, Time-weighted average concentration (ppm).

^bProbability of exposure exceeding the OELs.

^cProbability of exposure fractions exceeding unity.

^dTI, tolerance intervals.

performing the batch-making task were most likely below the TLV of the mixture ($P > 1 = 0.0002 \pm 0.000032$ tolerance intervals). However, although the calculation using the additive mixture formula for the bucket-washing task was less than unity (0.56), the employees involving in this task would have about a 24% chance of exceeding the TLV of the mixture based on the plot of the estimated probability distribution (Fig. 5). Note that the measurements for this task were obtained outside of respiratory protection.

For both tasks, the COSHH Essentials model recommended a control approach 'Special Advice' due to the risk of harm to an unborn child from exposure to toluene and the amount of toluene used in the task (Table 3). The recommended control of seeking special advice can be changed if toluene is substituted or the amount of toluene is minimized (from medium to small). Minimizing the frequency and/or the duration of the toluene exposure would not reduce the level of the CS. At the time of sample collection,

two occupational hygienists were employed in the department of environmental health and safety (EHS). They were performing annual routine sampling, supplying adequate respirators and other PPE, and providing EHS-related training sessions. Thus the recommendations of the COSHH Essentials model for Special Advice were being followed.

DISCUSSION

Comparison of exposure measurements and PER

It might be expected that the comparison between exposure measurements and PER's would show a consistent pattern for different chemicals as the different control strategies are examined. However, for both tasks, the comparison between the exposure measurements of the chemical components and the PERs of the corresponding chemicals did not show consistent agreement when the comparison was made per each control method. For instance, the

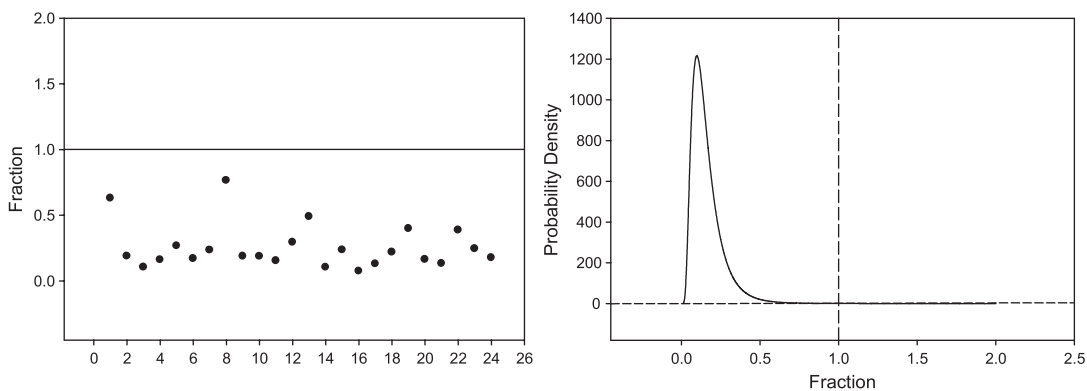


Fig. 4. Batch-making task: fractions from the additive mixture formula and estimated probability distribution.

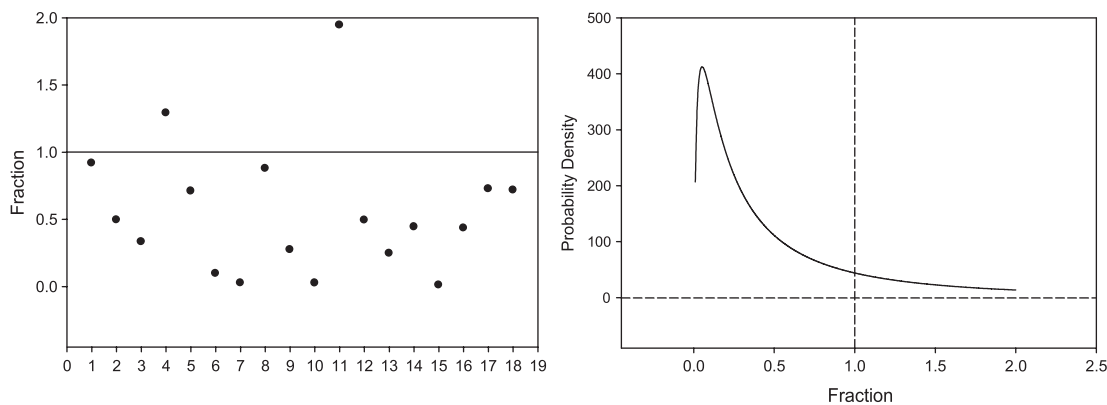


Fig. 5. Bucket-washing task: fractions from the additive mixture formula and estimated probability distribution.

PER estimated using CS 1 showed moderate agreement with the TWA measurements of the acetone exposures for both tasks, while the other chemicals showed poor agreement. In the present study, the volatility of chemical components in the mixture seemed to be a critical factor in this inconsistent agreement; the acetone and MEK have higher volatility than the ethylbenzene, toluene, and xylenes shown in Table 2. For example, the probability of the acetone exposures higher than the upper limit of the PER estimated using CS 3 was 0.9989, while chemicals with less volatility (i.e. ethylbenzene, toluene, and xylenes) showed high probability of exposure measurements within the PER ($L_L < P < L_U = > 0.9$). The findings from the comparisons in the present study indicate that it would be difficult to obtain good estimation of PER when the volatilities of chemical components in a mixture are not similar.

Another reason behind inconsistent agreement might be the complexity of control methods in place, i.e. the combined effect of several control methods. In the batch-making task, effective control of exposure was obtained through a mixture of containment and general ventilation, and in the bucket-washing task, effective control was obtained through a combination of containment (enclosed system), local exhaust, general ventilation, and respiratory protection. This situation of multiple levels of control is generally beyond a simple model although it may have been able to be approached through subdividing the tasks further (e.g. automated filling versus manual filling for the batch making and automatic wash versus manual scrub for the bucket washing); this leads to a discussion on the definition of task that is outside the scope of this paper.

Recommended control method from the COSHH Essentials web model

The recommended CS is obtained through combining the prediction of an exposure potential band and a health hazard band. The COSHH Essentials model in the present study suggested various control strategies for the tested chemicals and as a rule of thumb, the most stringent control approach, Special Advice, was selected for both tasks.

For the batch-making task, the probability for exposure of individual chemicals exceeding the OELs of regulatory and advisory standards was < 0.0006 and the probability of exposure fractions exceeding unity was 0.0002. This result indicates that it is very unlikely that employees involved with this task would be overexposed. For the bucket-washing task, the probability of exposure fractions exceeding unity

was 0.2375. Overall, probabilities for the bucket-washing task were higher than those for the batch-making task. This is because hand finishing of the interior of the buckets to remove residual paint or removal of the residual of washing solvents from the inside of the buckets could not be done automatically. LEV at this point would not be practical because of the need for manual cleaning of the buckets. In practice, there exist a number of circumstances where the LEV containment control method is impractical such as cleaning, maintenance, and emergency repair. For those circumstances where engineering controls are ineffective, typically appropriate PPE is used. Tischer *et al.* (2003) observed higher exposure measurements than the PER when small quantities of solvents (milliliter quantities) were applied over a large surface area. In the current study, the source of exposures was evaporation from the wet surface of the bucket, from the wet mop and from small quantities spilled onto the floor. At this facility, the employees who were performing the bucket-washing task are required to wear a half-mask respirator [(NIOSH (1987) and ANSI (1992)] Assigned Protection Factor: 10] and other required PPE including protective gloves and aprons. The probability of exposure fractions exceeding unity was ~ 0.2375 (measured from the outside of the respirator) for the bucket-washing task. The actual employees' exposure to the chemicals would be significantly lower than the observed exposure when the measurements are adjusted by the assigned protection factor. The probability of adjusted exposure fractions exceeding unity in this case is 0.0161 indicating that it is unlikely that an employee would exceed the OELs. From these observations, it was determined that the facility was already under an adequate control program administered by occupational experts, i.e. two occupational professionals performing baseline sampling of all tasks and routine sampling tasks with a timetable based on a scale according to the ratio of the baseline results to the limit value.

Experience of using the COSHH Essentials web model

Override of chemicals' health hazard. The web-based COSHH Essentials model (<http://www.coshh-essentials.org.uk/>) (HSE, 2005) was performed in addition to determining the recommended control methods based on the paper procedures (Maidment, 1998). An interesting question was raised about the selection of health hazard bands during the use of the web-based model. Toluene was defined as health hazard band D due to the R-phrase R63 (possible risk of harm to the unborn child).

Reallocation of this R-phrases, however, is possible to lower hazard group C if '(i) the lowest observed adverse effect level (LOAEL) for developmental toxicity, obtained from good quality animal studies, is $>5 \text{ mg kg}^{-1} \text{ day}^{-1}$ oral; or $>10 \text{ mg kg}^{-1} \text{ day}^{-1}$ dermal; or 0.025 mg l^{-1} 6-h day inhalation and (ii) there are no other R-phrases that require the substance to be assigned to hazard group D or E.' Reallocation to hazard group B, the hazard group of styrene which has an identical OEL to toluene, however, is not possible. Guest (1998) also mentioned that when sufficient data are available for substances toxic to reproduction, the substances could be assigned to a more or less stringent band. Toluene is one of the most common chemicals contained in paint products and sufficient data regarding the toxic effects of human and animal exposures are available. The US Environmental Protection Agency (EPA) Integrated Risk Information System (IRIS) reported a number of occupational studies of chronic inhalation exposure to toluene (<http://www.epa.gov/iris/subst/0118.htm>) (EPA, 2009). According to the studies listed in the US EPA IRIS, the LOAEL for toluene ranges from 0.026 mg l^{-1} 6-h day to 0.083 mg l^{-1} 6-h day. Since the LOAEL for toluene is $>0.025 \text{ mg l}^{-1}$ 6-h day and no other R-phrases of the other chemical components in the mixture fall within hazard group D or E, it should be possible to reassign toluene from hazard group D to C. However, reallocation of the hazard band D to C in the COSHH Essentials website program failed with an explanation of 'The chemical toluene may also cause harm if in contact with skin or eyes.' When the R-phrases R63 (possible risk of harm to the unborn child), R65 (harmful may cause lung damage if swallowed), and R67 (vapors may cause drowsiness and dizziness) were only selected, the user was able to override into a lower hazard band. On the other hand, when R38 (Irritating to skin) and/or R48/20 (Harmful, danger of serious damage to health by prolonged exposure through inhalation) were selected with R63, the model did not allow reassignment. The R-phrases R38 or R48/20 alone generates the hazard group A and C, respectively. If the web-based model is able to reallocate R-phrases into a step lower hazard band, the level of recommended CS can be reduced from Special Advice to 'Containment' (fully enclosed but allowing small-scale breaches of containment). For the batch-making task, most chemical addition is made with an enclosed system, although smaller volumes and solids are loaded by hand under general ventilation and it is difficult to describe this situation as 'general ventilation' or containment or some combination of the two. In our analysis, it

was considered as general ventilation and the chances of exceeding the OELs of individual chemicals or the combined OEL were very low. For the bucket-washing task, the containment control was likely effective for the automatic washing satisfying the current control strategy but ineffective for the task of removing the residual solvents in the buckets (manual cleaning). The web-based model recommended two control guidance sheets (CGSs) (S100—skin or eye contact and S101—selection of personal protective equipment) at the end of the model procedures because the task involved chemicals causing skin irritation. Although these do not provide detailed information for selection of adequate PPE, it might be useful to know the types of available PPE. In the present study, the current ventilation controls for the bucket-washing task were satisfactory in combination with selection of appropriate PPE. For example, in our model, adding a mandatory requirement of wearing a respirator for the bucket-washing employee reduced the probability of exposure fractions exceeding unity from 0.2375 to 0.0161. Thus, the recommendation to seek Special Advice was probably appropriate for the complexity of the situation. The inability to override into a lower hazard group even though the conditions for the override had been met might decrease the value of the model and the integrity of the recommended control and guidance from the model. Therefore, the COSHH Essentials model might usefully be updated with respect to this issue.

Consideration of existing control methods. The web-based COSHH Essentials model assumes no controls in place and general ventilation is the default. The inability to input existing control methods could limit the applicability of the model among the users. This also leads to a limitation of the model validation study because appropriate validation of the model would require disabling the existing controls, which is not a step to be taken lightly. Thus, it might be better if the COSHH Essentials model could be upgraded to allow for the input of controls (as is done in EASE 2.0) and to suggest a recommended control based on the existing control methods.

R-phrases. Bracker *et al.* (2009) performed a survey of participants who had used the COSHH Essentials model in their facility after training and reported difficulty in finding R-phrases. The same issue was also noted from the experiences of the web-based model by the authors in the present study. Thus, providing direct links to find R-phrases would be helpful. Although inconsistency of R-phrases has previously been reported, the Globally Harmonized System for Classification and Labeling of Chemicals

initiated in 1992 may provide consistent chemical hazard classification within the next few years.

Control guidance sheets. CGSs are provided for general and common tasks along with a recommended control method as an end product of the web-based COSHH Essentials model. For both tasks in the present study, the model provided three CGSs, G400-general principles, S100-skin or eye contact, and S101-selection of personal protective equipment. The guidance sheets included in the model are written in plain language to help users who do not have expertise in occupational hygiene. The web-based model also provides additional guidance, called 'direct advice topics,' for certain types of work tasks involving silica, wood dust, painting, and so on; this guidance allows users to download information without going through the COSHH Essentials model procedure. Additional task-specific CGSs for the various industry sectors are also available via internet searches such as <http://www.hse.gov.uk/pubns/guidance/> (Great Britain), http://bravo.ilo.org/legacy/english/protection/safework/ctrl_banding/toolkit/icct/sheets.htm (International Labor Organization), http://www.baua.de/cln_137/de/Themen-von-A-Z/Gefahrstoffe/EMKG/Schutzleitfaeden_content.html (Germany), <http://www.safeworkaustralia.gov.au/swa/HealthSafety/HazardsSafetyIssues/EssentialChemicalControls/HowToUse/Step3-Usingcontrolguidance.htm> (Australia), http://www.cdc.gov/niosh/pubs/hc_date_desc_nopubnumbers.html (NIOSH, USA), and <http://www.osha.gov/pls/publications/publication.html> (OSHA, USA). Since the guidance sheets listed in the model are limited to general and few specific job tasks, developing a searchable library of control guidance for many work tasks or direct linking to other resources might be useful to improve communication with the model users. Also, the COSHH Essentials model does not provide sufficiently detailed information to select an adequate respirator at the present time. Garrod and Rajan-Sithamparamadarajah (2003) proposed minimum or assigned protection factors for respirator protective equipment based on the hazard band of substances, amount of substances involved in task, and dustiness or volatility of substances. The selection of an adequate respirator in this manner does not require knowledge of OELs, but this proposal has not been fully evaluated yet.

CONCLUSIONS

For both tasks, the estimated PERs for the tested chemicals did not show consistent agreements against the exposure measurements when the com-

parison was made per each control method due to considerably different volatilities of the chemical components in the mixture but the recommended control was not driven solely by the exposure prediction band. Overall, the current study suggested that the COSHH Essentials model worked reasonably well by recommending Special Advice for the complex situation of multiple volatile chemical exposures in the two tasks studied at a medium-sized plant. As REACH moves forward, there will be a greater focus on models among the EU countries so that exposure levels can be predicted by using banding approaches and/or statistical algorithms (Ogden, 2010). Therefore, the findings of the current study provide positive information for implementation of the COSHH Essentials model. In addition, the experience of using the web-based COSHH Essentials model generated some suggestions to make the model be more widely applicable and to provide a more user-friendly tool.

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