Submission to Inspector-General of Biosecurity Review

Review title: Assessment of the effectiveness of biosecurity measures to manage the risks of brown marmorated stink bug (BMSB) entering Australia

Submitted by: Nordiko Quarantine Systems Pty Ltd 22-2-19

Summary:
Biosecurity measures implemented to manage the risks of BMSB entering Australia have led to a very significant increase in the number of fumigated shipping containers, treated overseas and in Australia.
This has had two unintended consequences in relation to fumigated containers:

1. Large backlog of fumigations – this can be alleviated by employing forced ventilation technology, leading to faster turnaround of fumigated containers
2. This has exposed a much larger number of Australian workers unloading containers, to residual fumigant exposure

We believe DAWR should take into consideration the application of technology to improve the throughput of fumigated containers. Also we suggest that DAWR has a duty of care in relation to Safe Work Australia guidelines and Chain of Responsibility legislation, to inform industry of the residual toxic gas risks in fumigated containers that its officers are aware of.

How This Submission Comes Under the Scope of the Review:
We encourage the Inspector-General to consider the following as part of the Review, as this relates to DAWR's responsibility as a key stakeholder for each of the **scope items:**

- **developing and verifying effectiveness of offshore BMSB management measures** – including assurance that containers treated by fumigation **offshore** are ventilated below the safe toxic gas level before export to Australia, and are properly marked as having been fumigated to warn Australian importers of the proven risk of further degassing in transit

- **BMSB profiling, assessment, inspection and treatment of conveyances and cargo arriving in Australia –** including assurance that containers treated **onshore** by fumigation are properly marked as such, and advice is given to importers that dangerous fumigant concentrations can arise from fumigated containers that have been ventilated down to the safe level, due to further gas desorption in transit locally from the fumigation site to the unpacking location

- **management of approved arrangements involved in onshore BMSB management activities, including reviewing the effectiveness of measures taken by industry to ensure compliance with biosecurity requirements** – taking into consideration the huge backlog in imported containers, affecting Australian industry, and the fact that forced ventilation technology will lead to faster throughput of container fumigations.

Also, reviewing the effectiveness of container fumigation and ventilation compliance with health and safety guidelines and requirements

- **approval/accreditation of offshore and onshore treatment providers** – ensuring such approval/accreditation takes into account treatment providers compliance with the residual toxic gas risk controls

- **engagement and consultation with industry and other stakeholders** – including engaging and informing industry about the availability of forced ventilation technology, to speed up the container fumigation process. Plus the important health and safety risks that thousands of people who unpack containers are exposed to in Australia on a daily basis due to the risk of exposure to residual Methyl Bromide and Sulfuryl Fluoride

Backlog of Containers Awaiting Fumigation:

There is insufficient fumigation capacity for the large volume of containers requiring fumigation treatment in Australia. The application of Australian made technology – designed specifically to achieve fast clearance of fumigated containers - will significantly reduce the time taken for the ventilation stage of the fumigation process:

- **Safe Work Australia Guidelines** (attached) refer to 30 minutes of forced ventilation, compared with minimum 12 hours of natural ventilation
- **INRS Paper (attached): Purging of Working Atmospheres Inside Freight Containers** – confirms that forced ventilation significantly accelerates clearance of the atmosphere in containers. INRS purchased Nordiko container forced ventilation equipment, to form part of these tests
- **Swedish Paper (attached): Work Inside Ocean freight Containers – Personal Exposure to Off-Gassing Chemicals** – confirming the risk to workers who unload fumigated containers, and recommending the application of forced ventilation

Increased Exposure of Australian Workers to Residual Fumigants due to BMSB Fumigations

Australian and international experience has shown that atmospheres inside containers that have been fumigated, either offshore or onshore, can often be well above the safe limits for personal exposure to toxic gases. Unsafe gas levels arise even in containers that have been ventilated below the safe level at the conclusion of fumigations, due to ongoing desorption from fumigated cargoes.

Gases such as methyl bromide and sulfuryl fluoride can be present at unsafe concentrations, without being able to be detected by smell. High level exposure can lead to acute physical effects, ongoing low level exposure can lead to chronic health effects.

Australian industry has needed to cope with this issue in relation to fumigated containers for many years, but the expanding range of BMSB target countries has meant that a much larger and growing number of importers are involved. Many of these have not had experience with fumigated containers and the risks involved. In our opinion DAWR has a duty to keep them properly informed, so they can take appropriate measures to protect the health and safety of their staff to residual fumigants.

Safe Work Australia conducted a review of toxic gases in import containers, including fumigants, which led to their issuance of guidelines around safe container unpacking in relation to residual methyl bromide and other hazardous chemicals. These publications set out the need to test for unsafe gas levels and employ forced ventilation or other procedures to provide a safe working atmosphere before entry.

Chain of Responsibility legislation was amended in Oct 18 to include the obligation for safe unloading from transport vehicles, which encompasses devanning of import containers. Stringent corporate and personal financial penalties and jail terms are set out in Section 26C.

We understand that DAWR staff who conduct tailgate inspections of containers have been issued with gas monitors capable of detecting low range methyl bromide concentrations, and work protocols prohibit them from entering fumigated containers. However – depot staff asked to extract container contents for closer examination, and those people ultimately unpacking fumigated containers, are not informed about the risks. Given that the DAWR has this knowledge, from a duty of care viewpoint this information should be shared.

Conclusion

We urge the Inspector-General to include consideration of the cost to industry of fumigated container waitlists at the ports, in relation to the benefits of supporting forced container ventilation technology, as one of the means to improve throughput.

In addition, taking on board the health and safety risks generated by the increased number of container fumigations in the Inspector General's final report, and recommended actions which flow from this review.

Nordiko will be in Canberra on Friday March 22nd 2019 and we would like to request a meeting with your office, to explain our submission in more detail.

Attachments:

- Safe Work Australia Guidelines:
  Managing Risks of Methyl Bromide Exposure When Unpacking Shipping Containers
- INRS (French Work Health Authority) paper showing the effectiveness of forced container ventilation compared with open door ventilation
- Karolinska Institute (Swedish University) paper confirming faster gas extraction times using forced ventilation technology

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safe work australia

MANAGING RISKS OF METHYL BROMIDE EXPOSURE WHEN UNPACKING SHIPPING CONTAINERS

INFORMATION SHEET

This Information Sheet provides guidance for workers and supervisors managing risks of methyl bromide exposure when unpacking shipping containers.

Workers may be exposed to other hazardous chemicals when unpacking containers. For information about handling methyl bromide and other hazardous chemicals safely you should refer to the relevant safety data sheet (SDS) or seek advice from a competent person.

Further information is in the:

- Information Sheet: *Managing risks of hazardous chemical exposure when unpacking shipping containers*
- Information Sheet: *Managing risks when unpacking shipping containers*
- AS 2476-2008: *General fumigation procedures*, and
- Code of Practice: *Managing risks of hazardous chemicals in the workplace*.

What is methyl bromide?

Methyl bromide is widely used as a fumigant to prevent unwanted pests, for example insects and rodents, from being imported into Australia.

It is a colourless non-flammable gas which is heavier than air and odourless at low concentrations.

Chloropicrin is sometimes added to methyl bromide to give off a strong, sharp and highly irritating odour so that it is possible to detect the presence of methyl bromide without special equipment.

What are the hazards?

Methyl bromide is a neurotoxic gas which can affect the central nervous system. It is suspected of causing genetic defects.

Methyl bromide is a dangerous cumulative poison. The effects of exposure can be delayed from 48 hours to several months after exposure.

What are the risks of exposure to methyl bromide?

Workers are usually exposed to methyl bromide by breathing in gas trapped in the container or between packages inside the container. They may also come into contact with methyl bromide when handling contaminated packages.

Depending on exposure levels it can cause headaches, dizziness, vomiting, nausea, tremors, slurred speech and irritation to the eyes, respiratory system and skin. Exposure to high concentrations may cause pulmonary oedema (fluid in the lungs) or death.

Workers may not realise they have been exposed to methyl bromide because it has no odour and the onset of symptoms is delayed.

How do you control the risks?

Exposure to methyl bromide can be eliminated or minimised, by:

- checking notices on containers for the presence of methyl bromide—if methyl bromide is present, refer to the SDS for information about selecting and using appropriate control measures
- venting containers before workers enter them to allow methyl bromide to dissipate—residual methyl bromide can remain after venting due to:
  - poor venting procedures
  - off-gassing from items in the container, or
  - entrapment of the gas in packaging
- capturing methyl bromide vented from the container using recapture technology
- training workers in safe working procedures for unpacking fumigated containers including training on how to use testing equipment and personal protective equipment (PPE), and
- providing appropriate PPE e.g. respirators.

The levels of methyl bromide that workers are exposed to must be minimised, so far as is reasonably practicable. Workers must not be exposed to methyl bromide in concentrations over five parts per million (5 ppm) averaged over eight hours.

Further information about workplace exposure standards is in the *Guidance on the interpretation of workplace exposure standards for airborne contaminants*.

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Safe work procedures for unpacking containers fumigated with methyl bromide include:

- treating the container as if it has been fumigated when unsure whether it has been fumigated or not
- placing the container in an open area with good natural ventilation and downwind from other activities
- preventing unauthorised access to the container using barriers and warning signs
- checking for fumigation warning notices (Figure 1) and clearance certificates

  Note: Not all fumigated containers are labelled as fumigated or are certified. Importers and freight forwarders may not always include this information in consignment documentation.

Figure 1 Example of fumigation warning notice

NOTES:
1 Symbol to be in accordance with AS 1319
2 Notice to be at least 140 mm x 100 mm external dimensions.
3 This Notice is not suitable for in-transit fumigations. Refer to the 'Australian Code for the Transport of Dangerous Goods'

- asking overseas suppliers or importers if the container has been fumigated, and
- testing the container for methyl bromide using a gas detector.

  Note: A safe reading at the entrance of the container does not mean the container was not fumigated or that further inside the container has been cleared of methyl bromide. A competent person should use the detector in various locations in and around the shipping container.

Venting

Venting is an important control used to reduce concentrations of methyl bromide and other hazardous chemicals to safe levels before workers enter and unpack containers.

Venting procedures include:

- locating containers in an open area with good natural ventilation and downwind from other activities
- using mechanical ventilation e.g. extraction or blowing for at least 30 minutes to remove methyl bromide before workers enter containers. Longer ventilation times may be needed if:
  - goods in the container have an absorbent quality e.g. wood, nuts and seeds, or
  - air flow has been restricted because of the way the goods have been packed— methyl bromide can settle in cavities or between items
- if mechanical ventilation is not reasonably practicable:
  - using natural ventilation for at least 12 hours before entering the container, or
  - testing the air in the container to ensure the methyl bromide level is below the exposure standard of 5 ppm
- partially unpacking to allow further venting if the goods are tightly packed, and
- using PPE during unpacking.

You should seek advice from a competent person:

- if you do not know what chemicals are present but suspect the air may be contaminated despite having followed venting procedures, or
- if you do not have the resources necessary to make the container safe.

Personal protective equipment

If respiratory PPE or other PPE such as protective clothing is required workers must be trained in how to properly use and maintain the equipment. When choosing PPE make sure it does not cause undue discomfort or introduce new hazards.

Further information is in:

- AS/NZS 1715:2009: *Selection, use and maintenance of respiratory protective equipment*
- AS/NZS 1716:2012: *Respiratory protective devices*, and
- AS/NZS 4501 Set: 2008: *Occupational protective clothing.*

Air testing equipment

Choose air testing equipment depending on the type of hazardous chemicals present and whether the goods are flammable.

You should seek advice from a competent person if you are unsure about what type of gas detector to use.

Further information

For further information see the Safe Work Australia website (www.swa.gov.au).

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Purging of Working Atmospheres Inside Freight Containers

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ABSTRACT

This article focuses on prevention of possible exposure to chemical agents, when opening, entering, and stripping freight containers. The container purging process is investigated using tracer gas measurements and numerical airflow simulations. Three different container ventilation conditions are studied, namely natural, mixed mode, and forced ventilation. The tests conducted allow purging time variations to be quantified in relation to various factors such as container size, degree of filling, or type of load. Natural ventilation performance characteristics prove to be highly variable, depending on environmental conditions. Use of a mechanically supplied or extracted airflow under mixed mode and forced ventilation conditions enables purging to be significantly accelerated. Under mixed mode ventilation, extracting air from the end of the container furthest from the door ensures quicker purging than supplying fresh air to this area. Under forced ventilation, purging rate is proportional to the applied ventilation flow. Moreover, purging rate depends mainly on the location at which air is introduced: the most favourable position being above the container loading level. Many of the results obtained during this study can be generalized to other cases of purging air in a confined space by general ventilation, e.g. the significance of air inlet positioning or the advantage of generating high air velocities to maximize stirring within the volume.

KEYWORDS: air cleaning; confined space; containers; computational fluid dynamics; fumigation; purging; stripping; tracer; ventilation

INTRODUCTION

The atmosphere in some freight containers can be polluted (Baur *et al.*, 2011; Preisser *et al.*, 2011, 2012; Poschadel *et al.*, 2012; Wagstaffe *et al.*, 2012) by vapours emitted by transported goods or residues from fumigation conducted to protect goods from pests (toluene, phosphine, formaldehyde, etc). Dockers and customs officers, handlers at logistics platforms, or destination companies are potentially exposed to these chemical agents, when opening, entering, or stripping containers. This situation represents a case of working in a confined space.

The purpose of this article is to provide information on the design of ventilation systems to prevent exposure to these pollutants. In an earlier study, Svedberg and Johanson (2013) injected a tracer gas into containers prior to opening them. They showed that tracer concentrations measured during stripping were effectively representative of exposure to the real pollutant.

Two methods were used in this study investigating the container purging process, namely:

- Tracer gas-based measurement conducted at a port facility
- Numerical flow simulations conducted using computational fluid dynamics software.

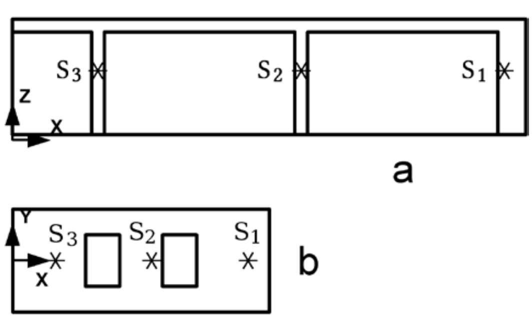
MATERIALS AND METHODS

Containers studied

Tests were conducted on the two most commonly used freight container sizes: length L = 12 m (40 feet) and = 6 m (20 feet). These containers were fitted with a 2-leaf door at the front face and were closed at the rear.

The 40-foot container had the following dimensions: length = 12 m, width = 2.4 m and height = 2.7 m. It was positioned perpendicular to a warehouse located 5.5 m from its front face. Its purging was studied for three degrees of filling:

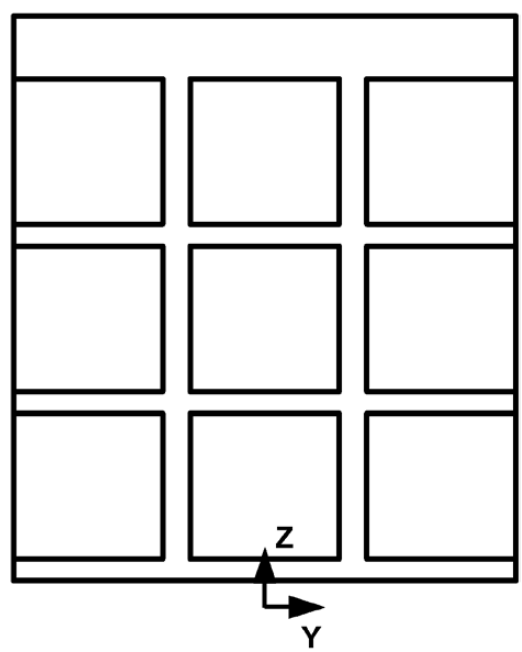
- *Full container*: the load comprised three 2.4 m high obstacles occupying the full width of the container (Fig. 1). The 1.85 m long rear obstacle rested against the rear wall. There were 0.3 m wide vertical gaps between the obstacles and a 0.65-m wide gap between the front obstacle and the door. The container degree of filling was 79.6%.
- *Partially full container*: the load comprised three groups of obstacles located in the same longitudinal positions and up to the same height as in the previous full container. Each group was composed of nine obstacles (Fig. 2) touching the side walls. Gaps between obstacles were 0.104–0.132 m wide. This arrangement modelled a load composed of objects held in frames or chassis. The container degree of filling was 61.7%.
- *Empty container*: this configuration represented the limiting case of a load composed of openwork objects offering low resistance to circulating air.



1 Sampling point positions (at respiratory tract level): (a) side view of 12 m long, full container, (b) top view of 6 m long, partially full container.

The 20-foot container had the following dimensions: length = 6 m, width = 2.4 m and height = 2.4 m. It was positioned in an enclosed area. Its purging was studied, for three degrees of filling:

- *Full container:* the load comprised three 2.0 m high obstacles occupying the full width of the container. The 0.85 m long rear obstacle was in contact with the rear wall. There were 0.3 m wide vertical gaps between the obstacles and a 0.65-m wide gap between the front obstacle and door. The container degree of filling was 66%.
- *Partially full container:* the load comprised two 0.8 m long × 1.2 m wide × 1.75 m high obstacles, positioned centrally with respect



2 Face view of 12 m long, partially full container.

to the width and at 1.7 m from the front and rear walls (Fig. 1). The degree of filling was 9.7%.

- *Empty container.*

A coordinate system with its origin at ground level and vertically in line of the centre of the rear wall was applied to the container. The *x*-axis extended longitudinally towards the container door, the *y*-axis extended horizontally across its width and the *z*-axis extended vertically upwards.

Ventilation conditions

The study involved three sets of ventilation conditions. Purging by natural ventilation was performed by simply opening the container door. Under mixed mode ventilation, opening of the door was combined with mechanical air blowing or extraction through an orifice created in the rear wall. Under forced ventilation, the door remained closed and all air introduction and extraction operations were performed through orifices in the walls.

Different orifice positions were tested:

- One 0.1 m diameter orifice drilled in the rear wall, 0.3 m below the ceiling (position coded R). In two specific simulations, the area of this orifice was multiplied by a factor of 5.1
- Two 0.1 m diameter symmetrical orifices used simultaneously and drilled in the two side walls, 0.6 m back from the door and 0.2 m above the floor (2SL coding)
- Two 0.1 m diameter symmetrical orifices used simultaneously and drilled in the two side walls, 0.6 m back from the door and 0.2 m below the ceiling (2SH coding)
- One 0.09 m diameter orifice drilled in the middle of the front face, 0.12 m below the ceiling (FH coding)
- One 0.09 m diameter orifice drilled in the middle of the front face, 0.14 m above the floor (FL coding).

The first three orifice positions represent prototype configurations developed within the scope of this study. A proposed purging apparatus consisting of a foam rubber seal penetrated by two short nozzles can be simulated as a combination of the last two orifice positions.

Experimental methods

Tracer tests were conducted using sulphur hexafluoride (low toxicity gas measurable at low concentration). Concentrations were measured using an Infraran SF6 Single Gas Analyser (Wilks Enterprise Inc., South Norwalk, CT, USA). The instrument sensory chamber volume is 0.45 l. The instrument flow rate is 10 l min^{-1}. The time for a sampling volume equal to seven times the instrument volume (3.15 l) is 18.9 s. Three measuring point positions were used, all located at a height of 1.5 m above the floor in the median longitudinal plane (Fig. 1):

- Point S_1 was located towards the front of the container, 0.5 m back from the door and therefore in front of the load
- Point S_3 was located towards the back of the container at a distance from the rear wall of 1 m (6 m long container) or of 2 m (12 m container). This point was in the middle of the vertical gap between the rear and intermediate obstacles
- Point S_2 was located towards the middle of the container at equal distance between points S_1 and S_3. This point was in the vertical gap between the intermediate and front obstacles.

The experimental protocol included a period during which tracer was injected into the container, followed by a period during which internal concentration uniformity was awaited (plateau reached at point S_3 and monitoring at other points). At the test initial time, the door was opened and/or the fan was started and the tracer concentration variation with time was recorded at one point of the volume. The instrument sampled and recorded continuously. The concentration was monitored at a single point during each test.

During the tests conducted outside, the wind velocity and direction were characterized using a weather station placed on the container roof, fitted with a cup anemometer measuring in the 1–80 m s^{-1} range. Ventilation flow rates were measured inline using a Pitot tube probe.

The site testing conditions for the natural ventilation conditions and for mixed mode or forced ventilation conditions are summarized in Tables 1 and 2, respectively. Tests X20 g and X40 m tested the effects of an additional external axial-flow fan located 1 m

Table 1. Summary of site tests under natural ventilation.

	Length (m)	Filling	Wind velocity (m s^{-1})	Temperature (°C)	Notes	Lowering times		
						t_1 (s)	t_2(s)	t_3(s)
X20a	6	Empty	0	9–15		316		
X20b	6	Empty	0	9–15				336
X20c	6	Partially full	0	9–15		306		
X20d	6	Partially full	0	9–15				229
X20e	6	Full	0	9–15			1158	
X20f	6	Full	0	9–15			986	
X20g	6	Full	0	9–15	(1)		392	
X40h	12	Empty	1.0–3.5	10–14				581
X40i	12	Empty	2.8–5.0	9–15				352
X40j	12	Empty	2.8–5.0	9–15				265
X40k	12	Full	2.8–5.0	9–15				1974
X40m	12	Full	2.8–5.0	9–15				2814
X40n	12	Full	2.8–5.0	9–15	(1)			3646

t_x is the concentration lowering time at sampling point x. (1): External fan positioned in front of door.

Table 2. Summary of site tests under mixed mode and forced ventilation (12 m long, full container).

	Flow (m^3 h^{-1})	Temperature (°C)	Air inlets	Air outlets	Lowering times	
					t_2 (s)	t_3(s)
Y40p	360	10–14	R	Door		775
Y40q	680	10–14	R	Door		378
Y40r	500	10–14	Door	R	360	
Y40s	500	10–14	Door	R		244
Z40t	<680	10–14	R	2SL		462
Z40u	<680	10–14	R	2SH		465
Z40v	<500	10–14	2SL	R		826
Z40w	<500	10–14	2SH	R		1301

t_x is the concentration lowering time at sampling point x. Coding of orifices: R = rear, SL = side low, SH = side high.

from the centre of the open container door. This extra fan was characterized by a 2 m s^{-1} axial air velocity generated at a distance of 1 m in front of it. During the outdoor tests, the wind direction was from the rear of the container towards the adjacent warehouse at an angle of incidence of ~45° with respect to the x-axis. The air velocity measured on the container roof varied between 2.8 and 5 m s^{-1} for tests X40i to X40n and between 1 and 3.5 m s^{-1} for tests X40h and Y40p to Y40s. The mixed mode ventilation tests involved only the orifice drilled through the rear wall and the forced ventilation tests involved this orifice combined with two side wall orifices, both either in a low position or in a high position. The initial tracer concentration measured at the start of purging varied between 3.2 and 9.5 ppm.

Numerical simulation methods

Numerical flow simulations were performed using FLUENT computational fluid dynamics software (ANSYS, 2010). This software program uses an iterative process to solve conservation equations (mass, momentum, tracer, etc.) by applying the finite volume method. The computation conditions applied corresponded to isothermal, transient and incompressible flows. Turbulence was simulated using the realizable k-epsilon model. Geometrical conditions were identical to those of the corresponding tests on site. Computations were based on the container of length 12 m under the following two conditions:

- Container empty under external natural ventilation
- Container full or partially full under forced ventilation.

For natural ventilation simulations, the container and the adjacent warehouse were incorporated in a large parallelepiped-shaped computation domain oriented in the wind direction. A horizontal wind velocity condition was imposed in the upstream face of this domain with a module $V(Z)$ varying as the following power function of the height above the ground (Parsons and Owen, 2005):

$$V(Z) = V_m (Z/Z_m)^a \quad (1)$$

In this equation, V_m is the meteorological wind velocity measured at the top of a mast of height Z_m, generally equal to 10 m. Exponent ‘a’ depends on the type of ground and was fixed as 0.14; this value corresponds to open ground with dispersed obstructions.

Under natural ventilation, the following initial conditions were applied:

- Inside the container: fluid at rest, uniform tracer concentration
- Outside the container: flow generated by preliminary steady-state simulation with container door closed and zero tracer concentration.

Transient flow simulation was started when the container door was opened and contact established between the interior and the surrounding atmosphere.

Under forced ventilation, the computation domain was limited to the interior of the container. The air was initially at rest and charged with a uniform concentration. At the start of the simulation, velocities for the studied ventilation flow were established in the inlet and outlet orifices.

Tests were conducted to ensure independence of results with respect to the time step used for resolution. A 10 ms time step under natural ventilation and a 40 ms time step under forced ventilation were chosen. In both cases, the results remained the same as those provided by simulations performed with a time step four times shorter. Grids used were as dense as possible prior to divergences appearing during resolution due to excessively high Courant numbers. During each simulation, the time-related variation in concentration was recorded at several points in the container, in particular at points S_1 to S_3 previous defined for the site measurements. The variation in average concentration in the container volume was also recorded.

Table 3 summarizes the simulation conditions under natural ventilation. The influencing parameters studied include wind strength, angle of incidence between wind direction and container longitudinal *x*-axis (for wind from behind the container) and adjacent warehouse presence or absence. Table 4 summarizes the simulation conditions under forced ventilation. The parameters studied include ventilation flow rate, inlet and outlet orifices location, rear orifice area, and degree of filling of the container volume. The 680 $m^3 h^{-1}$ flow rate used in most of the simulations corresponds to an air renewal rate of 8.74 vol h^{-1}.

Experimental validation

Application of the simulation methods used in this study to ventilation of confined spaces was validated with respect to laboratory experimental data published by Garrison *et al.* (1989). Measurements were taken on a confined space model comprising a cube

Table 3. Summary of simulations performed under natural ventilation (12 m long, empty container).

	Wind angle of incidence g (°)	Meteorological wind velocity V_m (m s^{-1})	Notes	Lowering times			
				t_1 (s)	t_2 (s)	t_3 (s)	t_a (s)
B44	45.0	4.4	(1)	671	764	785	684
C31	45.0	3.1		1103	1542	1595	1313
C44	45.0	4.4		734	1003	1148	878
C56	45.0	5.6		555	821	854	679
C70	45.0	7.0		451	623	638	522
D44	22.5	4.4		212	298	368	257
E44	67.5	4.4		1059	1305	1370	1123

t_x is the concentration lowering time at sampling point x.
(1) without adjacent warehouse.

Table 4. Summary of simulations performed under forced ventilation (12 m long, full or partially full container).

	Filling (%)	Rear orifice (cm^2)	Flow (m^3 h^{-1})	Air inlets	Air outlets	Lowering times			
						t_1 (s)	t_2 (s)	t_3 (s)	t_a (s)
G68	79.6	78	680	R	2SL	179	239	199	188
H68	79.6	78	680	R	2SH	219	256	216	209
I68	79.6	78	680	2SL	R	46	527	518	394
J68	79.6	78	680	2SH	R	146	413	573	287
K68	79.6	398	680	R	2SH	244	352	276	237
K136	79.6	398	1360	R	2SH	119	193	136	117
M68	61.7	78	680	2SL	R	142	277	339	313
P56	79.6	0	557	FH	FL	224	240	309	226

t_x is the concentration lowering time at sampling point x.
Coding of orifices: R = rear, SL = side low, SH = side high, FL = front low, FH = front high.

with an edge length $H = 609.6$ mm; a volume in which there was initially a deficient oxygen concentration of 10%. At the start of the test, a fresh airflow was introduced into the cavity through a vertical ventilation duct penetrating the model ceiling (Fig. 3) and recovery of the oxygen concentration was monitored at four sampling points. Supplying fresh air ensures a 20 vol h^{-1} renewal rate and the end of the ventilation duct was located above the model floor at a height of 0.8H.

Figure 4 compares time-related variations in the oxygen recovery rate between initial (c_0) and final atmospheric (c_f) levels at sampling points:

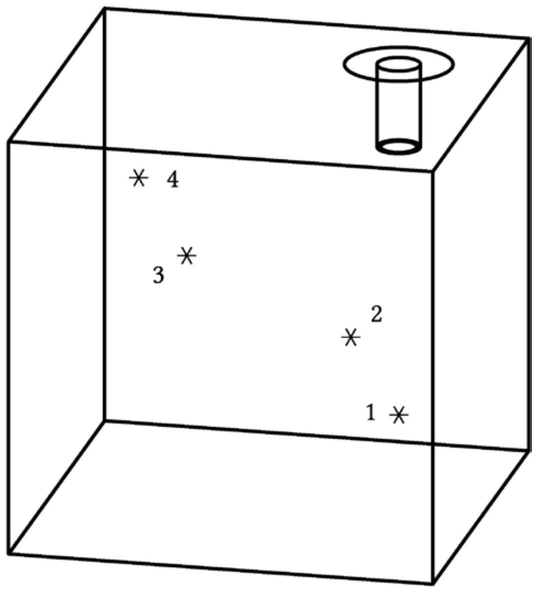
$$s(t) = \left(c(t) - c_0\right) / \left(c_f - c_0\right) \quad (2)$$

Agreement between measurements and simulation was totally satisfactory. For example, at sampling point 3, the difference between the measurements and the simulation was on average 0.06 and no greater than 0.08, when the oxygen recovery rate increased from 0 to 1. At some points, the computed oxygen recovery rate was slightly slower that the measured rate. Thus, at sampling point 4, after a 300-s time period, the measured oxygen recovery rate was 0.95, compared with 0.86 for the calculated rate.

RESULTS AND DISCUSSION

Introduction

Concentration lowering time *t* can be used to characterize ventilation performance. By convention, this time is defined in this article as the time interval after which the concentration no longer exceeds 1/10th of the initial concentration. Lowering time is helpful in comparing experimental or numerical configurations using relative values, but should not be used for estimating purging time for a real pollutant since it depends on both the initial internal concentration and the threshold limit value. Tables 1–4 provide concentration lowering times t_1, t_2, and t_3 at points S_1 to S_3 and t_a for the average concentration recorded during the simulations.



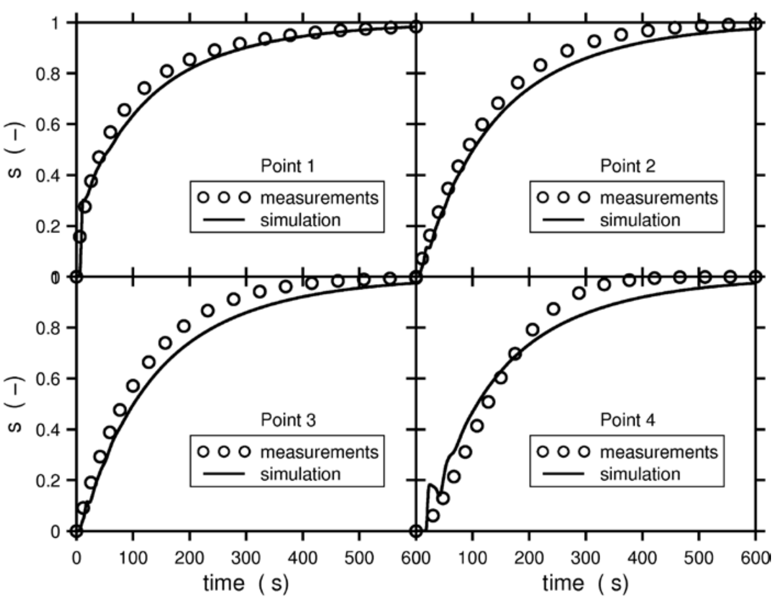
3 Confined space model used for validation.

Concentration time variation curves can be of various shapes depending on the testing conditions and the position inside the container. Concentration decrease can be regular, be subject to fairly high amplitude oscillations or may only start after a period of latency (e.g. in areas distant from air inlets). These different types of time variation can be observed in both measurements and simulations.

Natural ventilation

Container filling

Comparing (Table 1) site tests X40i and X40j, on the one hand, and tests X40k and X40m, on the other hand reveals that increasing the degree of filling of the 12 m long container increases markedly the concentration lowering time under natural ventilation: by a factor of around 8 (~300–2400 s). The same tendency



4 Time-related variations in oxygen concentration recovery at four sampling points inside model.

emerged for the 6-m long container (tests X20a to X20d, on the one hand, and tests X20e to X20f, on the other hand) although the sampling point position was not constant. This phenomenon is the natural result of the internal air circulation obstructions created by the container load.

Wind velocity

Outside natural purging rate is affected by environmental conditions and, as expected, an increase in wind velocity causes a decrease in concentration lowering times. Experimentally, this is the case when going from test X40h to test X40i (Table 1). Numerically, meteorological wind velocity influence, for a constant incidence, is reflected in simulations C31–C70 (Table 3). For example, the 3.1–7.0 m s^{-1} increase in this velocity reduces the average lowering time by a factor of 2.5: from 1313 to 522 s.

External back-up fan

Tests involving operation of an external back-up fan positioned in front of the open container door produced mixed results. For the container positioned in an enclosed area (Table 1, test X20g to be compared with tests X20e and X20f), the back-up fan reduces significantly the lowering time: by a factor of ~2.7. However, pollutants are then dispersed in the enclosed area. For the container in outside conditions (test X40n to be compared with tests X40k and X40m), the combined action of the wind and the external back-up fan proves ineffective in increasing the purging rate, the influence of the fan possibly even counteracting the effects of the wind.

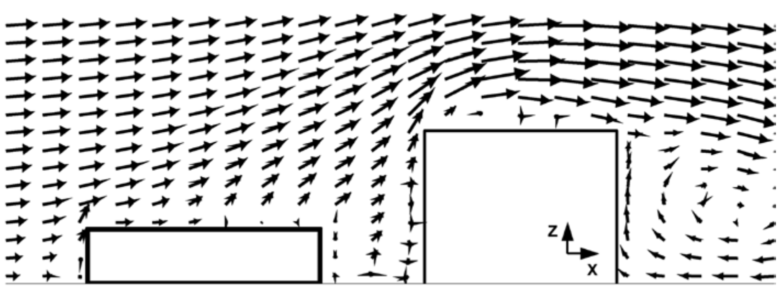
Wind direction

Simulations E44, C44, and D44 (Table 3), conducted for a constant velocity wind coming from behind the container, allow the study of the influence of wind direction, which is characterized by the angle of incidence between the wind and the container longitudinal axis.

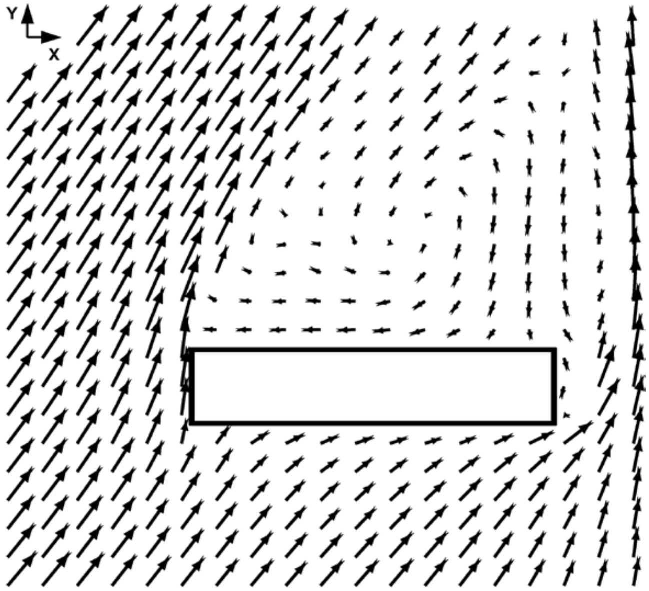
The purging rate increases significantly when this angle decreases, i.e. when the wind tends towards a direction parallel to the container and there is a warehouse in front of the container door. For example, a 67.5° to 22.5° decrease in angle reduces the average concentration lowering time from 1123 to 257 s: a reduction factor of 4.4. The container purging rate under natural ventilation therefore appears to be highly sensitive to wind direction with respect to the container. Wind direction proves more significant than wind strength within the scope of the configurations studied.

Variations in lowering times under the effect of changes in the wind direction may be linked to changes in the flow profiles in the vicinity of the container, especially near its open door. Figures 5–7 illustrate the overall flow conditions for the 45° angle of incidence. They show a number horizontal and vertical recirculation and wake zones downstream of the warehouse and the container, especially in front of the container front face. Purging results from the container internal air being put into movement by wind-generated flows present near the door opening. When the incidence changes into 22.5° (Fig. 8), velocities in this area increase strongly; this effectively reinforces the container ventilation and reduces the lowering time.

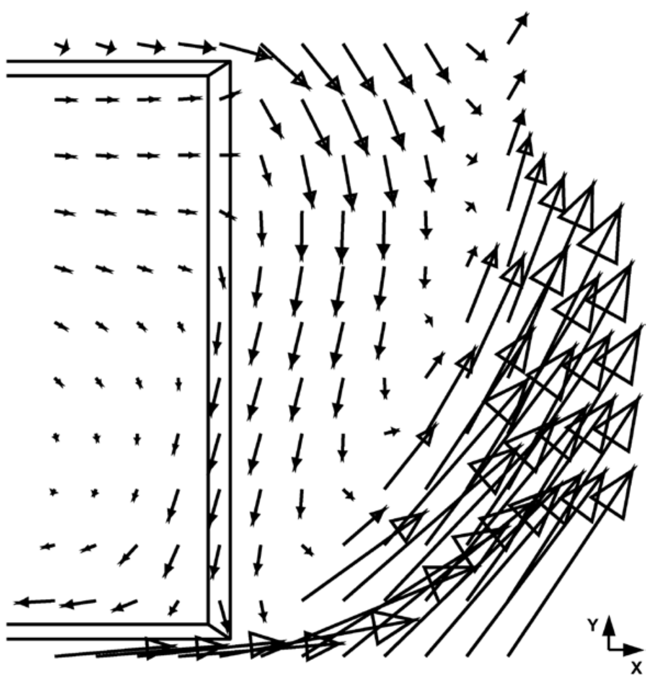
Moreover, the impact of the wind on both the container and the warehouse leads to creation of an area of reduced velocity above the container roof (Fig. 5). The air velocity measured in this area differs from the wind velocity upstream of the container.



5 Projection parallel to Y-axis of air velocities in container median longitudinal plane—simulation C44 (wind angle of incidence 45°).



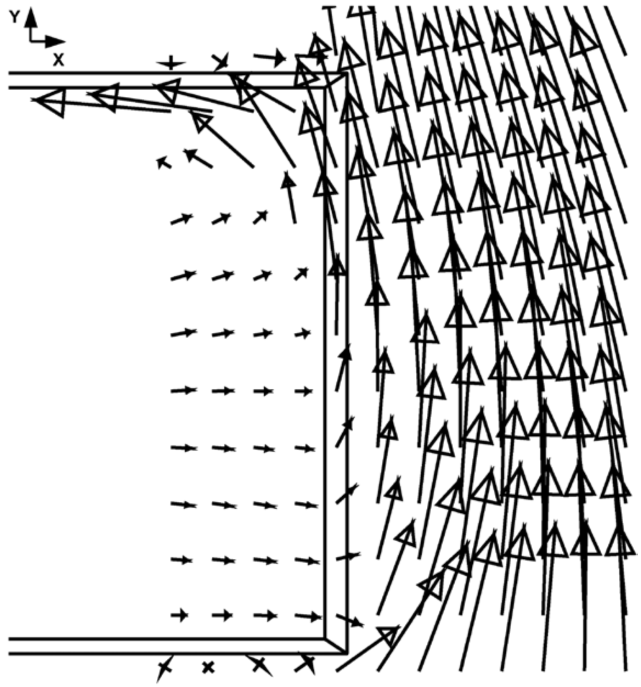
6 Projection parallel to Z-axis of air velocities in container median horizontal plane—simulation C44 (wind angle of incidence 45°).



7 Projection parallel to Z-axis of air velocities in container median horizontal plane near door opening—simulation C44 (wind angle of incidence 45°).

Warehouse in front of container

Simulation B44 was conducted with no warehouse in front of the container, but under the same wind conditions as in simulation C44. This change in the container environment modifies the flows in the vicinity of the container, but ultimately prompts fairly small



8 Projection parallel to Z-axis of air velocities in container median horizontal plane near to door opening—simulation D44 (wind angle of incidence 22.5°).

variations in lowering time (Table 3). This result is probably specific to the studied wind direction, but it reveals that the presence of a building forming an obstacle near a container to be inspected or stripped does not necessarily represent a hindrance to natural ventilation-based purging.

Purging progress inside container

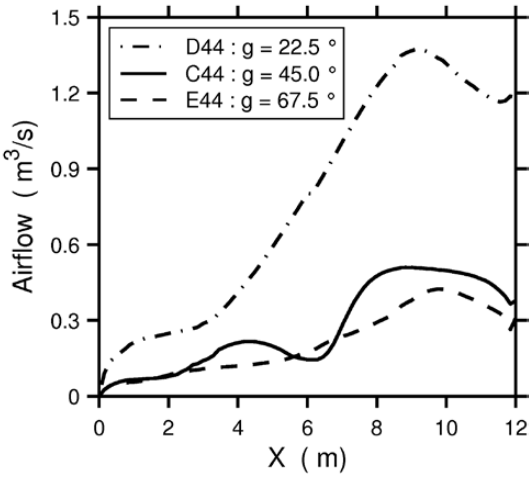
Wind-generated movement of the air at the front of the container propagates into its internal volume as horizontal and vertical vortices of different shape and intensity, depending on the wind strength and direction. However, the container rear wall was closed, so these exchanges died out towards its far end. Thus, the purging process tended to decelerate towards the rear of the container, as shown in Table 3: the concentration lowering time increased from point S_1 to point S_2 to point S_3.

Unpolluted air penetration within the container depends on the intensity of the exchanges in the longitudinal direction. These exchanges can be quantified by considering the air velocities at different vertical, normal cross sections parallel to the opening plane, and hence orthogonal to the longitudinal *x*-axis between the end of the container ($X = 0$) furthest from the door and the door opening ($X = L$). Each normal cross section is divided into a zone, in which the velocity component along the *x*-axis is positive, and a second zone, in which this component is negative. Integration of this component over each of the two zones provides values of two airflows crossing the normal cross section: Q_{dir} flowing towards the door opening, and Q_{inv} flowing in the opposite direction. These two flows are equal in the case of a container closed at the rear end.

Figure 9 illustrates the longitudinal profiles for horizontal scavenging flow Q_{dir} computed for a 4.4 m s^{-1} constant wind velocity. This figure shows that the air exchanges in the longitudinal direction decreased significantly towards the rear of the container. It also confirms the strong influence of the wind angle of incidence on the purging process. High horizontal scavenging flows (e.g. in configuration D44) led to short lowering times shown in Table 3.

Mixed mode ventilation

Onsite measurements based on mixed mode ventilation of a 12-m long full container (tests Y40p to Y40s



9 Longitudinal profile of horizontal scavenging flow for three wind angles of incidence under natural ventilation.

in Table 2) indicate very significant improvement in purging performance compared with previous results for natural ventilation (tests X40k and X40m in Table 1) despite lower wind velocities. Concentration lowering times under mixed mode ventilation varied from 244 to 775 s compared with 1974 to 2814 s under natural ventilation. Introducing mechanical ventilation effectively ensures that the horizontal scavenging flow remains at least equal to the flow delivered by the fan over the full length of the container.

The lowering times measured in tests Y40p and Y40q appear to be roughly inversely proportional to the flow delivered by the fan. This allows lowering times in tests Y40p to Y40s to be scaled, for comparison purposes, to a 680 m^3 h^{-1} common flow. Measurements then show that, under mixed mode ventilation, extracting air through a rear orifice produces shorter lowering times (222 s compared with 394 s on average) than blowing air into the container through this orifice. This result may perhaps be explained by the fact that rear wall extraction strengthens the natural ventilation air inputs through the door opening while, conversely, rear wall blowing tends to force the wind back outside the container.

Forced ventilation

Ventilation flow

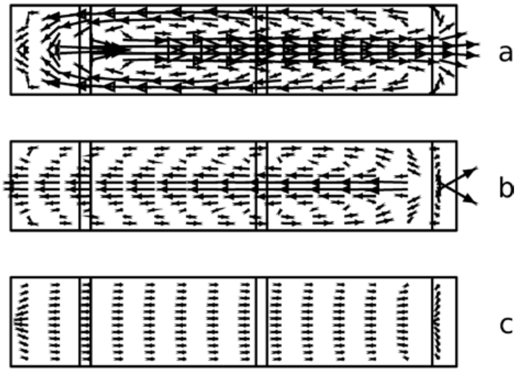
Onsite measurements under forced ventilation on the 12-m long container (series Z40t to Z40w in Table 2) revealed better purging performance compared to natural ventilation-based tests. However, the measured concentration lowering times did not approach the short times achieved under mixed mode ventilation. This difference was partly due to an increase in pressure losses caused by the air passing through small diameter side wall orifices (under forced ventilation) rather than through the whole door area (under mixed mode ventilation). The airflow could not be measured under forced ventilation, but the same fan as under mixed mode ventilation was used. This flow is undoubtedly lower than that implemented for the same configuration under mixed mode ventilation.

Simulation K136 was conducted under the same conditions as simulation K68, but with twice the ventilation flow (Table 4). The results reveal that the obtained lowering times are effectively halved with respect to the latter simulation. Under forced ventilation, purging rate is therefore proportional to the implemented flow.

Positioning of ventilation orifices

The concentration lowering times measured onsite (Table 2) with the rear wall orifice used as an air supply inlet (tests Z40t and Z40u) proved to be markedly shorter than those obtained with this orifice used as an extraction outlet (tests Z40v and Z40w). This difference persists, even after correcting the last two values using as a first approximation the flow ratio of 500/680 measured under mixed mode ventilation: 462 and 465 s, in the former case, compared with 607 and 957 s after correction, in the latter case. Use of the rear wall orifice as a supply inlet therefore enables the measured lowering times to be reduced by a factor of ~1.3–2.1. Table 4 reveals the same results for lowering times computed by simulation: the times for configurations G68 and H68 with the rear wall air inlet are less than those for configurations I68 and J68 with the rear wall outlet except for time t_1, discussed below. Air input through the rear wall orifice reduces the computed average lowering times by a factor of 1.4–2.1.

This influence of air input/output function, fulfilled by the rear wall orifice, on purging rate can be related to the container internal flow characteristics, in particular the air velocities in the unobstructed upper volume between the top of the load and the container ceiling. The velocity fields in the horizontal plane at mid height in this volume are shown in Fig. 10 for three simulations.



10 Projection parallel to Z-axis of air velocities in horizontal plane at mid-height between load and container ceiling: (a) Simulation G68 (rear air inlet and side low outlets), (b) Simulation J68 (side high inlets and rear outlet), and (c) Simulation I68 (side low inlets and rear outlet).

When air enters the container through the rear wall orifice, the jet from this orifice penetrates directly into the upper volume and generates high velocities therein both in the central direct flow and in the return flow near the side walls. By contrast, air entry through two symmetrical side wall orifices located near the front face leads to formation of two opposing transverse jets, whose initial velocity is reduced by half. These two jets strike each other at the centre of the container, and then disperse radially, thereby losing part of their momentum. Transverse jet impact occurs in the upper volume with high-level side wall orifices (J68), while with low-level side wall orifices (I68) the flow only reaches the upper volume after rising parallel to the front face and bending from vertical to horizontal.

As a result, air velocities in the upper volume decrease significantly from simulation G68 (or H68) to simulation J68 and to simulation I68. However, the study of the time variation curves for the concentration shows that the slowest decrease occurs inside the two vertical gaps between the rear and intermediate obstacles, on the one hand, and between the intermediate and front obstacles, on the other hand. These gaps are ventilated by air movement generated through contact with the adjacent flow established in the upper volume. Purging is therefore more efficient, when velocities are high in the upper unobstructed volume.

When air is introduced through the rear wall orifice, the height at which the side wall orifices are drilled has little influence on the purging rate. This result emerges from both the concentration lowering times measured at point S_3, during tests Z40t and Z40u (Table 2), and the times computed in simulations G68 and H68 (Table 4). Slight influence of the drilling height arises only in the purging of the vertical zone between the container door and the front obstacle. Point S_1 is located in this zone, which is irrigated by the total ventilation flow, when air leaves through the low-level side wall orifices (simulation G68). In the case of simulation H68, which involves the high-level side wall orifices, this zone is only ventilated by a secondary flow and this slightly increases lowering time t_1. Similar flow modifications would explain the difference between the times t_1 computed from simulations I68 and J68.

Simulation P56 involves two ventilation orifices located on the same container face (front) and models purging performed through an inserted foam rubber seal. The air velocity in these 0.09 m diameter orifices was set equal to the velocity in the rear wall orifice used in simulations G68 to J68. For comparison purposes, the lowering times computed from this simulation (Table 4) can be scaled to the 680 $m^3 h^{-1}$ flow and then become 183, 197, 253, and 185 s for t_1, t_2, t_3, and t_a, respectively. For the type of load considered, the purging performance achieved with combination P of orifices both located in the front face is therefore as good as that computed for combination G of orifices located at both ends of the container.

The flows computed in simulation P56 in the unobstructed upper volume beneath the container ceiling are in the opposite direction to those in simulation G68, but are of similar structure. The jet penetrating from the inlet orifice scavenges the full length of the container up to the end wall, then produces a return flow near the side walls. It generates high velocities which initiate air movement to ventilate the vertical gaps between the obstacles comprising the load. Furthermore, reversal of the jet direction in the upper volume between simulations P56 and G68 inverts the order of lowering times t_2 and t_3: the vertical gap above which the jet first passes being the best ventilated.

Air velocity in inlet orifice

The only difference between simulations K68 and H68 is the greater area of the rear wall inlet in simulation K68, which reduces the air velocity in this orifice by a factor of 5.1 for a constant ventilation flow. The results show that this reduction prompts a slight increase in lowering times, especially in the gaps between obstacles. However, the influence of rear inlet area on purging is ultimately fairly small since a variation by a factor of 5.1 alters the average lowering time by only 13%.

Container degree of filling

Simulation M68 was conducted under the same ventilation conditions as I68 but with a slightly lower degree of filling (61.7 *vs* 79.6%). Simulation M68 geometry incorporated a few horizontal and vertical unobstructed spaces within the load (Fig. 2). Despite their small width, these additional spaces prompted a tangible increase in purging rate due to their creation of new air passages favouring more uniform distribution of fresh air in the container volume. This improvement in purging performance is particularly sensitive in the vertical gaps between obstacles. Concentration lowering times at points S_2 and S_3 are thereby divided by factors of 2.3 and 1.5. On the other hand, the vertical zone between the door and the front of the load is no longer scavenged by all the flow, as it was in simulation I68, and this causes an increase in lowering time t_1.

CONCLUSION

Tracer gas-based measurements at a port facility and numerical simulations were used in this study to examine the container purging process. Application of a simulation method was experimentally validated using data from the literature on ventilation of a confined space subject to oxygen deficiency. The tests conducted allowed quantification of purging time variations in relation to various factors such as container size, degree of filling, or type of load. Three container ventilation modes were analysed.

Natural ventilation operates by simply opening the container door and would seem to be the most commonly used method at present. Its performance characteristics prove to be highly variable and dependent on environmental conditions, especially wind velocity and direction. The purging rate decreases when moving towards the rear end of the container. There are risks of exposure to pollution, when opening the door. The pollutant propagates throughout the surrounding enclosed area, if purging is performed indoors.

Use of a mechanically supplied or extracted airflow under mixed mode and forced ventilation conditions allows the purging process to be greatly accelerated. Mixed mode ventilation combines opening of the door with implementing an airflow towards the rear end of the container. Under these conditions, extracting air from the rear end of the container ensures faster purging than supplying air to this zone. Exposure risks when opening the door or when purging in an enclosed area are present under mixed mode ventilation, just as they are under natural ventilation.

Under forced ventilation, the container is closed and is ventilated through orifices drilled through its walls (this study included testing a number of prototype configurations) or through a foam insert between the door leaves. Under these conditions, the purging rate is proportional to the applied ventilation flow and mainly depends on the choice of air inlet position, which is likely to alter the purging time by a factor of up to 2. The most favourable position is above the load level because this allows penetration of the jet emerging from the inlet and generation of high air velocities, ensuring maximum stirring of the volume. Using a foam insert involves exposure risks during its installation or if its airtightness is damaged. This solution also assumes procurement of specific materials and requires additional handling. Use of orifices penetrating the container walls does not suffer these drawbacks, but requires amendments to freight container manufacturing standards to ensure they feature openings that can be easily made airtight and fitted with seals.

The container purging issue is related to the problem of general ventilation-based cleaning of air in a confined space. Resorting to this ventilation method may prove necessary in some circumstances, e.g. in cases of very widespread initial pollution (case of containers) or large size pollutant sources or technical impossibility of capturing emissions at source. Many of the results obtained for containers can be generalized to this type of cleaning situation, for example priority to be given to positioning air inlets or the advantage of generating high air velocities to ensure maximum stirring of the confined space volume.

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Work Inside Ocean Freight Containers—Personal Exposure to Off-Gassing Chemicals

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More than 500 million ocean freight container units are shipped annually between countries and continents. Residual levels of fumigants, as well as naturally occurring off-gassing chemicals emanating from the goods, constitute safety risks, which may affect uniformed workers upon entering the container. The aim of this study was to assess workers' exposure during stripping of containers and is the first study of its kind. First, an experimental tracer gas method was investigated to determine its usefulness to approximate real exposures from gaseous fumigants and off-gassing volatile organic compounds (VOCs). Nitrous oxide was injected and left to distribute in the closed containers. The distribution of the tracer gas and initial (arrival) concentrations of off-gassing volatiles were measured prior to opening the containers. Second, personal exposure (breathing zone) and work zone air monitoring of both tracer gas and VOCs were carried out during stripping. Adsorbent tubes, bag samples, and direct-readings instruments (photoionization detector and Fourier transform infrared spectrometry) were used. The distribution studies with nitrous oxide, and the high correlation between the former and VOCs (r^2 ~ 0.8) during stripping, showed that the tracer gas method may well be used to approximate real exposures in containers. The average breathing zone and work zone concentrations during stripping of naturally ventilated 40-foot containers were 1–7% of the arrival concentrations; however, peaks up to 70% were seen during opening. Even if average exposures during stripping are significantly lower than arrival concentrations, they may still represent serious violations of occupational exposure limits in high-risk containers. The results from this and previous studies illustrate the need to establish practices for the safe handling of ocean freight containers. Until comprehensive recommendations are in place, personnel that need to enter such containers should, in addition to appropriate personal protective equipment, have access to equipment for measuring contaminants and for applying forced ventilation when necessary.

Keywords: confined space; exposure assessment; fumigation; prevention; sea container

INTRODUCTION

Globalization of trade has increased the volume of goods transported by ocean freight containers. In 2010, the worldwide container port throughput was 540 million units, that is the total number of containers handled by ports annually, expressed in 20-foot equivalent units (UNCTAD, 2012).

Goods, packaging, and wood pallets shipped in ocean freight containers may require voluntary or mandatory fumigation with gaseous pesticides to prevent pests and microbiological attacks on the goods and to stop their spread between countries and continents. Goods and packaging material themselves may also emit harmful volatile chemicals, which either occur naturally or remain after the production process, all of which will accumulate in the air inside the closed container. Residual levels of fumigants and off-gassing chemicals constitute health risks, which may affect unprepared workers upon entering the container. Many harmful substances, e.g. carbon monoxide, benzene, and phosphine, do not carry with them distinct inherent warning

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characteristics such as unpleasant odour or irritative properties.

Methyl bromide, sulphuryl fluoride, phosphine, chloropicrin, and hydrogen cyanide are examples of typical fumigation chemicals. Methyl bromide is being phased out but until substitutes are available for all situations in which it is currently employed it may still be used in accordance with the International Standards for Phytosanitary Measure, ISPM 15 protocol (FAO, 2009).

Fumigation can either be performed by preshipping application and ventilation (methyl bromide, sulphuryl fluoride) or by using an in-transit dose that maintains an effective level during transport (phosphine). Phosphine treatment is mostly carried out by placing small packages containing a powder or pellets of metallic phosphide, typically aluminium phosphide inside the container. During transportation, the phosphide reacts with atmospheric water vapour to form toxic phosphine gas and leaves a trace of solid harmless aluminium hydroxide (Windholz, 1983).

Fumigated containers that have not been ventilated before they are loaded on board fall within the scope of the International Maritime Dangerous Goods Code published by the International Maritime Organization (IMO, 2012). Such containers must carry warning signs, according to chapter 5.5 of the Code, indicating the chemical used and date of treatment. They must also be accompanied by correct transportation documents specifying the fumigation procedures. Detailed information is published in the IMO Recommendations covering the safe use of pesticides in ships, applicable to the fumigation of cargo transport units (IMO, 2008). Interestingly, the very same recommendation states that there is widespread non-compliance regarding signage and required documentation. Such lack of compliance raises serious concerns, as the warning sign is the first, and perhaps only, message the worker receives that the container air could be hazardous.

Stripping, a term used for unloading the goods inside a container, is normally done in container terminals and warehouses strategically located in various parts of a country. The content is typically stripped, rearranged, and reloaded onto trucks for delivery to retail outlets. A large number of warehouse workers are engaged on a daily basis in stripping and may spend several hours each day inside containers. When preparing for this study, we identified serious shortcomings in work routines and our impression is that the most common practice is to require uninformed and unprotected workers to strip the containers without knowing anything about their contents with respect to fumigants and off-gassing chemicals.

Occupational groups such as coast guards, customs officers, and food inspectors may be exposed to high levels of air contaminants as they enter unventilated containers to inspect cargo and hollow spaces, at times even crawling in the narrow space between the goods and the container ceiling. Down the distribution line, there is a low-grade exposure risk among retail personnel, consumers, and others handling goods that have been shipped in affected containers. Experimental studies have shown that methyl bromide, chloropicrin, and sulphuryl fluoride may absorb in consumer goods followed by slow release over long periods of time (Scheffrahn *et al.*, 1987; Knol *et al.*, 2005). Symptoms such as headache, concentration and memory problems, dizziness and nausea, irritation of the skin and mucous membranes, neurological and neuropsychological impairment, and reactive airways dysfunction syndrome have been reported among patients after contact with fumigants (Preisser *et al.*, 2011). Two case reports directly related to work inside containers are described in a recent article by Preisser *et al.* (2012).

Considering the size of the container transportation industry, there are surprisingly few peer-reviewed studies reporting from screening ocean freight containers for toxic substances. In one of these few, just >2000 incoming containers were investigated in the Port of Hamburg during a 10-week period in 2006 (Baur *et al.*, 2010). The most frequent contaminants found were formaldehyde (59%) and benzene (19%) and, among the fumigants, methyl bromide (14%), phosphine (4.5%), and chloropicrin (1.7%).

Among the non-peer-reviewed studies, roughly 300 randomly selected import containers were examined in 2002 in the Port of Rotterdam (Knol-de Vos, 2002). Methyl bromide, formaldehyde, and phosphine were found in 21% of the containers. In 5% of the 300 containers, the levels of these fumigants exceeded the Dutch 8-h occupational exposure limits (OEL). In a study of 50 000 containers in the Benelux container terminals during 2010, volatile chemicals were identified and grouped according to the type of goods transported. The most common chemicals identified were 1,2-dichloroethane, carbon monoxide, formaldehyde, toluene, and benzene at a frequency of ~2% each. Phosphine was present in

0.08% and methyl bromide in 0.06% of the containers (Luyts, 2010).

Personal exposure to 13 selected residual chemicals is reported in a recent hazard surveillance published by the Safe Work Australia (2012). Residual chemicals were detected in 74 of the 76 investigated containers. The most common volatiles were toluene, C2-alkylbenzenes, and methyl bromide. In 8% of the containers, personal peak levels exceeded the Australian national workplace exposure standards (WES) for chloropicrin and formaldehyde. None of 12 personal samples, covering the entire duration of stripping a container (2–3 h), exceeded the WES.

We have previously sampled arrival concentrations in 101 randomly selected incoming containers in the Port of Gothenburg, Sweden, in 2010 (Svedberg and Johanson, 2011). Trace amounts of the fumigant carbonyl sulphide were found in one container (1 p.p.m.). Most containers had detectable levels of volatile chemicals; most commonly methanol (78% of the containers), hydrocarbons (47%), carbon monoxide (45%), and ammonia (15%). Of the measurements taken, 7% were above or well above the Swedish 8-h OEL. Aside from representing random variability and true differences, the deviating results in the above studies also reflect different detection limits and other technical limitations in the analytical methods.

In spite of the sometimes high concentrations found in the screening studies, we found no reports in the scientific literature regarding workers' exposure. The aim of this study was to assess workers' exposure to volatile chemicals during complete stripping operations and evaluate them in relation to the initial arrival concentrations.

METHODS

Study locations

Two major Swedish retail businesses were studied as their import containers were stripped of their content in their respective central distribution warehouse. The containers were positioned as usual with the container doors in the rear facing the inside of the warehouse. Once positioned, a distance of ~0.5–1.0 m free passage to the open air around the perimeter of the container remained. This open space was normally closed during stripping by the use folding curtains operated by pressurized air. In both warehouses, the loading docks were separated from the storage area by large doors that remained closed except during passage.

Preparation of containers

Only 40-foot containers were included in the study since they are likely to cause a higher exposure than the shorter 20-foot type. The contents of the containers were cartons of various sizes with electronics, tools, shoes, and sporting goods. The containers were filled to an estimated 80–100%. The containers targeted for the study were opened, and three sampling sites were arranged at 12, 6, and 0 m from the door as follows. For the 12-m position, six sections of 2 m × 16 mm stiff polyvinyl chloride tubings were fitted in line and positioned in the space between the goods and the container ceiling. Similarly, three sections were fitted for the 6-m position. Immediately inside the doors, the sampling lines were connected to a short 10-mm diameter nylon tube, which snugly fit between the rubber door seals when closed. Only the short nylon tube was used for the 0-m position.

Tracer gas studies

Although some import containers have sufficient arrival concentrations of off-gassing volatile organic compounds (VOCs), their appearance may be too rare and unpredictable to be practically useful for personal exposure studies. For this reason, we wanted to investigate if an experimental tracer gas method could approximate the behaviour of real contaminants. The tracer gas chosen was nitrous oxide (N_2O), which was added prior to stripping the container. Nitrous oxide has several advantages: it does not normally occur in containers, it is harmless at the concentrations used, and it has a distinct infrared signal, which can easily be monitored. Nitrous oxide is commonly utilized in ventilation studies as well as in medical applications. The Swedish 8-h OEL for nitrous oxide is 100 p.p.m., and the 15-min short-term OEL is 500 p.p.m. (SWEA, 2011).

After closing the prepared containers, nitrous oxide was injected from a gas cylinder through the 6-m sample line. The application was gauged to reach a final concentration of ~500 p.p.m., however, due to a varying degree of free airspace from one container to another, the target concentration was highly approximate. The tracer gas was let to disperse for at least 24 h before the container was ready for stripping. This part of the study was only conducted after approval by the Regional Swedish Ethics Committee and informed consent by the workers involved in container stripping.

Initial concentrations

Initial concentrations of the tracer gas and any naturally occurring off-gassing chemicals were measured in all three sampling positions immediately before opening the container doors for stripping. Air was pumped directly to a gas cell for measurement with a Fourier transform infrared (FTIR) spectrometer and, using the outlet air from the gas cell, with a direct reading photoionization detector (PID). Alternatively the air was sampled in bags for later analysis by FTIR and PID as well as for collection on adsorbent tubes. Further details on the analytical methods are given below.

Personal exposure monitoring

Personal monitoring was arranged to determine the average exposure during a complete stripping process. All tested containers were ventilated naturally during stripping through the open container doors. Typically, a 40-foot container was stripped in 2–3 h. In one of the companies, two workers unloaded the goods onto pallets, while a third person operated a forklift removing loaded pallets and delivering a stack of empty ones when required. The other company made use of a conveyor belt that extended into the container. Only one person inside the container unloaded goods onto the conveyor.

The persons working inside the container were equipped with backpacks to accommodate equipment for bag and adsorbent tube sampling and for the PID instrument. In case there was a shift of personnel, the equipment was transferred to the new worker. The sampling and monitoring started prior to opening the container doors and continued until the container was completely emptied.

Bag sampling (six containers). A 10-l sample bag (Tedlar®) was placed in the backpack and connected to a sample pump (SKC Model 224-PCXR7) set at a flow rate of 200 ml min^{-1}, giving an effective sample time of just <50 min per bag. The sample tube inlet was positioned in the breathing zone near the workers' lapel. The bag was replaced when nearly full. Analyses of the contents of the sample bags were done on-site by FTIR in six containers and by PID in two of them.

Direct reading PID instrument (three containers). The PID instrument was placed in the backpack and used in 'hygiene' mode for continuous personal monitoring. One-minute average readings were logged. The sample nozzle had a dorsal position slightly above shoulder height.

Adsorbent sampling (three containers). Adsorbent tubes (Anasorb 747) were connected to a sample pump (GSA SG 350ex) set at a flow rate of 333 ml min^{-1}. The sample tube inlet was positioned in the breathing zone near the workers' lapel.

Work zone monitoring

The work zone was defined as the work area within an arm's length distance from the worker and is a close approximation of the personal exposure. A diaphragm pump (KNF Type NO26 1.2 AN.18, KNF Neuberger GmbH, Freiburg-Munzingen, Germany) continuously pulled work zone air at an effective flow rate of 5 l min^{-1} through a 10-mm diameter sample line to the FTIR instrument positioned outside the container. The sample line was positioned not to obstruct the workers' movements and was continually repositioned as the work zone gradually moved towards the front end of the container. Air samples were collected as 30-s to 2-min averages, the shorter times to observe peak exposures during opening of the containers and the longer to enhance the detection limits as the levels tapered off.

Chemical analyses

Fourier transform infrared. Two FTIR instruments were used in this study; a Bomem MB 100 and a MB 3000 (Bomem Inc., Quebec, Canada). They were equipped with a 1-m, 10-m, or 20-m analytical gas cell, the optical path length depending on application and configuration. Qualitative and quantitative analyses of nitrous oxide and VOCs were based on library spectra from Infrared Analysis Inc. (Irvine, CA, USA). Concentrations >100 p.p.m. of nitrous oxide were quantified by creating a calibration file with a set of spectra based on the Hitran2000 spectral database (Griffith, 1996; Rothman *et al.*, 2003).

Photoionization detector. A hand-held PID (ppbRAE Plus, RAE Systems, San Jose, CA, USA) with a built-in data logger was used to measure the VOCs.

Adsorbent tubes. Analyses were done using gas chromatography-mass spectrometry (GC-MS) technique in scan mode, dichloromethane extraction, and a phenyl-dimethylpolysiloxane column (Eurofins Pegasus lab, Uppsala, Sweden). The VOCs were determined in the 80–300°C boiling point range and expressed as toluene equivalents.

RESULTS

Dispersion of tracer gases and legitimacy of the tracer gas method

A well-distributed tracer gas is a precondition for reliable ventilation and exposure studies. The concentration of the tracer gas after 22–25 h of equilibration is shown in Fig. 1. As the absolute concentrations are of no interest, they are expressed relative to those measured at 6 m, i.e. at the injection point. In all seven containers, the relative concentration was lower inside the doors (0 m) and in five containers, it was also lower at the front end (12 m). This pattern remained after 42 h (tested in two containers, Fig. 2). The distribution of tracer gas resembled that of naturally occurring VOCs as illustrated in Fig. 3 and is an illustration that the tracer gas method well approximates the behaviour seen with off-gassing chemicals.

Exposure measurements

The measurements of personal and work zone samples in six 40-foot containers are summarized in Table 1. All exposure levels are expressed relative to the initial concentrations recorded inside the doors (0 m) just before opening. This reference point was selected since it is, in the normal handling in container terminals, accessible by inserting a sample nozzle between the rubber seals around the doors. There was some variability between the measurements depending on the sampling and analytical method, but the aggregate results showed personal exposures levels between 1 and 7% of the concentrations in the unopened containers. The personal exposure based on FTIR analysis of nitrous oxide collected in bag samples showed an average exposure of 2.0 ± 0.82% (n = 6) of the initial concentrations. The results from FTIR and PID measurements showed good agreement, while the results from adsorbent sampling yielded slightly higher figures of 5.4–6.7%.

The average levels recorded by continuous work zone monitoring showed good agreement with those collected by personal sampling. The graphs in Fig. 4 illustrate representative work

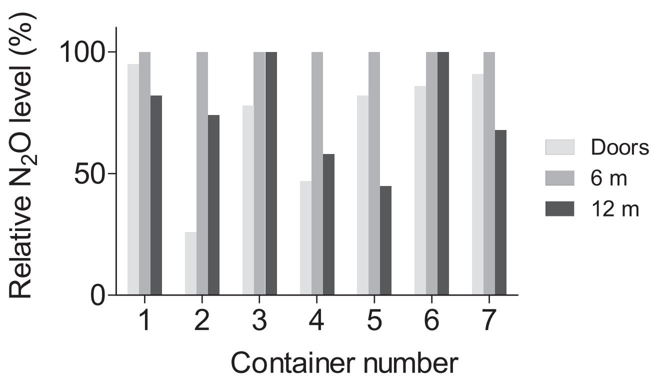

Fig. 1. Distribution of nitrous oxide (N_2O) tracer gas after 22–25 h of equilibration in seven containers. The concentrations are expressed relative to that at the site of injection, i.e. at 6 m.

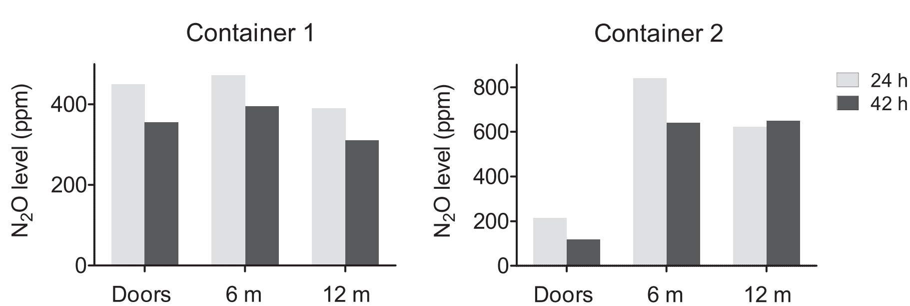

Fig. 2. Distribution of nitrous oxide (N_2O) tracer gas injected at the 6-m position after 24 and 42 h of equilibration.

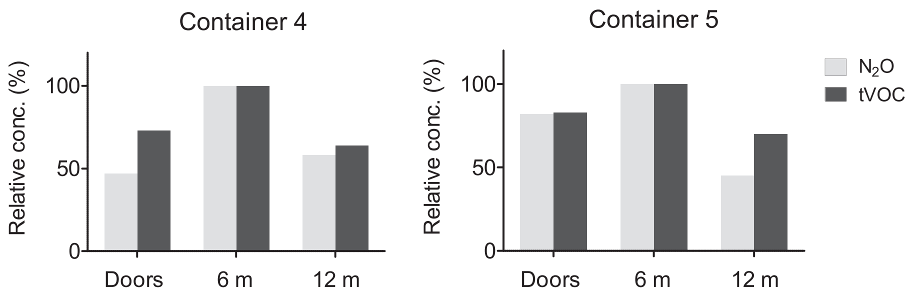

Fig. 3. Concentrations of naturally occurring VOCs and nitrous oxide (N_2O) tracer gas and in two containers after 24 h of equilibration of the tracer gas. The concentrations are expressed relative to that measured at 6 m, the site of N_2O injection.

Table 1. Personal and work zone samples collected during stripping of six containers. The concentrations are expressed relative to the initial concentration just inside the doors before opening the container.

Analyte	Method	Container ID					
		4	5	8	9	10	11
		Stripping time (min)					
		184	90	173	74	110	145
		Relative concentration (%)					
Personal sampling							
VOC	Adsorbent tube	4.7	6.7	5.4	—	—	—
VOC[a]	FTIR bag sample	2.1	1.4	2.8	—	—	—
N_2O[a]	FTIR bag sample	2.2	1.3	3.4	1.2	1.6	2.3
VOC[a]	PID bag sample	—	1.1	2.1	—	—	—
VOC	PID continuous	1.7	2.7	3.1	—	—	—
Work zone sampling							
VOC	FTIR continuous	0.7	1.2	—	—	—	—
N_2O	FTIR continuous	1.4	0.7	—	1.3	1.7	1.5
Peak exposure at container opening[b]							
N_2O work zone	FTIR	3.8	3.7	—	10	2.0	6.3
VOC personal	PID	3.0	70	3.9	—	—	—

—, no data available.
[a]Parallel samples extracted from the same sample bags.
[b]Measured as 0.5-min or 1-min averages.

zone data monitored by FTIR in three containers (nos 9, 10, 11) and from continuous personal monitoring with the PID instrument in one container (no. 5). Upon opening the containers, peak exposures were occasionally observed. These peaks were usually <10% of the initial concentration (based on 1-min averages) but reached 70% in one case. Disregarding the opening peaks, the readings fluctuated between 2 and 4% throughout the remainder of the stripping operation.

In two containers, both stuffed with boxes with sneakers, the levels of naturally occurring VOCs were sufficient to follow the time-trend during stripping and compare with the behaviour of the tracer gas. When VOCs and the tracer gas were analysed in the same FTIR spectra, they showed comparable time-trends and correlation coefficients (r^2) of ~0.8, as illustrated in Fig. 5. This is an additional illustration that the use of a tracer gas may well approximate real exposures. In these two containers, the initial concentrations of total VOCs (measured by GC–MS) were 169 and 219 mg m^{-3}, expressed as toluene equivalents. The dominating VOC was toluene (91 and 68%, respectively, of the total VOCs). Benzene (0.7 and 4 mg m^{-3}, respectively), 2-butanone, ethylbenzene, xylene, heptane, cyclohexylmethane and ethyl acetate were also detected.

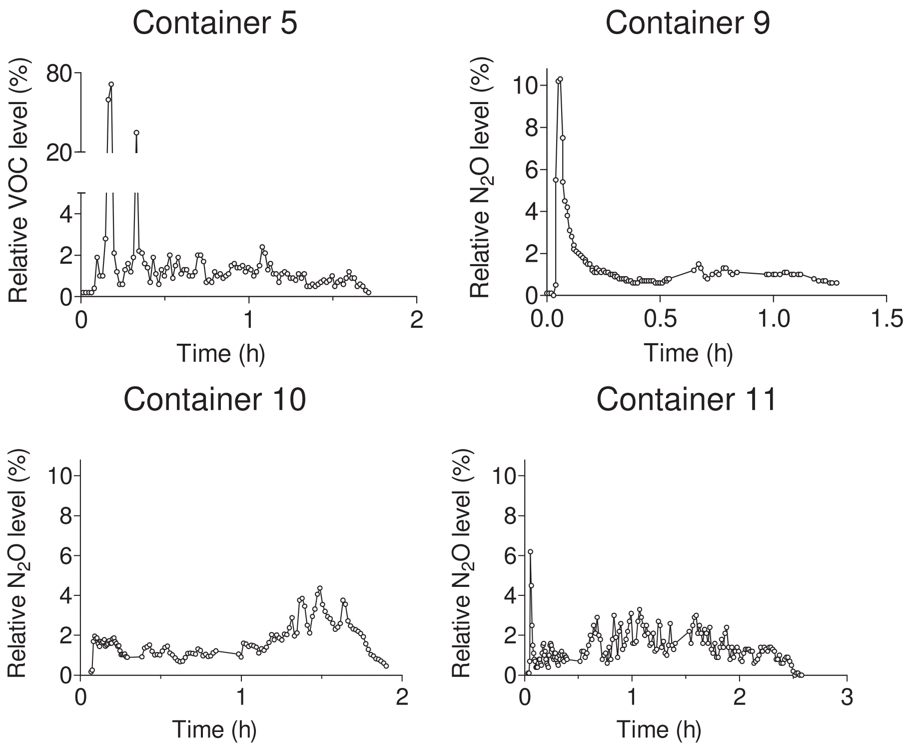

Fig. 4. Results from personal monitoring of VOCs by PID (container 5) and work zone monitoring of nitrous oxide (N_2O) tracer gas by FTIR (containers 9–11). The concentrations are expressed relative to the initial concentration inside the door prior to opening the container. Note the broken *y*-axis of the VOC graph.

DISCUSSION

Based on the findings in this study, we conclude that workers' average exposure to off-gassing chemicals during stripping of containers is usually significantly lower (1–7%) than might be expected if only the concentration in the unopened container is considered. Still, peak exposures may occur, in our study reaching as high as 70% of the initial concentration. Such episodes raise concerns for acute health effects and justify preventive measures prior to opening. The low average exposures and the brief peak exposures may explain why only a handful of case reports that directly can be related to the work inside freight containers have been reported in the scientific literature. In spite of the few case reports, we suspect that exposure incidents during container stripping are quite common but only occasionally reported to official reporting centres. Under-reporting may explain why sporadic exposure to high and potentially toxic levels of fumigants and off-gassing VOCs has hitherto not been thoroughly investigated by the scientific community. The workers carrying out stripping in our study expressed that the containers frequently carried unpleasant odours that from time-to-time prevented stripping. Such containers were left for natural ventilation before re-entry. Alternatively, workers were instructed to wear respiratory equipment. However, many chemicals lack warning properties and it is difficult to tell from smell only when a factual risk exists.

Our results draw attention to the need to particularly identify high-risk containers and establish routines how they should be handled safely. As an example, in one of the studies listed in the Introduction, 368 p.p.m. phosphine was recorded in one container (Luyts, 2010). An assumed exposure to 18 p.p.m. phosphine during stripping (5% of 368 p.p.m.) would be 60-fold higher than the current Swedish 8-h OEL of 0.3 p.p.m. and is likely to be lethal or life threatening, as suggested by rodent 4-h LC_{50} values of ~10–30 p.p.m. (NRC, 2007). Should a risk container be identified it would thus not be acceptable to allow workers to enter by referring to studies showing that their exposure will be a minor fraction of the concentration in the unventilated container. Furthermore, the frequently observed lower concentrations

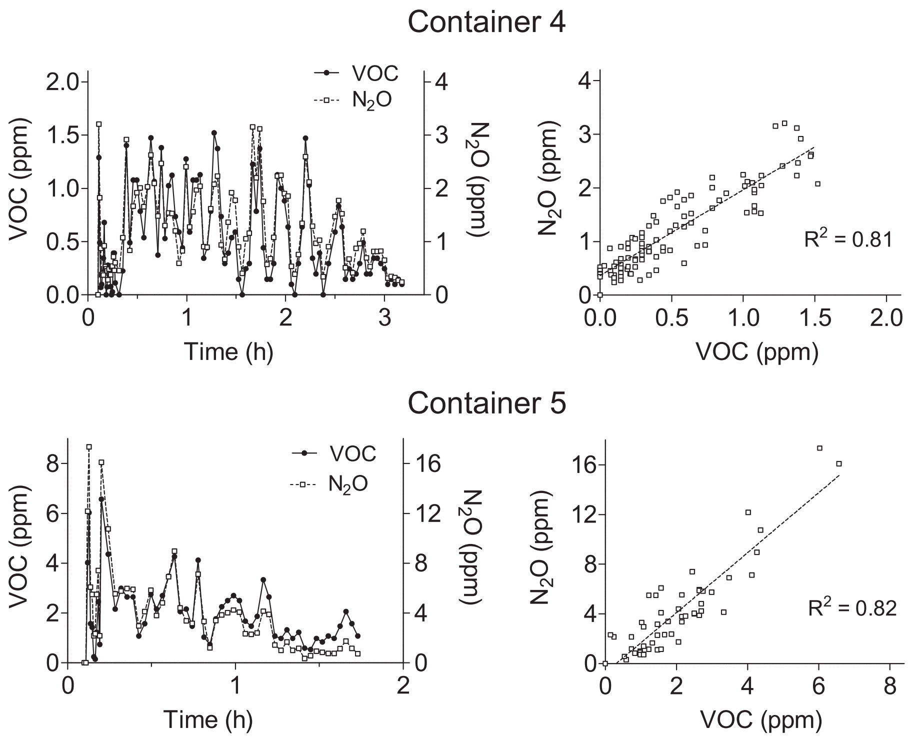

Fig. 5. Work zone levels of VOCs and nitrous oxide (N_2O) tracer gas (left panes) and their correlation (right panes) as measured by FTIR in two containers.

inside the doors compared with deeper inside the container might lead to an underestimation of the overall exposure during the entire stripping cycle.

A plausible explanation why some containers produce a distinct short peak at the time of opening, while others show none or an extended peak is the filling degree of the container. A fully loaded container is not likely to release large volumes of container air upon opening the doors. Another possibility is that the subject carrying the personal monitoring equipment temporarily stepped away from the container, and the opening peak was not captured by the instruments. The increase in concentrations of tracer gas observed towards the end of the stripping of container 10 in Fig. 4, could possibly reflect the variation of concentrations seen inside containers, as illustrated in Fig. 3.

The saw tooth fluctuations seen in Figs 4 and 5 were likely reflections of the intermittent nature of the work caused by restrictions in the flow chain. Thus, as new groups of boxes were removed, new portions of tracer gas and VOC-containing air were released to the work zone. One might suspect that the fluctuations also reflect the repositioning of the FTIR sample line as the work zone progressively moved into the container. This is contraindicated by the PID measurements, which were carried out at a fixed position in the breathing zone near the mouth and, nevertheless, show a similar variability.

A limitation in this study is that we only measured exposures in containers with boxed cargo. Stripping of other types and formats of cargos, such as sacks, bales, lumber, machine components, or tires, may take longer and could result in higher VOC exposures. Other occupational groups, such as customs inspectors (see Introduction), may encounter much higher exposure levels, even approaching those encountered before opening the container. Additional studies covering other types work tasks and cargos are needed to get a more complete picture.

Altogether, our observations form a strong argument that the tracer gas method to a large extent approximates the real exposure scenario, at least for stripping of boxed goods. The tracer gas method may be the only acceptable experimental approach to estimate personal exposure to fumigants and other highly toxic substances that cannot easily be investigated in experimental exposure studies. Twenty-four hours of equilibration of the tracer gas appears to be sufficient and is also the time recommended by the IMO for the reversed purpose to reach adequate penetration of fumigants into the goods during fumigation (IMO, 2008). The similar concentration profiles between the off-gassing chemicals and the tracer gas (Fig. 3) and similar work zone data (Fig. 5) indicate good penetration of the tracer gas into the goods. The ambient temperature is described by the IMO to affect penetration time during fumigation, and it will likely also affect the equilibration of tracer gases and emission of off-gassing chemicals. The conditions during this field study varied between minimum of −3°C at night and midday temperatures in the 5–15°C range. It is expected that higher ambient temperatures increase the off-gassing resulting in higher initial concentrations. On the other hand, high or variable temperatures may introduce increased air movement in the containers, resulting in more natural ventilation and lower concentrations.

All ocean freight containers have small openings in the top corners to provide limited natural ventilation. These openings and, in addition, possible leaking rubber seals around the doors may explain our observation of an uneven distribution of tracer gas and VOCs. This inhomogeneity may also be caused by air movements in parts of the container, as solar radiation heats one side of the container only. A third explanation may be that high and low emitting goods are stuffed in different parts of the container.

Labelling is mandatory for fumigated containers, i.e. those treated with specific chemical substances defined as fumigants. However, labelling is not required for containers carrying goods that emit other hazardous chemicals, usually as a result of post-production off-gassing. Ideally, containers stuffed with such goods should also be labelled or, better, the volatiles should be eliminated from the products before shipping. Until this has been achieved, the safest practice is to measure every incoming container and pre-ventilate them thoroughly as needed. Monitoring of container air is relatively easily implemented at high volume container terminals but may be more difficult to implement at small-size terminals workplaces and particularly in developing countries. Pre-ventilation is a cost-effective approach that can more easily be made available to any size of the terminal. Although our study suggests that the natural ventilation occurring via the open container doors eliminates a major part of the air pollutants in the work zone, it should be emphasized that pre-ventilation should be carried out in those containers where high concentrations of harmful substances (above the OELs) have been detected.Depending on the type of goods transported, harmful concentrations may be present in a large percentage of the incoming containers. There is thus a pressing need to find technical solutions to facilitate rapid air sampling and efficient ventilation prior to opening the container.

Unfortunately, the current container design makes safe and speedy sampling and ventilation prior to opening the doors technically difficult. This shortcoming tends to promote risky work behaviour (such as using smell as the sole warning signal) to avoid unwanted and costly lag times in the transport logistics. The Australian Customs and Border Protection Service require testing for fumigants by drilling two to three small holes in the container (ACBPS, 2012). The Canadian Border Service Agency (CBSA) has recognized that the procedures used to ensure that a container is safe before entry severely delay the throughput, and they have accordingly initiated a study to alleviate such delays (CBSA, 2008).

We propose that the container manufacturers provide pre-installed ventilation ports at the front end of the container where an external portable extraction fan can be connected and thereby forcing fresh air into the container through the doors left ajar. Such experiments are currently underway and will be reported in due course. We also propose pre-installed internal sample lines that allow sampling of air in the front, middle, and rear of the container. The sample lines would be accessible from the outside at the rear end (door end) of the closed container via through connections. Screening and identification of risk containers could thus be carried out routinely and systematically, even on stacked or tightly stored containers. Resources and preventive actions may then be more effectively directed to the problem containers.

The results from this and previous studies illustrate the need to establish practices for the safe handling of ocean freight containers. Until comprehensive recommendations are in place, those needing to enter such containers should have access to equipment for measuring contaminants and/or applying forced ventilation if necessary. Personal protective equipment should be used, and rescue strategies made available to individuals who need to enter unventilated containers with unknown hazards.

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