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Investigating ozone-induced decomposition of surface-bound permethrin for conditions in aircraft cabins

Abstract The reaction of ozone with permethrin can potentially form phosgene. Published evidence on ozone levels and permethrin surface concentrations in aircraft cabins indicated that significant phosgene formation might occur in this setting. A derivatization technique was developed to detect phosgene with a lower limit of detection of 2 ppb. Chamber experiments were conducted with permethrin-coated materials (glass, carpet, seat fabric, and plastic) exposed to ozone under cabin-relevant conditions (150 ppb O_3, 4.5/h air exchange rate, $< 1\%$ relative humidity, 1700 ng/cm^2 of permethrin). Phosgene was not detected in these experiments. Reaction of ozone with permethrin appears to be hindered by the electron-withdrawing chlorine atoms adjacent to the double bond in permethrin. Experimental results indicate that the upper limit on the reaction probability of ozone with surface-bound permethrin is $\sim 10^{-7}$. Extrapolation by means of material-balance modeling indicates that the upper limit on the phosgene level in aircraft cabins resulting from this chemistry is ~ 1 μg/m^3 or ~ 0.3 ppb. It was thus determined that phosgene formation, if it occurs in aircraft cabins, is not likely to exceed relevant, health-based phosgene exposure guidelines.

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Key words: Permethrin; Ozone; Phosgene; Aircraft cabin; Surface chemistry; Oxidation byproducts.

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Practical Implications
Phosgene formation from ozone-initiated oxidation of permethrin in the aircraft cabin environment, if it occurs, is estimated to generate levels below the California Office of Environmental Health Hazard Assessment acute reference exposure level of 4 μg/m^3 or ~ 1 ppb.

Introduction

'Disinsection' is the practice of spraying passenger aircraft interiors with insecticide to prevent the spread of disease vectors and invasive species. Regular insecticide spraying was discontinued in the United States in 1979, but several countries (at least 21) still permit or require disinsection (NRC, 2002; DOT, 2007). Planes that have been disinsected can travel worldwide, even to countries where disinsection is not allowed.

Publicly available data on the type and amount of insecticides used in aircraft cabins are sparse, but they suggest that the most commonly used aircraft insecticides are permethrin and d-phenothrin (Maddalena and McKone, 2008). Permethrin is used as a 'residual' pesticide (i.e., designed for long-lasting effectiveness) and d-phenothrin as a 'non-residual' pesticide (i.e., only for immediate effectiveness). Chemically, the difference between the two compounds is the substitution of two methyl groups ($-CH_3$) on the d-phenothrin molecule with two chlorine atoms on the permethrin molecule. Chlorine substitution makes permethrin more likely to partition to surfaces and more resistant to degradation.

In addition to direct exposure, another potential hazard associated with pesticide use is exposure to degradation products of the primary chemicals. One example occurs in the case of the insecticide malathion, which is oxidized to the more toxic compound, malaoxon, by reaction with the hydroxyl radical (Brown et al., 1993). In the aircraft cabin environment, ozone is of concern as an oxidizing agent. Permethrin possesses a terminal dichlorovinyl group, a carbon-carbon double bond with two chlorine atoms, and cleavage of this double bond by ozone would be anticipated to produce two primary carbonyls – a carboxaldehyde and phosgene – as shown in Figure 1 (Dowideit and von Sonntag, 1998; Ruzo et al., 1986; Class, 1991).

Phosgene is a highly toxic gas, infamous for its use as a chemical warfare agent in World War I (CDC, 2006). The dominant exposure route for phosgene is inhalation. It is a pulmonary agent that causes respiratory and cardiovascular failure at high concentrations. At lower concentrations it can cause eye and throat irritation, difficulty breathing, and coughing. Milder symptoms may be immediate and more severe symptoms may be delayed for up to two days (ATSDR, 2007).

Ozone, a strong oxidant, is commonly present in aircraft cabins owing to ventilation with ozone-containing air of the upper troposphere and lower stratosphere. Federal Aviation Regulations state that ozone is not to exceed 250 ppb at any time above 32,000 ft and 100 ppb for a time-weighted average of any 3-h period during flight above 27,000 ft (NRC (National Research Council), 2002). Ozone levels on the order of 10–100 ppb can be encountered on US domestic flights when planes are not equipped with ozone converters or on transoceanic flights (Bhangar et al., 2008). Several recent cabin air quality studies have established that reactions with surfaces and surface-bound residues consume a significant fraction of the ozone that enters the cabin, and these reactions produce volatile byproducts of ozone-initiated chemistry (Wisthaler et al., 2005; Tamás et al., 2006; Weschler et al., 2007; Coleman et al., 2008).

The production of phosgene from the reaction of ozone and permethrin, both of which may be present in the aircraft cabin, has been predicted (Ruzo et al., 1986; Class, 1991), but not measured. To date, the branching ratio or yield of phosgene formed from ozonation of a compound that contains the dichlorovinyl group on a surface has been measured in only one study, which was conducted with cypermethrin, another surface-bound insecticide (Segal-Rosenheimer and Dubowski, 2007). In this investigation, the researchers used a 'thick' layer (much greater than one monolayer) of insecticide and very high concentrations of ozone (3–50 ppm). The yield, defined as moles of phosgene formed per mole of cypermethrin reacted, was estimated to be 6–10% in those experiments. The reaction of ozone with a dichlorovinyl-containing pesticide and the formation of phosgene have not been measured under typical aircraft cabin conditions.

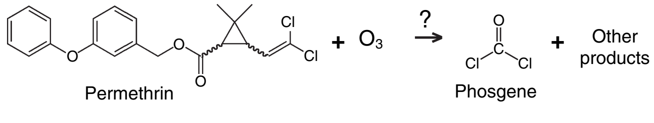

Fig. 1 Permethrin might react with ozone at the double bond to produce phosgene, a highly toxic substance

The objective of this study was to determine if phosgene could be formed at levels of concern in the aircraft cabin environment from the reaction of ozone with permethrin. The project was conducted in three phases. First, a literature search was combined with modeling estimates to evaluate the potential for phosgene formation under cabin-relevant conditions. Second, laboratory experiments were performed in which permethrin-sprayed cabin materials were exposed to ozone at cabin-relevant conditions. As part of the experiments, a derivatization method was developed to detect low levels of phosgene. Third, results from the experiments were incorporated into an ozone transport and uptake model to estimate the upper limit of phosgene levels to be expected in aircraft cabins.

Characterizing the potential for phosgene formation

Pyrethroid surface concentrations

There are two main methods of disinsection, 'aerosol' and 'residual' (WHO, 1995). The aerosol treatment is applied as needed when flying to countries that require disinsection; the insecticide is applied by discharging aerosol cans along the cabin aisles before or during flight. Airlines that frequently fly to regions that require disinsection may opt to perform residual treatment, where a much higher surface concentration is applied less frequently. In the residual treatment, an aqueous solution of insecticide is applied using a low-pressure sprayer.

The two aerosol treatment procedures that involve permethrin – 'pre-flight' and 'pre-embarkation' – are designed to deliver 0.35 g of solution per m^3 using aerosol cans containing 2% permethrin (in the case of 'pre-embarkation' treatment, the spray also contains 2% d-phenothrin). The number of cans used is based on the size of the aircraft. In studies where cabin insecticide residue levels have been measured, most insecticide is concentrated on upward facing surfaces, which is to be expected because of gravitational settling of spray droplets. Using an estimated typical horizontal surface area per volume in the cabin of $\sim 1\ m^2/m^3$ and assuming that all of the permethrin sprayed lands on these surfaces, the estimated surface concentration of permethrin would be $\sim 700\ ng/cm^2$.

For residual treatment, WHO guidelines (1995) state that an air spray gun or a pressure garden sprayer may be used to deliver an aqueous solution of 2% permethrin to all surfaces in an unoccupied cabin approximately every eight weeks. This procedure is designed to deliver a concentration of 20,000 ng/cm^2 to treated surfaces.

In Figure 2, estimated surface concentrations from WHO-recommended application rates are compared to measured surface concentrations. Details of the surface concentration studies are discussed in the following paragraph. For reference, the concentration of a monolayer of permethrin molecules on a smooth surface corresponds to $\sim$100 ng/cm^2.

Berger-Preiss et al. (2004, 2006) measured insecticide concentrations in the gas-phase and on surfaces during and after spraying pyrethroid insecticides in planes parked on the tarmac. The 2004 study aimed to replicate in-flight spraying (e.g., 'top-of-descent'), and reported a median value of $\sim$50 ng/cm^2 of pyrethrins on upward surfaces. The 2006 study simulated a 'pre-embarkation' treatment procedure, i.e. spraying shortly before passengers board, and reported typical values of $\sim$100–1200 ng/cm^2 of d-phenothrin on 'mainly horizontal areas.' A recent investigation by NIOSH of pesticide illness among flight attendants reported permethrin levels associated with residual disinsection measured in a Boeing 747-400 aircraft by staff at an unnamed airline (Sutton et al., 2007). Permethrin levels on these surfaces varied by six orders of magnitude, with a median of 160 ng/cm^2, a mean of 59,000 ng/cm^2, and a maximum of 3,600,000 ng/cm^2. An informal investigation by a flight attendant using a wipe method found a surface concentration of 170–690 ng/cm^2 of permethrin on a B747-400 that had been subject to residual spray treatment (NRC, 2002).

In summary, these limited data suggest that residual spraying of insecticides would commonly produce residual levels on upward-facing surfaces in aircraft cabins of the order of 100–1000 ng/cm^2 for permethrin, although much higher levels may also occur. The mass of permethrin in cabin air is estimated to be at least six orders of magnitude lower than the mass on cabin surfaces based on measured gas-phase ($\sim$1 ng/m^3; Spicer et al., 2004) and surface concentrations. This comparison substantiates the appropriateness of focusing on the fate of surface-bound rather than gaseous permethrin.

Potential phosgene formation

To estimate the phosgene level that may be produced in the cabin environment, we apply a material balance on phosgene, as shown in Equation 1, that incorporates the two major processes: the formation of phosgene from reaction of ozone with permethrin-covered upward-facing surfaces and the loss of phosgene by means of ventilation.

$$\frac{dC_{\mathrm{phos}}}{dt} = Yv_{\mathrm{d}}\frac{S_{\mathrm{h}}}{V}C_{\mathrm{ozone}} - \lambda C_{\mathrm{phos}}. \tag{1}$$

The rate of phosgene generation is expressed as the product of several terms: yield, Y (moles of phosgene formed per mole of ozone consumed in reaction with the surface); deposition velocity, v_{d} (m/h); surface-to-volume ratio for horizontal surfaces, S_{h}/V (m^2/m^3);

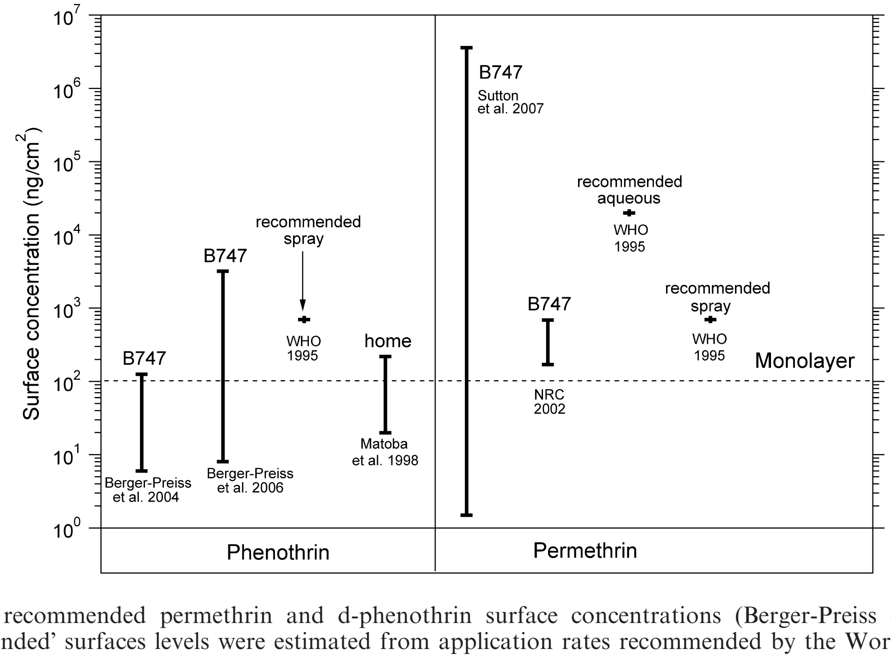

Fig. 2 Measured and recommended permethrin and d-phenothrin surface concentrations (Berger-Preiss et al., 2004, measured pyrethrins). 'Recommended' surfaces levels were estimated from application rates recommended by the World Health Organization (WHO, 1995)

and cabin ozone level, C_{ozone} (ppb). The term accounting for phosgene removal represents the phosgene level in the cabin air, C_{phos} (ppb), multiplied by the cabin air exchange rate, λ (per h). At steady state or on a time-averaged basis, the cabin level of phosgene can be estimated using Equation 2.

$$C_{\text{phos}} \approx \frac{C_{\text{ozone}} v_{\text{d}} (S_{\text{h}}/V) Y}{\lambda}. \tag{2}$$

Representative values can be substituted for the various parameters in Equation 2. A typical peak-hour ozone level for US domestic flights without a converter is 30 ppb (Bhangar et al., 2008). Based on chamber and simulated cabin experiments, a typical value of v_{d} is ~3 m/h (Tamás et al., 2006). A reasonable estimate for the horizontal surface-to-volume ratio for the cabin environment would be $S_{\text{h}}/V \sim 1$ m^2/m^3. A representative value for the outdoor air exchange rate (λ) of the aircraft cabin is ~10/h (NRC, 2002). Segal-Rosenheimer and Dubowski (2007) estimated that the oxidative yield (Y) of phosgene from cypermethrin was ~6–10%; a value of 10% (0.1) is used in this preliminary estimate.

For these conditions, a phosgene level of 1 ppb might be sustained in the aircraft cabin as a result of ozone-induced oxidation of permethrin. Higher phosgene levels could result from the presence of higher-than-typical ozone levels. This analysis has assumed that permethrin reacts with ozone at a rate that is controlled by external mass transport of ozone to cabin surfaces. If, on the other hand, slow kinetics for ozone reacting with surface-bound permethrin is the rate-limiting step, then the result would be lower cabin phosgene levels than estimated here.

Phosgene exposure guidelines

The US Environmental Protection Agency's Integrated Risk Information System lists a reference concentration (RfC) for chronic inhalation exposure to phosgene of 0.3 μg/m^3, which corresponds to 0.09 ppb in cabin conditions (0.8 atm, 23°C). 'The RfC is an estimate (with uncertainty spanning perhaps an order of magnitude) of a continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime' (EPA, 2005).

The California Office of Environmental Health Hazard Assessment has established an acute reference exposure level for phosgene of 4 μg/m^3 or 1.2 ppb (at 0.8 atm and 23°C). This level applies to a one-hour exposure period. Exposure at this level or below is considered to be adequate to protect against mild adverse effects from phosgene exposure (OEHHA, 1999).

Occupational exposure limits are typically set at much higher values than are environmental exposure limits. The US Occupational Safety and Health Administration's Permissible Exposure Limit (PEL) for phosgene is 0.4 mg/m^3 or 120 ppb (at 0.8 atm and 23°C; OSHA, 1986). The PEL is the concentration of a substance to which most workers can be exposed without adverse effect averaged over a normal 8-h workday or a 40-h work week. Typically, the occupational limit would be considered to apply for workers whose job entails either production of phosgene or its use in chemical manufacturing.

Hence, the range of exposure limits for these various guidelines is 0.09–120 ppb, dependent on the exposure duration and the population that the standard or guideline is intended to protect.

Phosgene chemical characteristics

Phosgene can undergo hydrolysis to form hydrochloric acid (HCl) and carbon dioxide as shown here:

$$\mathrm{Cl_2CO} + \mathrm{H_2O} \rightarrow \mathrm{CO_2} + 2\mathrm{HCl}.$$

There is conflicting information about the rate and importance of hydrolysis for phosgene degradation. Dowideit and von Sonntag (1998) determined that phosgene formed in water from ozonolysis of a dichlorovinyl group is hydrolyzed to HCl so rapidly (hydrolysis rate of ~9/s) that phosgene is considered to be an intermediate product. The US Agency for Toxic Substances & Disease Registry guidelines state that phosgene is 'not very water-soluble and hydrolysis is slow' (ATSDR, 2007). Kindler et al. (1995) studied the atmospheric fate of phosgene and determined that it rapidly hydrolyzes in aqueous solution, but that it is not reactive toward water vapor. In the atmosphere this means that hydrolysis could occur after uptake of phosgene into cloud droplets; in the aircraft cabin, this process might feasibly occur in surface-phase water on materials.

In humid environments, water sorbs to certain surfaces, depending on their chemical constitution. For example, cotton will sorb water to an extent of 7% of its dry weight at 70% relative humidity (RH); however, Teflon resists sorbing water at any RH (Destaillats et al., 2006). The relative humidity in aircraft cabins during extended cruise flight is quite low, typically ~10%, because the ambient air, which is the supply air of the cabin, is virtually free of water at cruising altitude (9–12 km). The only significant steady source of RH in the cabin is from respiration and evaporation of water from passengers' skin (NRC, 2002). Although RH in the cabin during flight is low, some water is likely associated with most surfaces during some portion of a typical flight, and there is the potential for elevated local RH on the surfaces in near proximity to the passengers. The effect of surface moisture on phosgene formation is unknown. Most experiments in this study were conducted under very low relative humidity, mimicking the conditions expected for the aircraft cabin and minimizing the possibility of phosgene decomposition by hydrolysis.

Experimental investigations

Laboratory research was undertaken to develop a method to detect low levels of phosgene, perform a calibration using that method, and then measure phosgene formed from permethrin applied to real cabin surfaces and exposed to ozone under cabin-relevant conditions. A preliminary set of experiments, described by Coleman (2009), was also conducted in which direct gas-phase detection of phosgene was attempted using gas chromatography with electron capture detection (GC-ECD).

Materials

Permethrin (1000 μg/ml in methanol), phosgene (20% in toluene), triethylamine (≥99%), and 3,4-dimercaptotoluene (≥97%) were purchased from Sigma Aldrich (St. Louis, MO, USA). Methanol high performance liquid chromatography grade (HPLC grade) was purchased from Fisher Scientific (Pittsburgh, PA, USA).

Detection method and chemical analysis

Gaseous phosgene was sampled by bubbling air through liquid in an impinger. The impinger arrangement is shown in Figure 3, and the derivatization reaction is illustrated in Figure 4. The impinger solution contained toluene with 3,4-dimercaptotoluene (DMT), a phosgene derivatizing agent, and triethylamine (Et_3N), a catalyzing agent. The derivatization product is referred to here as phos-DMT. An earlier study by Muir et al. (2005) served as the basis for the phosgene detection method developed in this study.

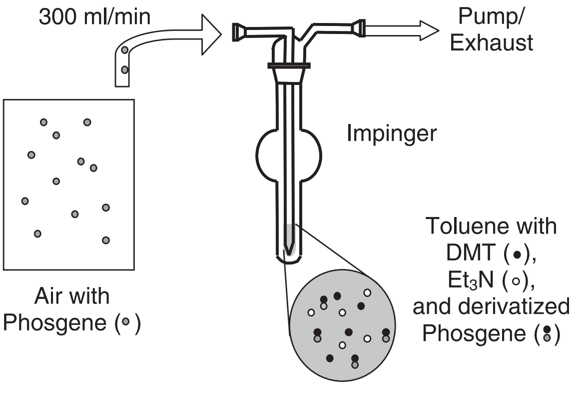

Fig. 3 Schematic of the derivatization technique for phosgene. Gaseous phosgene is bubbled through a liquid solution of toluene containing the derivatizing agent dimercaptotoluene (DMT), and a catalyzing agent triethylamine (Et_3N)

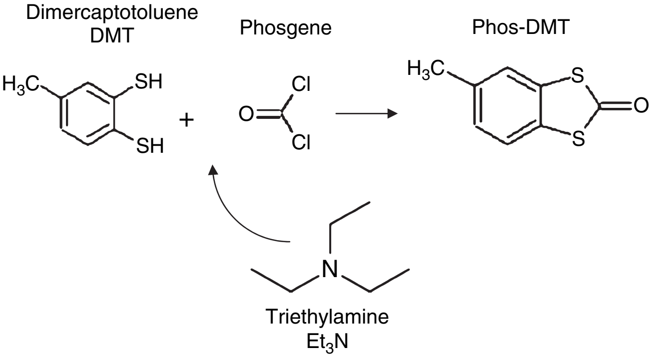

Fig. 4 Derivatization reaction for phosgene with dimercaptotoluene and triethylamine based on the work of Muir et al. (2005)

Liquid injection of impinger solution was analyzed by gas chromatography (GC; Agilent 6890, Santa Clara, CA, USA) with electron capture detector (ECD; Agilent G2397-65505) and mass selective detector (MSD; Agilent 5975). In this configuration, the sample was split between the ECD and the MSD, which provided the advantage of having high sensitivity chromatographic detection of halogenated compounds, but also mass detection of compound fragments. The MSD was operated in regular full-scan and in selective ion monitoring (SIM) mode in some cases to achieve higher sensitivity to the phosgene derivative. The ions detected in SIM mode were at m/z ratios of 182, 154, and 121.

The derivatizing solution contained 0.4 mM DMT and 6 mM Et_3N. The impinger contained 3 ml of derivatizing solution in 1 h experiments and 6 ml of derivatizing solution in 4 h experiments. The impinger was submerged in an ice bath to minimize volatilization of the toluene or derivatizing agents. The impinger solution was immediately removed after an experiment was conducted and analyzed on the GC-ECD-MSD. Duplicate samples – sealed and kept at room temperature – from the same experiment were run within 24 h and showed good repeatability.

Calibrations

Two phosgene-derivative calibrations were performed: (1) a ‘direct’ derivatization calibration in which phosgene was injected into impinger solution and analyzed, and (2) a ‘bag’ calibration in which phosgene was added to a bag and bubbled through the impinger solution as it would be in an experiment.

Direct calibration. The direct calibration was performed by adding various dilutions of phosgene in toluene to 3 ml of impinger solution (which had not had air bubbled through it) and injecting 1 μl samples of the solution into the GC-ECD-MSD. The number of moles of phosgene injected onto the column (in the form of phos-DMT) was calculated from the amount of phosgene added to the solution and the size of the injection; 100% derivatization was assumed. Calibration points included 0.3, 0.6, 1.25, and 2.5 pmol injected onto the column. The calibration curve exhibited good linearity (R^2 = 0.989 for MSD in SIM mode and R^2 = 0.996 for ECD) for 0.6 to 2.5 pmol on the column. The lowest calibration point, 0.3 pmol, could not be detected with the ECD and was not reliably detected with the MSD.

Of the detection methods tested (ECD, MSD full scan, and MSD in SIM mode), phos-DMT detection by MSD in SIM mode proved to be optimal, and this detection method is emphasized throughout the remaining sections. The lower limit of detection was 0.6 pmol of phosgene on the column. The study from which this method was adapted was able to achieve a lower limit of detection of 0.2 pmol on the column (Muir et al., 2005).

Bag calibration. The bag calibration was performed by injecting a known amount of phosgene diluted in toluene into a 100 l Teflon bag filled with clean, dry air. Phosgene-containing air was drawn from the bag, through the impinger, derivatized *in situ*, using a vacuum-induced flow rate of 300 ml/min. After 1 h (18 l sampled), the experiment was stopped, the volume of the remaining impinger solution was measured (typically 2 ml of the 3 ml remained), and 1 μl samples of impinger solution were injected into the GC-ECD-MSD.

Calibration experiments were conducted for 1, 2, 5, and 10 ppb of phosgene in a bag. The height of the peak corresponding to 2 ppb was at least three times greater than the fluctuation in the baseline of the chromatogram, but the peak for 1 ppb was not. Thus, the lower limit of phosgene detection with this impinger and derivatization method was established to be 2 ppb of phosgene. Phosgene levels of 2, 5, and 10 ppb produced a linear calibration curve (R^2 = 0.94).

Experiments

Individual materials including glass and aircraft cabin surfaces (carpet, seat fabric, plastic wall covering) were sprayed with permethrin and exposed to ozone in a chamber. The conditions of the experiments are shown in Table 1. The 40-l cubic chamber was constructed from Teflon sheets (Figure 5). Before each experiment, the chamber was cleaned with methanol wipes, and the chamber was quenched with ozone.

Table 1 Conditions of permethrin oxidation experiments with impinger derivatization detection technique[a]

Expt ID	Material	Exhaust ozone (ppb)[b]	Permethrin coverage (ng/cm^2)	Experiment duration (h)	AER (per h)	RH (%)
1	Glass (long, blank)	170	0	4	4.5	<1
2	Glass (long)	170	1700	4	4.5	<1
3	Glass (blank)	170	0	1	4.5	<1
4	Glass (base case)	150	1700	1	4.5	<1
5	Carpet	~90	1700	1	4.5	<1
6	Wall covering	160	1700	1	4.5	<1
7	Seat fabric	~80	1700	1	4.5	<1
8	Glass (high ozone)	~600	1700	1	1.5	<1

[a] The base-case and deviations from the base-case conditions are shown in gray.

[b] The ozone supply level was 170 ppb in all experiments except experiment 5 in which the supply level was 150 ppb and experiment 8 in which the supply level was ~600 ppb.

Four materials were tested; glass, carpet, plastic, and seat fabric. Borosilicate glass plates (25 cm × 25 cm × 0.32 cm, McMaster-Carr, Atlanta, GA, USA) were used as the nonreactive, smooth surface in chamber experiments and had an area of 625 cm^2. Samples of cabin surfaces (carpet, plastic, and seat fabric) were obtained from manufacturers and airlines via Boeing. The plastic sample was from a new (unused) plastic-coated wall covering. The carpet sample was from a used runner (aisle carpet) that had been in service on an aircraft for approximately 18 months since cleaning (total duration in service was unknown). The seat fabric sample was from used seat covering that had been in service for 18 months since its last cleaning. Cabin material samples were 25 cm × 23 cm for a nominal surface area of 580 cm^2.

As shown in Figure 5, ozone-containing dry air was introduced through a nozzle in the top of the chamber, 33 cm above the plate or material, at a flow rate of 3.0 l/min (corresponding to an air exchange rate, AER, of 4.5/h); the chamber outlet was located 8 cm from the front and 8 cm from bottom of the chamber on the right side. From the outlet flow, 1.4 l/min was diverted to an ozone monitor, 300 ml/min was bubbled through

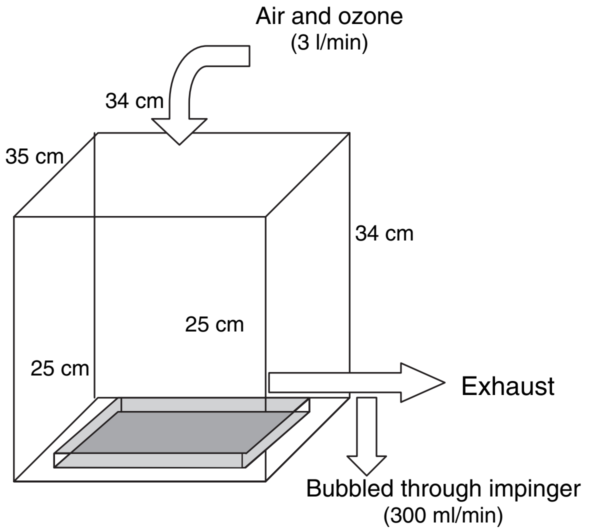

Fig. 5 Schematic of 40-l Teflon chamber for continuous flow, surface-bound permethrin oxidation experiments

an impinger using a vacuum pump, and the remainder was exhausted. Most experiments lasted 1 h; some experiments were conducted for a longer period of 4 h.

The chamber AER (4.5/h) was approximately one-half to one-fourth of the typical cabin AER (10–20/h). The ozone level in the supply was 150–170 ppb, which is higher than typical, but consistent with aircraft ozone regulations and within the range of measured concentrations. One experiment was performed under 'extreme' conditions with a very high ozone level of 600 ppb and a low AER of 1/h. Relative humidity is low during flight, $\sim$10% RH, and was kept as low as possible in experiments, $<1\%$, to minimize the possibility of hydrolysis.

A mass of 1 mg of permethrin (as a 1 ml solution of 1000 μg/ml in methanol) was sprayed onto the plate or cabin material using a Badger® airbrush spray gun (Badger, Franklin Park, IL, USA; part number 350 with fine tip) (Wells et al., 2008). The methanol was allowed to evaporate for 5 min, and then the glass plate or material was placed in the bottom of the chamber immediately prior to starting the experiment. This method delivered a nominal surface coverage of $\sim$1700 ng/cm^2, which is $\sim$17× the nominal monolayer coverage rate ($\sim$100 ng/cm^2) and comparable in magnitude to 'pre-flight' or 'pre-embarkation' insecticide spraying guidelines ($\sim$700 ng/cm^2). At this level, there was a visible residue on the glass but not on cabin surfaces. The surface-to-volume ratio of the permethrin sprayed area in the test chamber was 1.5 m^2/m^3 similar to the S/V ratio for horizontal surfaces in the cabin (the surfaces most likely to be coated in permethrin) of $\sim$1 m^2/m^3.

Results

The 'base case' experiment was performed with a glass plate coated in 1700 ng/cm^2 of permethrin exposed to 150 ppb O_3 for 1 h (Table 1). Experiments were also conducted under the base-case conditions with real cabin materials: carpet, seat fabric, and plastic. Variations on the baseline experimental conditions were performed to determine the effects of certain experimental parameters: a longer experiment was performed; an experiment with much a higher ozone level was performed (which necessitated reducing the AER because of system limitations); and a blank experiment was performed with no permethrin. Phosgene formation was not detected in any of the experiments.

The presence of chlorine atoms adjacent to the double bond in permethrin are likely responsible for permethrin's low reactivity with ozone. Chlorine atoms tend to withdraw electron density from the double bond in permethrin, causing the bond to be less reactive with ozone. The effect of neighboring chlorines on ozone reactivity can be illustrated with chlorine-substituted ethene-based molecules. The substitution of one chlorine atom reduces the reactivity of ethene by 35× (Ljubic and Sabljic, 2002) and substituting two chlorine atoms for hydrogen atoms reduces the reactivity of ethene by 240× (Avzianova and Ariya, 2002). In the system under study here, it does not appear that a surface-enhanced reaction is occurring between ozone and permethrin.

Another, indirect pathway for phosgene formation is possible in an ozone-permethrin system. The reaction of ozone with an alkene is a chain-initiating reaction that produces other oxidizing agents such as the hydroxyl radical (OH•), which reacts much more rapidly than ozone with alkenes (Atkinson and Arey, 2003). Ozone could feasibly react with other unsaturated compounds on an indoor surface, form OH•, and OH• could then react with permethrin to form phosgene. The formation of phosgene from OH• radical-oxidation of a gas-phase dichlorovinyl compound, dichlorvos, has been detected (Feigenbrugel et al., 2006). However, phosgene was not detected in the present experiments, even with ozone-reactive aircraft cabin materials serving as the substrate.

Another possibility, that could have occurred even if the reaction is slow, is that phosgene was formed but was subsequently hydrolyzed to HCl on the surface. Materials were exposed to lab air at $\sim$50% RH for several hours before being placed in the chamber and water could have remained sorbed to material surfaces during the experiments reported here. However, it is unlikely that the materials used in the present study had substantially more sorbed water than materials in aircraft cabins.

Implications for phosgene exposure in aircraft cabins

In the 40-l chamber experiments, the maximum concentration of phosgene that could have been formed and remained undetected is <2 ppb. If we assume that phosgene was being produced in the chamber, and (for estimation purposes) that production is occurring at a steady-state rate throughout the experiments, then the phosgene concentration in the chamber is reasonably approximated by Equation 2, where S_h corresponds to the permethrin-sprayed surface area of the substrate material in the chamber.

Equation 2 can be rearranged to determine the maximum possible deposition velocity, $v_{d,max}$, to the permethrin-coated surface given the maximum possible phosgene level, $C_{phos,max}$, that could have been produced and remained undetected, as shown in Equation 3. A maximum phosgene yield of 0.1 is assumed in the following calculations.

$$v_{d,max} \approx \frac{C_{phos,max}\lambda}{C_{ozone}(S_h/V)Y}. \tag{3}$$

For base-case conditions (experiment 4, Table 1), the maximum deposition velocity of ozone to a permethrin-coated surface is:

$$v_{\mathrm{d,max}} \approx \frac{2\ \mathrm{ppb} \times 4.5/\mathrm{h}}{150\,\mathrm{ppb} \times 1.5/\mathrm{m} \times 0.1} = 0.4\mathrm{m/h} = 0.01\ \mathrm{cm/s}.$$

Phosgene formation was not detected under even more severe conditions in the high ozone, low AER experiment, which indicates an even lower maximum deposition velocity. Under these conditions (experiment 7, Table 1), the maximum deposition velocity is:

$$v_{\mathrm{d,max}} \approx \frac{2\mathrm{ppb} \times 1.5/\mathrm{h}}{600\mathrm{ppb} \times 1.5/\mathrm{m} \times 0.1} = 0.03\mathrm{m/h} = 0.001\mathrm{cm/s}.$$

Deposition velocities determined in an experimental chamber setting can be extrapolated to an environment of interest, in this case the aircraft cabin environment, using a model of ozone transport and uptake developed by Cano-Ruiz et al. (1993) and Morrison and Nazaroff (2002). The extrapolation calculation involves determining the reaction probability of the material (or as in this case, a chemical residue) and the flow conditions in both environments. Reaction probability, γ, represents uptake efficiency and is defined here as the rate of ozone uptake by permethrin divided by the rate at which ozone strikes the surface. As shown in Figure 6, reaction probabilities of cabin materials (and most indoor surfaces) are in the *transition* or *transport-limited* deposition regimes (Coleman et al., 2008). Thus, deposition velocity commonly depends on airflow conditions, which are parameterized by the friction velocity, u^*. However, the estimated deposition velocity for permethrin is very low, indicating that the reaction of ozone on a permethrin-coated surface would be in the *kinetically limited* regime, for which the rate is independent of flow conditions. The deposition velocity in the kinetically limited regime is related to the reaction probability by Equation 4 (Cano-Ruiz et al., 1993).

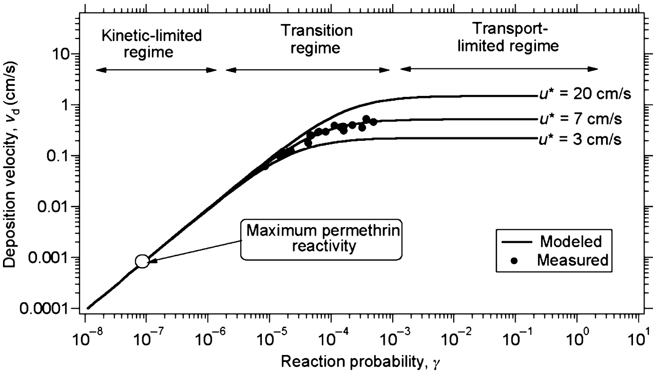

Fig. 6 Deposition model for reactive gas uptake on indoor surfaces (Cano-Ruiz et al., 1993; Morrison and Nazaroff, 2002) with kinetically limited, transition, and transport-limited deposition regimes shown. The measured data points are from chamber studies of ozone deposition to cabin materials (Coleman et al., 2008). The reaction probability for ozone with surface-bound permethrin was found to be $< 10^{-7}$

$$v_{\mathrm{d}} \approx \frac{\gamma \langle v \rangle}{4}. \tag{4}$$

The Boltzmann velocity, $\langle v \rangle$, is 3.6×10^4 cm/s for O_3 at 293 K. This equation can be rearranged to determine the maximum reaction probability for a permethrin-covered surface:

$$\gamma_{\max} \approx \frac{4 \times 0.001\ \mathrm{cm/s}}{3.6 \times 10^4\ \mathrm{cm/s}} = 10^{-7}. \tag{5}$$

Because the uptake of ozone by permethrin is in the kinetically limited regime, the deposition velocity measured in the chamber can be used directly for estimating conditions in the cabin. The steady-state approximation is employed here to determine an approximate upper bound on the time-averaged phosgene level in the cabin. Substituting typical values for the cabin environment without an ozone converter (30 ppb O_3, ~1/m for horizontal S/V ratio, and an air exchange rate of 10/h), one obtains an estimate for the maximum phosgene concentration in the cabin of 0.009 ppb or 0.03 μg/m^3.

$$C_{\mathrm{phos}} < \frac{30\ \mathrm{ppb} \times 0.03\mathrm{m/h} \times 1/\mathrm{m} \times 0.1}{10/\mathrm{h}} = 0.009\ \mathrm{ppb} = 0.03\,\mu\mathrm{g/m}^3\ \text{(aircraft, typical)}.$$

Under more extreme conditions, the ozone level might be as high as 200 ppb (Bhangar et al., 2008) and the surface-to-volume ratio for material coated in permethrin might be higher, for example, ~5/m. In this case the maximum phosgene level might conceivably be 1 μg/m^3, or ~50× higher than the estimate for typical conditions.

$$C_{\mathrm{phos}} < \frac{200\ \mathrm{ppb} \times 0.03\mathrm{m/h} \times 5/\mathrm{m} \times 0.1}{10/\mathrm{h}} = 0.3\ \mathrm{ppb} = 1\ \mu\mathrm{g/m}^3\ \text{(aircraft, upper limit)}.$$

The experiments in this study indicate that ozone-permethrin reactions in the cabin could be responsible for – at maximum – a phosgene level of 1 μg/m^3. This study supports a conclusion that the OSHA limit of 400 μg/m^3 would certainly not be exceeded in aircraft cabins. Phosgene formation also appears unlikely to exceed the OEHHA limit of 4 μg/m^3. Acute exposure at or below this guideline is considered to be adequate to protect against mild adverse health effects (OEHHA, 1999); thus, in the absence of specific guidelines for aircraft cabins, this seems to be an appropriate indicator for evaluating aircraft cabin exposures. The most stringent phosgene exposure guideline is the USEPA's RfC of 0.3 μg/m^3, which is designed to protect even sensitive populations from adverse effects owing to chronic low-level exposures. It seems that sensitive persons would be unlikely to fly frequently, so this guideline may be overly stringent for a health-risk assessment in aircraft cabins.

Permethrin, ozone, and phosgene in other indoor environments

Permethrin is the most frequently used pyrethoid pesticide in the US (ATSDR, 2003). It is approximated that 2 million pounds of permethrin are applied in the United States each year, ~30% by homeowners, ~40% by professionals in non-agricultural settings, 3% in mosquito abatement programs, and the remainder in agricultural settings (EPA, 2006). Permethrin is also registered for use in lice shampoo (EPA, 2006).

The relevant differences between aircraft cabins and building environments are that building air-exchange rates are much lower, the typical relative humidity in buildings is higher (~50%), and the surface area per volume is somewhat lower than in the cabin environment (Coleman, 2009). Ozone is present in buildings and homes because of ventilation with ozone-containing outdoor air. It may also be present because of an indoor source such as an ozone-generating 'air purifier' or certain office equipment. Methods of pyrethroid application are similar in the aircraft cabin as in buildings – spray cans, foggers, and pressurized sprayers – and the resulting surface concentrations are similar to those in the cabin. Matoba et al. (1998) used the 'crack and crevice' method to apply d-phenothrin in a chamber experiment that simulated spraying in an apartment (23 m^3 chamber volume, AER = 1.5/h, 60% RH). As shown in Figure 2, the average concentration on the floor (the only horizontal surface) was 220 ng/cm^2 after spraying.

If phosgene were formed at low levels in building environments owing to ozone reactions with chlorinated insecticides, it could be a cause for concern. One can substitute typical values for residential and commercial environments into Equation 2 to approximate the maximum possible phosgene levels expected in buildings based on the experiments reported here. A typical indoor ozone concentration is ~10 ppb and the surface-to-volume ratio for permethrin sprayed surfaces is likely to be ~ 1 m^2/m^3. Air exchange rates in buildings are about an order of magnitude lower than in aircraft cabins, ~1/h (Murray and Burmaster, 1995) vs. ~10/h (NRC, 2002). The estimated maximum deposition velocity for buildings is the same as for the chamber because the deposition velocity was determined to be kinetically limited. Therefore,

$$C_{\mathrm{phos}} < \frac{10\ \mathrm{ppb} \times 0.03\mathrm{m/h} \times 1/\mathrm{m} \times 0.1}{1/\mathrm{h}}$$
$$= 0.03\ \mathrm{ppb} = 0.1\mu\mathrm{g/m}^3\ \text{(buildings, typical).}$$

The value calculated for typical conditions is of similar magnitude to the reference concentration of 0.3 μg/m^3 for chronic inhalation exposure recommended by the EPA (EPA, 2005). Members of sensitive populations (very young, very old, and ill people), for which this health guideline may be most important, are not likely to spend much time in flight, but do spend a significant amount of time in their homes and in other buildings (such as hospitals).

While small amounts of permethrin may be degraded by ozone-initiated chemistry, the dominant removal or degradation mechanism for permethrin and similar compounds in the indoor environment remains unknown. In soil, permethrin is degraded by aerobic and anaerobic degradation or photolysis (CDPR, 2003). However, these degradation pathways are likely to be much less rapid in the indoor environment.

Conclusions

Phosgene was identified as a potential reaction product of ozone and permethrin, the latter being the most common aircraft cabin residual insecticide. Published studies indicate that surface levels of permethrin in aircraft cabins that have been recently treated (within weeks) are 10–1000 ng/cm^2 or higher. Based on likely levels of surface permethrin and cabin-air ozone, it was deemed conceivable that phosgene production could occur in planes at levels of potential concern with regard to health guidelines.

A derivatization method was developed to detect gaseous phosgene with a lower limit of detection of 2 ppb. Experiments were conducted in which permethrin-coated glass and cabin materials (carpet, seat fabric, and plastic) were exposed to ozone under cabin-relevant conditions in a continuously ventilated chamber. Phosgene was not detected in any of the experiments, presumably because the chlorine atoms neighboring the double bond in permethrin are strongly electron withdrawing, which greatly reduces the tendency of ozone to react at this site.

Based on these experiments, it does not appear likely that ozone reaction with permethrin is a significant source of phosgene in the aircraft cabin environment. These experiments did not conclusively prove that phosgene is not formed, rather that the formation rate is below a certain level. It was estimated that phosgene formation, if it occurs in the cabin, is not likely to exceed relevant health guidelines (<1 ppb), even under the highest reported levels of ozone in aircraft cabins.

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References

Atkinson, R. and Arey, J. (2003) Atmospheric degradation of volatile organic compounds, *Chem. Rev.*, **103**, 4605–4638.

ATSDR (Agency for Toxic Substances & Disease Registry) (2003) *Toxicological profile for pyrethrins and pyrethroids*, Atlanta, GA, U.S. Department of Health and Human Services, Public Health Service. http://www.atsdr.cdc.gov/tfacts155.html (last accessed 2 October, 2009).

ATSDR (Agency for Toxic Substances & Disease Registry) (2007) *Medical management guidelines for phosgene*, Atlanta, GA, U.S. Department of Health and Human Services, Public Health Service. http://www.atsdr.cdc.gov/mhmi/mmg176.html (last accessed 2 October, 2009).

Avzianova, E.V. and Ariya, P.A. (2002) Temperature-dependent kinetic study for ozonolysis of selected tropospheric alkenes, *Int. J. Chem. Kinet.*, **34**, 678–684.

Berger-Preiss, E., Koch, W., Behnke, W., Gerling, S., Kock, H., Elflein, L. and Appel, K.E. (2004) In-flight spraying in aircrafts: determination of the exposure scenario, *Int. J. Hyg. Environ. Health*, **207**, 419–430.

Berger-Preiss, E., Koch, W., Gerling, S., Kock, H., Klasen, J., Hoffmann, G. and Appel, K.E. (2006) Aircraft disinsection: exposure assessment and evaluation of a new pre-embarkation method, *Int. J. Hyg. Environ. Health*, **209**, 41–56.

Bhangar, S., Cowlin, S.C., Singer, B.C., Sextro, R.G. and Nazaroff, W.W. (2008) Ozone levels in passenger cabins of commercial aircraft on North American and transoceanic routes, *Environ. Sci. Technol.*, **42**, 3938–3943.

Brown, M.A., Petreas, M.X., Okamoto, H.S., Mischke, T.M. and Stephens, R.D. (1993) Monitoring of malathion and its impurities and environmental transformation products on surfaces and in air following an aerial application, *Environ. Sci. Technol.*, **27**, 388–397.

Cano-Ruiz, J.A., Kong, D., Balas, R.B. and Nazaroff, W.W. (1993) Removal of reactive gases at indoor surfaces: combining mass transport and surface kinetics, *Atmos. Environ.*, **27A**, 2039–2050.

CDC (Centers for Disease Control and Prevention) (2006) *Facts about phosgene*, Atlanta, GA, U.S. Department of Health and Human Services. http://www.bt.cdc.gov/agent/phosgene/basics/facts.asp (last accessed 2 October, 2009).

CDPR (California Department of Pesticide Regulation) (2003) *Environmental fate of permethrin*, Sacramento, CA, California Environmental Protection Agency. http://www.cdpr.ca.gov/docs/emon/pubs/fatememo/permethrin.pdf (last accessed 2 October, 2009).

Class, T.J. (1991) Determination of pyrethroids and their degradation products in indoor air and on surfaces by HRGC-ECD and HRGC-MS (NCI), *J. High. Resolut. Chromatogr.*, **14**, 446–450.

Coleman, B.K., 2009. *Exposure-relevant ozone chemistry in occupied spaces*. Dissertation, Berkeley, CA, University of California.

Coleman, B.K., Destaillats, H., Hodgson, A.T. and Nazaroff, W.W. (2008) Ozone consumption and volatile byproduct formation from surface reactions with aircraft cabin materials and clothing fabrics, *Atmos. Environ.*, **42**, 642–654.

Destaillats, H., Singer, B.C., Lee, S.K. and Gundel, L.A. (2006) Effect of ozone on nicotine desorption from model surfaces: evidence for heterogeneous chemistry, *Environ. Sci. Technol.*, **40**, 1799–1805.

DOT (U.S. Department of Transportation) (2007) *Aircraft disinsection requirements*, Washington, DC, U.S. Department of Transportation, Office of Transportation Policy, Safety and Health Team. http://ostpxweb.dot.gov/policy/SafetyEnergyEnv/disinsection.htm (last accessed 2 October, 2009).

Dowideit, P. and von Sonntag, C. (1998) Reaction of ozone with ethene and its methyl- and chlorine-substituted derivatives in aqueous solution, *Environ. Sci. Technol.*, **32**, 1112–1119.

EPA (U.S. Environmental Protection Agency) (2005) *Toxicological review of phosgene*, Washington, DC, U.S. Environmental Protection Agency, Integrated Risk Information System (IRIS). http://www.epa.gov/iris/toxreviews/0487-tr.pdf (last accessed 2 October, 2009).

EPA (U.S. Environmental Protection Agency) (2006) *Permethrin facts [Reregistration eligibility decision (RED) fact sheet]*, Washington, DC, U.S. Environmental Protection Agency, Prevention, Pesticides, and Toxic Substances. http://www.epa.gov/oppsrrd1/REDs/factsheets/permethrin_fs.htm (last accessed 2 October, 2009).

Feigenbrugel, V., Le Person, A., Le Calvé, S., Mellouki, A., Muños, A. and Wirts, Z. (2006) Atmospheric fate of dichlorvos: photolysis and OH radical-initiated oxidation studies, *Environ. Sci. Technol.*, **40**, 850–857.

Kindler, T.P., Chameides, W.L., Wine, P.H., Cunnold, D.M. and Alyea, F.N. (1995) The fate of atmospheric phosgene and the stratospheric chlorine loadings of its parent compounds: CCl_4, C_2Cl_4, C_2HCl_3, CH_3CCl_3, $CHCl_3$, *J. Geophys. Res.*, **100**, 1235–1251.

Ljubic, I. and Sabljic, A. (2002) Theoretical study of the mechanism and kinetics of gas-phase ozone additions to ethene, fluoroethene, and chloroethene: a multireference approach, *J. Phys. Chem. A*, **106**, 4745–4757.

Maddalena, R.L. and McKone, T.E. (2008) *Insecticide exposures on commercial aircraft: a literature review and screening level assessment*, Berkeley, Lawrence Berkeley National Laboratory, Paper LBNL-1246E.

Matoba, Y., Takimoto, Y. and Kato, T. (1998) Indoor behavior and risk assessment following residual spraying of d-phenothrin and d-tetramethrin, *Am. Ind. Hyg. Assoc. J.*, **59**, 191–199.

Morrison, G.C. and Nazaroff, W.W. (2002) The rate of ozone uptake on carpet: mathematical modeling, *Atmos. Environ.*, **36**, 1749–1756.

Muir, B., Cooper, D.B., Carrick, W.A., Timperley, C.M., Slater, B.J. and Quick, S. (2005) Analysis of chemical warfare agents III. Use of bis-nucleophiles in the trace level determination of phosgene and perfluoroisobutylene, *J. Chromatogr. A*, **1098**, 156–165.

Murray, D.M. and Burmaster, D.E. (1995) Residential air exchange rates in the United States: empirical and estimated parametric distributions by season and climate region, *Risk Anal.*, **15**, 459–465.

NRC (National Research Council) (2002) *The Airliner Cabin Environment and the Health of Passengers and Crew*. National Research Council Committee on Air Quality in Passenger Cabins of Commercial Aircraft, Washington, D.C., National Academy Press.

OEHHA (California Office of Environmental Health Hazard Assessment) (1999) *Determination of acute reference exposure levels for airborne toxicants. Acute toxicity summary: Phosgene*, Sacramento, CA, California Environmental Protection Agency. http://www.oehha.ca.gov/air/acute_rels/pdf/75445A.pdf (last accessed 2 October, 2009).

OSHA (Occupational Safety & Health Administration) (1986) *Sampling and analytical methods: Phosgene*, Washington, DC, US Department of Labor. http://www.osha.gov/dts/sltc/methods/organic/org061/org061.html (last accessed 2 October, 2009).

Ruzo, L.O., Kimmel, E.C. and Casida, J.E. (1986) Ozonides and epoxides from ozonization of pyrethroids, *J. Agric. Food. Chem.*, **34**, 937–940.

Segal-Rosenheimer, M. and Dubowski, Y. (2007) Heterogeneous ozonolysis of cypermethrin using real-time monitoring FTIR techniques, *J. Phys. Chem. C*, **111**, 11682–11691.

Spicer, C.W., Murphy, M.J., Holdren, M.W., Myers, J.D., MacGregor, I.C., Holloman, C., James, R.R., Tucker, K. and Zaborski, R. (2004) *Relate air quality and other factors to comfort and health symptoms reported by passengers and crew on commercial transport aircraft (Part I)*. Atlanta, Georgia, American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE Project 1262-TRP).

Sutton, P.M., Vergara, X., Beckman, J., Nicas, M. and Das, R. (2007) Pesticide illness among flight attendants due to aircraft disinsection, *Am. J. Ind. Med.*, **50**, 345–356.

Tamás, G., Weschler, C.J., Bakó-Biró, Z., Wyon, D.P. and Strøm-Tejsen, P. (2006) Factors affecting ozone removal rates in a simulated aircraft cabin environment, *Atmos. Environ.*, **40**, 6122–6133.

Wells, J.R., Morrison, G.C. and Coleman, B.K. (2008) Kinetics and reaction products of ozone and surface-bound squalene, *J. ASTM Int.*, **5**, JAI101629.

Weschler, C.J., Wisthaler, A., Cowlin, S., Tamás, G., Strøm-Tejsen, P., Hodgson, A.T., Destaillats, H., Herrington, J., Zhang, J. and Nazaroff, W.W. (2007) Ozone-initiated chemistry in an occupied simulated aircraft cabin, *Environ. Sci. Technol.*, **41**, 6177–6184.

WHO (World Health Organization) (1995) *Report of the information consultation on aircraft disinsection*. International Programme on Chemical Safety, Geneva, Switzerland, World Health Organization.

Wisthaler, A., Tamás, G., Wyon, D.P., Strøm-Tejsen, P., Space, D., Beauchamp, J., Hansel, A., Märk, T.D. and Weschler, C.J. (2005) Products of ozone-initiated chemistry in a simulated aircraft environment, *Environ. Sci. Technol.*, **39**, 4823–4832.