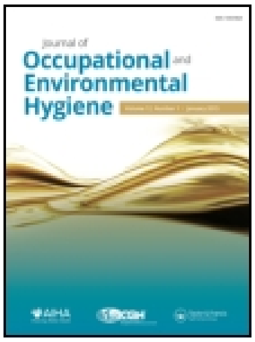

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Hexavalent chromium and isocyanate exposures during military aircraft painting under crossflow ventilation

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ABSTRACT

Exposure control systems performance was investigated in an aircraft painting hangar. The ability of the ventilation system and respiratory protection program to limit worker exposures was examined through air sampling during painting of F/A-18C/D strike fighter aircraft, in four field surveys. Air velocities were measured across the supply filter, exhaust filter, and hangar midplane under crossflow ventilation. Air sampling conducted during painting process phases (wipe-down, primer spraying, and topcoat spraying) encompassed volatile organic compounds, total particulate matter, Cr[VI], metals, nitroethane, and hexamethylene diisocyanate, for two worker groups: sprayers and sprayer helpers ("hosemen"). One of six methyl ethyl ketone and two of six methyl isobutyl ketone samples exceeded the short term exposure limits of 300 and 75 ppm, with means 57 ppm and 63 ppm, respectively. All 12 Cr[VI] 8-hr time-weighted averages exceeded the recommended exposure limit of 1 μg/m^3, 11 out of 12 exceeded the permissible exposure limit of 5 μg/m^3, and 7 out of 12 exceeded the threshold limit value of 10 μg/m^3, with means 38 μg/m^3 for sprayers and 8.3 μg/m^3 for hosemen. Hexamethylene diisocyanate means were 5.95 μg/m3 for sprayers and 0.645 μg/m^3 for hosemen. Total reactive isocyanate group—the total of monomer and oligomer as NCO group mass—showed 6 of 15 personal samples exceeded the United Kingdom Health and Safety Executive workplace exposure limit of 20 μg/m^3, with means 50.9 μg/m^3 for sprayers and 7.29 μg/m^3 for hosemen. Several exposure limits were exceeded, reinforcing continued use of personal protective equipment. The supply rate, 94.4 m^3/s (200,000 cfm), produced a velocity of 8.58 m/s (157 fpm) at the supply filter, while the exhaust rate, 68.7 m^3/s (146,000 cfm), drew 1.34 m/s (264 fpm) at the exhaust filter. Midway between supply and exhaust locations, the velocity was 0.528 m/s (104 fpm). Supply rate exceeding exhaust rate created re-circulations, turbulence, and fugitive emissions, while wasting energy. Smoke releases showing more effective ventilation here than in other aircraft painting facilities carries technical feasibility relevance.

KEYWORDS
Aircraft painting; hexavalent chromium; isocyanates; ventilation

Introduction

National Institute for Occupational Safety and Health (NIOSH) researchers investigated ventilation system performance—the effectiveness of contaminant removal and worker exposure control—in an aircraft paint finishing hangar. This topic addresses potentially hazardous chemicals, such as isocyanates and hexavalent chromium, present during painting of F/A-18C/D strike fighter aircraft. The appropriateness of the existing respiratory protection program was also evaluated.

Isocyanates are respiratory sensitizers and are one of the leading chemical causes of occupational asthma in the US and many other industrialized countries. Affected workers must take steps to eliminate exposure to prevent symptom progression, often by leaving their jobs or moving to different roles. Irritation to the mucous membranes of the eyes and gastrointestinal and respiratory tracts can lead to tearing, nasal congestion, dry/sore throat, cold-like symptoms, shortness of breath, wheezing, and chest tightness. Moreover, the most serious cases of chemical sensitization to isocyanates can result in severe asthma attacks, which are sometimes fatal.[1,2] Isocyanate products can contain a mixture of monomeric diisocyanates and oligomeric isocyanates. While the

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toxicity of monomeric diisocyanates is well-known, higher molecular weight isocyanates, the oligomers, also can cause health effects.[3,4]

Potential health effects of exposure to other chemicals in aircraft paints include central nervous system depression and nasal cancer, linked to various solvents[5] and chromates,[6] respectively. Ideally, the ventilation system controls to below occupational exposure limits (OELs) set by regulatory and advisory organizations, such as NIOSH recommended exposure limits (RELs), OSHA permissible exposure limits (PELs), and American Conference of Governmental Industrial Hygienists (ACGIH©) threshold limit values (TLVs©), while limiting releases to the ambient. Table 1 provides a list of salient OELs.[7] In the aircraft painting process, however, adequate protection against possible chemical sensitization to isocyanates and exceedance of Cr(VI) OELs requires controlling exposures down to levels that may be feasible only when a respiratory protection program supplements engineering controls.

OSHA standard, 29 CFR 1910.94 – *Ventilation*, requires that spray booths maintain an air velocity in the booth cross-section of 100 fpm (0.508 m/s), from Table G-10, Minimum Maintained Velocities Into Spray Booths.[8] However, an OSHA interpretation of 1910.94 prepared for the facility in this study stated that its hangar is a spray area rather than a booth. Recent communication between NIOSH and OSHA suggested that the large size of the painting hangars leads to the spray area designation. This painting operation must comply with training and respiratory protection standards and ensure compliance with 29 CFR1910, Subpart Z, which provides PELs for most of the materials involved in this study.[9] The hexavalent chromium (Cr[VI]) standard, 29 CFR 1910.1026, also must be considered. Specifically, part (f)(1)(ii), on painting large aircraft, allows respiratory protection to achieve the PEL (5 μg/m^3), if 8-hr TWA concentrations controlled through other methods do not exceed 25 μg Cr[VI]/m^3, "unless the employer can demonstrate that such controls are not feasible."[10]

The subject facility was designed to meet the 100 fpm velocity requirement, although measurements showed the supply delivered more than needed (Table 2). The design velocity was chosen to: (1) prevent explosions, (2) reduce overspray, and (3) protect worker health. In this aircraft painting operation, items 2 and 3 are addressed also to some extent by modern paint application methods. These include using high-volume low-pressure (HVLP) spray guns, which significantly reduce paint overspray, and the airline respirators worn by the sprayers and some sprayer helpers ("hosemen"). Interestingly, the ACGIH recommends only 50 fpm (0.254 m/s) for large vehicle paint booths.[11] The current study included comprehensive personal and area air sampling under the observed ventilation conditions, with four field surveys conducted between June 2009 and April 2010.

Plant and process description

This study occurred in a hangar bay, where approximately 20 aircraft are painted per year, by a team of 7 painters, termed artisans by the Navy: the foreman, 2 sprayers, 2 hosemen, and 2 workers who would rotate in as a sprayer or hoseman or do various jobs, such as material inventory and equipment preparation. One entire bay wall is a door to the outside that swings open for moving aircraft in and out. This door contains the supply plenum and filter. Supply air flows from this end of the bay to the exhaust filter on the opposing wall.

The bay is one of two in a large hangar. An accordion door (folding wall) separates the two bays when only one bay is required, as with painting of strike fighter aircraft or helicopters (blades removed). For wheeling in larger (cargo, transport) aircraft the supply walls of both bays are opened like a gate, the accordion door is folded and the two bays become one big hangar, served by two identical ventilation systems, side-by-side. The accordion door is the wall on the right shown in Figure 1.

The Specialty Coatings Group receives the aircraft after it has been abrasive blasted. When the aircraft enters the bay, it is first sanded until smooth with hand held sanders. Next, the aircraft surfaces are examined for defects. These are then "potted," i.e., repaired with epoxy putty, which is sanded down when cured. The artisans then wipe-down the plane with rags soaked in a mixture of methyl ethyl ketone (MEK) and methyl isobutyl ketone (MIBK). Air sampling began here (phase one) and the workers were given the job classification "wiper."

In phase two the aircraft was sprayed with a chemically-cured, two-component epoxy polyamide, water reducible primer paint. Phase three was spraying the aircraft using a chemically cured, two-component polyurethane topcoat paint in both light and dark gray. During sanding, wipe-down, and painting, the ventilation system is running at full capacity. Spray painting involves three military-specification (MIL-SPEC) products (Deft, Inc., Irvine CA): green primer, and the two topcoat colors: dark gray paint for the airframe's upper surfaces and light gray paint for the lower. Leading the list of hazardous materials are hexavalent chromium (Cr[VI]) in the primer and hexamethylene diisocyanate (HDI) in the topcoats. Two sprayers and two hosemen work during painting, while workers assigned a role in the next phase wait near the supply air wall.

Table 1. Evaluation criteria for air sampling results collected during spray painting, fleet readiness center southwest, Naval Base Coronado specialty coatings, Building 465, Bay 6.[7,9,12]

Compound	Cas #	Lower Explosive Limit (%)	OSHA Permissible Exposure Limit	NIOSH Recommended Exposure Limit	Other Exposure Limits
Total particulate not otherwise regulated	NA	NA	TWA 15 mg/m^3	NA	ACGIH TLV TWA 10 mg/m^3 (using an **inhalable** particulate sampler)
Hexavalent chromium	7440-47-3	NA	TWA 0.005 mg/m^3	TWA 0.001 mg/m^3	ACGIH TLV TWA 0.010 mg/m^3 (insoluble)
Barium	7440-39-3	NA	NA	TWA 0.5 mg/m^3	ACGIH TLV TWA 0.5 mg/m^3
Chromium	7440-47-3	NA	TWA 0.5 mg/m^3	TWA 0.5 mg/m^3	NIOSH IDLH 250 mg/m^3
Copper	7440-50-8	NA	TWA 1 mg/m^3	TWA 1 mg/m^3	NIOSH IDLH 100 mg/m^3
Strontium	7440-24-6	NA	NA	NA	NA
Tin	7440-31-5	NA	TWA 2 mg/m^3	TWA 2 mg/m^3	NIOSH IDLH 100 mg/m^3
Titanium	7440-32-6	NA	NA	NA	NA
Nitroethane	79-24-3	3.4	TWA 100 ppm	TWA 100 ppm	NIOSH IDLH 1000 ppm
1,2,4-Trimethylbenzene	95-63-6	0.9	NA	TWA 25 ppm	ACGIH TLV TWA 25 ppm; EU TWA 20 ppm; NIOSH IDLH 1000 ppm
1,3,5-Trimethylbenzene	108-67-8	0.9	NA	TWA 25 ppm	ACGIH TLV TWA 25 ppm; NIOSH IDLH 1000 ppm
2-butoxyethanol	111-76-2	1.1	TWA 50 ppm	TWA 5 ppm	ACGIH TLV TWA 20 ppm; NIOSH IDLH 700 ppm
Cumene	98-82-8	0.9	TWA 50 ppm	TWA 50 ppm	NIOSH IDLH 900 ppm
Ethyl benzene	100-41-4	1.2	TWA 100 ppm	TWA 100 ppm	ACGIH TLV TWA 20 ppm; NIOSH STEL 125 ppm; NIOSH IDLH 800 ppm
Methyl n-amyl ketone	110-43-0	1.1	TWA 100 ppm	TWA 100 ppm	ACGIH TLV TWA 50 ppm; NIOSH IDLH 800 ppm
Methyl ethyl ketone	78-93-3	1.4	TWA 200 ppm	TWA 200 ppm	NIOSH STEL 300 ppm; NIOSH IDLH 3000 ppm
Methyl isobutyl ketone	108-10-1	1.4	TWA 100 ppm	TWA 50 ppm	ACGIH TLV TWA 20 ppm; NIOSH STEL 75 ppm; NIOSH IDLH 500 ppm
n-Butyl acetate	123-86-4	1.7	TWA 150 ppm	TWA 150 ppm	NIOSH STEL 200 ppm; NIOSH IDLH 1700 ppm
Toluene	108-88-3	1.1	TWA 200 ppm	TWA 100 ppm	ACGIH TLV TWA 20 ppm; EU TWA 50 ppm; OSHA Ceiling 300 ppm; OSHA 10 min. Max. peak 500 ppm; NIOSH STEL 150 ppm; NIOSH IDLH 500 ppm
Hexamethylene diisocyanate (HDI) monomer	822-06-0	0.9	NA	TWA 0.035 mg/m^3	NIOSH Ceiling 0.140 mg/m^3 (10 min.); ACGIH TLV TWA 0.034 mg/m^3
Total Reactive Isocyanate Group (NCO)	NA		NA	NA	UK-HSE WEL TWA 0.020 mg/m^3; UK-HSE STEL 0.070 mg/m^3

NA = none vailable.
% = percent.
CAS # = Chemical Abstracts Service registry number.
OSHA = Occupational Safety and Health Administration.
NIOSH = National Institute for Occupational Safety and Health.
mg/m^3 = milligrams of analyte per cubic meter of air.
ppm = parts analyte per million parts air.
TWA = time-weighted average.
STEL = short term exposure limit (15 min.).
ACGIH TLV = American Conference of Governmental Industrial Hygienist Threshold Limit Value.[7]
IDLH = Immediately Dangerous to Life or Health.
EU = European Union.
UK-HSE = United Kingdom Health and Safety Executive.[12]
WEL = Workplace Exposure Limit.

Hangar temperature is maintained near 75°F, heated with steam coils in the supply fans if necessary. There is no cooling, and the hangar can reach 80°F on warmer days in the mild climate of San Diego. After primer application and again after application of both paints, the artisans exit to the outdoors, and the bay is brought up to 120°F to bake the coatings, while the airflow is reduced to 25% of the full-flow condition used for painting.

Table 2. Airflow indicators.

Flow Variable	Conditions	Supply [range]	Bay Midplane [range]	Exhaust [range]
Measured Velocity mean, m/s (fpm) [range in fpm] {Number of Measurements}	Before priming	0.792 (156) [131, 189] {43}	0.542 (107) [52, 161] {16}	1.42 (279) [188, 316] {24}
Volumetric Rate mean, m^3/s (cfm)		94.1 (199,000)	74.0 (157,000)	72.5 (154,000)
Normalized Velocity mean, m/s (fpm)		0.686 (135)	–	0.529 (104)
Filter Pressure Drop (in. water)				1.33
Measured Velocity mean, m/s (fpm) [range in fpm] {Number of Measurements}	After topcoat	0.803 (158) [122, 193] {43}	0.513 (101) [45, 140] {16}	1.28 (252) [83, 357] {24}
Volumetric Rate mean, m^3/s (cfm)		95.1 (202,000)	70.1 (148,000)	65.4 (139,000)
Normalized Velocity mean, m/s (fpm)		0.696 (137)	–	0.479 (94.2)
Filter Pressure Drop (in. water)				1.67
Measured Velocity mean, m/s (fpm) [range in fpm] {Number of Measurements}	All data	0.798 (157) [122, 193] {86}	0.528 (104) [45, 161] {32}	1.34 (264) [83, 357] {48}
Volumetric Rate mean, m^3/s (cfm)		94.4 m^3/s (200,000 cfm)	72.2 m^3/s (153,000 cfm)	68.7 m^3/s (146,000 cfm)
Normalized Velocity mean, m/s (fpm)		0.691 (136)	–	0.504 (99.3)

Normalized air velocities (V_{CS}) are based on the cross-sectional area (A_{CS}) of the bay: $V_{CS} = (A/A_{CS})$ V, where A and V are the face area and face velocity of the supply or exhaust openings.

Engineering controls

Four supply and four exhaust fans serve the bay, with exhaust rpm linked to supply function via variable frequency drive (VFD) controllers. Two supply fans are equipped with steam heat elements. The ventilation system was designed to maintain a safe and healthy work environment, to control and collect sanding particulate and paint overspray before they enter the ambient, and

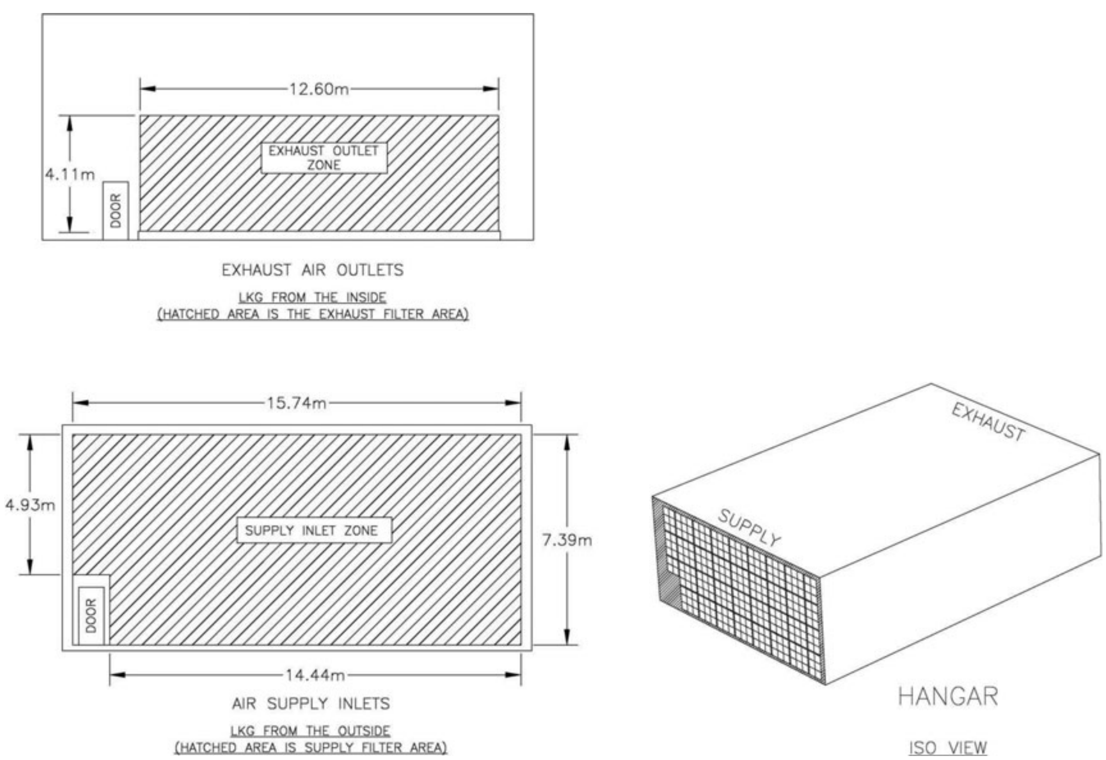

Figure 1. Drawing showing filter area of the aircraft painting bay.

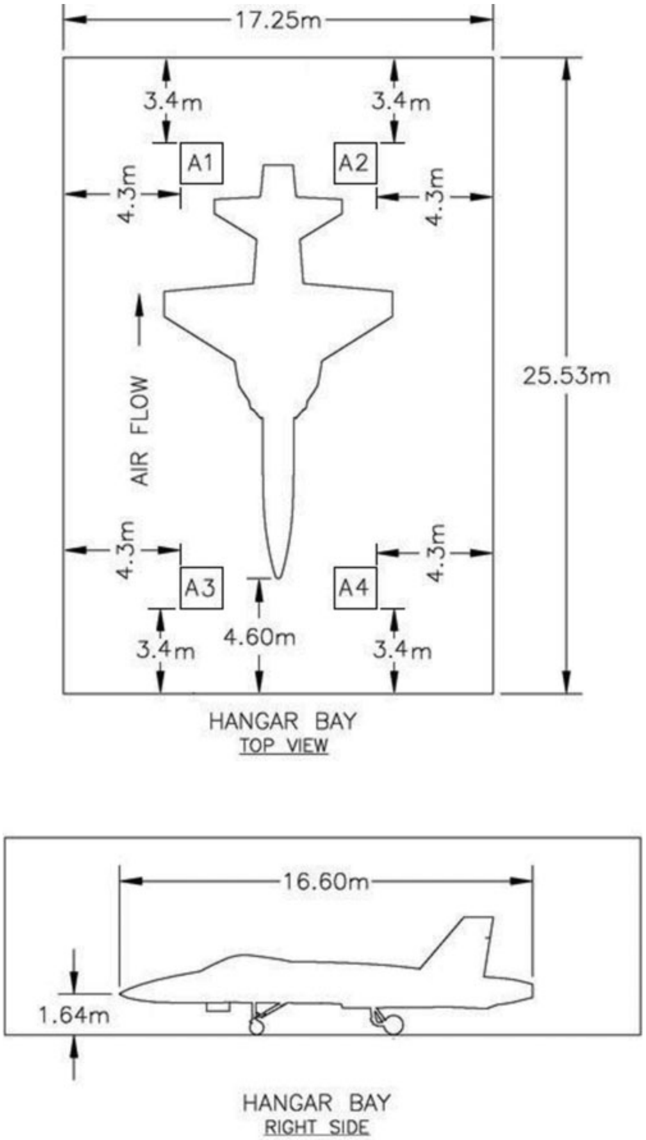

Figure 2. Drawing showing interior of bay, F/A-18C/D Hornet aircraft, and area sample locations (A1–A4).

to maintain the temperature needed for painting operations. Performance is sensitive to exhaust filter loading, and the current replacement criterion is a pressure drop of 2.5 in water gauge across the filter bank. Figures 1 and 2 show the configuration of the bay, filters, and aircraft, with a supply wall blowing air toward an exhaust wall at the opposite end of the bay.

Personal protective equipment

All hangar personnel wore Tyvek suits and neoprene gloves. Airline hood respirators were always used by the sprayers. The hosemen were observed to wear either full-face continuous flow airline respirators or full-face air-purifying respirators (APRs) fitted with combination organic vapor and particulate cartridges. These two respirator types have assigned protection factors (APF) of 1000 and 50, respectively.[13] Respirators are needed because the ventilation system by itself does not adequately protect against Cr[VI] and isocyanates. The respirators also reduce exposure to VOCs and other airborne stressors, either gas or aerosol.

Methods

Ventilation evaluation

Velocities were measured using an AMD-860AirData Multimeter (Shortridge Instruments, Inc., Scottsdale, AZ), with current calibration certification, a Shortridge VelGrid, two sections of 20-ft Tygon tubing, and a 25-ft extension pole. Basic system operation, i.e., which fans were on or off, was observed by noting the operational setting or sequence number, initially verified by climbing up to the hangar building roof and noting sound and vibration from individual fans. Secondarily, a facility computer was sometimes available with software that tracked the performance of the exhaust fans. The facility's air permit from the San Diego Air Pollution Control Board requires exhaust filter pressure drop to be "maintained between 0.5 and 2.25" in water gauge and that "exhaust fans and exhaust filters …are installed and operating properly."[14]

Exhaust pressure drop was read from the control room manometer before each painting phase to verify proper operation. Also, differential pressures were measured across bay/ambient, bay/control room, and control room/ambient, using the ShortRidge AirData Multimeter. Filter face velocities were measured before and after painting, on two separate survey dates, on a grid overlaying the physical grid formed by the filter housing beams (Figures 3 and 4). During one survey, velocity measurements were taken in a matrix of 16 locations in a plane midway between supply and exhaust.

Air sampling

Air sampling conducted to evaluate concentrations of compounds in paints, primers, and solvents used on F/A-18C/D Hornet strike fighter aircraft occurred under existing, full-flow ventilation conditions, on three separate surveys: July 23, 2009; August 4, 2009; and April 13, 2010. One Hornet was painted per survey. Sampling was performed in all three phases of the painting process during each survey: wipe-down, primer, and topcoat. Each of the five job classifications, e.g., primer-hoseman, was populated by two workers per survey, for a total of 30 sampled workers. Four areas were sampled (Figure 2) per survey

Figure 3. Industrial hygienist measuring supply air velocity, using extension pole to reach high on the filter.

for a total of 12. Each sampled worker and area sample tripod was fitted with multiple pumps and sampling trains.

Using Material Safety Data Sheets (MSDS) as a guide, air samples were collected for select VOCs, total particulate matter (TPM), Cr[VI], select metals, nitroethane, and HDI. The source of Cr[VI] was the epoxy polyamide primer, which contained barium chromate and zinc chromate. During the aircraft wipe-down phase, only VOC samples were collected. VOCs, TPM, Cr[VI], select metals, and nitroethane samples were collected during the primer phase. VOCs, TPM, select metals, and HDI air samples were collected during the topcoat phase. Both personal breathing zone (PBZ) and area air samples were collected during all phases. PBZ samples were collected by attaching, to a worker's belt, an air sampling pump connected by Tygon tubing to the sample media, attached to the outside of their Tyvek hood. Area samples were collected on tripods at four corners surrounding the F/A-18C/D Hornet, two upwind of the source (aircraft) and two downwind, as shown in Figure 2. The area sample media were approximately 5 ft above the floor.

VOCs sampled included: 2-butoxyethanol, also known ethylene glycol butyl ether (EGBE); n-butyl acetate; cumene; ethyl benzene; methyl amyl ketone

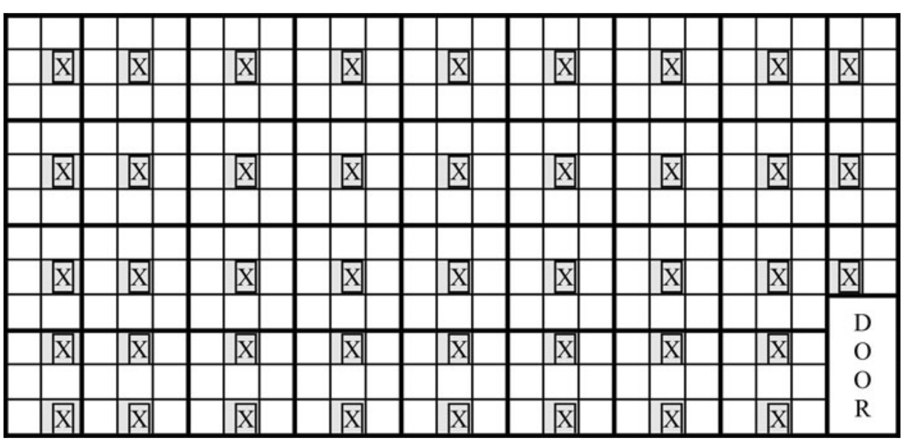

Figure 4. Supply velocity measurement matrix of 43 locations on the filter, viewed from inside the bay.

(MAK); methyl ethyl ketone (MEK), also known as 2-butanone; methyl isobutyl ketone (MIBK); toluene;1,2,4-trimethylbenzene; and 1,3,5-trimethylbenzene. Samples were collected on charcoal tubes (100 mg front section and 50 mg back section) at air sampling flow rates of 50 ml/min and 200 ml/min. Charcoal tubes were analyzed using NIOSH Method 1501,[15] modified to accommodate MEK, MIBK, MAK, and EGBE by changing the desorbing solvent from carbon disulfide to a 5% n-propanol/95% carbon disulfide solution.

TPM and Cr[VI] air samples were collected on pre-weighed polyvinyl chloride (PVC) filters (37 mm diameter and 5.0 μm pore size) at a flow rate of 2.0 L per minute (lpm). TPM and Cr[VI] were analyzed according to NIOSH Methods 0500 and 7605, respectively.[16,17] The select metals sampled included barium (Ba), chromium (Cr), copper (Cu), tin (Sn), strontium (Sr), and titanium (Ti), collected on pre-weighed PVC filters (37 mm diameter and 5.0 μm pore size) at a flow rate of 2.0 lpm. The filters were first analyzed for TPM gravimetrically according to NIOSH Method 0500, then digested and analyzed for metals according to NIOSH Method 7303.[18] Nitroethane samples were collected using XAD-2 tubes (600 mg front section and 300 mg back section) at 50 ml/min and analyzed according to NIOSH Method 2526.[19] The select metals and nitroethane were only collected as area samples.

HDI was collected on glass fiber filters (37 mm diameter) impregnated with 1-(9-anthracenyl-methyl)piperazine (MAP) at 1.0 lpm. Filters were field extracted in 5 ml solutions of acetonitrile with 1×10^{-4} M MAP. Impingers containing 15 ml butyl benzoate with 2×10^{-4} M MAP collected HDI alongside the filters. Analyses followed NIOSH Method 5525.[20] Oligomeric HDI is presented as isocyanate functional group (NCO) mass. HDI monomer is presented as monomer mass and NCO group mass, the latter enabling oligomer comparison.

During each of the three surveys, two wipers sampled for VOCs took approximately 30 min to clean the aircraft with solvent-soaked rags. Two sprayers and two hosemen were sampled for VOCs, TPM, and Cr[VI] during primer spraying, which lasted from 30–50 min. Two sprayers and two hosemen were sampled for VOCs and HDI during the light and dark gray topcoat phase, lasting between 75 and 100 min. Thus, each job classification was sampled six times.

Sampling was performed only during the specific painting phases (wipe-down, priming, topcoat) rather than over the work shift. Because Cr(VI) and HDI exposures occurred only in one phase, e.g., Cr(VI) during priming, task-specific sampling was an efficient method. VOC exposures occurred in all three phases, and the 8-hr TWA was constructed as the sum of contributions to the 8-hr TWAs from each phase. The sampled phases included material handling and tool clean-up tasks. Sampling began (ended) as the artisans put on (took off) their required PPE. Break or lunch occurred between phases, in a separate building.

Isocyanate samples were analyzed by the Chemical Exposure & Monitoring Branch (CEMB) of NIOSH (Cincinnati, OH). Bureau Veritas North America (Novi, MI) performed all other analyses. CEMB and Bureau Veritas are accredited by the American Industrial Hygiene Association.

Results

Air velocities

As shown in Table 2, the supply rate of 94.4 m^3/s (200,000 cfm) produced a velocity of 0.798 m/s (157 fpm) at the supply filter. The supply filter area was nearly as large as the bay cross-sectional area, and when the supply rate was divided by the cross-sectional area, the resulting normalized velocity was 0.691 m/s (136 cfm/ft^2), which exceeded the design specification of 0.508 (m3/s)/m^2 (100 cfm/ft^2). Comparing measurements before and after painting operations, the most noticeable difference was increased pressure drop across the exhaust filter, with loading from overspray. Interestingly, the range of exhaust filter face velocities also increased—the flow became less uniform—going from [0.995 (188), 1.61 (316)] m/s (fpm) (before primer spraying) to [0.422 (83), 1.81 (357)] m/s (fpm) (after topcoat spraying). The exhaust rate of 68.7 m^3/s (146,000 cfm) produced a filter face velocity of 1.34 m/s (264 fpm).

Dividing this rate by the bay cross-sectional area resulted in 0.504 (m^3/s)/m^2 or 99.3 cfm/ft^2; thus, the exhaust system was generally functioning to achieve the design specification, although filter loading decreased the exhaust rate and widened the velocity distribution across the filter (Table 2). Before primer spraying, the exhaust velocity ranged from 0.955 m/s (188 fpm) to 1.61 m/s (316 fpm), whereas the range expanded to [0.422 (83), 1.81 (357)] m/s (fpm) after topcoat spraying. More paint was visible on the lower than the upper surfaces of the exhaust filter, and the measured velocity increased with height above the bay floor. This pattern was more pronounced after topcoat spraying.

Air sampling

Air sampling results from the three surveys were tabulated and summarized into the three phases: aircraft wipe-down, primer spray painting, and topcoat spray

Table 3. Summary of notable exposures during aircraft paint finishing.

Operation and Job	Statistic	Duration (min.)	MEK (ppm)	MIBK (ppm)	TPM (mg/m^3)	Cr[VI] (µg/m^3)	HDI monomer (µg HDI/m^3)	HDI monomer (µg NCO/m^3)	HDI oligomer (µg NCO/m^3)	TRIG (µg NCO/m^3)
Wipe-down	N	6	6	6	N/A	N/A	N/A	N/A	N/A	N/A
Wiper	Gmean [8-hr TWA][a]	27	57 [3.2]	63 [3.5]						
	95th %-ile [8-hr 95th %-ile]		380 [20]	490 [26]						
Primer application	N	6	6	6	6	6	N/A	N/A	N/A	N/A
Hoseman	Gmean [8-hr TWA]	34	0.22 [0.015]	0.56 [0.039]	4.3 [0.30]	120 [8.3]				
	95th %-ile [8-hr 95th %-ile]		1.3 [0.13]	4.6 [0.46]	8.9 [0.54]	260 [18]				
Sprayer	Gmean [8-hr TWA]	37	0.42 [0.032]	1.1 [0.087]	18 [1.4]	500 [38]				
	95th %-ile [8-hr 95th %-ile]		22 [1.5]	20 [1.4]	25 [1.9]	640 [52]				
Topcoat application	N	6	6	6	6[b]	N/A	6	6	6	6
Hoseman	Gmean [8-hr TWA]	79	0.88 [0.14]	1.2 [0.19]	4.1 [0.68]		3.99 [0.645]	2.06 [0.332]	42.7 [6.90]	45.2 [7.29]
	95th %-ile [8-hr 95th %-ile]		1.8 [0.26]	2.4 [0.35]	8.2 [1.7]		11.2 [2.13]	5.56 [1.06]	148 [24.9]	152 [26.0]
Sprayer	Gmean [8-hr TWA]	89	0.95 [0.17]	1.6 [0.30]	17 [3.2]		32.2 [5.95]	16.1 [2.97]	259 [47.9]	276 [50.9]
	95th %-ile [8-hr 95th %-ile]		4.1 [0.80]	6.5 [1.3]	23 [4.8]		45.8 [7.33]	22.9 [3.66]	448 [70.7]	471 [74.4]
Full Shift Total										
Wiper & Hoseman	Gmean 8-hr TWA [8-hr 95th %-ile]	480	3.4 [20]	3.7 [27]	0.98 [2.2]	8.3 [18]	0.645 [2.13]	0.332 [1.06]	6.90 [24.9]	7.29 [26.0]
Wiper & Sprayer	Gmean 8-hr TWA [8-hr 95th %-ile]	480	3.4 [22]	3.7 [29]	4.6 [6.7]	38 [52]	5.95 [7.33]	2.97 [3.66]	47.9 [70.7]	50.9 [74.4]

[a]All mean 8-hr TWAs were calculated as geometric means.
[b]Estimated from area samples and personal samples.

painting. During all three phases, the ventilation system was at full flow. Summary statistics included the number of samples, geometric process and 8-hr TWA means, and 95th percentile concentrations (process and 8-hr TWAs, assuming a lognormal distribution underlies the samples). In the reporting below, "mean" refers to geometric mean. For calculations where a third or less of the results were below the limit of detection (LOD), the left-sensored values were replaced by either the LOD divided by the square root of 2 or the LOD divided by 2, depending on whether the geometric standard deviation was less than or equal to 3 or greater than 3, respectively. When at least half of the results were below the LOD, the LOD was used in the mean calculation and reported as less than the resultant value to clearly indicate the overestimation.[21,22] Table 3 condenses noteable exposures by process, and Table 4 lists individual worker exposures.

Aircraft wipe-down

During the approximately 30 min of wipe-down, most of the full-shift VOC exposures occurred, with MEK and MIBK means for workers performing this task of 57 ppm and 63 ppm, respectively. One of six samples exceeded the MEK short-term exposure limit (STEL: ACGIH = 300 ppm, NIOSH = 300 ppm), and two of six exceeded the MIBK STEL (ACGIH = 75 ppm, NIOSH = 75 ppm). One of the six personal samples showed concentrations of 670 ppm for MEK and 920 ppm for MIBK, which are at least an order of magnitude higher than the other five samples. In addition, there was more than 50% breakthrough of MEK on this sample. While these values were retained in the calculations, it is possible this sample was an anomaly. In any case, the exposure was adequately controlled by air-purifying respirators (APRs), which have an assigned protection factor (APF) of 10 or 50, for half-face or full-face types, respectively. Full-shift OELs (MEK:

Table 4. Individual results as short-term samples and 8-hr TWAs.

Sample Date	Work Activity	Worker ID	MEK (ppm)
4/13/2010	Wipe-down	015	16
4/13/2010	Wipe-down	016	22
7/23/2009	Wipe-down	017	32
7/23/2009	Wipe-down	018	63
8/4/2009	Wipe-down	019	71
8/4/2009	Wipe-down	007	670
Sample Date	**Work Activity**	**Worker ID**	**MIBK (ppm)**
4/13/2010	Wipe-down	015	14
4/13/2010	Wipe-down	016	20
7/23/2009	Wipe-down	017	48
7/23/2009	Wipe-down	018	63
8/4/2009	Wipe-down	019	77
8/4/2009	Wipe-down	007	920
Sample Date	**Work Activity**	**Wroker ID**	**MEK 8-hr TWA (ppm)**
8/4/2009	Primer hoseman	001	0.01
7/23/2009	Primer sprayer	002	0.02
4/13/2010	Light sprayer	003	0.03
7/23/2009	Dark hoseman	004	0.03
4/13/2010	Primer sprayer	005	0.05
7/23/2009	Light sprayer	006	0.05
7/23/2009	Primer sprayer, light hoseman, dark hoseman	007	0.07
4/13/2010	Light sprayer	008	0.12
8/4/2009	Primer sprayer, dark sprayer	009	0.15
8/4/2009	Primer sprayer, light sprayer	008	0.15
8/4/2009	Light hoseman, dark hoseman	010	0.18
7/23/2009	Primer hoseman, dark hoseman	011	0.27
8/4/2009	Dark sprayer, light hoseman	012	0.28
8/4/2009	Primer hoseman, light sprayer, dark hoseman	013	0.28
7/23/2009	Dark sprayer	014	0.56
7/23/2009	Light sprayer	013	0.56
4/13/2010	Wipe-down, primer hoseman, light hoseman	015	1.3
4/13/2010	Wipe-down, primer hoseman, light hoseman	016	1.4
7/23/2009	Wipe-down	017	1.7
7/23/2009	Wipe-down, primer hoseman, light hoseman	018	3.4
8/4/2009	Wipe-down	019	4.1
4/13/2010	Primer sprayer	020	4.2
8/4/2009	Wipe-down	007	35
Sample Date	**Work Activity**	**Wroker ID**	**MIBK 8-hr TWA (ppm)**
8/4/2009	Primer hoseman	001	0.04
4/13/2010	Light sprayer	005	0.05
4/13/2010	Primer sprayer	003	0.05
7/23/2009	Primer sprayer	002	0.06
7/23/2009	Dark hoseman	004	0.10
8/4/2009	Primer sprayer, dark sprayer	010	0.13
4/13/2010	Light sprayer	008	0.16
7/23/2009	Light sprayer	006	0.16

Table 4. Continued

Sample Date	Work Activity	Wroker ID	MIBK 8-hr TWA (ppm)
7/23/2009	Primer sprayer, light hoseman, dark hoseman	007	0.21
8/4/2009	Primer sprayer, light sprayer	009	0.35
8/4/2009	Light hoseman, dark hoseman	008	0.35
8/4/2009	Dark sprayer, light hoseman	012	0.35
8/4/2009	Primer hoseman, light sprayer, dark hoseman	013	0.37
7/23/2009	Primer hoseman, dark hoseman	014	0.79
7/23/2009	Dark sprayer	013	0.79
7/23/2009	Light sprayer	011	0.94
4/13/2010	Wipe-down, primer hoseman, light hoseman	015	1.2
4/13/2010	Wipe-down, primer hoseman, light hoseman	016	1.3
7/23/2009	Wipe-down	017	2.5
4/13/2010	Primer sprayer	020	2.5
7/23/2009	Wipe-down, primer hoseman, light hoseman	018	3.4
8/4/2009	Wipe-down	019	4.5
8/4/2009	Wipe-down	007	48
Sample Date	**Work Activity**	**Worker ID**	**TPM 8-hr TWA (mg/m^3)**
7/23/2009	Primer hoseman	018	0.11
8/4/2009	Primer hoseman	001	0.29
7/23/2009	Primer hoseman	011	0.30
4/13/2010	Primer hoseman	015	0.32
8/4/2009	Primer hoseman	013	0.35
4/13/2010	Primer hoseman	020	0.63
7/23/2009	Primer sprayer	002	0.69
8/4/2009	Primer sprayer	009	1.3
4/13/2010	Primer sprayer	016	1.3
8/4/2009	Primer sprayer	008	1.5
4/13/2010	Primer sprayer	005	1.8
7/23/2009	Primer sprayer	007	1.9
Sample Date	**Work Activity**	**Worker ID**	**Cr[VI] 8-hr TWA (µg/m^3)**
7/23/2009	Primer hoseman	018	3.0
7/23/2009	Primer hoseman	011	7.7
8/4/2009	Primer hoseman	001	7.9
8/4/2009	Primer hoseman	013	9.3
4/13/2010	Primer hoseman	015	10
4/13/2010	Primer hoseman	020	18
7/23/2009	Primer sprayer	002	22
8/4/2009	Primer sprayer	009	35
4/13/2010	Primer sprayer	016	37

(Continued on next page)

Table 4. Continued

Sample Date	Work Activity	Worker ID	Cr[VI] 8-hr TWA (μg/m³)
8/4/2009	Primer sprayer	008	42
4/13/2010	Primer sprayer	005	44
7/23/2009	Primer sprayer	007	55
Sample Date	Work Activity	Worker ID	HDI monomer 8-hr TWA (μg HDI/m³)
7/23/2009	Light hoseman	018	0.45
4/13/2010	Light hoseman	015	0.92
7/23/2009	Dark hoseman	004	1.2
4/13/2010	Light hoseman	016	1.5
7/23/2009	Light hoseman	007	1.6
8/4/2009	Light sprayer, dark hoseman	013	2.5
8/4/2009	Dark sprayer, light hoseman	012	2.5
7/23/2009	Dark sprayer	014	2.7
7/23/2009	Light sprayer	013	2.7
8/4/2009	Light sprayer	008	3.0
8/4/2009	Dark sprayer	009	3.0
7/23/2009	Dark sprayer	011	3.1
7/23/2009	Light sprayer	006	3.1
4/13/2010	Light sprayer	008	5.8
4/13/2010	Light sprayer	003	7.8
Sample Date	Work Activity	Worker ID	TRIG 8-hr TWA (μg NCO/m³)
7/23/2009	Light hoseman	018	4.6
7/23/2009	Dark hoseman	004	14
4/13/2010	Lighthoseman	015	18
8/4/2009	Light sprayer, dark hoseman	013	19
8/4/2009	Dark sprayer, light hoseman	012	19
7/23/2009	Light hoseman	007	19
4/13/2010	Light hoseman	016	19
7/23/2009	Dark sprayer	014	19
7/23/2009	Light sprayer	013	19
7/23/2009	Dark sprayer	011	23
7/23/2009	Light sprayer	006	23
8/4/2009	Light sprayer	008	28
8/4/2009	Dark sprayer	009	28
4/13/2010	Light sprayer	008	61
4/13/2010	Light sprayer	003	80

Yellow highligh = NIOSH, ACGIH, or UK-HSE OEL exceeded. Red highlight = OSHA PEL exceeded.

REL = 200 ppm, PEL = 200 ppm, TLV = 200 ppm and MIBK: REL = 50 ppm, PEL = 100 ppm, TLV = 20 ppm) were not exceeded (Table 3). After wipe-down, workers would become either sprayers or hosemen. For workers in the sprayer job classification for the remainder of the day, the MEK and MIBK 8-hr TWAs were 3.4 ppm and 3.7 ppm, respectively. The 8-hr TWAs were essentially the same for the hosemen, since the means were dominated by wipe-down exposures, and subsequent job classification had negligible effect. Table 5 shows area means for MEK and MIBK at the four tripods, with the upwind results (tripods #3 and #4) near or below the LOD.

Aircraft primer spray painting

VOC results for the primer spray painting phase are summarized in Table 6. While measureable levels of 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, 2-butoxyethanol (EGBE), MEK, and MIBK were detected in these samples, 1,2,4-trimethylbenzene and 1,3,5-trimethylbenzene will not be discussed here as the levels were well below the OEL of 25 ppm. Mean PBZ sample results for EGBE, MEK, and MIBK for sprayers were 2.5, 0.42, and 1.1 ppm, respectively, and for hosemen: 0.36, 0.22, and 0.56 ppm.

EGBE 8-hr TWAs were 0.19 ppm and 0.025 ppm for sprayers and hosemen—below the OELs (REL = 5 ppm, PEL = 50 ppm)—and only during primer painting were concentrations clearly above the LOD. Note that MEK and MIBK full-shift TWAs were reported in the wipe-down section. All the EGBE, MEK, and MIBK results were well below the STELs during primer spraying.

As worker 8-hr TWAs, all 12 Cr[VI] samples exceeded the NIOSH REL of 1 μg/m³, 11 out of 12 exceeded the OSHA PEL of 5 μg/m³, and 7 out of 12 exceeded the ACGIH TLV of 10 μg/m³, with means of 38 μg/m³ and 8.3 μg/m³ for sprayers and hosemen, respectively. With Cr[VI] exposures occurring only during primer painting, it is noteworthy that mean exposures for both sprayers and hosemen exceeded the NIOSH REL and the OSHA PEL. All 6 hoseman exposures, however, were below 25 μg/m³, so that controlling to below the PEL of 5 μg/m³ using respiratory protection complied with the OSHA chromium standard, for this job group. Reducing the *sprayer* exposure (outside the respirator) through engineering controls must still be accomplished to come into compliance using respirators. TPM and Cr[VI] concentrations sampled during primer painting were 18 mg TPM/m³ and 500 μg Cr[VI]/m³ for sprayers and 4.3 mg TPM/m³ and 120 μg Cr[VI]/m³ for hosemen (Tables 3 and 7).

Table 4 shows that sprayers' and hosemen's 8-hr TWAs for TPM were all below the OELs (TLV = 10 mg/m³, PEL = 15 mg/m³), and Table 3 reports mean 8-hr TWAs as 1.4 and 0.30 mg/m³, respectively. Because TPM was measured using 37 mm PVC filters in closed-face cassettes (CFC) and not inhalable particulate samplers, comparison to the inhalable fraction TLV carries the uncertainty of size selection difference between the two methods. A recent study found that an IOM inhalable sampler collected from 1.62 to 2.97 more mass than the CFC.[23] As the highest TPM 8-hr TWA was 1.9 mg/m³, exceeding the TLV would require the real inhalable mass to be 5.3 times greater than the CFC result. The conclusion that the TPM TLV and PEL were not exceeded is then apparently consistent with the reported IOM/CFC performance ratio. TPM and Cr[VI] area means for downwind tripods were 4.8 mg/m³ TPM and 160 μg/m³ Cr[VI] for tripod #1 and 1.6 mg/m³ TPM and 44 μg/m³ Cr[VI] for tripod #2. Upwind, TPM was below the LOD, while

Table 5. Summary of select VOC air concentrations during F/A-18C/D hornet wipe-down.

Work Activity or Sample Location	Sample Type [Mean Volume] (L)	Number of Samples [Task Duration Mean] (min)	1, 2, 4-Trimethyl-benzene Gmean (ppm)	1, 3, 5-Trimethyl-benzene Gmean (ppm)	2-Butoxyethanol Gmean (ppm)	Cumene Gmean (ppm)	Ethyl-benzene Gmean (ppm)	Methyl Amyl Ketone Gmean (ppm)	Methyl Ethyl Ketone Gmean {95th %-tile} (ppm)	Methyl Isobutyl Ketone Gmean {95th %-tile} (ppm)	N-Butyl Acetate Gmean (ppm)	Toluene Gmean (ppm)
Wipe-down Worker	P [5.5]	6 [27]	<0.02[a]	<0.02	<0.05	<0.02	<0.03	<0.04	57 {380}	63 {490}	<0.03	0.05[b]
Tripod #1	A [4.0]	6 [32]	<0.03	<0.03	<0.07	<0.04	<0.04	<0.06	1.7[b]	2.0	<0.06	<0.02
Tripod #2	A [4.4]	6 [35]	<0.03	<0.03	<0.07	<0.04	<0.04	<0.06	1.6	2.3	<0.05	<0.03
Tripod #3	A [4.3]	6 [34]	<0.03	<0.03	<0.08	<0.04	<0.04	<0.06	<0.3	0.21[b]	<0.05	<0.03
Tripod #4	A [4.4]	6 [35]	<0.03	<0.03	<0.08	<0.04	<0.04	<0.06	<0.08	0.10[b]	<0.05	<0.03

[a]When at least half of the sample results were below the limit of detection, the LOD was used in the mean calculation and reported as less than the resultant value.
[b]A third or less of the sample results contributing to the mean calculation were less than the limit of detection and were replaced by either the LOD /$\sqrt{2}$ or the LOD/2.

Cr[VI] means were 0.29 µg/m^3 and 0.46 µg/m^3 for tripods #3 and #4, respectively.

Area samples for select metals collected during primer application (Table 8) also included TPM, as it was available gravimetrically during metals analysis, which detected Ba, Cr, and trace amounts of Cu and Sr. Only trace amounts of nitroethane were detected (Table 9).

Aircraft topcoat painting

During the topcoat phase, mean HDI monomer 8-hr TWAs were 5.95 µg/m^3 for sprayers and 0.645 µg/m^3 for hosemen (Table 3). None of the 15 personal samples exceeded an HDI OEL (REL = 35 µg/m^3, TLV = 34 µg/m^3). However, concentrations of Total Reactive Isocyanate Group (TRIG)—the total of HDI monomer and HDI oligomer in terms of NCO group mass—showed

Table 6. Summary of select VOC air concentrations during primer spray painting.

Work Activity or Sample Location	Sample Type [Mean Volume] (L)	Number of Samples [Task Duration Mean] (min.)	1, 2, 4-Trimethyl-benzene Gmean (ppm)	1, 3, 5-Trimethyl-benzene Gmean (ppm)	2-Butoxy-ethanol Gmean {95th %-tile} (ppm)	Cumene Gmean (ppm)	Ethyl-benzene Gmean (ppm)	MAK Gmean (ppm)	MEK Gmean {95th %-tile} (ppm)	MIBK Gmean {95th %-tile} (ppm)	N-Butyl Acetate Gmean (ppm)	Toluene Gmean (ppm)
Primer Sprayer	P [7.5]	6 [37]	1.3	0.40	2.5 {3.6}	0.06	<0.02	<0.03	0.42[b] {22}	1.1 {20}	<0.02	0.03[b]
As 8-hr TWA	P	6			0.19 {0.29}				0.032[b] {1.5}	0.087 {1.4}		
Primer Hosemen	P [6.9]	6 [34]	0.34	0.11	0.36[b] {1.2}	<0.02	<0.02	<0.03	0.22[b] {1.3}	0.56 {4.6}	<0.03	<0.02
As 8-hr TWA	P	6			0.025[b] {0.0856}				0.015[b] {0.13}	0.039 {0.46}		
Tripod #1	A [5.2]	6 [41]	0.63	0.19[b]	1.1	0.04[b]	<0.03	<0.05	<0.2	0.19[b]	<0.04	<0.03
Tripod #2	A [5.2]	6 [41]	0.29	0.0[b]	0.57	<0.03	<0.03	<0.05	<0.1	0.13[b]	<0.04	<0.03
Tripod #3	A [5.4]	6 [43]	<0.1[a]	<0.04	<0.1	<0.03	<0.03	<0.05	0.12[b]	0.14[b]	<0.04	<0.03
Tripod #4	A [4.9]	6 [39]	0.07[b]	<0.04	0.14[b]	<0.03	<0.03	<0.05	<0.1	<0.1	<0.06	<0.03

[a]When at least half of the sample results were below the limit of detection, the LOD was used in the mean calculation and reported as less than the resultant value.
[b]A third or less of the sample results contributing to the mean calculation were less than the limit of detection and were replaced by either the LOD /$\sqrt{2}$ or the LOD/2.

Table 7. Summary of TPM and Cr[VI] air concentrations during primer spray painting.

Work Activity or Sample Location	Sample Type [Mean Volume] (L)	Number of Samples [Task Duration Mean] (min)	Total Particulate Matter Gmean {95th %-tile} (mg/m^3)	Hexavalent Chromium Gmean {95th %-tile} (µg/m^3)
Primer Sprayer	P [74]	6 [37]	18 {25}	500 {640}
Primer Hosemen	P [68]	6 [34]	4.3 {8.9}	120 {260}
Tripod #1	A [83]	3 [41]	4.8 {9.8}	160 {310}
Tripod #2	A [78]	3 [41]	1.6[b] {3.7}	44 {98}
Tripod #3	A [86]	3 [43]	<0.7[a]	0.29[b]
Tripod #4	A [80]	3 [39]	<0.7	0.46[b]

[a]When at least half of the sample results were below the limit of detection, the LOD was used in the mean calculation and reported as less than the resultant value.
[b]A third or less of the sample results contributing to the mean calculation were less than the limit of detection and were replaced by either the LOD /$\sqrt{2}$ or the LOD/2.

Table 8. Summary of TPM and select metals air concentrations during primer spray painting.

Work Activity or Sample Location	Sample Type [Mean Volume] (L)	Number of Samples [Task Duration Mean] (min)	Total Particulate Matter Gmean (mg/m^3)	Barium Gmean (µg/m^3)	Chromium Gmean (µg/m^3)	Copper Gmean (µg/m^3)	Strontium Gmean (µg/m^3)	Tin Gmean (µg/m^3)	Titanium Gmean (µg/m^3)
Tripod #1	A [83]	3 [41]	5.7	710	270	1.1[b]	3.5	<7	<2
Tripod #2	A [81]	3 [41]	2.0	240	90	<1	1.1	<7	<2
Tripod #3	A [87]	3 [43]	<0.7[a]	0.58	<3	<0.8	<0.2	<6	<2
Tripod #4	A [80]	3 [39]	<0.7	0.73[b]	<5	1.3[b]	<0.2	<7	<2

[a]When at least half of the sample results were below the limit of detection, the LOD was used in the mean calculation and reported as less than the resultant value.
[b]A third or less of the sample results contributing to the mean calculation were less than the limit of detection and were replaced by either the LOD /$\sqrt{2}$ or the LOD/2.

6 of 15 samples exceeded the United Kingdom-Health and Safety Executive (UK-HSE) workplace exposure limit (WEL) of 20 µg/m^3. The U.S. does not have a TRIG OEL at this time. The UK has a STEL of 70 µg/m^3, in addition to the WEL.[4,22] The topcoat paint consists mostly of HDI oligomers, with less than 1% HDI monomer, making pertinent the use of an OEL that encompasses exposure to both the monomeric and oligomeric forms of HDI like the UK-HSE WEL for TRIG. TRIG 8-hr TWAs in Table 4 show 50.9 µg/m^3 for sprayers and 7.29 µg/m^3 for hosemen.

Table 3 shows mean personal exposures for sprayers during topcoat application: 32.2 µg/m^3 HDI monomer (16.1 µg/m^3 NCO), 259 µg/m^3 HDI oligomer, and

Table 9. Summary of nitroethane air concentrations during primer spray painting.

Work Activity or Sample Location	Sample Type [Mean Volume] (L)	Number of Samples [Task Duration Mean] (min)	Nitroethane Gmean (ppm)
Tripod #1	A [2.0]	3 [41]	0.26[b]
Tripod #2	A [1.9]	2 [37]	0.38
Tripod #3	A [2.2]	3 [43]	<0.[a]
Tripod #4	A [2.0]	3 [39]	<0.2

[a]When at least half of the sample results were below the limit of detection, the LOD was used in the mean calculation and reported as less than the resultant value.
[b]A third or less of the sample results contributing to the mean calculation were less than the limit of detection and were replaced by either the LOD /$\sqrt{2}$ or the LOD/2.

Table 10. HDI monomer and HDI oligomer air concentrations during topcoat spray painting.

Sample Date	Work Activity or Sample Location	Sample Type	Sample Time (min.)	Air Sample Volume (m^3)	Hexamethylene Diisocyanate Monomer Mean (µg HDI/m^3)	Hexamethylene Diisocyanate Monomer Mean (µg NCO/m^3)	Hexamethylene Diisocyanate Oligomer Mean (µg NCO/m^3)	Total Reactive Isocyanate Group Mean (µg NCO/m^3)
7/23/2009	Hosemen A	P	102	0.1038	11.3	5.62	130	136
7/23/2009	Hosemen B	P	96	0.1006	4.48	2.24	44.3	46
7/23/2009	Sprayer A	P	95	0.0957	27.3	13.7	180	193
7/23/2009	Sprayer B	P	102	0.1037	29.1	14.6	198	212
7/23/2009	Tripod #1	A	105	0.1067	8.97	4.48	147	152
7/23/2009	Tripod #2	A	114	0.1160	2.59	1.29	36.5	37.8
8/4/2009	Hosemen A	P	83	0.0839	1.93	0.97	27.6	28.6
8/4/2009	Hosemen B	P	75	0.0755	<0.7	<0.4	<3	<3
8/4/2009	Sprayer A	P	95	0.0951	25.0	12.5	178	190
8/4/2009	Sprayer B	P	90	0.0917	31.5	15.7	279	295
8/4/2009	Tripod #1	A	93	0.0948	3.67	1.84	46.0	47.8
8/4/2009	Tripod #2	A	91	0.0934	14.2	7.11	119	126
8/4/2009	Tripod #3	A	97	0.0950	<0.5	<0.3	<2	<2
8/4/2009	Tripod #4	A	98	0.1015	<0.5	<0.3	<2	<2
4/13/2010	Hosemen A	P	66	0.0627	10.8	5.40	133	139
4/13/2010	Hosemen B	P	54	0.0546	8.21	4.10	153	157
4/13/2010	Sprayer A	P	78	0.0830	35.9	18.0	356	374
4/13/2010	Sprayer B	P	75	0.0754	49.6	24.8	484	509
4/13/2010	Tripod #1	A	135	0.1327	3.27	1.64	103	105
4/13/2010	Tripod #2	A	135	0.1316	3.83	1.91	82.1	84.0
4/13/2010	Tripod #3	A	135	0.1405	<0.3	<0.1	<0.3	<0.3
4/13/2010	Tripod #4	A	137	0.1344	<0.3	<0.1	<0.3	<0.3
4/13/2010	Tripod #1	A[a]	135	0.1346	11.0	5.49	142	148
4/13/2010	Tripod #2	A[a]	135	0.1374	11.2	5.58	139	145
4/13/2010	Tripod #3	A[a]	135	0.1344	<0.6	<0.3	<0.5	<0.5
4/13/2010	Tripod #4	A[a]	137	0.1391	<0.6	<0.3	<0.5	<0.5

[a]Impinger Sample.

Table 11. Summary of select VOC air concentrations during topcoat spray painting.

Work Activity or Sample Location	Sample Type [Mean Volume] (L)	Number of Samples [Task Duration Mean] (min)	1, 2, 4-Trimethyl-benzene Gmean (ppm)	1, 3, 5-Trimethyl-benzene Gmean (ppm)	2-Butoxy-ethanol Gmean (ppm)	Cumene Gmean (ppm)	Ethyl benzene Gmean (ppm)	MAK Gmean {95th %-ile} (ppm)	MEK Gmean {95th %-ile} (ppm)	MIBK Gmean {95th %-ile} (ppm)	N-Butyl Acetate Gmean {95th %-ile} (ppm)	Toluene Gmean (ppm)
Paint Sprayer	P [18]	6 [89]	0.09	2.0	0.07 [b]	<0.01	0.09	9.2 {15}	0.95 {4.1}	1.6 {6.5}	4.7 {7.1}	<0.02
As 8-hr TWA	P	6						1.7 {2.6}	0.17 {0.80}	0.30 {1.3}	0.86 {1.3}	
Paint Hosemen	P [18]	6 [79]	0.02	0.45	0.04 [b]	<0.01	0.02 [b]	1.8 {3.2}	0.88 {1.8}	1.2 {2.4}	0.94 {1.7}	<0.01
As 8-hr TWA	P	6						0.29 {0.51}	0.14 {0.26}	0.19 {0.35}	0.15 {0.32}	
Tripod #1	A [14]	6 [111]	0.03[b]	0.68	<0.04	<0.01	0.03 [b]	2.5	0.31	0.41	1.2	<0.01
Tripod #2	A [14]	6 [113]	0.03[b]	0.70	0.04 [b]	<0.01	0.02 [b]	2.6	0.05	0.12	1.3	<0.01
Tripod #3	A [15]	4 [116]	<0.01[a]	<0.01	<0.02	<0.01	<0.01	<0.02	<0.02	<0.01	<0.02	<0.01
Tripod #4	A [15]	4 [118]	<0.01	<0.01	<0.02	<0.01	<0.01	<0.02	0.03[b]	0.05[b]	<0.02	<0.01

[a]When at least half of the sample results were below the limit of detection, the LOD was used in the mean calculation and reported as less than the resultant value.
[b]A third or less of the sample results contributing to the mean calculation were less than the limit of detection and were replaced by either the LOD /$\sqrt{2}$ or the LOD/2.

Table 12. Summary of TPM and select metals air concentrations during topcoat spray painting.

Work Activity or Sample Location	Sample Type [Mean Volume] (L)	Number of Samples [Task Duration Mean] (min)	Total Particulate Matter Gmean (mg/m³)	Barium Gmean (μg/m³)	Chromium Gmean (μg/m³)	Copper Gmean (μg/m³)	Strontium Gmean (μg/m³)	Tin Gmean (μg/m³)	Titanium Gmean (μg/m³)
Tripod #1	A [226]	3 [111]	3.0	<0.2	<1	<0.3	<0.1	<2	39
Tripod #2	A [217]	3 [113]	3.4	<0.1	<1	0.30[b]	<0.07	<2	45
Tripod #3	A [232]	3 [115]	<0.2[a]	<0.1	<1	<0.3	<0.07	<2	<0.7
Tripod #4	A [241]	3 [118]	<0.2	<0.1	<1	<0.3	<0.07	<2	<0.7

[a]When at least half of the sample results were below the limit of detection, the LOD was used in the mean calculation and reported as less than the resultant value.
[b]A third or less of the sample results contributing to the mean calculation were less than the limit of detection and were replaced by either the LOD /$\sqrt{2}$ or the LOD/2.

276 μg/m^3 TRIG. For hosemen the means were 3.99 μg/m^3 HDI monomer (2.06 μg/m^3 NCO), 42.7 μg/m^3 HDI oligomer, and 45.2 μg/m^3 TRIG. Means were formed from the individual results in Table 10. For the two tripods downwind from the aircraft, monomer, NCO, and oligomer area concentrations were 4.76, 2.38, and 88.7 μg/m^3 for tripod #1 and 5.21, 2.60, and 70.9 μg/m^3 for tripod #2, respectively. Results for upwind tripods were below the LODs. During one survey, impinger samples were collected alongside the filters for comparison. Tripod #1 had 11.0 μg/m^3 (impinger) vs. 3.27 μg/m^3 (filter) for HDI monomer and 148 μg/m^3 vs. 103 μg/m^3 for HDI oligomer. Tripod #2 showed 11.2 μg/m^3 (impinger) vs. 3.83 μg/m^3 (filter) for HDI monomer and 139 μg/m^3 vs. 82.1 μg/m^3 for HDI oligomer.

The VOC results summarized in Table 11 indicate only MAK, MEK, MIBK, and n-butyl acetate as clearly above LODs, with PBZ sample means 9.2, 0.95, 1.6, and 4.7 ppm, respectively, for sprayers and 1.8, 0.88, 1.2, and 0.94 ppm, for hosemen. While 8-hr TWAs for MEK and MIBK were reported for individual artisans earlier in the Wipe-down section, sprayers as a job category had MAK and n-butyl acetate 8-hr TWAs of 1.7 and 0.86 ppm, respectively, with 0.29 ppm and 0.15 ppm for hosemen. All personal samples were below the OELs (MAK: REL = 100 ppm, PEL = 100 ppm and n-butyl acetate: REL = 150 ppm, PEL = 150 ppm), and topcoat painting was the only phase with concentrations above the LOD. Area means for MAK, MEK, MIBK and n-butyl acetate (Table 11) followed the pattern where upwind samples were near or below the LOD. Of the metals in Table 12, only titanium was detected at notable levels, with means 39 μg/m^3 on tripod #1 and 45 μg/m^3 on tripod #2.

Discussion

The imbalance in the ventilation system—the supply rate substantially exceeds the exhaust rate—creates large circulations, additional turbulence, fugitive emissions, and wastes energy (especially due to the large, sometimes tempered, bay air volume). As fugitive emissions occurred along the length of this bay under positive pressure, the supply rate dropped to the bay midplane flow rate, which then diminished to the exhaust rate (Table 2).

Another way to think about the excess capacity is to calculate a normalized velocity, by dividing the volumetric flow through the supply filter, 94.4 m^3/s, by the bay cross-sectional area, 137 m^2, resulting in 0.691 m/s (136 fpm). This conceptual velocity must be distinguished from the measured supply filter face velocity of 0.798 m/s (157 fpm). In comparing 0.691 m/s (136 fpm) to the work-zone design velocity of 0.508 m/s (100 fpm), the excess is clear. Also, this normalized velocity was higher than the velocity measured midway between supply and exhaust, because the midplane flow was influenced also by the exhaust flow.

While the supply fans were clearly overspecified, exhaust filter bank resistance determines to some extent whether exhaust can match supply, and keeping filters at the lower end of their maintenance life, i.e., filter pressure drop, would reduce flow resistance. Lowering, then, the filter replacement benchmark from a Δp of 622 Pa (2.5 in. water) to 498 Pa (2.0 in. water) would be a good operating policy change toward system balance. A layer of inexpensive felt-like material (not as designed) was observed on top of the pre-filter, i.e., a pre-pre-filter or "pre-layer," added to protect downstream filter material from sanding particulate and paint droplet loading, thereby reducing filter replacement frequency (cost). However, the intended exhaust velocity and airflow pattern in the bay cannot be achieved with extra flow blockage, especially when pre-layer loading disrupts the uniform face velocity field. Also, energy costs increase as exhaust fans work harder to deliver the required flow.

The ventilation system inadequately controlled exposures in this operation, without additional reduction provided by respiratory protection. OSHA regards this large facility as a "spray area," which does not have a specific air velocity requirement, unlike a "spray booth," which requires 100 fpm (0.508 m/s). With mean Cr[VI] concentrations during primer application 100 times greater for sprayers than the OSHA PEL concentration, control measures are clearly needed. Because balanced ventilation adhering to 29 CFR 1910.94 (100 fpm) would still need supplementation with appropriate respirators, the level of protection engineering controls must deliver is best defined by the aircraft painting section of the OSHA hexavalent chromium standard. In other words, controlling Cr[VI] concentrations below 25 μg/m^3, as an 8-hr TWA, is probably a more applicable performance metric than maintaining an air velocity of 100 fpm (0.508 m/s). That being said, a balanced flow of 0.508 m/s (100 fpm) has not been tried for this operation, and this condition might be more effective than the trials presented here.

Hosemen wearing full-face APRs (APF of 50) rather than airline respirators during primer application causes concern. The resulting Cr[VI] exposure is below the REL, but not by a comfortable margin of safety, as the highest individual and 95th percentile 8-hr TWAs were 18 and 16 μg/m^3, respectively. Applying the APF of 50 results in 0.36 and 0.32 μg/m^3 or 36% and 32% of the REL (1 μg/m^3). Use of full face airline respirators by the hosemen would relieve this concern because the APF is 200 times greater.

Variation in exposure among individual workers highlights the importance of control strategies additional to ventilation. Table 4 shows Worker 007 having the highest exposures in whatever job he performed. The study team observed that this individualworked harder and longer than most of his cohort. During wipedown, his process exposures were more than ten times the mean, and this extreme excursion is likely due to his subtask within wipedown of actually reaching into the barrel of solvent to obtain soaked rags for himself and the other wiper. As a work practice control, tongs should be used, or another means of extracting the rags at a distance from the solvent surface, and the container should be closed immediately. That only one of two workers on one of three sample dates had this high exposure suggests variation in material handling technique.

As monomeric HDI represents less than 1% of the NCO content of HDI paint products, oligomeric HDI is the primary source of isocyanate expsosure. Only the airborne route was documented in this study. However, workers had limited exposed skin during paint application, as they wore Tyveks, gloves, and either full-face respirators or air-supplied hoods.

Conclusion and recommendations

The respiratory protection program should remain in place to protect aircraft painting artisans from significant exposures to MEK and MIBK. Additionally, moving the hosemen from full-face APRs into air-supplied hoods during primer application would provide enhanced protection against Cr[VI] exposure. Hosemen should be trained to avoid being downwind of the sprayers or the spray plume by staying behind the sprayers, opposite the spray direction. During topcoat painting, the possibility of isocyanate exposure exceeding the UK-HSE STEL of 0.070 mg/m^3 further mandates respirator use.

While existing ventilation practices combined with appropriate use of supplied-air hoods and full-face APRs adequately controlled exposures, air pollution permit compliance, energy footprint, and possibly exposure control could be improved by balancing the supply flow rate to the exhaust flow rate. The exhaust already provides the correct volumetric flow rate to produce a velocity of approximately 0.508 m/s (100 fpm) in the bay cross section, depending on exhaust filter pressure drop.

Replacing the exhaust pre-layer more frequently and lowering the filter replacement Δp from 622 Pa (2.5 in. water) to 498 Pa (2.0 in. water) would be good steps toward system balance. Lower capacity supply fans or lower RPM operation are system balancing techniques worth considering.

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Disclaimer

The findings and conclusions in this article have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.

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