



## In-Depth Survey Report

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### **Experimental and Numerical Research on the Performance of Exposure Control Measures for Aircraft Painting Operations, Part III**

Naval Base Coronado, Fleet Readiness Center Southwest, San Diego, California

Marine Corps Air Station Cherry Point, Havelock, North Carolina

Joint Base Lewis-McChord, Tacoma, Washington

Sioux City Air National Guard Base, Sioux City, Iowa

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**Division of Applied Research and Technology**

**Engineering and Physical Hazards Branch**

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**DEPARTMENT OF HEALTH AND HUMAN SERVICES**

**Centers for Disease Control and Prevention**

**National Institute for Occupational Safety and Health**



**Sites Surveyed:** Fleet Readiness Center Southwest  
Naval Base Coronado  
Building 465

Joint Base Lewis-McChord  
Hangar building 1160

Marine Corps Air Station Cherry Point

Iowa Air National Guard Painting Facility

**NAICS Code:** 491110

**Survey Dates:** March 13-16, 2011,  
December 17-19, 2012  
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## **Abstract**

Aircraft painting can be a hazardous process. Ventilation and other protective measures are necessary to prevent exposure of workers to toxic chemicals, such as isocyanates and chromates, which are contained in the paints. In 2008, researchers from CDC/NIOSH began work on a collaborative project with the U.S. Navy to evaluate ventilation in a Navy aircraft painting hangar at Naval Base Coronado as part of the Navy Environmental Sustainability Development to Integration (NESDI) program. Computational fluid dynamics (CFD) modeling was used in conjunction with on-site tracer gas experiments to assess air flow conditions in the hangar and to investigate design alternatives. The project determined that a reduction in delivered airflow might not increase contaminant exposure. This counterintuitive finding resulted in an interest in expanding the project to encompass more sites around the U.S. with support from the Environmental Security Technology Certification Program (ESTCP). Three additional sites were chosen for study inclusion: Marine Corps Air Station Cherry Point, Sioux City Air National Guard Base, and Joint Base Lewis-McChord. A four-step process of site assessment, CFD analysis, tracer gas validation, and exposure testing was planned for the assessment of each site. However, work on this ESTCP hangar ventilation project was officially halted in February, 2014, and remains unfinished. The four-step assessment protocol has been completed for the Naval Base Coronado site. The other three sites remain at various stages of the site assessment process. Initial site visits suggest these locations are good candidates for additional investigation. Continuing research and the implementation of more efficient ventilation systems at these locations could yield significant benefits in the form of energy cost savings and better worker protection. This report provides a summary of results from the site visits and discusses areas of potential future research.

## **Introduction**

### **Background for Control Technology Studies**

The National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC), is the primary Federal agency engaged in occupational safety and health research. Located in the Department of Health and Human Services, it was established by the Occupational Safety and Health Act of 1970. This legislation mandated NIOSH to conduct a number of research and education programs separate from the standard setting and enforcement functions carried out by the Occupational Safety and Health Administration (OSHA) in the Department of Labor. An important area of NIOSH research deals with methods for controlling occupational exposure to potential chemical and physical hazards. The Engineering and Physical Hazards Branch (EPHB) of the Division of Applied Research and Technology has been given the lead within NIOSH to study the engineering aspects of health hazard prevention and control.

Since 1976, EPHB has conducted a number of assessments of health hazard control technology on the basis of industry, common industrial process, and/or specific control techniques. Examples of these completed studies include the foundry industry; various chemical manufacturing or processing operations; spray painting; and the recirculation of exhaust air. The objectives of each of these studies have been to document and evaluate effective control techniques for potential health hazards in the industry or process of interest and to create a more general awareness of the need for or availability of an effective system of hazard control measures.

These studies involve a number of steps or phases. Initially, a series of walk-through surveys is conducted to select plants or processes with effective and potentially transferable control concepts. Next, in-depth surveys are conducted to determine the control parameters and the effectiveness of these controls. The reports from these in-depth surveys are then used as a basis for preparing technical reports and journal articles on effective hazard control measures. Ultimately, the information from these research activities builds the data base of publicly available information on hazard control techniques for use by health professionals who are responsible for preventing occupational illness and injury.

This particular study was conducted to gain a better understanding of worker exposure to the hazardous chemicals contained in paints and to propose methods of control that will protect the workers from these hazards. Controlling or eliminating exposures to occupational hazards is the fundamental method of

protecting workers. Traditionally, a hierarchy of controls will be used as a means of determining how to implement feasible and effective control solutions for this study. One representation of this hierarchy can be summarized as follows:

- Elimination
- Substitution
- Engineering Controls (e.g., ventilation)
- Administrative Controls (e.g., reduced work schedules)
- Personal Protective Equipment (e.g., respirators)

In this project, the effectiveness and efficiency of ventilation systems in several aircraft refinishing facilities were evaluated, along with the appropriateness of the existing respiratory protection program. As the paint used to coat airplanes contains hazardous chemicals, exposures must be assessed and minimized.

### **Background for this Study**

Workers in aircraft painting facilities are exposed to a variety of hazardous chemicals. Aircraft paints commonly contain hexavalent chromium and various organic solvents which have been linked to nasal cancer [NIOSH 2013] and central nervous system depression [Levy B.S. and D.H. Wegman 1988], respectively. They also contain isocyanates, which are one of the leading chemical causes of occupational asthma in the US and many other industrialized countries. Effects of isocyanate exposure include powerful irritation to the mucous membranes of the eyes, and gastrointestinal and respiratory tracts, which can lead to eye tearing, nasal congestion, dry/sore throat, cold-like symptoms, shortness of breath, wheezing and chest tightness. The most serious cases of exposure are due to chemical sensitization to isocyanates and can result in severe asthma attacks which are sometimes fatal [NIOSH 1996, 2006].

Clearly, worker exposure control is of utmost importance in aircraft painting operations. Proper ventilation of painting facilities is necessary for achieving this end. Ventilation systems are ideally used to efficiently control the concentration of the paint contaminants below regulatory and advisory occupational exposure limits (OELs), while also limiting releases to the outdoor environment. These limits include OSHA Permissible Exposure Limits (PELs), American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) and NIOSH Recommended Exposure Limits (RELs)

OSHA standard, 29 CFR 1910.94 – *Ventilation*, requires that paint booths maintain an air velocity in the booth cross-section of 100 fpm (0.508 m/s) [CFR a]. This

design criterion is based on empirical data gathered in the 1950s. At that time, the first goal of painting ventilation was explosion protection. However, the explosion risks, along with other worker health risks, have been reduced in more recent years by modern paint application methods. These include the use of high-volume low-pressure (HVLP) spray guns, which significantly reduce paint overspray, and the airline respirators worn by the workers when applying primer and paint to control exposure to volatile organic compounds (VOCs), isocyanates, chromates and other chemical stressors. Furthermore, high-VOC paints are no longer used. For some perspective, the ACGIH recommends only 50 fpm (0.254 m/s) for large vehicle paint booths [ACGIH 2010]. A recent OSHA interpretation of 29 CFR 1910.94 acknowledges that aircraft painting hangars are classified as “spray areas” rather than spray booths. OSHA provides no flow-rate guidelines for spray areas, so this classification effectively exempts aircraft painting hangars from the 100 fpm (0.508 m/s) target of 29 CFR 1910.94. Because large painting hangars are not bound by the 100 fpm (0.508 m/s) regulation, it is permissible to explore the concept of reduction of delivered airflow (thus reducing ventilation costs), in facilities that were designed for 100 fpm (0.508 m/s), as long as worker safety is not compromised and outdoor releases comply with facility operating permits. However, the OSHA PELs apply to painting processes, irrespective of the applicability of the spray booth ventilation specification. This set of circumstances calls for a better understanding of what ventilation rate, as a speed of air, is most effective.

In 2008, researchers from CDC/NIOSH began work with Naval Facilities Engineering Service Center (NAVFAC ESC) engineers and Navy Medical Center San Diego (NMCS) industrial hygienists on a collaborative project to evaluate ventilation in a Navy aircraft painting hangar as part of the Navy Environmental Sustainability Development to Integration (NESDI) program. The goal of this project was to keep worker exposures to air contaminants, including hexavalent chromium (Cr[VI]), hexamethylene diisocyanate (HDI), methyl isobutyl ketone (MIBK), and others, at or below concentrations that meet regulatory health and safety standards, while limiting the environmental footprint, e.g., energy use and operational costs of paint hangar ventilation. The NESDI study was conducted in a hangar at Naval Base Coronado (NBC) in San Diego, CA. NBC operates two buildings, numbered 464 and 465, which contain a total of eight painting bays designed for the refinishing of Navy F/A-18C/D Hornet strike fighter aircraft. Each of these bays costs between \$4000 and \$5000 in electricity per month; buildings 464 and 465 normally accrue over \$400,000 per year in electric costs. Over 90% of that electricity is used by the supply and exhaust fans, which are designed to meet the 100 fpm (5.08 m/s) airflow OSHA standard.

Initial field observations of the ventilation in Bay 6 at NBC found that the ventilation system was unbalanced, in that it provided more supply than exhaust, which led to an inefficient and complicated flow pattern. Computational Fluid Dynamics (CFD) simulations suggested that correcting this imbalance could improve the efficiency of contaminant removal while decreasing the energy requirements of the supply blowers [NIOSH 2011]. Continuing evaluations of the ventilation system were based on a combination of field studies and CFD simulations conducted in 2009-2011. CFD and tracer gas monitoring results showed that decreasing the ventilation airflow from 100 fpm to 75 fpm (0.508 m/s to 0.381 m/s) would also decrease, on average, the chemical concentrations near workers. At the higher velocity, CFD simulations suggested that turbulent airflows around the aircraft and the workers would promote mixing of air contaminants in the breathing zone and increase exposure, rather than directing those contaminants efficiently toward the exhaust. Reducing the flow rate to 75 fpm (0.381 m/s) decreased turbulence and slightly increased the overall effectiveness of local contaminant removal.

The finding that worker protection could be maintained, or possibly improved, while also reducing the energy requirements of painting ventilation, led to interest from the Department of Defense (DOD) Environmental Security Technology Certification Program (ESTCP) in expanding the project to include other aircraft painting operations. Site visits took place at Naval Base Coronado in San Diego, California, Cherry Point Marine Corps Air Station in Havelock, North Carolina, Sioux City Air National Guard Base in Sioux City, Iowa, and Joint Base Lewis-McChord in Tacoma, Washington. Due to project cancellation, air monitoring was performed only at Coronado, though ventilation measurements were accomplished at all sites. CFD modeling was performed at Coronado and Cherry Point. Project acceptance by base command, industrial hygienists, bioenvironmental engineers, and energy managers was achieved at all sites.

### **Results of Previous Studies**

In early 2008, preliminary CFD simulations were performed to model the relationship between air velocity and worker exposure levels in a Navy aircraft painting hangar. Air velocities of 100 and 50 fpm (0.508 and 0.254 m/s) were compared for roughly approximate aircraft, worker, and source representations. The results showed only a small increase in exposure at 50 vs 100 fpm (0.254 vs 0.508 m/s) [NIOSH 2011]. With promising test-of-concept results in hand, NAVFAC initiated a project that received funding from the Navy Energy Security Demonstration Initiative (NESDI). A walk-through survey was conducted June 16-19, 2009, in a hangar at NASNI. Personal and area air sampling (for Cr[VI], HDI,

and any other contaminants found on the material safety data sheets) was performed, and hangar dimensions, geometric details, and ventilation boundary conditions were collected to set-up high-fidelity CFD simulations. Next, the ventilation system's ability to control air contaminants was evaluated through comprehensive personal and area air sampling of all solvent, primer, and topcoat constituents, on July 22 and August 3, 2009 and April 13, 2010. Three visits were needed to monitor three painting processes (typically spaced days or weeks apart), which provided statistical characterization of exposures. CFD simulations were performed and validated based on the ventilation settings available at the time of the 2009-2010 field studies. An initial tracer gas study was conducted April 12 and 14, 2010 to evaluate the performance of the hangar ventilation system under a number of supply/exhaust ventilation settings.

All air velocities ( $V_{CS}$ ) stated in this report concerning NASNI, whether measured or simulated using CFD, are based on the cross-sectional area ( $A_{CS}$ ) of the hangar, using the formula

$$V_{CS} = \frac{A}{A_{CS}}V$$

where A and V are the face area and face velocity of the supply or exhaust openings. This approach was used to facilitate comparison of exhaust and supply velocities in terms of balance and to make comparisons with spray operations, ventilation regulations and guidance, which are expressed as velocities rather than volumetric flow rates.

The results from the 2009 and 2010 ventilation measurements, air sampling, tracer gas studies, and CFD simulations are available in a NIOSH report [NIOSH 2011], which indicated that:

1. The system was unbalanced with supply at 136 fpm (0.691 m/s) and exhaust at 99.0 fpm (0.503 m/s). Balancing the air supply and exhaust could improve exposure control, consistent with standard ventilation practice.
2. From tracer gas measurements, 3/4 of the normal supply and exhaust rates provided the lowest concentrations, when compared to full flow: supply = 136 fpm (0.691 m/s); exhaust = 99.0 fpm (0.503 m/s) and half-flow: supply = 73.4 fpm (0.373 m/s); exhaust = 49.0 (0.249 m/s). 3/4-flow was a supply velocity of 102 fpm (0.518 m/s) and an exhaust velocity of 68.9 fpm (0.350 m/s). However, the only statistically significant difference among ventilation settings was between 3/4-flow and half-flow, which had the

lowest and highest concentrations, respectively, at measurement locations that had been observed during painting.

3. CFD simulations showed a large increase in contaminant concentration at typical worker locations when the supply rate exceeded the exhaust rate, compared to when the supply and exhaust rates were equal. "Balancing," as in item 1, means maintaining a very small negative pressure, perhaps approximately -0.05 in. water (-0.0934 mmHg).
4. Based on personal sampling of workers during typical aircraft refinishing operations, the ventilation system did not adequately control worker exposure to below OELs and required the use of respiratory protection, as was already being done.
5. Because all materials measured in the aircraft refinishing process were less than 1% of any LEL, explosion from chemical concentrations was not an issue.
6. Additional tracer gas and CFD simulations were needed to fill the following information gaps:
  - a. Tracer gas studies were performed only on the system in the unbalanced state. Additional tracer studies are needed under balanced conditions.
  - b. CFD simulations were performed under balanced ventilation boundary conditions and under a hypothetical positive pressure scenario, rather than the measured unbalanced boundary conditions. Additional CFD simulations are needed that use the measured supply and exhaust velocities.

Thus, in March 2011, NIOSH researchers conducted another tracer gas evaluation of the Navy aircraft hangar under four additional ventilation settings, each of which provided negative pressure conditions. There were a total of four supply air blowers and four exhaust air fans located on the roof that served supply and exhaust plenums on opposite walls of the hangar. Each ventilation setting corresponded to a supply and exhaust fan combination. For example, a setting of 3/4-supply and 4/4-exhaust indicates that three of the four supply fans were operating, while all four exhaust fans were operating. The four ventilation settings (and velocities in fpm [m/s]) were as follows:

Setting 1: 1/4 supply (43.3 [0.220]) and 2/4 exhaust (49 [0.249])  
Setting 2: 2/4 supply (73 [0.371]) and 3/4 exhaust (65 [0.330])  
Setting 3: 2/4 supply (73 [0.371]) and 4/4 exhaust (99 [0.503])  
Setting 4: 3/4 supply (108 [0.549]) and 4/4 exhaust (99 [0.503])

Tracer gas experiments were conducted over two nights, while normal hangar operations continued during the daytime. Sulfur hexafluoride (SF<sub>6</sub>) was released continuously and measured at five observed worker locations, using MIRAN SappHRe portable real-time infrared monitors (Thermo Scientific). Several 15-minute trials were run, in a randomized factorial design, with ventilation settings the independent variable and time-averaged SF<sub>6</sub> concentration the dependent variable [NIOSH 2012]. Results from each night were reported separately because the source and measurement locations and exhaust filter pressure drop could not be held precisely constant between nights.

On night one, only settings 1 and 4 were tested. Results from night one indicated that setting 1 had statistically significantly higher mean tracer gas concentrations than setting 4 (1742 vs. 249.7 ppb). On night two, tracer gas testing was conducted for settings 2, 3, and 4. Results from night two indicate that mean tracer gas concentrations were statistically significantly higher for setting 2 than for settings 3 and 4 (1526 vs. 353.7 and 1193 ppb, respectively). There were no statistically significant differences between mean tracer gas concentrations of settings 3 and 4.

The studies occurred on two consecutive nights, because the process of setting up equipment, altering system configurations, repeating trials (with time between trials to reach a stable condition), and taking down equipment (to make the bay ready for the next day's painting operation) took several hours, even for testing only two or three air velocities. Also, some system configurations required additional consultation with the HVAC technicians, who were not available during the second shift. Care was taken to not make system changes that risked interference with normal operations, which began at 0600 hrs. While the source, measurement locations and settings were duplicated as closely as possible on the second night, some variability probably existed in the placement of the MIRAN instrument intakes and the source placement. Thus, the data from each night were analyzed separately. Even with the environmental variabilities, sufficient data were collected to make comparisons between tracer concentrations resulting from the flow fields created by Setting 4 (3/4 supply and 4/4 exhaust) and by Settings 1, 2, and 3.

Based on these tracer gas tests and CFD simulations, along with the results of the original study [NIOSH 2011], the following conclusions and recommendations were made:

### Conclusions

1. The first round of tracer gas experiments (reported in NIOSH [2011] and referred to in the current report as Tracer Experiments I) and the CFD simulations of those conditions both indicated that the 3/4-flow (3 out of 4 supply and 3 out of 4 exhaust fans operating) resulted in lower exposures than either the half- or full-flows.
2. The existing equipment that serves Bay 6 cannot deliver a flow that is balanced. It should be modified to deliver a flow where the supply rate and exhaust rate are nearly equal, with the exhaust rate slightly higher to maintain a small negative gauge pressure for the purpose of containment. With only four supply fans and four exhaust fans, along with the VFD controller on the exhaust fans that seemed unresponsive to supply changes, the system could not be adjusted with enough precision to achieve a balanced state. In other words, while operating 4 supply fans and 4 exhaust fans resulted in a positive pressure imbalance, turning off one of the supply fans resulted in a negative pressure imbalance (too much exhaust).
3. Using air velocities that were achievable during tracer experiments on the existing ventilation system, it was found (during Tracer Experiments II) that increasing the average velocity in the hangar from 43.3 to 85.3 fpm (0.220 to 0.433 m/s) lowered the spatial average across the monitoring locations (from 1742 to 249.7 ppb). Increasing the average velocity from 66.1 to 75.3 fpm (0.336 to 0.383 m/s) lowered the average concentration (from 1526 to 353.7 ppb), while increasing the average velocity from 75.3 to 85.3 fpm (0.383 to 0.433 m/s) increased the average concentration (from 353.7 to 1193 ppb). Thus, Tracer Experiments I and II both support the concept that a moderate velocity (nominally 75 fpm [0.38 m/s]) is not less protective than the higher velocities that were studied.

### Recommendations

1. Achieving balanced flow (perhaps  $-0.04 \pm 0.002$  in. water gauge [ $-0.0747 \pm 0.00374$  mmHg]), if prevention of fugitive emissions to the environment is desired) through capital improvements at the site should be considered, based on ventilation standard practice [ACGIH 2013].
2. After balancing or any other system modifications, follow-up tracer gas testing, process air sampling, and velocity sampling should be done to verify ventilation improvements.
3. Correcting the pressure imbalance should include replacing appropriate exhaust filters, pre-filters, or pre-layers during moderate or high filter loading to reduce pressure drop and save energy. The filter pressure drop value at which filters will be replaced should be recommended by NAVFAC

ESC and the filter manufacturer. Balancing the system and improving system maintenance will improve operational efficiency.

4. Measurements of the concentration of flammable or explosive materials in air should be made directly in the exhaust stream to demonstrate compliance with NFPA 33: "Standard for Spray Application Using Flammable or Combustible Materials 2011," if any significant changes are made to the existing ventilation system or settings. The current study did not include this specific measurement because no flammable materials were used in the tracer studies and because previous area air sampling during aircraft painting under the existing ventilation indicated that no explosion hazard was present.
5. In addition to correcting existing paint finishing hangar ventilation systems, innovative designs should be explored using CFD. Reducing the hangar cross-sectional area to more closely fit each aircraft size and maintain a desired velocity at a lower flow rate, directing supply air to the work zones more precisely, and bringing exhaust terminals closer to contaminant sources are examples of possible paths to consider that may reduce worker exposures, while also reducing associated energy costs.
6. Any changes in ventilation operation should include provisions to prevent possible safety hazards (e.g., doors blowing open or closed) created by changes in hangar pressure.

## **Description of Facilities**

In addition to the Naval Base Coronado site that was evaluated during the previous NESDI study, three new sites were chosen for inclusion in the ESTCP project: Marine Corps Air Station Cherry Point, Sioux City Air National Guard Base, and Joint Base Lewis-McChord. When evaluating candidate sites, primary evaluation factors included condition of the hangar, type of ventilation system, adjustability of ventilation system, ability to monitor energy use, and coordination depth with facility personnel. Study inclusion required that a site be willing to participate, that it had the ability to achieve the ventilation criterion of a reasonably balanced and uniform 100 fpm (0.508 m/s), and that it would be modifiable in the sense of reducing the characteristic air velocity by approximately 25 fpm. While velocities will vary significantly at various locations within a hangar, a practical criterion was the absence of backflow in the zone that includes the work area.

### **Marine Corps Air Station Cherry Point**

Marine Corps Air Station Cherry Point is home to the 2<sup>nd</sup> Marine Aircraft Wing. Fleet Readiness Center East (FRC East) operates two aircraft painting hangars at

Cherry Point: one cross-draft hangar with one large bay and one downdraft hangar which can be broken up into 4 smaller bays. These hangars commonly service MH-53, AH-1, V-22, and CH-46 rotary-wing aircraft, as well as the AV-8 Harrier fixed-wing aircraft. Based on discussions with FRC East and a site visit it was decided that only the cross draft paint hangar would be evaluated during this study, as modern paint hangars are typically designed to the cross draft specification.

During the initial walkthrough of the cross flow hangar (Figure 1), the team observed that only 2 out of 4 supply fans and 6 out of 8 exhaust fans were operational. Maintenance and repair of the system was discussed with site engineers, and funding for the extensive repairs needed was identified as a large issue.

The process to sand and paint an aircraft takes approximately 4 days using 2 production shifts per day. The only process observed during the site visit was sanding of an MH-53 airframe. Side doors remained open to provide more outside air to cool the hangar while workers were inside; however, it is unclear whether these doors remain open during the painting process. Across the doorways a significant pressure differential was observed, with the bay negative with respect to the outside. Airflow measurements were obtained at both the supply and exhaust walls. The supply filters arrayed on the wall appeared to be clean and were labeled as having a minimum efficiency rating value (MERV) of 9, which is often used in commercial and hospital buildings. The MERV index was created by the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE). Measured velocity across the supply filter wall ranged from 34-140 fpm (0.173-0.711 m/s) with an average of 60 fpm (0.305 m/s). A number of filter-mounting brackets were not closed properly, and there were also several instances where the filter was folded back on itself, leaving large gaps between the filter and the door frame, resulting in the higher velocities. The exhaust wall filter was significantly coated with paint overspray, and measurements there showed zero airflow on one side of the bay. On the other side, the exhaust filter system had a low velocity of around 40-70 fpm (0.203-0.356 m/s). Replacement of the filter is based on static pressure loss across the whole door filter system. As a result, the filter layer directly exposed to paint becomes significantly obstructed and does not function as designed – creating a dead zone on the lower side of the exhaust door. During any future analysis of the hangar it will be important for these filters to be relatively clean.



Figure 1. View of the MCAS Cherry Point Helicopter Painting Hangar.

### **Sioux City Air National Guard Base**

The Sioux Gateway Airport hosts the 185<sup>th</sup> Air Refueling Wing of the Iowa Air National Guard. It is also home to the Iowa Air National Guard Paint Facility. This facility handles the painting of a variety of fixed and rotary-wing aircraft, such as the A-10 Thunderbolt, the F-15 Eagle, the F-16 Fighting Falcon, and the UH-60 Blackhawk. The facility has painted more than 500 aircraft since it opened in 2000. The paint facility consists of two hangars, designated Bay 3 and Bay 5 (Figure 2).

#### Bay 3 Paint Hangar

- Dimensions (paint bay inside hangar building): L = 69' (21.0 m), W = 53' (16.2 m), H (middle) = 22' (6.71 m), H (sides) = 16' (4.88 m).
- 2 Supply fans
- 2 Exhaust fans
- Preliminary airflow measurements inside the bay were 77-97 fpm (0.391-0.493 m/s)
- Measurements at the filters were 161-191 fpm (0.818-0.970 m/s), high due to acceleration around filter support grid.

### Bay 5 Paint Hangar

- Dimensions: (paint bay inside hangar building): L = 76'-79' (23.2–24.1 m), with staggered, sliding, supply filter panels, W = 64' (19.5 m), H-middle = 25' (7.62 m), H-sides = 17' (5.18 m).
- 2 supply fans
- 3 Exhaust fans
- Preliminary airflow measurements inside the bay were 55-83 fpm (0.279-0.422 m/s)
- Measurements at the filters: supply ~112 fpm (0.569 m/s), exhaust ~78 fpm (0.396 m/s), perhaps at a paint-clogged area.

### Paint schedule:

- Friday place Aircraft in bay; Monday no work; Tuesday work start with completion expected on Thursday or Friday.

### Paints used:

- AKZO NOBEL Flat Grey ECM-F-6118, 6270,6176,6251, 6320, 6375, 7038 (black)
- Notable potentially hazardous materials: hexamethylene isocyanate monomer, oligomer, and polymer.
- AKZO NOBEL Epoxy primer (2 hr) 10P8-11; Epoxy Primer High Solids 10P20-13
- Notable potentially hazardous material: hexavalent chromium.
- CARC paints: Sherwin Williams Black F93B506; Green F93G505; paint catalyst V93V502
- Notable potentially hazardous materials: 1-Methyl-2-Pyrrolidone, carbon black.
- Paint gun type: high-volume, low-pressure (HVLP).

### Energy and Ventilation Systems:

- There is a facility-wide energy meter. Installing sub meters for the air handling units would assist painting related energy assessments.
- Outside air is heated in the air handling unit using natural gas and then distributed to the larger building envelope that contains Bays 3 and 5. Supply air enters Bay 3 through the open sliding door opposite the exhaust wall filter bank. Supply air enters Bay 5 through ceiling slot diffusers at the large sliding door through which aircraft enter. Covering the opposite wall is the exhaust filter bank.

- During periods when the AHUs are not moving air through and maintaining temperature in the facility, there are additional blower heaters to keep temperatures stable for paint curing.



Figure 2. Interior of Bay 5 of the Iowa Air National Guard Paint Facility.

### **Joint Base Lewis-McChord**

The US Air Force's McChord Air Force Base and the US Army's Fort Lewis were merged in 2010 to form Joint Base Lewis-McChord (JBLM). The base hosts more than 40,000 members of the military and 15,000 civilian workers, and serves as home to I Corps and the 62<sup>nd</sup> Airlift Wing (62 AW). The 62<sup>nd</sup> flies the Boeing C-17 Globemaster III transport aircraft in support of combat and humanitarian airlift operations around the world.

McChord AFB C-17 Painting Hangar

Hangar building 1160 on JBLM, designated a Corrosion Control Facility (CCF), was chosen as a study site. The main production in this facility is paint finishing of the C-17 Globemasters of 62 AW. The building and ventilation system appear to have been designed and built for painting the C-17, specifically. The rear walls are angled and the rear door is positioned to fit closely the swept wings and the nose of this aircraft. The ventilation system design is a hybrid of ceiling supply units and end-wall exhaust hoods. The 182 supply openings are arrayed in a pattern that focuses supply air on the aircraft. The eight exhaust hoods are positioned near the aircraft—about 25 feet from the leading edges of the wings and nose (Figures 3 and 4). The ventilation system is modern and utilizes variable frequency drive (VFD) controllers. However, the current system has only a small number of settings that can be selected by the operators.

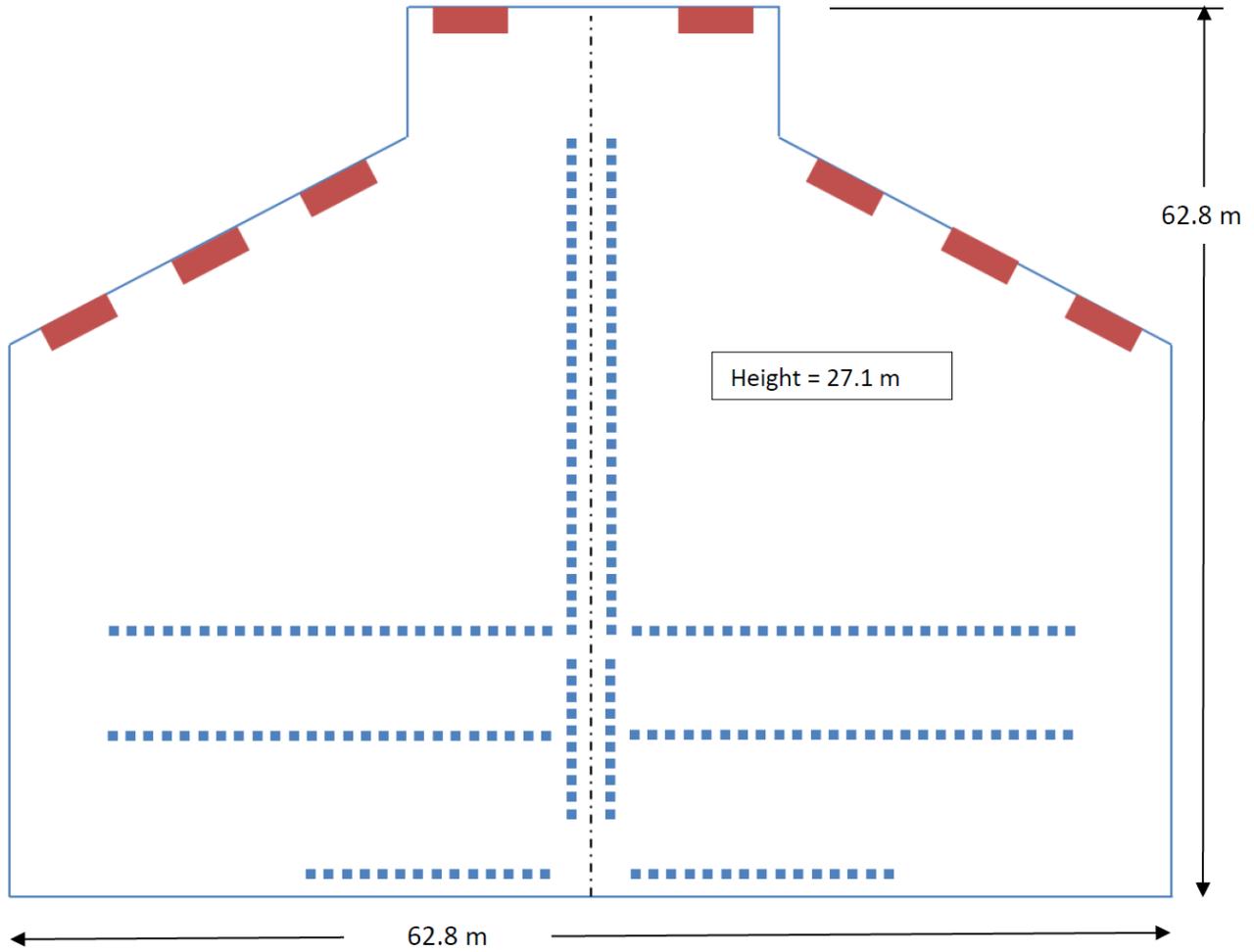


Figure 3. JBLM hangar Building 1160 ventilation system schematic (top view). Ceiling-mounted supply openings are drawn in blue, while the end-wall exhaust hoods are drawn in red.



Figure 4. Photo of the JBLM corrosion control hangar. The eight large exhaust hoods are visible along the back wall, and the small square supply inlets can be seen on the ceiling (circled in red).

#### Fort Lewis Helicopter Painting Hangar

A second possible study site at JBLM was also visited: a helicopter painting facility which regularly handles the refinishing of UH-60 Blackhawk and OH-58 Kiowa aircraft. The hangar bay is 61 feet (18.6 m) long, 30 feet (9.14 m) wide, and 20 feet (6.10 m) high. Air is supplied and exhausted through floor-to-ceiling filter banks, embedded in columns, at each of the four corners of the hangar. The two columns on either side of the hangar bay door serve as exhaust, while the two columns on the opposite side of the hangar serve as supply (see Figures 5 and 6)

During the site visit, NIOSH researchers were able to observe an annual ventilation certification test conducted by an Army industrial hygienist. A smoke candle was used to observe the flow pattern in the hangar. The test clearly showed effective directional flow from the supply end to the exhaust end, with relatively little turbulence.



Figure 5. The Fort Lewis helicopter painting hangar. The exhaust filter columns can be seen on either side of the hangar door.

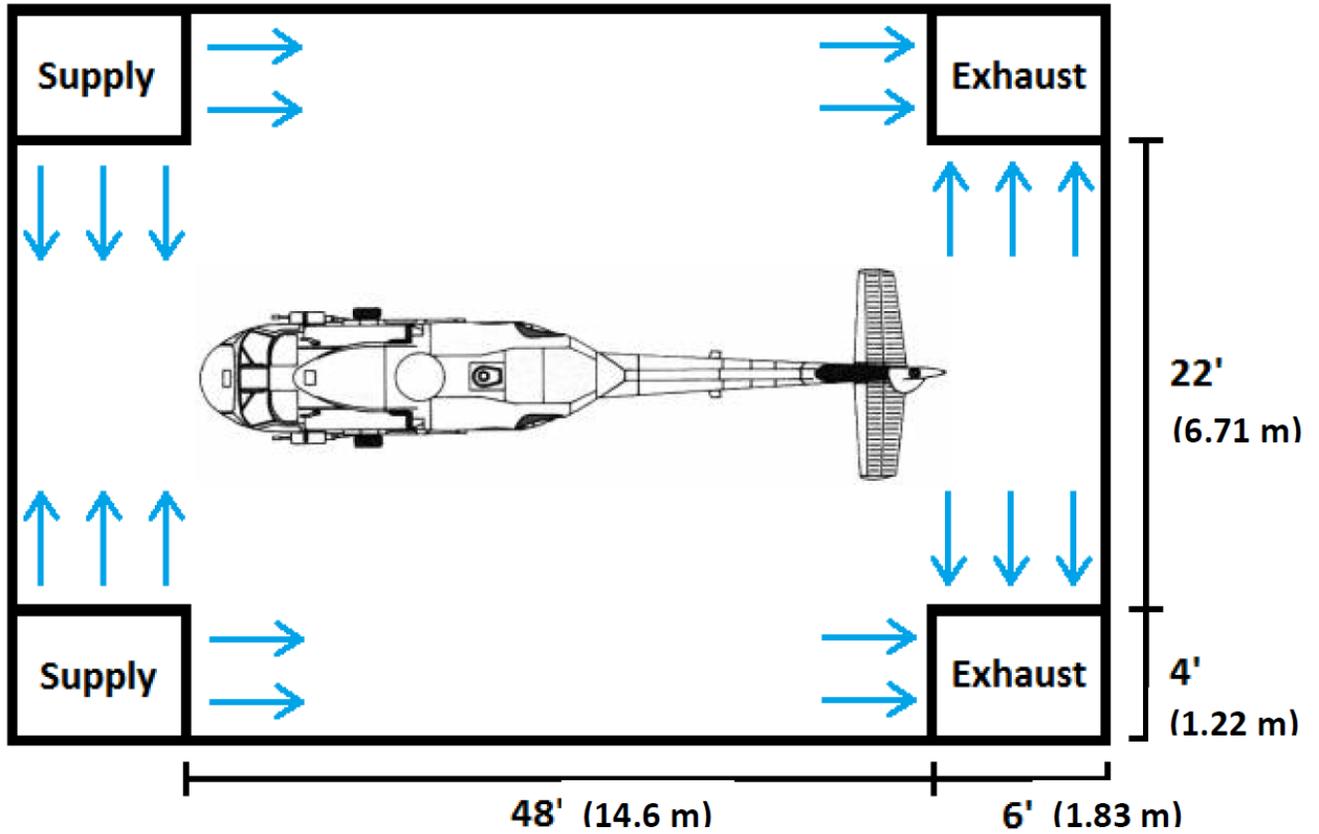


Figure 6. Overhead schematic of the Fort Lewis helicopter painting hangar.

## **Naval Base Coronado**

Tracer gas and CFD simulations were conducted in a hangar designed for the refinishing of Navy F/A-18C/D Hornet strike fighter aircraft, an activity managed by the Naval Air System Command (NAVAIR), Fleet Readiness Center Southwest (FRCSW), Naval Base Coronado (NBC), San Diego, CA. FRCSW is located on the north end of Coronado Island. NBC is recognized by a congressional resolution as the birthplace of naval aviation. It is homeport to the aircraft carriers, U.S.S. Carl Vinson and U.S.S. Ronald Reagan. The base has more than 230 stationed aircraft. With the carriers in port, the working population of the station is nearly 35,000 military and civilian personnel.

The refinishing of whole aircraft is performed in Buildings 464 and 465, each of which contain two hangars. Each hangar is composed of two bays. Thus, Building 464 houses Bays 1,2,3,4 and Building 465 contains Bays 5,6,7,8, respectively. This study occurred in Bay 6 (shown in Figure 7), where approximately twenty aircraft are painted per year. Refinishing of strike fighter aircraft takes place in one bay of a large two-bay hangar. 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. An accordion door separates the two bays when only one bay is required. To accommodate larger aircraft (such as the C-2), the supply walls of both bays are opened like a gate, the accordion door is retracted and the two bays become one big hangar, served by two identical ventilation systems.

Bay 6, in Building 465 of FRCSW, is served by four supply blowers and four exhaust fans, with exhaust fan speed served by VFD controllers. Two of the supply blowers are equipped with steam heating elements. The design functions of this ventilation system are to maintain a safe and healthy work environment, to control and contain sanding particulate and paint overspray, and to maintain the temperature required for painting operations. Figures 8 and 9 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.



Figure 7. Photo of the refinish of an F-18 aircraft in Bay 6 of Building 465 at Naval Base Coronado.

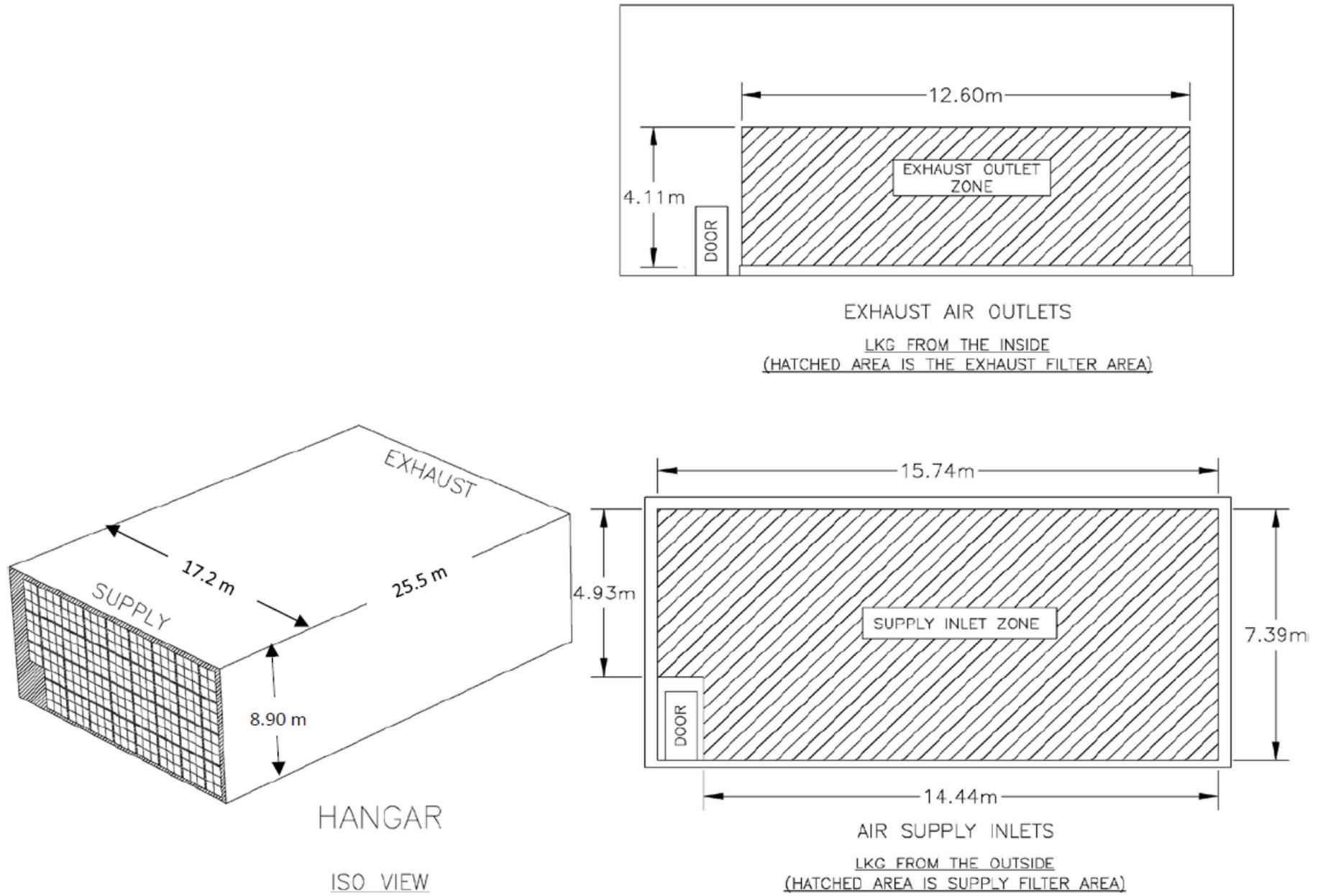


Figure 8. Drawing showing the filter area of the aircraft painting bay.

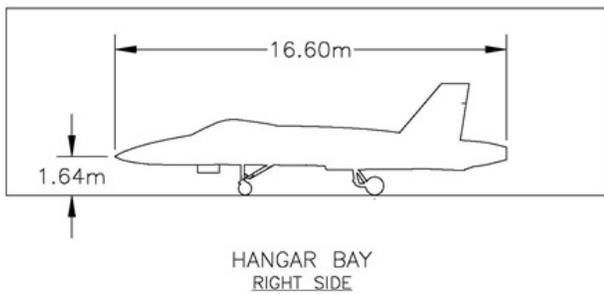
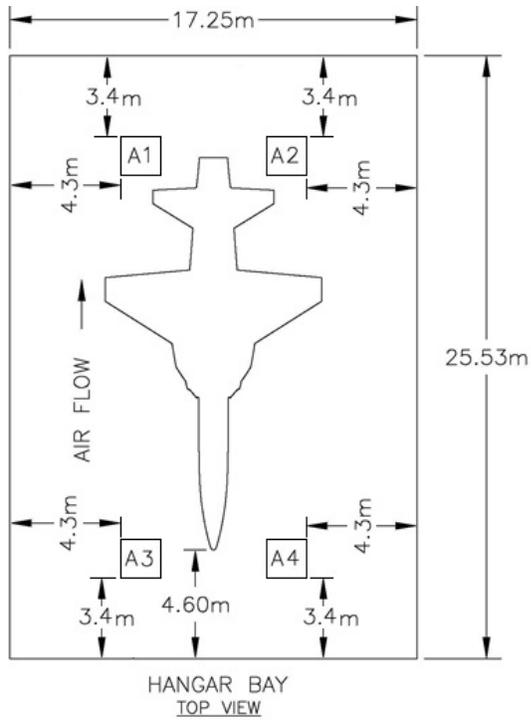


Figure 9. Drawing showing painting bay, F/A-18C/D Hornet, and area sample locations (A1 – A4).

## **Methodology**

The ESTCP project utilized a four-step analysis process for any given site, with one site visit at each step. The first site visit would be to assess the site for appropriateness. The site would be assessed based on a number of criteria, such as condition of the hangar, type of ventilation system, adjustability of ventilation system, ability to monitor energy use, and coordination depth with facility personnel. Study inclusion required that a site be willing to participate, that it had the ability to achieve the ventilation criterion of approximately 100 fpm (0.508 m/s), as an average across the hangar cross-section adjacent and upwind of the aircraft, and that it would be modifiable in the sense of reducing the characteristic air velocity by approximately 25 fpm (0.127 m). Sites would be rejected if they were slated for renovation, if they displayed poor operation and maintenance, if they used water-wash filtration systems, or if they were otherwise not representative of DOD painting hangars in general. Alternatively, a site with well-functioning ventilation at approximately 75 fpm (0.381 m/s) that could be brought to 100 fpm (0.508 m/s) would also be a good candidate. Airflow measurements for all sites were made using a Shortridge Instruments Airdata Multimeter ADM-860C (with a VelGrid probe) that had been factory calibrated within the past year.

If the site was deemed appropriate for further study, a second site visit would be made in order to assess energy usage on the site and characterize the hangar for CFD simulation. This would include measuring the dimensions of the hangar, gathering information on the ventilation configuration, and obtaining flow rate measurements. If possible, baseline exposure monitoring would also be conducted during standard painting operations. This site visit would be followed by a period of extensive CFD modeling of the existing system to assess the effects of alternative ventilation configurations and lower flow rates.

After CFD modeling, a third site visit would take place to conduct tracer gas testing in the hangar. A tracer gas, such as sulfur hexafluoride, would be released in the hangar-- with no people inside-- at the normal supply/exhaust flow rate and at lower flow rates, and concentrations would be measured at various locations. Numerical simulation data would then be compared to the tracer gas results in order to assess the accuracy of CFD predictions. Finally, a fourth site visit would be made for the purpose of assessing worker exposure at reduced flow rate configurations. Tracer studies being conducted without the effect of workers on flow patterns and CFD simulations being computed with stationary rather than moving workers are limitations of the methodology that highlight the importance of real process, worker exposure monitoring.

This four-step process of site assessment, CFD analysis, tracer gas validation, and exposure testing has been successfully completed for the Naval Base Coronado site. The other three sites remain at various stages of the process. Table 1 summarizes the steps that were completed at each visited site.

Table 1. Project completion status by site

SITE	WALKTHROUGH	VENTILATION MEASUREMENTS	EXPOSURE SAMPLING	TRACER STUDIES	CFD ANALYSIS	FOLLOWUP EXPOSURE SAMPLING
MACS Cherry Point	X	X			X	
Sioux City ANGB	X	X				
McChord AFB	X	X				
Ft. Lewis	X	X				
Naval Base Coronado	X	X	X	X	X	X

### CFD Methods

CFD is a numerical method that solves the system of equations that describe fluid behavior by using a computational grid. CFD is essential in this study due to its ability to model and anticipate the results of a wide range of ventilation modifications prior to potentially costly implementation that is generally impractical on a trial basis. Performance information is more useful and cost-effective before modifications are made. CFD modeling has been conducted for only two of the four ESTCP sites: Naval Base Coronado and MCAS Cherry Point.

#### Naval Base Coronado

All total particulate and hexavalent chromium samples for primer coating were collected on pre-weighed PVC filters and analyzed by NIOSH Methods 0500 [NIOSH 1994a] and 7605 [NIOSH 1994b], respectively, or OSHA Method 215 [OSHA 1998]. Sampling by OSHA methods was performed for CrVI and for isocyanates, because Navy industrial hygienists collaborating on the study were interested in comparing results of their sampling protocol (which is to use the OSHA methods) to the NIOSH results. The initial F-18 painting samples were analyzed for isocyanates using treated glass fiber filters with NIOSH Method 5525 [NIOSH 1994c], while the post-modification painting samples were analyzed using this method and also treated glass fiber filters with OSHA Method 42 [OSHA 1983], the ASSET EZ4-NCO dry-sampler tube [Halpenny and Brown 2013], and impingers with NIOSH Method 5525.

CFD simulations for the NBC hangar were performed for a variety of ventilation settings representing both balanced and unbalanced flow rates. Balanced flow rates of 43.3, 65, 75, 86.6, 100, and 108 fpm (0.220, 0.330, 0.381, 0.440, 0.508, and 0.549 m/s) were modeled along with unbalanced flow rates of 73/49, 108/65, and 139/99 fpm (0.706/0.503 m/s) supply/exhaust velocities. The unbalanced rates were representative of conditions which would result from turning off certain fans in the existing ventilation equipment to reduce air flow, while the balanced conditions would require more extensive modifications to equalize supply and exhaust rates.

In the CFD model, a contaminant with the physical properties of methyl isobutyl ketone (MIBK) was emitted, in both vapor and liquid droplet forms, from the hand areas of two simulated workers placed at commonly observed spraying locations, at a flow rate specified by the spray gun manufacturer. For the model, the MIBK vapor density was 4.23 kg/m<sup>3</sup>, about 3.5 times denser than air, and its viscosity was 6.70 x 10<sup>-6</sup> kg/m-s, which is less than half as viscous as air. The MIBK droplets were given their documented density of 800 kg/m<sup>3</sup> (specific gravity 0.8) and a diameter of 10 µm. The overall fluid properties were allowed to vary according to the fraction of contaminant in the contaminant-air mixture that composed "air" in the hangar. Turbulence was modeled using the form of the Reynolds-averaged Navier–Stokes (RANS) k-ε model that incorporates renormalization group theory (RNG) [Wilcox, 1998a]. With turbulence intensity and length scale used as boundary conditions, intensity was set at 10 percent, and length scale was set at one meter for the large filter area and one tenth of a meter for the sprayers. Between grid points, variables such as contaminant concentration were interpolated using the first-order upwind scheme.

A nine-million cell mesh file of an F/A-18C/D Hornet was provided by NAVFAC ESC, working with the User Productivity Enhancement, Technology Transfer and Training (PETTT) Program. The mesh was generated using Gridgen software (Pointwise, Inc., Fort Worth TX). The geometry for CFD modeling is shown in Figure 10. NIOSH provided solid models representing workers in Tyvek<sup>®</sup> suits (Figure 11), using Solidworks (Dassault Systemes SolidWorks Corp., Concord MA). The geometry and mesh were imported by NIOSH into the CFD solver and post-processor, Fluent 6.3 (ANSYS, Inc., Canonsburg PA). Remaining model inputs were based on building and ventilation measurements taken during the site visits. The solution utilized a RANS turbulence model and was steady-state. Solution instability was addressed by setting the under-relaxation parameters for pressure correction, velocity, and turbulence very low, at 0.2 or even 0.1. For this reason, a second order discretization was not attempted, and the reported results come from the first order upwind scheme [Patankar 1980].

Validation of the full-domain simulation was pursued through comparison with experimental air velocity and contaminant concentration fields. The boundary conditions included the most common position of wing flaps, elevators, and rudders, based on NIOSH observations of the painting process. The CFD simulations were performed at NIOSH using Fluent 6.3.

The CFD simulations were each run for 38,000 iterations. Convergence levels were achieved such that the normalized residuals (measures of relative error in the equations that govern fluid motion) were below  $10^{-4}$ , except in the case of species ( $<10^{-5}$ ) and eddy dissipation rate (slightly greater than  $10^{-4}$ ). The "stiffness" or resistance to decreases in error of the eddy dissipation rate equation is typical of indoor airflow CFD simulations. The species concentration never reached a clearly asymptotic steady-state but was observed to achieve stationarity, with regular fluctuations within a consistent, limited range. The constant and large number of iterations (38,000) was used as the ultimate convergence requirement to ensure that comparisons among the three flow conditions were free of convergence errors, or that at least the convergence error was very small and similar for all flow conditions, which would still allow a reasonably accurate comparison.

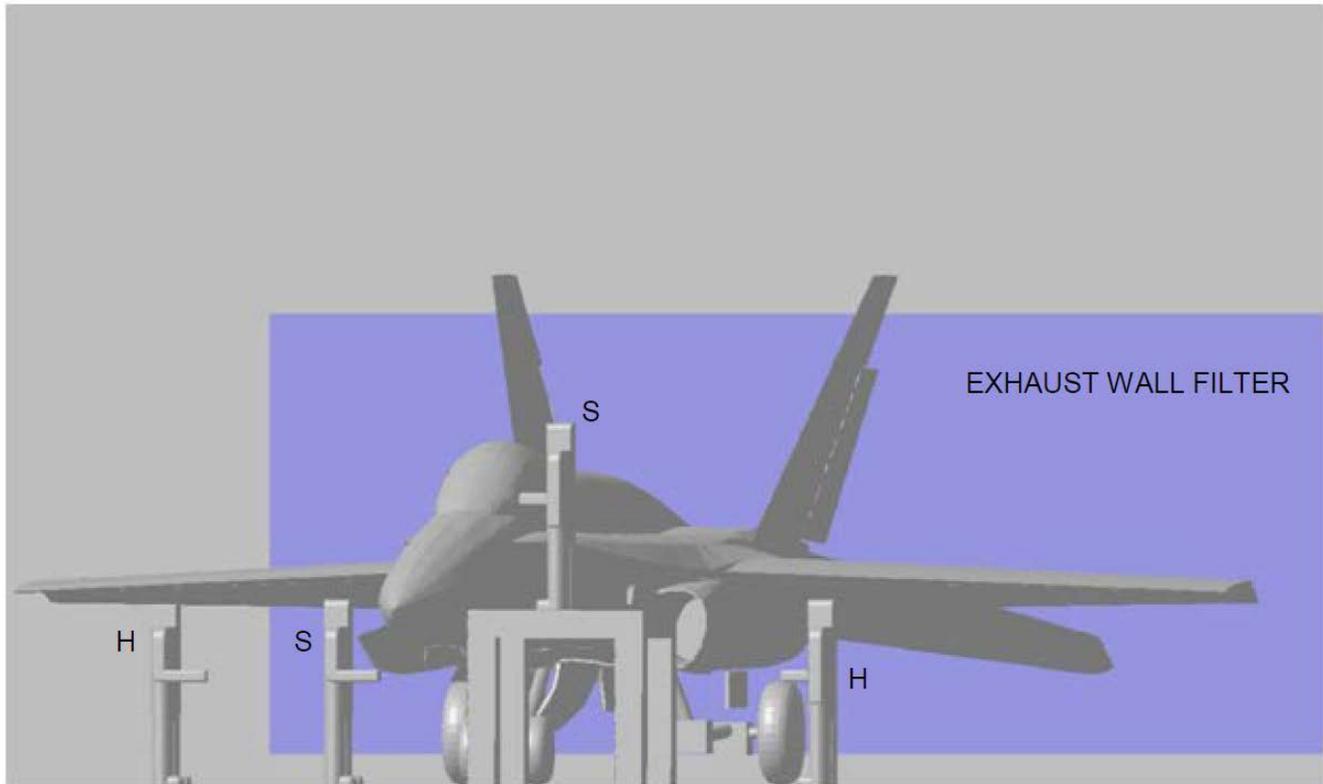


Figure 10. Geometry of workers, exhaust wall filter, and F/A-18C/D Aircraft. Hosemen (H) are further from the aircraft and further downwind than sprayers. The contaminant source is located at the end of the sprayers' (S) right arms. One sprayer is on a scaffold.

#### Marine Corps Air Station Cherry Point

The modeling for MCAS Cherry Point was conducted in collaboration with researchers at the University of Kansas, with similar methods to those used by NIOSH for the NBC site. The Kansas team was brought in to provide an independent CFD perspective. Measurements made during a NIOSH site visit were used to construct a three-dimensional mesh of the hangar (Figure 12). Geometry of an MH-53 helicopter, the most frequently-painted aircraft type, was provided by MCAS engineers in the form of an ANSYS Design Modeler file. This file was developed into a computational mesh after inserting the geometry for five workers (Figures 12 and 13). The worker geometry is identical to what was used in the NBC simulations and represents a person of average height wearing a Tyvek<sup>®</sup> suit, as might be expected during regular painting operations. Three of the workers were made to represent sprayers, and two were made to represent helpers. The

arms of the three sprayers served as contaminant injection points, with an injection velocity of 10 m/s, based on spray gun specifications. The simulated workers did not move.

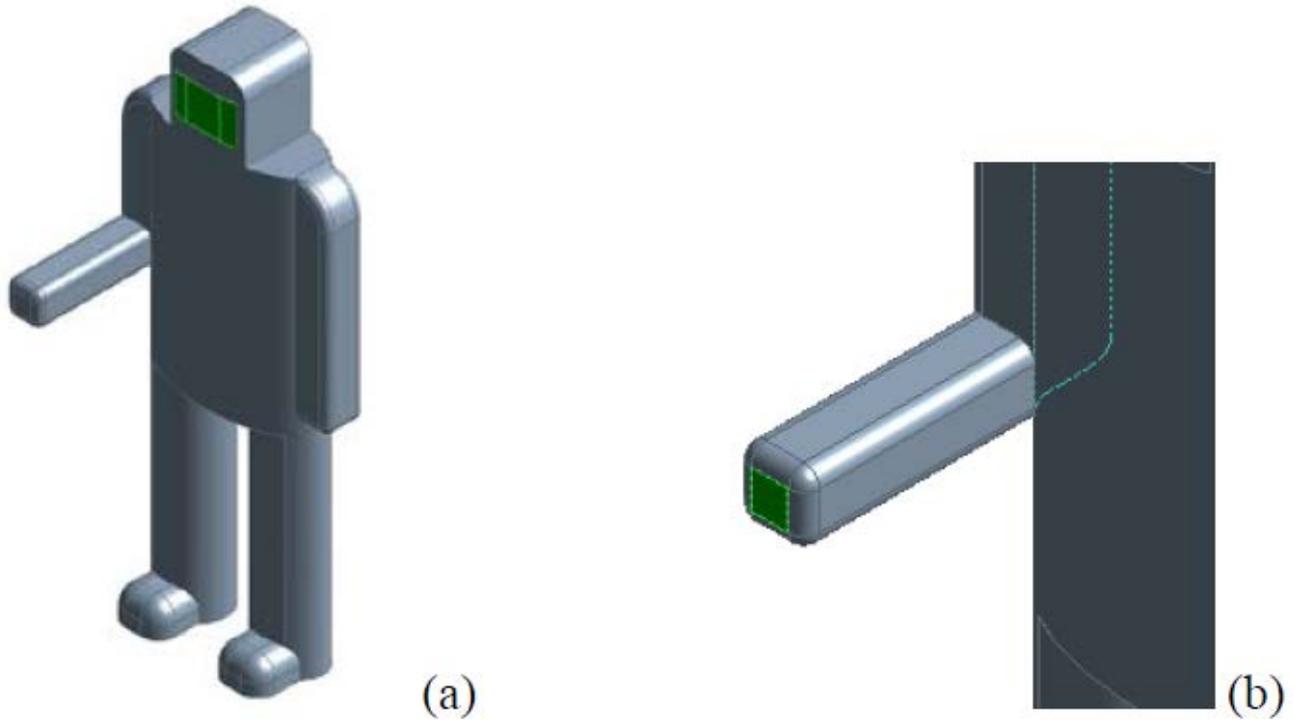


Figure 11. (a) Full worker geometry, with face region highlighted. (b) Close-up of worker arm, with injection region highlighted.

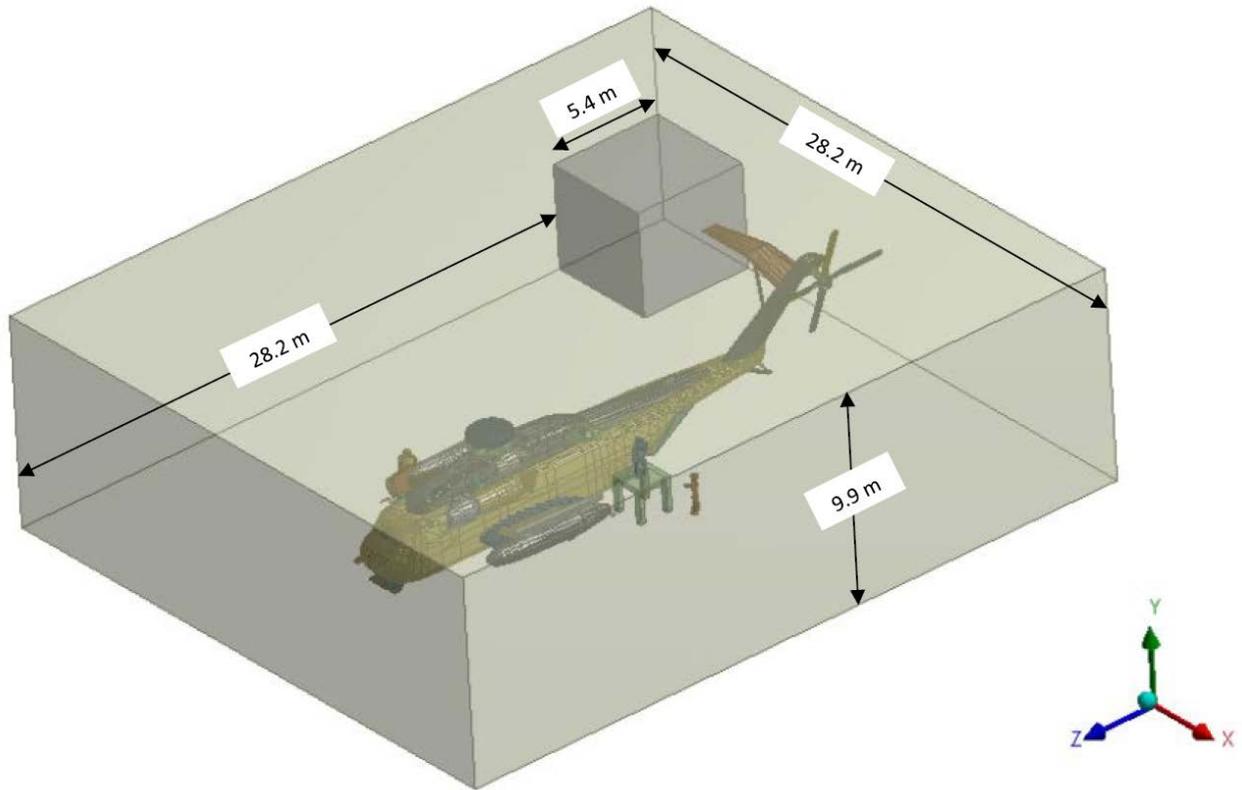


Figure 12. Overview of MCAS Cherry Point Hangar Geometry

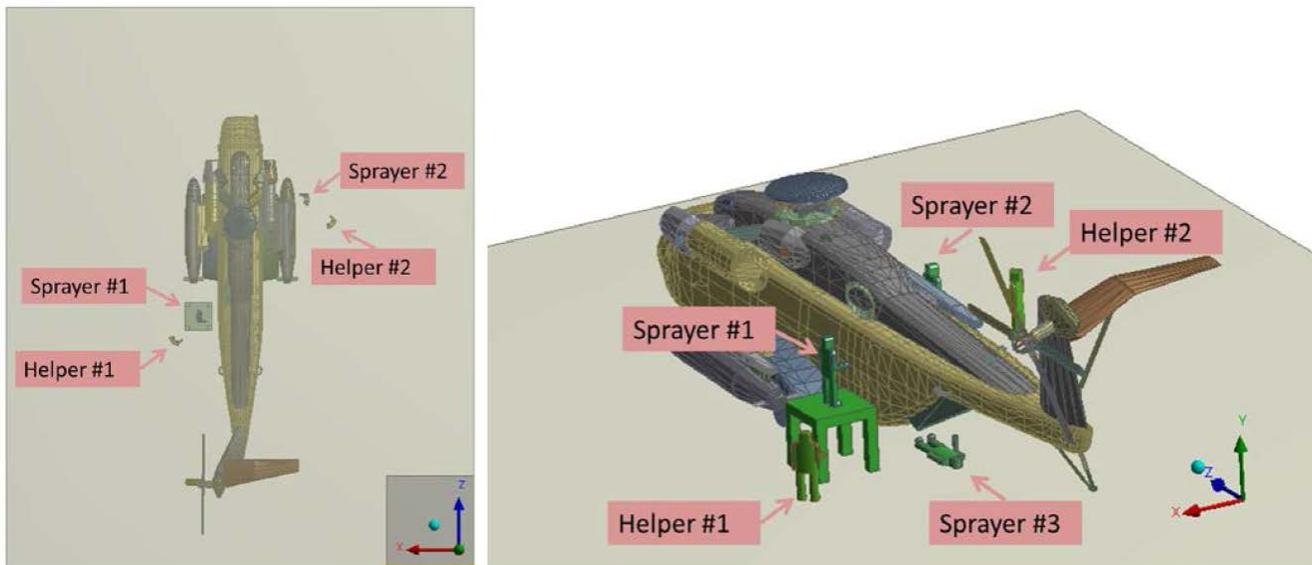


Figure 13. Overhead and isometric views of worker positions relative to MH-53 helicopter geometry.

## **Results**

### **Naval Base Coronado**

Figures 14 and 15 summarize the results of CFD modeling for the NBC hangar, by showing the steady-state converged concentrations at observed worker locations and the arithmetic and geometric means over these locations. Examination of Figure 14 shows that the two least effective rates are 43.3 fpm (0.220 m/s) and the unbalanced 108 fpm (0.549 m/s) supply – 65.0 fpm (0.330 m/s) exhaust scenario. These rank first and second highest, respectively, by concentration level at four out of five locations in the solution field. The main pattern is also seen in the spatial average of the entire hangar at a level of the typical standing breathing zone (BZ height) and in the mean of the probe locations. While the BZ height calculation reflects the rate of removal from the whole space, the specific probe locations were chosen based on observations of where workers are located during the process and includes perceived worst case zones.

Figure 14 also shows the similarity of 65.0 fpm (0.330 m/s) and 86.6 fpm (0.440 m/s), especially at critical worker locations. In the difficult to ventilate area under the landing gear hatch, the 65.0 (0.330) and 86.6 fpm (0.440 m/s) concentrations

are 402 and 401 ppm. While the location geometric mean for 65.0 fpm of 532 ppm is somewhat higher than the 505 ppm for 86.6 fpm (0.440 m/s), 65.0 fpm (0.330 m/s) has lower concentrations than 86.6 fpm (0.440 m/s) at the two sprayer locations (which represent the highest exposures): 738 ppm and 2212 ppm vs. 857 ppm and 2279 ppm. The lowest concentrations occurred for the balanced 108 fpm (0.549 m/s) rate, for all locations other than portside hoseman, which had the lowest concentration at the 108/65.0 fpm (0.549/0.330 m/s) supply/exhaust condition.

Additional CFD simulations (Figure 15) using what is generally considered a more accurate turbulence model (RNG k-epsilon) and a much more time-consuming convergence criterion ( $10^{-4}$ ) show that 75 fpm (0.381 m/s) produces lower concentrations than 100 fpm (0.508 m/s) at the locations where the concentrations are highest. Although the CFD results are closer to being log-normally distributed than to being normally distributed, Figure 15 includes the arithmetic mean because the geometric mean was possibly overly influenced by the concentrations that were very close to zero. The RNG k-epsilon model results show concentrations generally lower than the previous simulations that used the standard k-epsilon turbulence model and a higher convergence error tolerance. A reasonable interpretation is that the RNG k-epsilon model and the lower convergence error tolerance resolved the steep, near-source concentration gradients more precisely, with less numerical diffusion. Therefore, the second set of simulations was at least as accurate as the first set, if not more so.

Considering again the unbalanced 108/65.0 fpm (0.549/0.330 m/s) scenario, it is worth noting that this relatively ineffective and inefficient situation is meant to reflect the imbalance measured in Bay 6, although at lower velocities. The measured supply velocity was 136 fpm (0.691 m/s) and the exhaust 99.0 fpm (0.503 m/s), taken as the average of traverses across the filter face before and after painting. Lower velocities were chosen for the CFD model because 136 fpm (0.691 m/s) exceeds the current Navy design velocity of 100 fpm (0.508 m/s) by enough to seem impractical for this project.

The inability of the exhaust to keep pace with the supply is due to the pressure drop across the exhaust wall filter bank. As the filters get loaded with overspray, the flow resistance increases, resulting in a decrease in overall flow and a channeling of exhaust flow through the cleaner areas of the filter wall, further reducing the ventilation effectiveness where concentrations are highest. The pressure observed during this flow measurement was 1.67 in. water (3.12 mmHg) gauge. The filter material is not replaced until the pressure drop reaches 2.5 in.

water (4.67 mmHg) gauge. The clean filter bank, without any accumulated material, has a pressure drop of approximately 0.50 in. water (0.934 mmHg) gauge. NAVFAC ESC engineers have observed Bay 6 as being balanced or under slight negative pressure with respect to the ambient, presumably when the pressure drop is at the very low side of the replacement cycle or when no filter pre-layer is present.

In the simulated dispersion of 10µm MIBK droplets shown by Figure 16, the effect of supply-exhaust balancing is evident in the narrower, tighter pattern of particle paths. The top image (unbalanced) shows a more diffuse jumble of paths, while in the bottom image (balanced), the paths are more convective, although still not linear. In the figure, red particles are launched by the port-side sprayer and green by the starboard-side sprayer. The simulations did not include droplet evaporation.

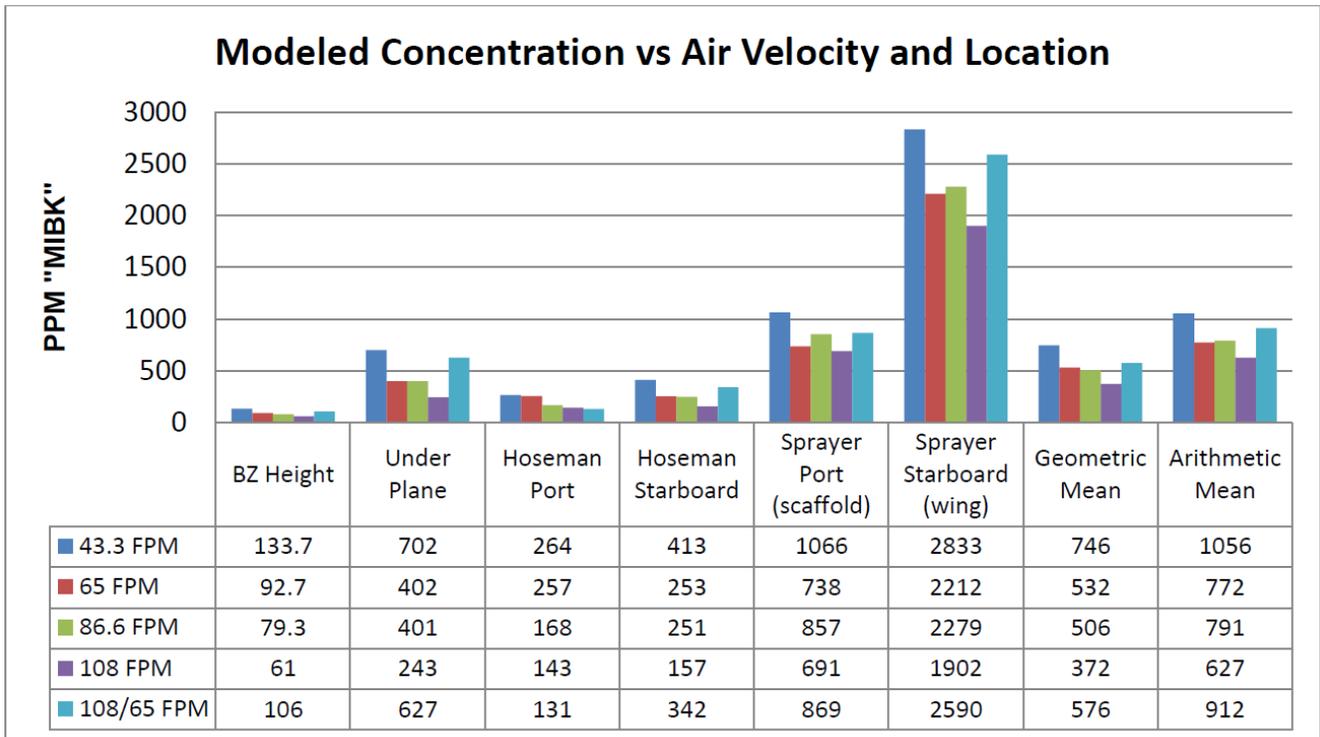


Figure 14. Concentrations of a simulated gas with the properties of MIBK calculated using CFD, for various air velocities and observed worker locations. 108/65 fpm (0.549/0.330 m/s) indicates the unbalanced condition of 108 fpm (0.549 m/s) of supply and 65 fpm (0.330 m/s) of exhaust.

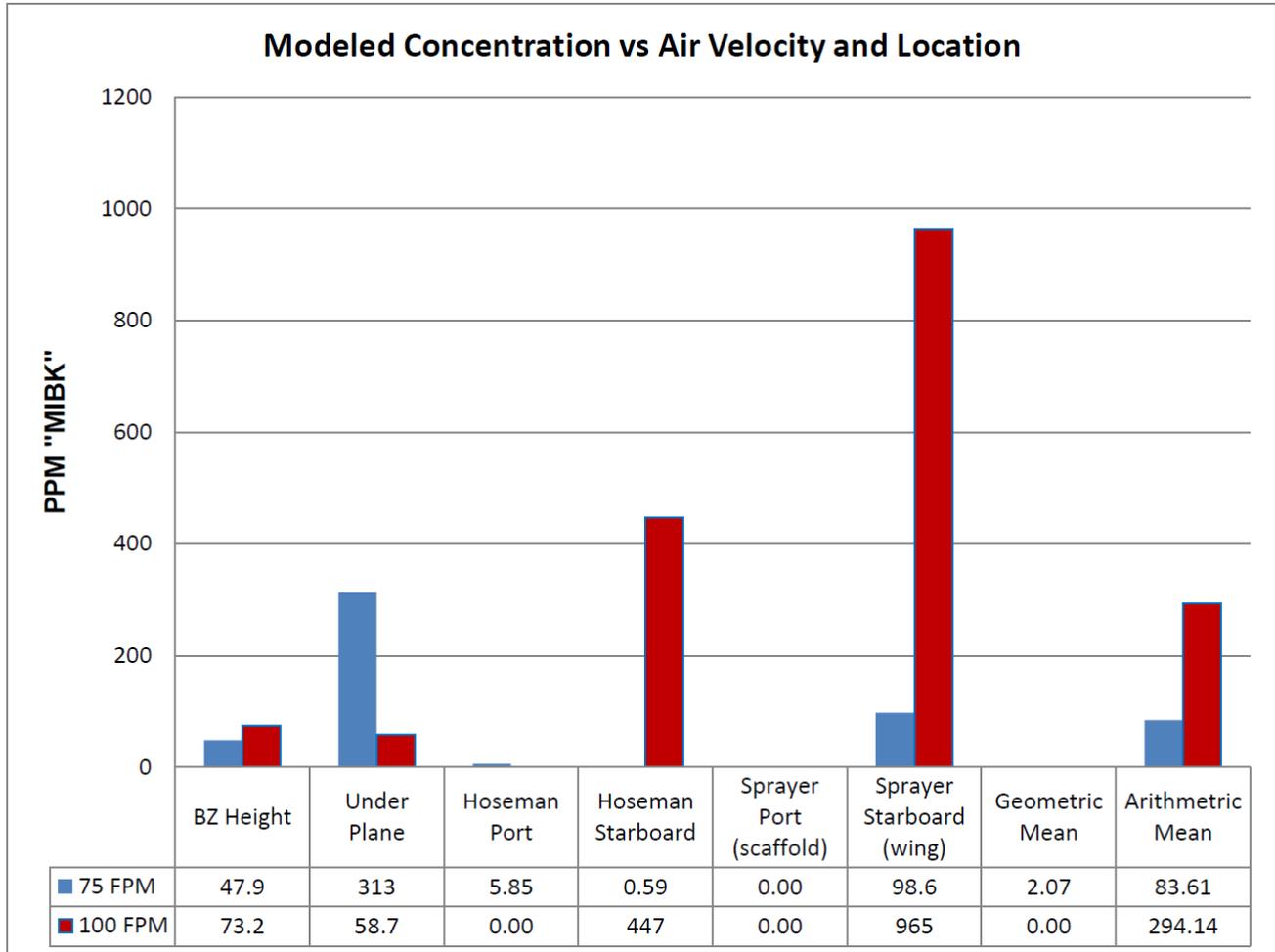


Figure 15. CFD results at 75 fpm (0.381 m/s) and 100 fpm (0.508 m/s) using the RNG k-epsilon turbulence model and a convergence criterion of  $10^{-4}$  for the normalized residuals. The lower flow rate yields greater protection on average.

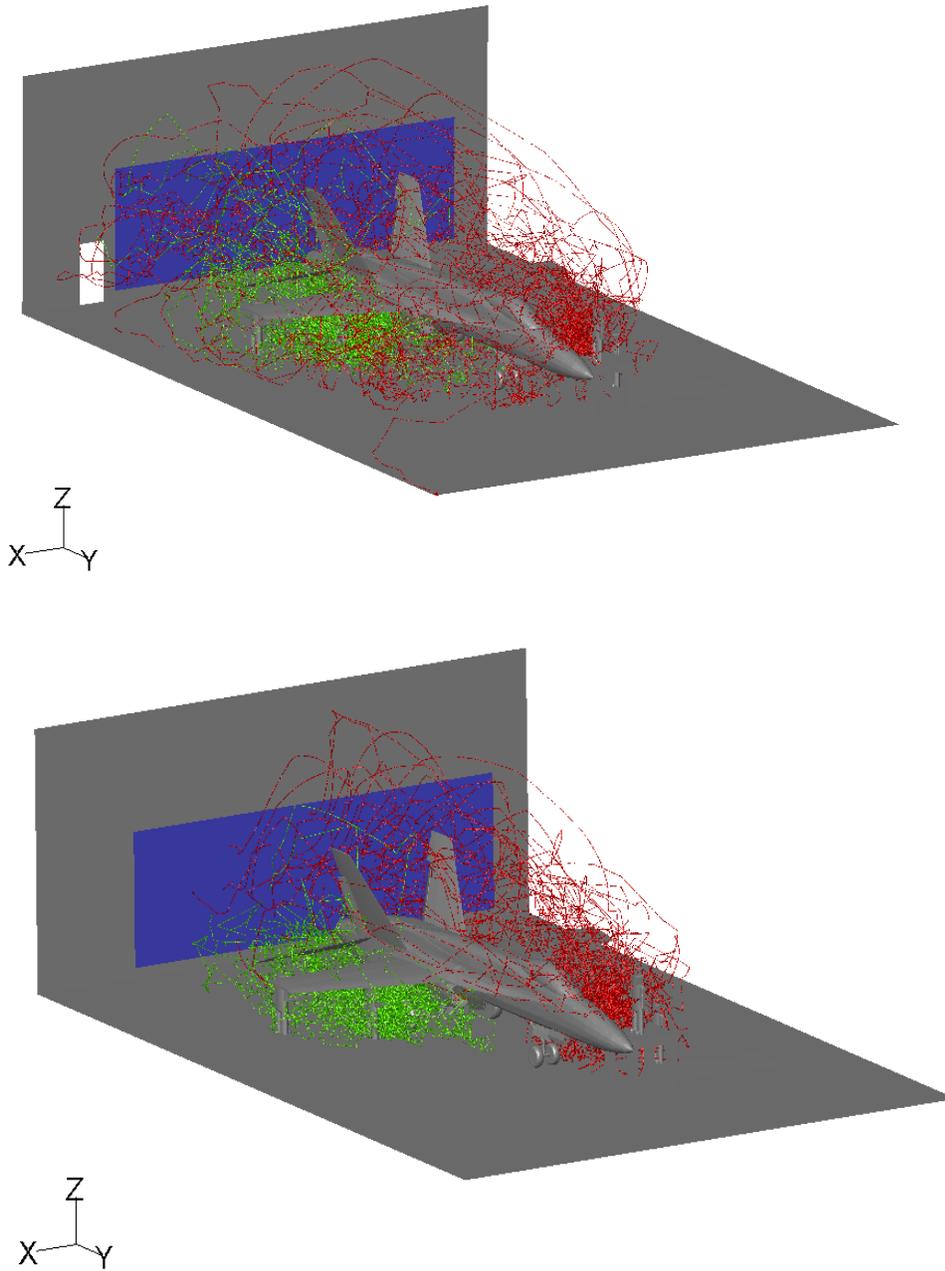


Figure 16. Particle tracks for the unbalanced 108 fpm supply (0.549 m/s) – 65.0 fpm (0.330 m/s) exhaust case (top image) and the balanced 65.0 fpm (0.330 m/s) case (bottom image). The balanced case shows less particle dispersion.

In addition to CFD modeling, tracer gas experiments were also conducted in the hangar using sulfur hexafluoride (SF<sub>6</sub>). The concentrations of SF<sub>6</sub> were compared among the three unbalanced flow rates--half, 3/4, and full capacity of the supply blowers--with the exhaust attempting to match this rate and falling short. In other words, the tracer gas experiments were conducted with this system operating normally, then with one of four supply-exhaust pairs powered down and then with two supply-exhaust pairs down. The comparisons showed that the tracer concentrations at the five monitoring locations was higher for half-flow than for 3/4-flow, with statistical significance (95% confidence intervals did not overlap, as shown in Figure 17 and Table 2). No statistically significant difference was found between half-flow and full-flow or 3/4-flow and full-flow. The 3/4-rate had the lowest mean SF<sub>6</sub> concentration. In this unbalanced condition of 102 fpm (0.518 m/s) of supply and 68.9 fpm (0.350 m/s) of exhaust, the velocity measured at the hangar midpoint (i.e. the cross-section that includes the aircraft) was 73.6 fpm (0.374 m/s).

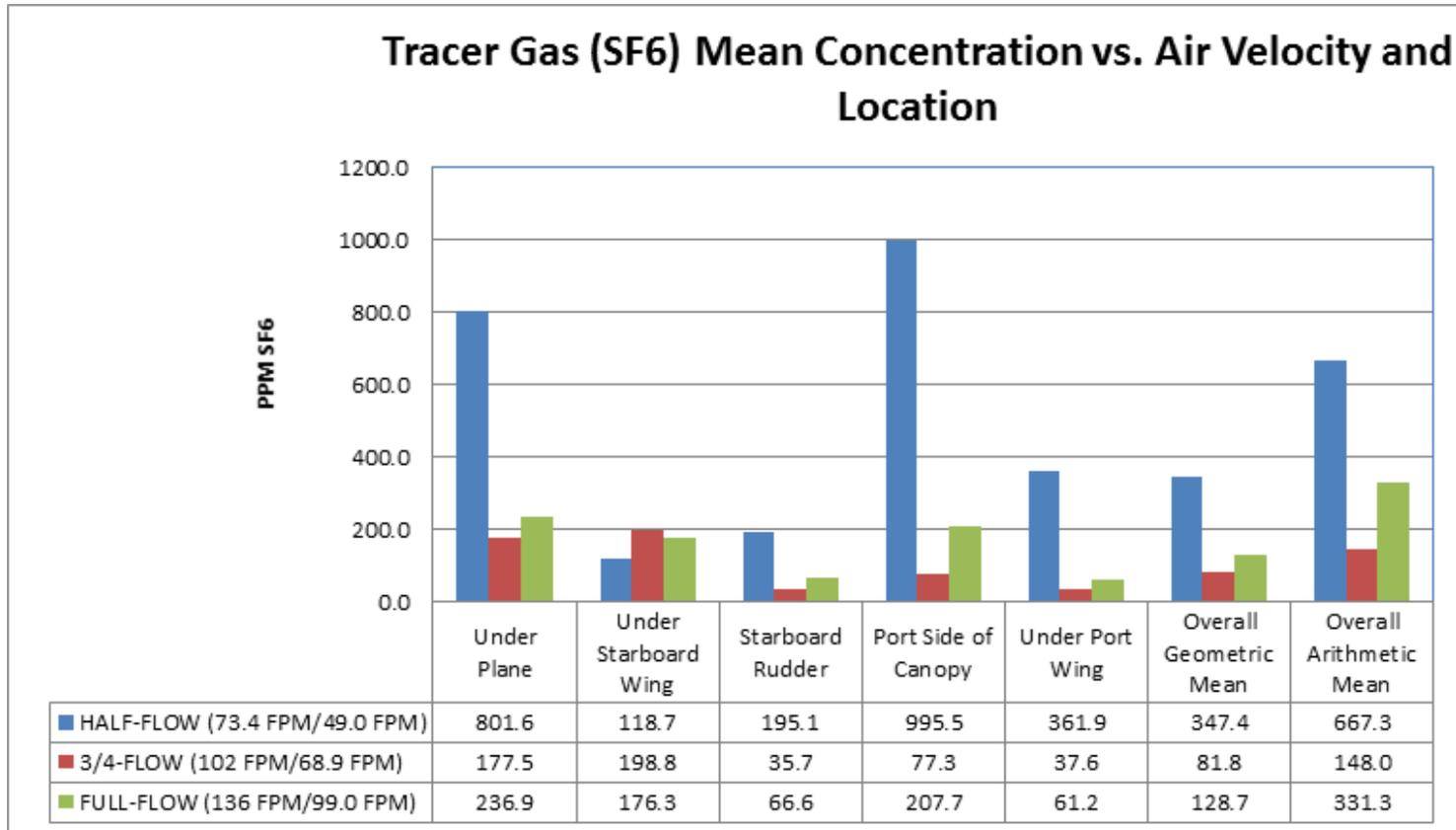


Figure 17. Time-averaged concentrations of SF<sub>6</sub> by measurement location and ventilation system status. Values at the five locations are geometric means for trials of three source configurations. Overall geometric and arithmetic means were calculated over the (5 x 3 = 15) individual observations.

Table 2. Tukey's studentized range (HSD) test for tracer gas log mean concentration. Comparisons significant at the 0.05 level are indicated by \*\*\*.

<b>Velocity Comparison</b>	<b>Difference Between Tracer Gas Log Means</b>	<b>Simultaneous 95% Confidence Limits</b>		
half vs full	1.364	-	3.005	
half vs 3/4	1.961	0.2762	3.787	***
3/4 vs full	-0.5968	-2.391	1.197	

Figure 18 shows the simulated MIBK concentrations modeled using CFD alongside the tracer gas experiment concentrations, as means across the monitoring locations. To more clearly compare the predicted effects of adjusting the ventilation velocity, the data were normalized by dividing the CFD concentrations by the tracer gas concentration at full-flow. As only the first set of CFD simulations were based on the unbalanced conditions measured in the hangar, only these simulations were used in the comparison with the tracer experiments. CFD simulations and tracer experiments show a similar decrease in concentration when the flow was lowered from full- to 3/4-flow. In Figure 18, the tracer experiments indicated a large increase in normalized concentration (from 0.5 to 2.2 times larger than the full-flow concentration) when the flow rate was decreased further, from 3/4- to half-flow. In the CFD simulations, however, there appears to be no discernable difference between the spatial average concentrations at 3/4- and half-flows. Possible reasons for the discrepancy between methods will be given in the Discussion section, but it is worth noting in Figure 18 that not seeing concentration rise in the CFD model, at the lowest velocity, might mean that this behavior is shifted to a still lower velocity. The measured hangar velocities varied spatially (Table 4), whereas the boundary conditions used in the simulations were uniform across the filter faces. It would follow that the simulations created a more uniform and therefore effective velocity field for the purpose of contaminant removal, with fewer flow reversals. Low-speed large-scale fluctuations are difficult to accurately capture using CFD

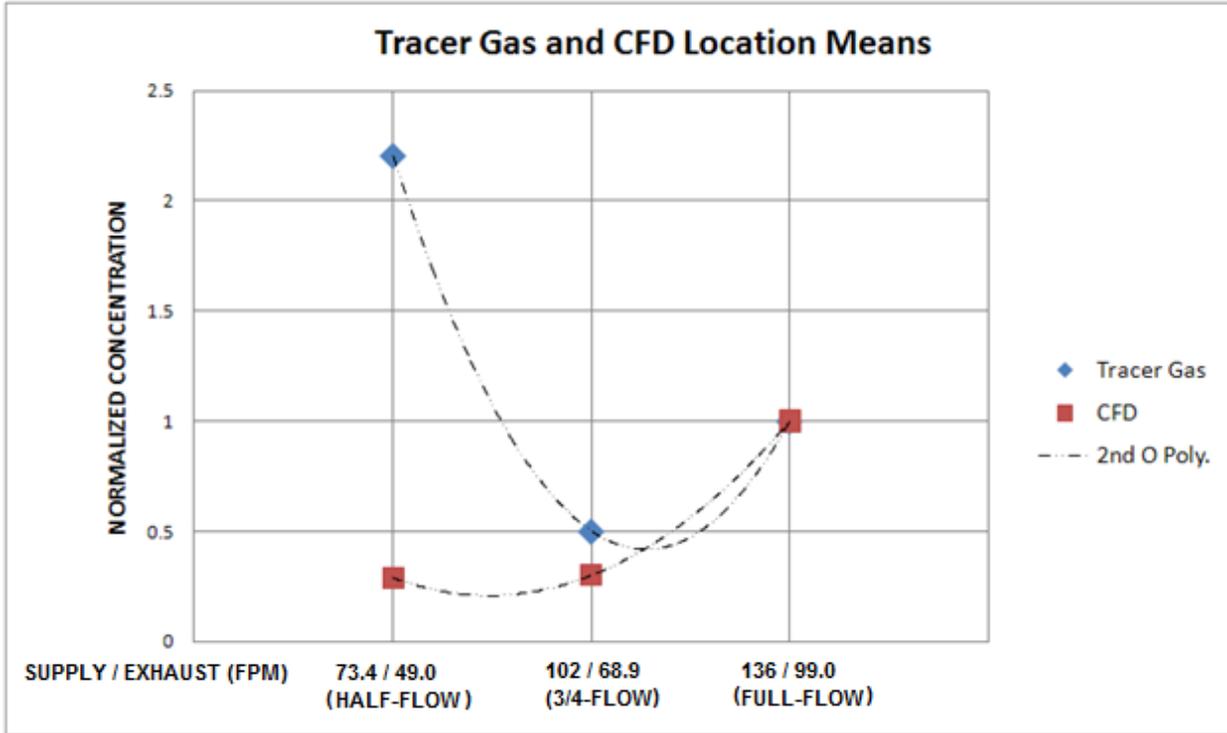


Figure 18: Five-location-mean concentrations for CFD simulations and tracer gas experiment means, as a function of flow rate.

Another way to evaluate the effect of flow reduction is through pair-wise comparisons. In Figure 19, the tracer location means are shown in blue, along with their 95% error bars for the multiple comparison test (Tukey's studentized range HSD test). The plot shows that both CFD and tracer experiments indicate higher concentrations for half- than for full-flows. Half-flow concentrations were statistically significantly higher than 3/4-flow concentrations. For the 3/4 vs. full comparison, CFD and tracer diverge in their prediction, with CFD showing 3/4-flow concentrations higher than full-flow concentrations and the tracer experiments showing 3/4-flow concentrations as lower than full-flow concentrations. The CFD prediction is within the 95% confidence limits for the tracer measurements at all flow conditions shown.

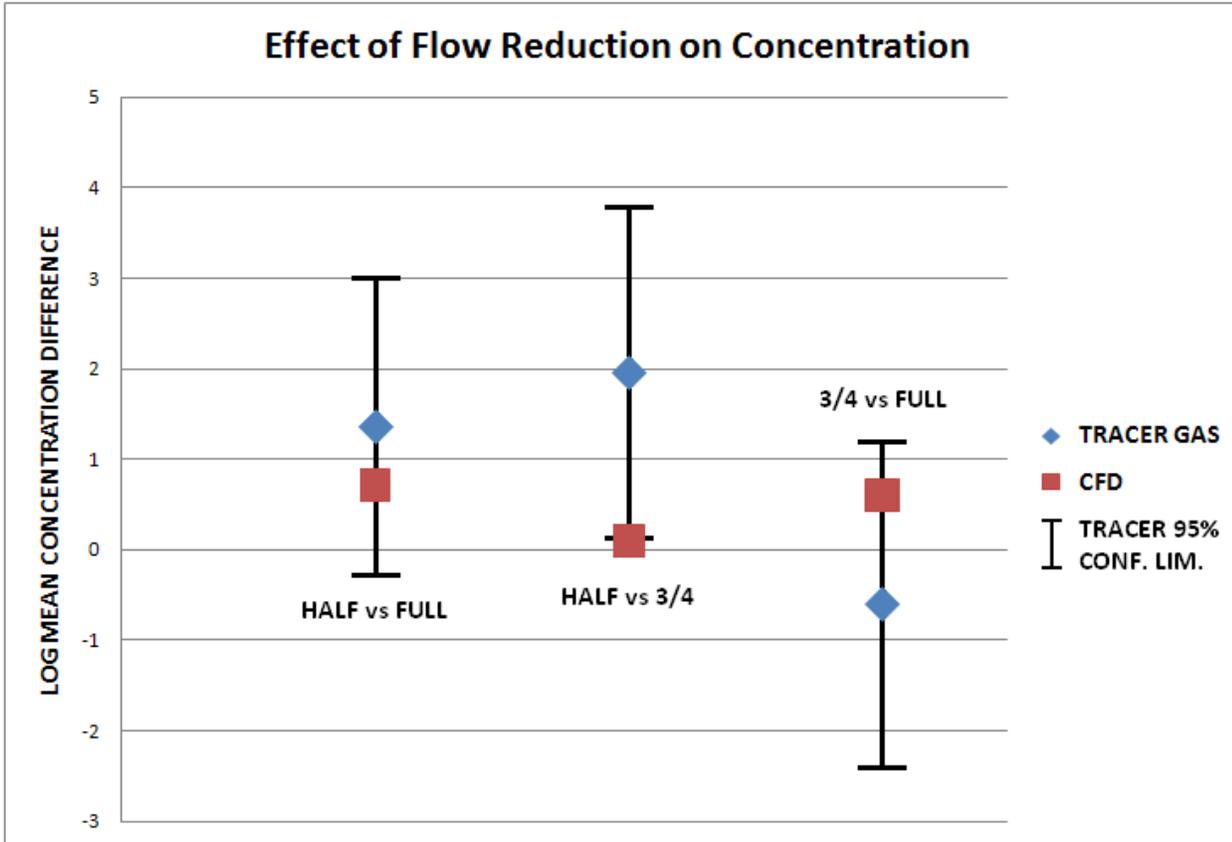


Figure 19: Flow rate comparison by CFD and tracer gas methods.

Follow-Up Survey

Navy personnel modified ventilation at the NBC painting bays following NIOSH recommendations based on the results of initial field surveys and CFD, with the goal of correcting the unbalanced flow conditions. NIOSH conducted a follow-up survey in July of 2014 to assess the impact of these modifications.

Air velocity measurements were collected in Bays 1 and 4 of Building 464 and in Bays 5-8 of Building 465 at NBC. The supply and exhaust filter banks in these bays are smaller than the cross-sectional area of the hangar. Thus, for ease of comparison, the velocity measurements taken at the supply and exhaust filters were normalized to the area of the hangar cross-section. Mean normalized air velocity was 108 fpm (0.549 m/s) at the supply banks, 83.9 fpm (0.426 m/s) at the exhausts, and 94.2 fpm (0.479 m/s) in the middle of the bays, halfway between the supply and exhaust filter banks. In Bay 6, which was the only bay investigated during the initial site visit, the supply/exhaust balance was significantly improved, with 114 fpm (0.579 m/s) at the supply and 109 fpm

(0.554 m/s) at the exhaust, compared to 136 fpm (0.691 m/s) supply and 99 fpm (0.503 m/s) exhaust observed during the initial site study (Tables 3 and 4).

Total particulate and hexavalent chromium air concentrations were measured in the current survey during primer application of an F-18 aircraft for a sprayer, a helper, or hoseman, and downstream of the aircraft (Table 5). Total particulate results, measured by NIOSH Method 0500, for sprayers and hosemen from the current survey, are compared to results from the initial survey in Figure 20. The total particulate measured in the current survey compared to the geometric mean concentration measured in the initial survey was 14 mg/m<sup>3</sup> compared to 18 mg/m<sup>3</sup> for the sprayers and 5.9 mg/m<sup>3</sup> compared to 4.3 mg/m<sup>3</sup> for the hosemen.

Hexavalent chromium results from the current and initial surveys are presented in Figure 21. In 2009, NIOSH Method 7605 was used to collect six samples downwind of the aircraft, six samples for sprayers and six samples for hosemen. In 2014, two sampling methods were used, NIOSH Method 7605 and OSHA Method 215, to collect two samples, one with each method, downwind of the aircraft, for a sprayer and for a hoseman. The arithmetic mean results from the current survey, compared to results from the initial survey, were 200 µg/m<sup>3</sup> vs. 530 µg/m<sup>3</sup> for the sprayers, 91 µg/m<sup>3</sup> vs. 150 µg/m<sup>3</sup> for the hosemen, and 160 µg/m<sup>3</sup> vs. 120 µg/m<sup>3</sup> for the downstream location. The downstream location in the current survey was in between the tail section of the aircraft and the exhaust, whereas the downstream location in the initial survey was downstream of the wing-ends where less painting occurs. The hexavalent chromium results, comparing the single value in the current survey measured by NIOSH Method 7605 to the geometric mean value from the initial survey measured using the same method, for the sprayers was 360 µg/m<sup>3</sup> compared to 500 µg/m<sup>3</sup>; for the hosemen was 170 µg/m<sup>3</sup> compared to 120 µg/m<sup>3</sup>; and for the downstream location was 250 µg/m<sup>3</sup> compared to 83 µg/m<sup>3</sup>.

Air sampling to determine isocyanate concentrations was conducted during painting of an F-18 aircraft to allow for comparison with samples collected by the same method-- reagent coated glass fiber filters (GFFs) analyzed by NIOSH Method 5525-- during the initial survey (Table 5). The HDI monomer concentration in terms of mass of NCO, comparing the single measurement from the current survey to the geometric mean value from the initial survey, for the sprayers was 15.4 µg/m<sup>3</sup> compared to 16.1 µg/m<sup>3</sup>; for the hosemen was 9.79 µg/m<sup>3</sup> compared to 2.06 µg/m<sup>3</sup>; and for the downstream location was 5.80 µg/m<sup>3</sup> compared to 2.49 µg/m<sup>3</sup>. The HDI oligomer concentration, comparing the single measurement from the current survey to the geometric mean value from the initial

survey, for the sprayers was 725  $\mu\text{g}/\text{m}^3$  compared to 259  $\mu\text{g}/\text{m}^3$ ; for the hosemen was 673  $\mu\text{g}/\text{m}^3$  compared to 42.7  $\mu\text{g}/\text{m}^3$ ; and for the downstream location was 4.43  $\mu\text{g}/\text{m}^3$  compared to 79.3  $\mu\text{g}/\text{m}^3$ . The downstream sample in the current survey was not extracted in the field so the oligomer result will be biased low.

Air sampling for isocyanates was also conducted during painting of an E-2 aircraft and a C-2 aircraft using reagent coated GFFs analyzed by NIOSH method 5525. The geometric mean HDI monomer concentration in terms of mass of NCO, comparing NIOSH GFF results from the current survey to those from the initial survey, for the sprayers was 5.55  $\mu\text{g}/\text{m}^3$  compared to 16.1  $\mu\text{g}/\text{m}^3$  and for the hosemen was 3.17  $\mu\text{g}/\text{m}^3$  compared to 2.06  $\mu\text{g}/\text{m}^3$ . The mean HDI oligomer concentration, comparing the results from the current survey to those from the initial survey, for the sprayers was 243  $\mu\text{g}/\text{m}^3$  compared to 259  $\mu\text{g}/\text{m}^3$  and for the hosemen was 127  $\mu\text{g}/\text{m}^3$  compared to 42.7  $\mu\text{g}/\text{m}^3$ .

Air samples collected during a parts painting process showed HDI monomer concentrations of non-detect and HDI oligomer concentrations of non-detect (NIOSH GFF) and 4.86  $\mu\text{g}/\text{m}^3$  (ASSET), for the sprayer. Area results were 0.69, 0.92 and 1.20  $\mu\text{g}/\text{m}^3$  HDI monomer in terms of NCO mass, and 1.49, 30.0 and 119  $\mu\text{g}/\text{m}^3$  HDI oligomer, for the NIOSH GFF, OSHA GFF and ASSET methods, respectively.

A total of four methods were used in the current survey to measure isocyanate air concentrations: ASSET EZ4-NCO Dry Sampler, NIOSH Method 5525 closed-faced cassette reagent coated filters, OSHA Method 42 open-faced cassette reagent coated filters, and NIOSH Method 5525 impingers. Side-by-side ASSET samplers, NIOSH filters and OSHA filters were used for personal monitoring of sprayers and hosemen (resulting in 15 samples total for sprayers and 7 for hosemen), and NIOSH impingers were used side-by-side with these methods for area air sampling. Results for the four methods are presented in Table 5 and Figure 22. To compare results for all methods, it was necessary to convert the OSHA filter results from mass of HDI oligomer to mass of NCO by dividing by a factor of four. This is based on the fact that the most common HDI oligomers (HDI biuret, HDI isocyanurate, and the dimer and trimer of those species) contain on average 25% NCO by weight, so the NCO content of the bulk standard can be calculated to be a fourth of the % by weight oligomeric HDI. The geometric mean HDI monomer concentration in terms of mass of NCO, comparing all results from the current

survey to those from the initial survey, for the sprayers was 4.31  $\mu\text{g}/\text{m}^3$  compared to 16.1  $\mu\text{g}/\text{m}^3$  and for the hosemen was 3.88  $\mu\text{g}/\text{m}^3$  compared to 2.06  $\mu\text{g}/\text{m}^3$ . The mean HDI oligomer concentration (as NCO), comparing all results from the current survey to those from the initial survey, for the sprayers was 400  $\mu\text{g}/\text{m}^3$  vs. 259  $\mu\text{g}/\text{m}^3$  and for the hosemen, 275  $\mu\text{g}/\text{m}^3$  vs. 42.7  $\mu\text{g}/\text{m}^3$ .

Considering only the F-18 isocyanate measurements, the follow-up sampling results across the three methods were, for the monomer, 45.31  $\mu\text{g}/\text{m}^3$  NCO (sprayers) and 3.88  $\mu\text{g}/\text{m}^3$  (hosemen), and for the oligomer, 356  $\mu\text{g}/\text{m}^3$  NCO (sprayers) and 275  $\mu\text{g}/\text{m}^3$  (hosemen).

Figures 23 and 24 show side-by-side isocyanate method results for sprayers and hosemen during painting of an E-2 and C-2 aircraft. The geometric mean HDI oligomer results for sprayers and hosemen during E-2 painting, comparing ASSET to NIOSH GFF methods, were 638  $\mu\text{g}/\text{m}^3$  vs. 169  $\mu\text{g}/\text{m}^3$  for sprayers and 284  $\mu\text{g}/\text{m}^3$  vs. 55  $\mu\text{g}/\text{m}^3$  for hosemen. The mean HDI oligomer results for sprayers during C-2 painting, comparing the ASSET, NIOSH GFF and OSHA GFF methods, were 419  $\mu\text{g}/\text{m}^3$ , 242  $\mu\text{g}/\text{m}^3$  and 251  $\mu\text{g}/\text{m}^3$ , respectively.

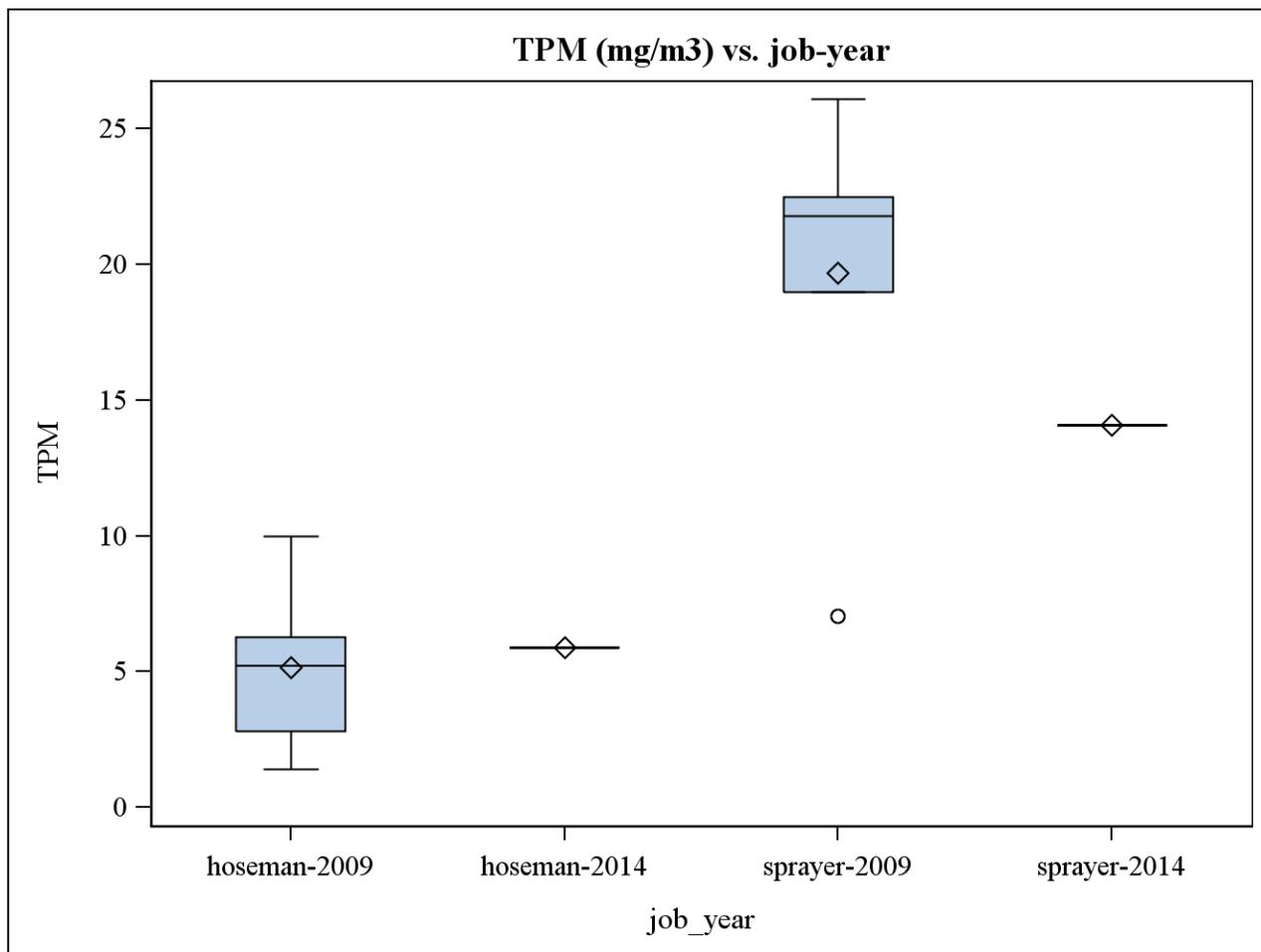


Figure 20. Total Particulate Matter (TPM) air concentrations measured for six sprayers and six hosemen in 2009 at 104 fpm (0.528 m/s), with the 10<sup>th</sup> and 90<sup>th</sup> percentiles shown, and for one sprayer and one hoseman in 2014 at 80 fpm (0.406 m/s). Values of the arithmetic means are represented with diamonds, and an outlier in the sprayer-2009 column is represented with a circle.

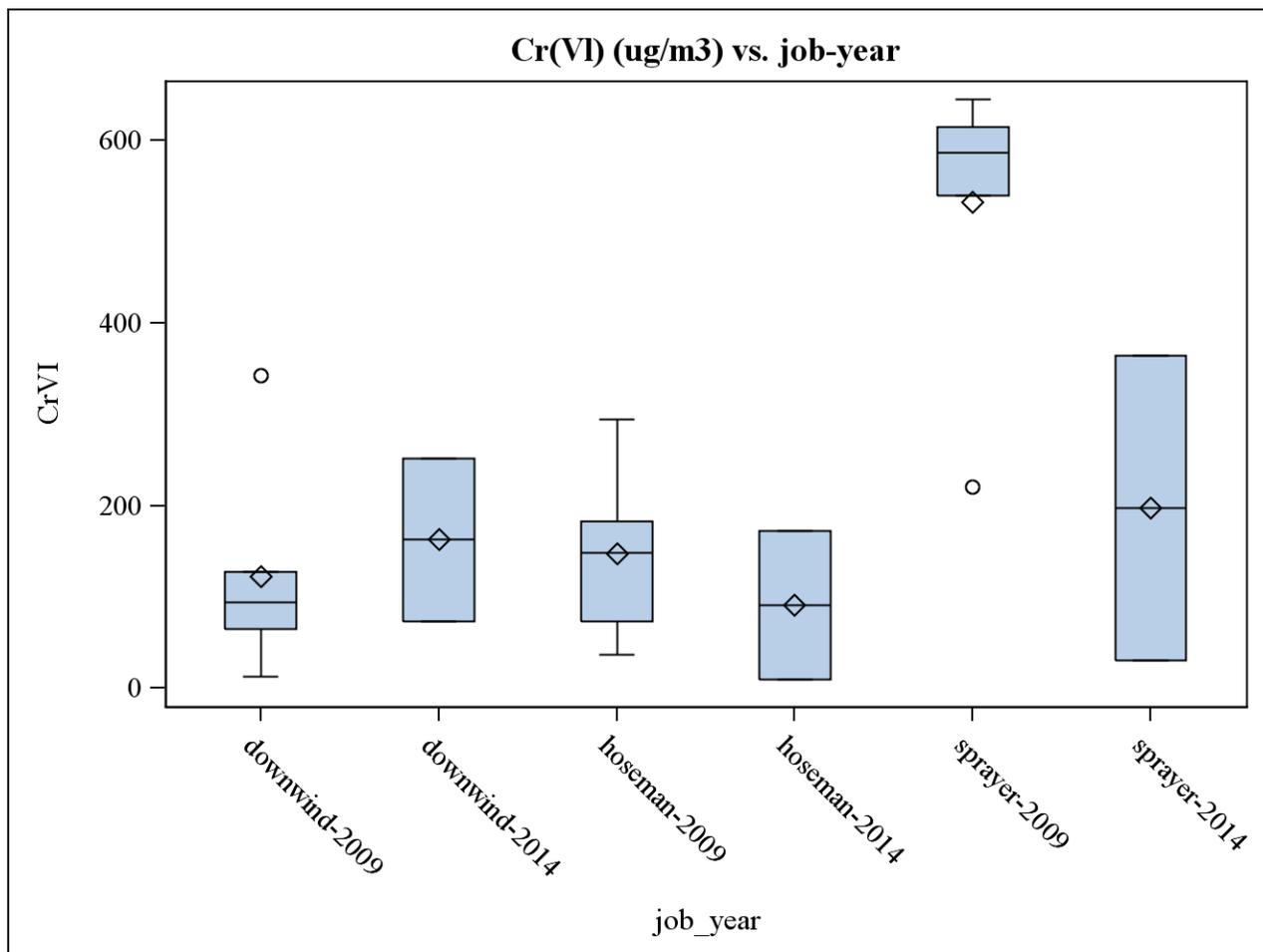


Figure 21. Cr(VI) air concentrations measured downwind of the aircraft and for sprayers and hosemen during painting of an F-18 aircraft in 2009, at 104 fpm (0.528 m/s), and 2014, at 80 fpm (0.406 m/s). The 10<sup>th</sup> and 90<sup>th</sup> percentiles are shown for 2009, and outliers are represented with a circle. Results from 2014 have only two samples per category making medians and means equal, with low and high values as the bottom and top of the box, respectively.

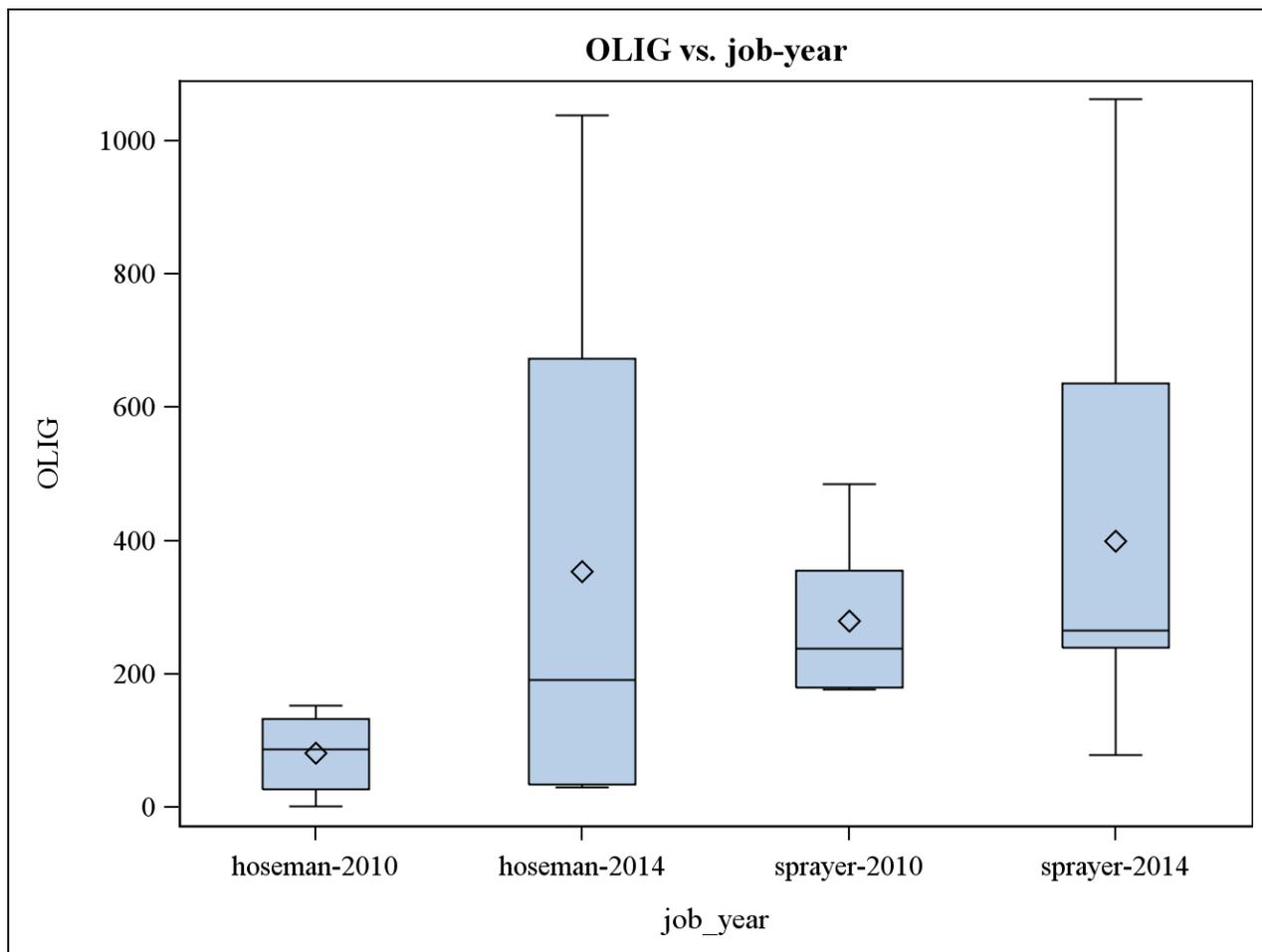


Figure 22. HDI oligomer concentrations (in  $\mu\text{g}/\text{m}^3$ ) measured for hosemen and sprayers in 2010, at 104 fpm (0.528 m/s) and 2014, at 80 fpm (0.406 m/s). The 10<sup>th</sup> and 90<sup>th</sup> percentiles are shown.

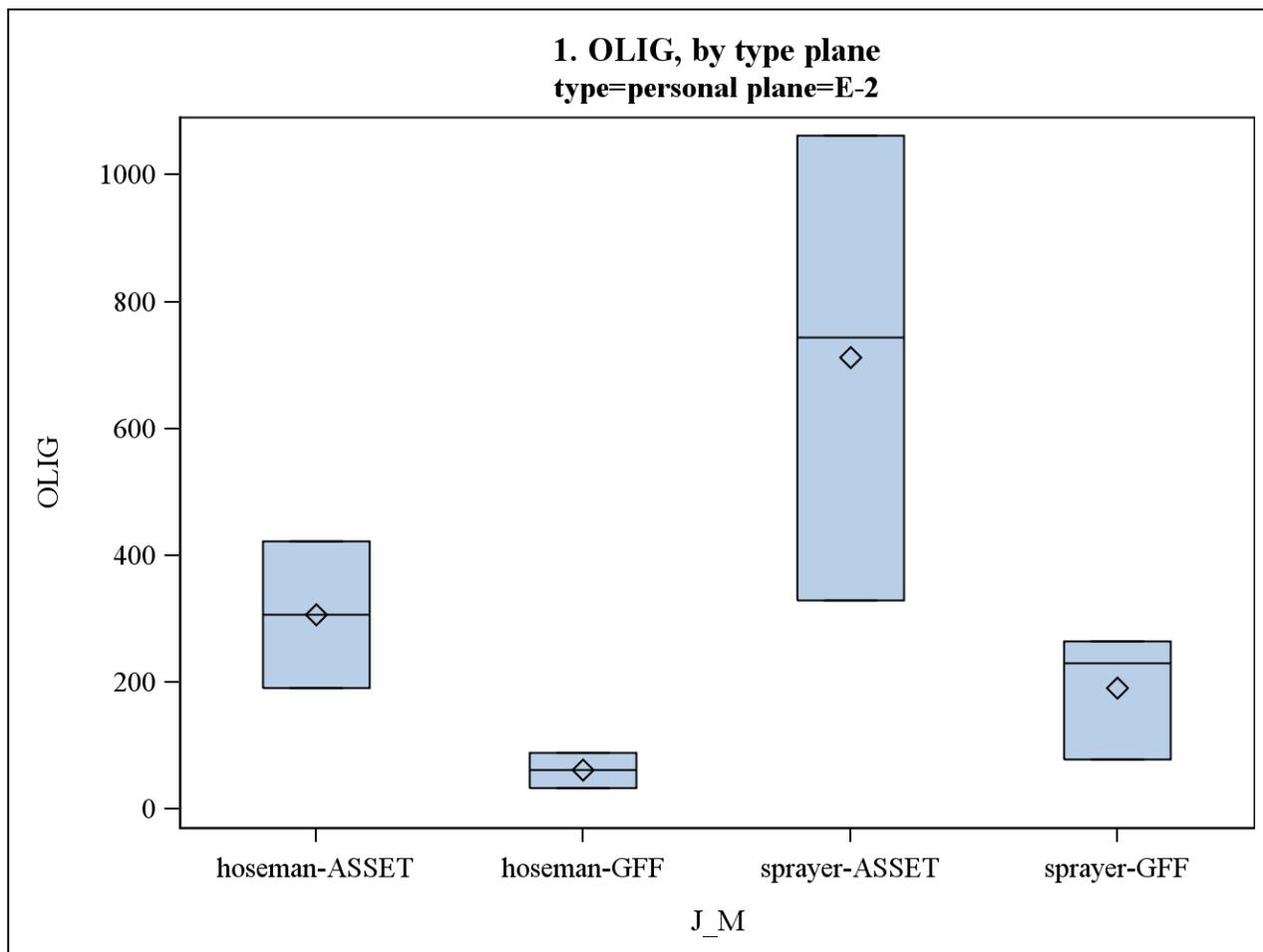


Figure 23. HDI oligomer concentrations (in  $\mu\text{g}/\text{m}^3$ ) measured using side-by-side ASSET and NIOSH GFF samplers during painting of an E-2 aircraft.

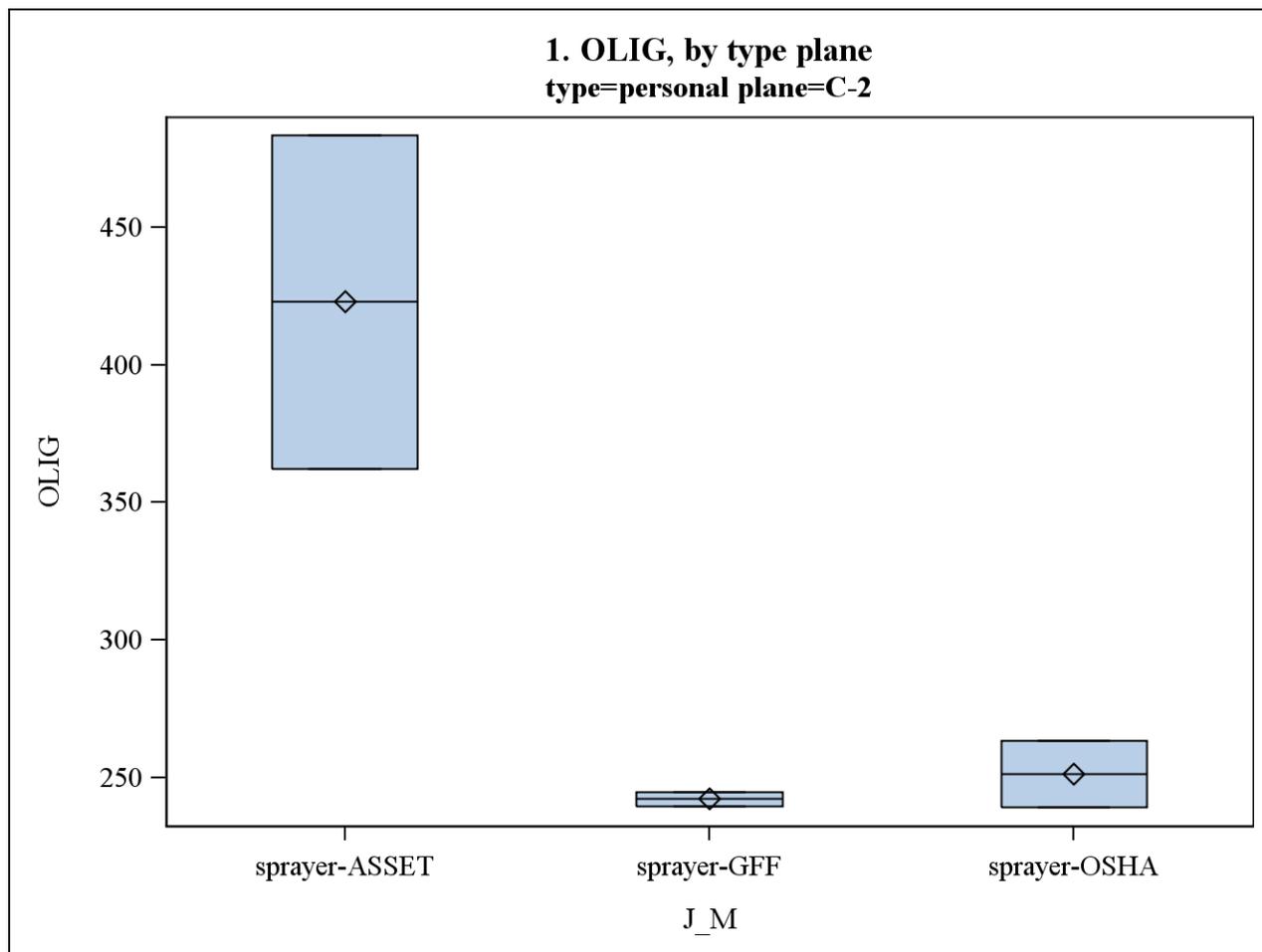


Figure 24. HDI oligomer concentrations (in µg/m<sup>3</sup>) measured using side-by-side ASSET, NIOSH GFF and OSHA GFF samplers during painting of a C-2 aircraft.

Table 3. Summarized air velocity data. Means and ranges are reported in fpm, and means are also reported in m/s. Supply and exhaust values are normalized to the cross-sectional area of the hangar bays. No mid-hangar measurements were gathered in Bay 1 because there was no aircraft in the bay.

Location	Aircraft	Supply		Mid-hangar		Exhaust	
		mean (range)	mean[m/s]	mean (range)	mean[m/s]	mean (range)	mean[m/s]
Bay 1	none	91.5 (71-126)	0.465			94.1 (30-115)	0.478
Bay 4	F-18	93.6 (41-137)	0.475	113 (51-257)	0.574	57.0 (19-105)	0.290
Bay 5	H-53	133 (44-249)	0.676	82.0 (50-140)	0.417	65.0 (19-109)	0.330
Bay 6	H-60	114 (97-137)	0.579	114 (84-148)	0.579	109 (66-136)	0.554
Bay 7	E-2	114 (39-159)	0.579	83.5 (41-114)	0.424	96.2 (67-118)	0.489
Bay 8	E-2	106 (96-118)	0.538	78.8 (54-100)	0.400	82.3 (10-129)	0.418

Table 4. Comparison of mean air velocity data gathered in Bay 6 during the initial survey to measurements obtained during 2014 follow-up survey, after ventilation was modified to reduce flow imbalance.

Location	Measured Velocity (fpm)				Velocity Normalized to Cross Section Area (fpm)			
	Initial Survey [m/s]		Post-modification [m/s]		Initial Survey [m/s]		Post-modification [m/s]	
Supply	157 (122-193)	0.798	132 (112-158)	0.671	136 (106-167)	0.691	114 (97-137)	0.579
Mid-Hangar	104 (45-152)	0.528	114 (84-148)	0.579	104 (45-152)	0.528	114 (84-148)	0.579
Exhaust	264 (83-358)	1.34	290 (177-362)	1.47	99 (31.1-134)	0.503	109 (66-136)	0.554

**Table 5: Process information, ventilation measurements, and process duration TWAs**

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
Mid-Hangar	Mean Velocity (fpm)	104	20	81.1	8	81.1*	8	80.0	8
	Paint Quantity (gal)	13	1	16	1	18	1	7/13	1
	Paint Formula HDI-monomer NCO/oligomer (%)	0.143/9.97	1	0.022/4.53	1	0.016/5.16	1	0.043/9.27	1
Sprayer mean/geo-mean [range]	ASSET ( $\mu\text{g}/\text{m}^3$ ) HDI Monomer			11.4/11.0 [7.32, 14.2]	3	5.44/5.43 [5.15, 5.74]	2	10.6	1
	Monomer-NCO			5.65/5.41 [3.54, 7.12]	3	2.71/2.70 [2.55, 2.87]	2	5.40	1

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
	Oligomer-NCO			712/638 [329, 1062]	3	423/419 [362, 484]	2	1115	1
	NIOSH (µg/m <sup>3</sup> ) HDI Monomer	33.1/32.2 [25.0, 49.6]	6	11.3/10.5 [6.06, 14.2]	3	7.31/7.25 [6.37, 8.26]	2	30.9	1
	Monomer-NCO	16.5/16.1 [12.5, 24.8]	6	5.61/5.24 [3.03, 7.06]	3	3.65/3.62 [3.18, 4.13]	2	15.4	1
	Oligomer-NCO	279/259 [178, 484]	6	191/169 [78.6, 265]	3	242/242 [240, 245]	2	725	1
	OSHA (µg/m <sup>3</sup> ) HDI Monomer					<2.8/<2.8 [<2.7, <2.9]	2	<3.9	1

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
	Oligomer-NCO					245/245 [240, 250]	2	97.4	1
	Total particulate (mg/m <sup>3</sup> ) NIOSH	20/18 [7.0, 26]	6					14	1
	Hexavalent chromium (µg/m <sup>3</sup> ) NIOSH	530/500 [220, 650]	6					360	1
	Hexavalent chromium OSHA							31	1

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
Hoseman mean/geo-mean [range]	ASSET (µg/m <sup>3</sup> ) HDI Monomer			5.18/4.86 [3.39, 6.97]	2			7.09	1
	Monomer-NCO			2.51/2.36 [1.67, 3.36]	2			3.50	1
	Oligomer-NCO			307/284 [191, 422]	2			593	1
	NIOSH (µg/m <sup>3</sup> ) HDI Monomer	6.19/3.99 [<0.7, 11.3]	6	3.88/3.62 [2.49, 5.27]	2			19.6	1
	Monomer-NCO	3.10/2.06 [<0.4, 5.62]	6	1.93/1.81 [1.24, 2.63]	2			9.79	1

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
	Oligomer-NCO	81.7/42.7 [<3, 153]	6	61.5/54.9 [33.8, 89.2]	2			673	1
	OSHA (µg/m <sup>3</sup> ) HDI Monomer							<3.4	1
	Oligomer-NCO							<42.2	1
	Total Particulate (mg/m <sup>3</sup> ) NIOSH	5.2/4.3 [1.4, 10]	6					5.9	1

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
	Hexavalent chromium ( $\mu\text{g}/\text{m}^3$ ) NIOSH	150/120 [37, 300]	6					170	1
	Hexavalent chromium OSHA							9.5	1
Downstream mean/geo-mean [range]	ASSET ( $\mu\text{g}/\text{m}^3$ ) HDI Monomer			8.49/3.63 [0.961, 22.3]	3			12.4	1
	Monomer-NCO			4.16/1.79 [0.475, 10.9]	3			6.03	1

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
	Oligomer-NCO			546/195 [42.2, 1475]	3			1778	1
	NIOSH (µg/m <sup>3</sup> ) HDI Monomer	6.09/4.98 [2.59, 14.2]	6	8.72/5.49 [<1.3, 15.5]	3			11.6†	1
	Monomer-NCO	3.05/2.49 [1.29, 7.11]	6	4.36/2.75 [<0.65, 7.75]	3			5.80†	1
	Oligomer-NCO	89.0/79.3 [36.5, 147]	6	95.9/34.2 [4.68, 249]	3			4.43†	1
	NIOSH impinger (µg/m <sup>3</sup> ) HDI Monomer	11.1/11.1 [11.0, 11.2]	2	6.55/3.40 [1.00, 16.2]	3				

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
	Monomer-NCO	5.54/5.53 [5.49, 5.58]	2	3.30/1.71 [0.501, 8.18]	3				
	Oligomer-NCO	140.5/140.5 [139, 142]	2	29.1/27.3 [19.9, 44.7]	3				
	OSHA (µg/m <sup>3</sup> ) HDI Monomer			<1.9 [<1.9, <1.9]	3			<3.3	1
	Oligomer-NCO			30.4/27.4** [<23.8, 50.0]	3			133***	1
	Total particulate (mg/m <sup>3</sup> ) NIOSH	4.0/2.8 [,0.7, 11]	6					10***	1

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
	Hexavalent chromium (µg/m <sup>3</sup> ) NIOSH	120/83 [13, 340]	6					250***	1
	Hexavalent chromium OSHA							74	1

\*Assumed to be the same as the velocity during E-2 painting, as the C-2 was painted in the same bay, although one month later.

\*\*Values below the LOQ were divided by √2 for calculation of means.

\*\*\*The area sampler was placed between the tail section and exhaust—the worst case location—whereas previous area samples included two locations downstream of the wing ends, where less painting occurs.

†Filter not extracted in-field as described in method protocol

Table 5 provides a comparison of real exposure data for paint finishing operations on three aircraft and two airflow velocities, although the matrix is not complete. Only for the F-18 are two velocities tested for the same aircraft design. The shading in the table illustrates four outcomes of the comparison.

- Orange = the lower velocity has higher exposure.
- Yellow = the lower velocity has exposure that is within the range of the higher velocity, but is probably higher.
- Green = the lower velocity has exposure that is within the range of the higher velocity, but is probably lower.
- Blue = the lower velocity has lower exposure.

The interpretation of these outcomes is not strictly statistical, because only one replicate for the F-18 lower velocity sampling was available, due to the termination of the project. Exposure was interpreted as higher (orange) or lower (blue) if the single value was higher or lower, respectively, than the range of the baseline data, i.e. outside the range. If the single value was within the baseline range, the finding was not conclusive but the comparison outcome was still noted as higher (yellow) or lower (green), based on the mean.

### **Marine Corps Air Station Cherry Point**

Figures 25 and 26 display simulated contaminant plumes modeled using CFD, comparing the 75 fpm (0.381 m/s) and 100 fpm (0.508 m/s) flow rates. Figure 25 illustrates the far-field, low-concentration zone using colored iso-surfaces which indicate a contaminant mole fraction of 0.01. Yellow is for the contribution of sprayer #1, purple for sprayer #2, and green for sprayer #3. The size of the low-concentration plume decreases at the higher flow-rate. Figure 26 presents a similar comparison for the near-field, high-concentration zone using iso-surfaces of 0.03 mole fraction. There is no significant difference in the size of these high-concentration plumes between the two flow rates, after 5,000 iterations.

Figure 27 summarizes the iterative history of the breathing zone concentration scalar variable for each of the three sprayers at each of the three simulated flow rates of 50, 75, and 100 fpm (0.508 m/s). Each airflow condition was run for approximately 50,000 iterations. While the graphics in Figures 25 and 26 at 5,000 iterations were indistinguishable by flow rate, between 6,000 and 12,000 iterations the lower speed cases have the higher mole concentrations. After approximately 22,000 iterations, the solutions are characterized by a somewhat stationary oscillation, i.e. the concentrations are no longer trending. Figure 27 also shows that for sprayer locations #1 and #2, 75 and 100 fpm (0.381 and 0.508 m/s) are indistinguishable after 22,000 iterations, while 50 fpm (0.254 m/s) remains higher until 30,000. Finally, for a given simulated airflow, sprayer #3 experiences the highest concentration, while sprayer #2 experiences the lowest.

Figure 28 illustrates the importance of taking the solution deep into iterative convergence, well after the residuals have been reduced to generally accepted convergence values, as the concentration field is obviously still changing. Concentration is a scalar quantity and can be thought of metaphorically as the “tail that wags the dog,” in the sense that adequate solution convergence in the concentration field requires that iterations continue beyond what is typically required for flow field convergence.

Figure 29 provides the concentrations at the locations of the three sprayers and the two helpers, for the three velocities considered here, as an average over the final 5,000 iterations of the deep convergence region. For Sprayer 1, the lowest concentration occurs at 100 fpm (0.508 m/s). For Sprayer 2, the concentration is actually lowest at 50 fpm (0.254 m/s), slightly greater at 75 fpm (0.381 m/s), and highest at 100 fpm (0.508 m/s). Sprayer 3 (working under the fuselage) has exposure that is not well controlled by the ventilation system, although higher velocity is more protective. However, the outcomes for the hoseman or helper job

classification show a different pattern, because of increased distance from the spray source. For Helpers both 1 and 2, 75 fpm (0.381 m/s) is the most protective, although velocity seems to have little effect for Helper 2 (and Sprayer 2). Team 2 has the lowest exposures.

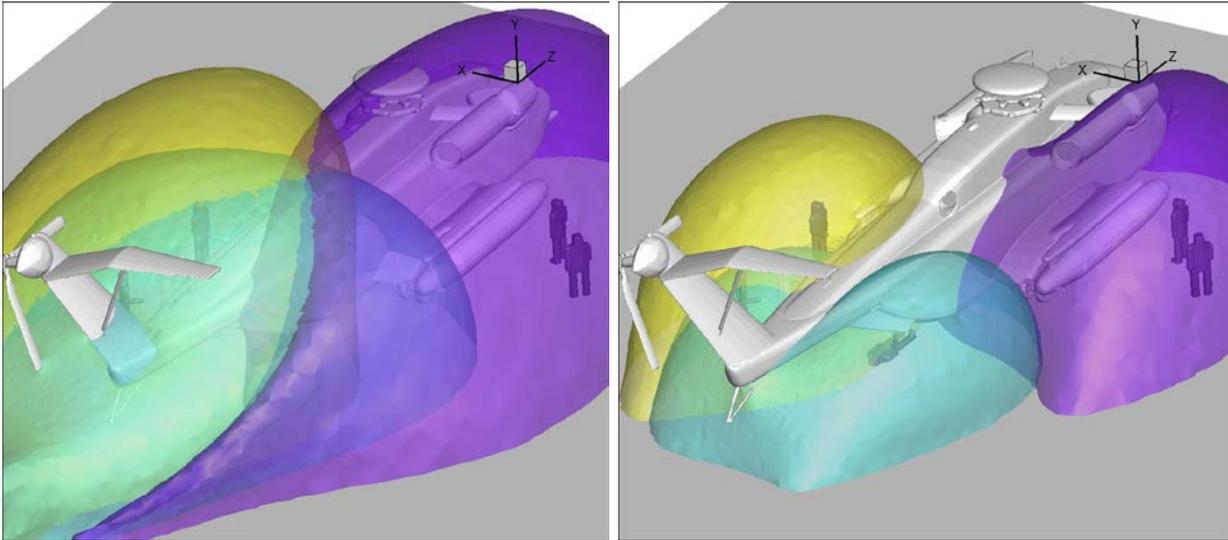


Figure 25. CFD iso-surface plots of the far-field, low-concentration zone at 75 fpm (0.381 m/s) (left) and 100 fpm (0.508 m/s) (right). The colored surfaces indicate a contaminant mole fraction of 0.01. A different color is used to represent the influence of each of the three spray teams. The 100 fpm (0.508 m/s) flow rate appears slightly more effective at dispersing contaminants (i.e., has smaller high-concentration zones).

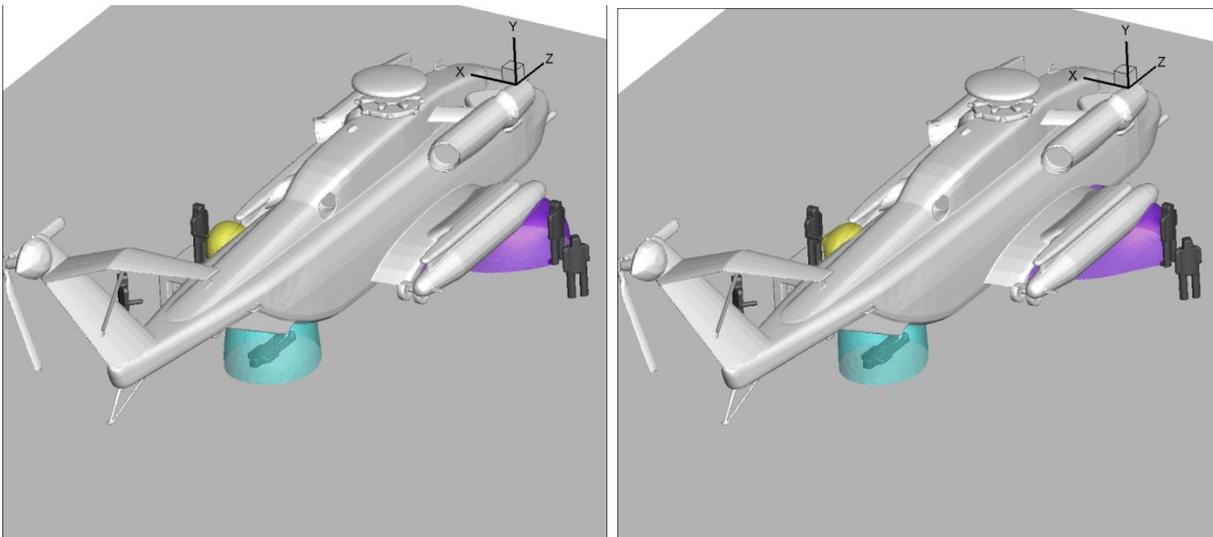


Figure 26. CFD iso-surface plots of the near-field, high-concentration zone at 75 fpm (0.381 m/s) (left) and 100 fpm (0.508 m/s) (right). The colored surfaces indicate a

contaminant mole fraction of 0.03. Minimal difference is observed between the two flow rates.

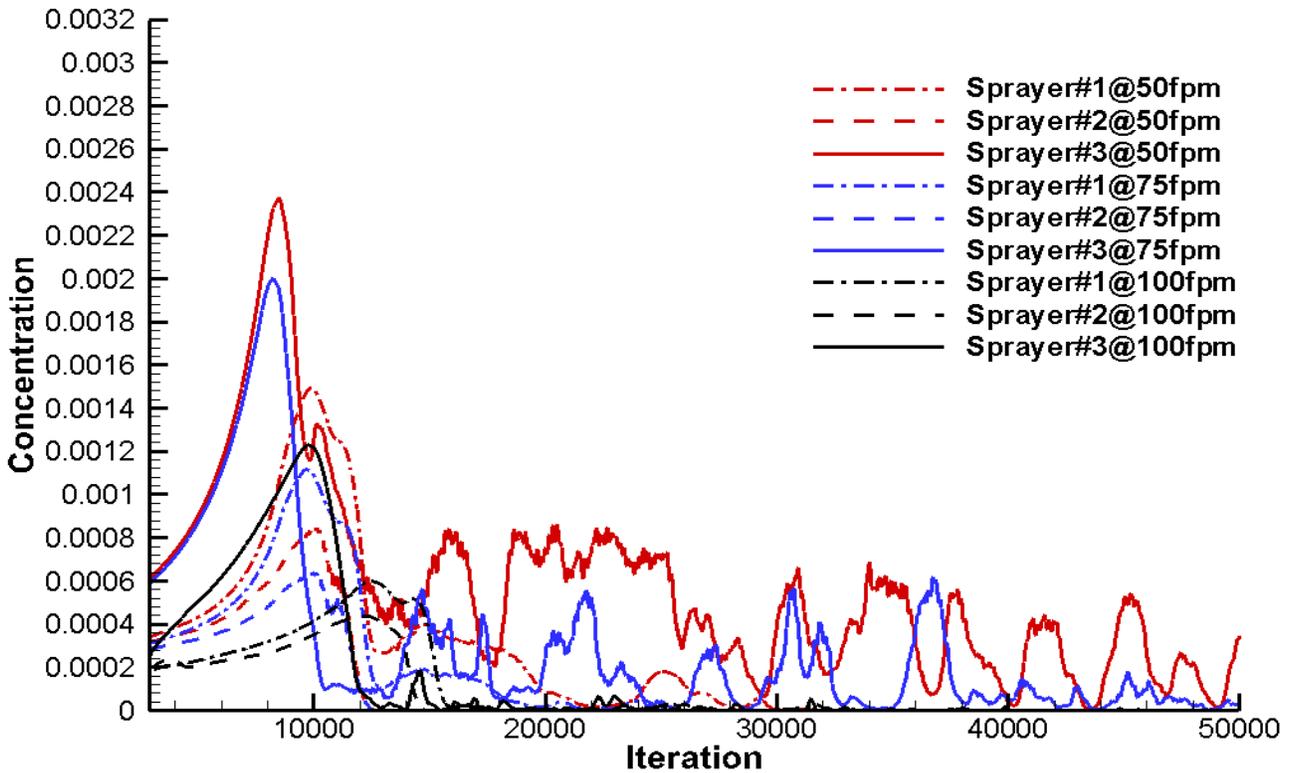


Figure 27. A graph of contaminant concentration (volumetric mole fraction) vs. iteration of the CFD model, for each of the three sprayers, at each of the three simulated flow velocities, 0.254, 0.381, and 0.508 m/s.

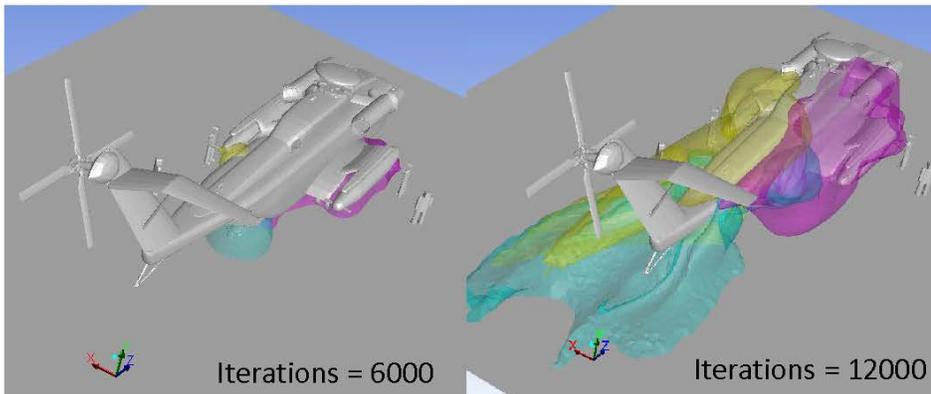


Figure 28. Illustration of the importance of deep iterative convergence as shown by the change in the shape of the 0.03 mole fraction iso-surfaces generated by each sprayer.

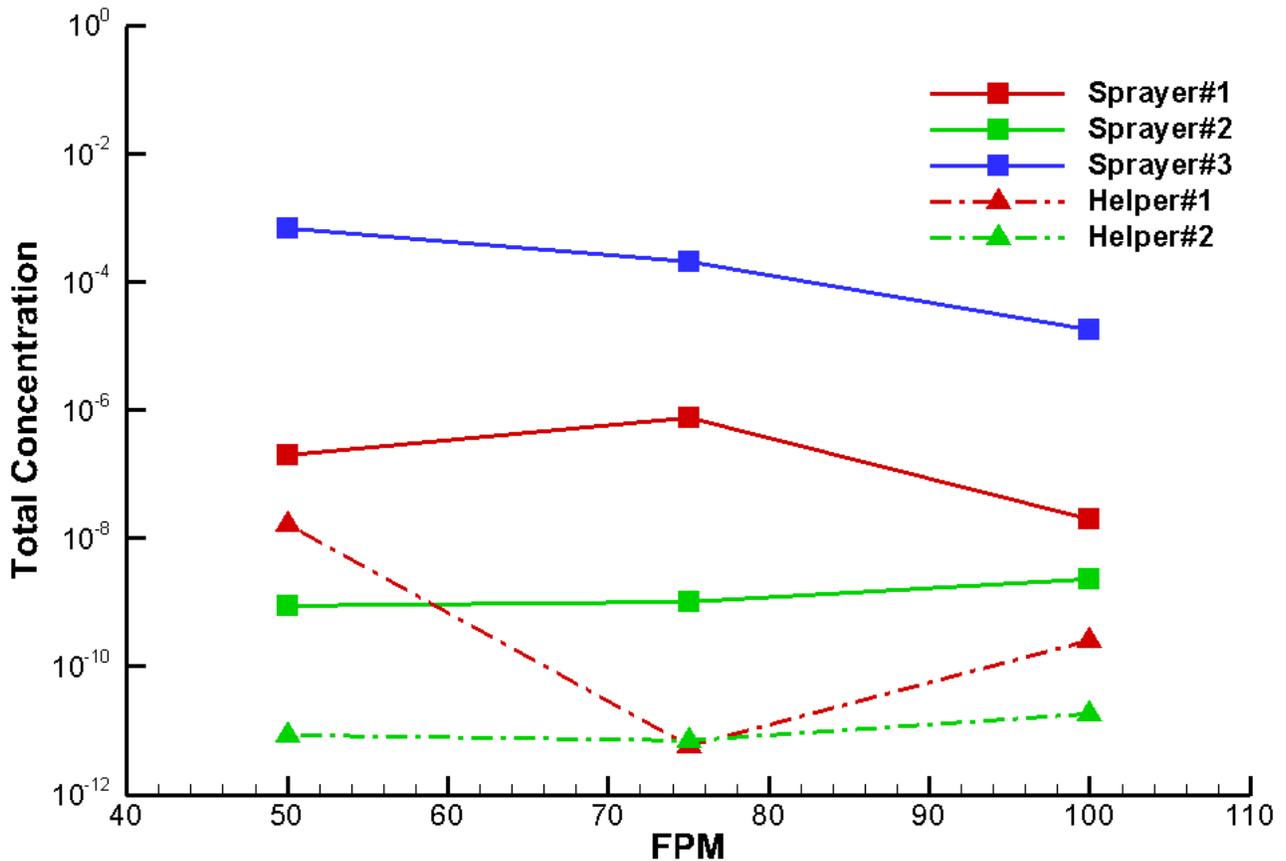


Figure 29. Modeled concentration (volumetric mole fraction), using all sprayers as sources, as a function of velocity at five worker locations during H-53 painting. The average over the final 5,000 iterations is presented.

**Sioux City Air National Guard Base**

Only one site visit was made to the Sioux City Iowa Air National Guard Paint Facility, where F-15 and F-16 aircraft are painted. Along with basic hangar characterization observations, some preliminary airflow measurements were collected. In the Bay 3 paint hangar, average velocities across the faces of the supply and exhaust filters were observed to be 161 and 191 fpm (0.818 and 0.970 m/s), respectively. Velocities elsewhere inside the bay ranged from 77 to 97 fpm (0.391 to 0.493 m/s). In the Bay 5 hangar, airflow was not as strong, with average velocities of 112 fpm (0.569 m/s) across the supply filters and 78 fpm (0.396 m/s) across the exhaust filters. At various locations within the working space of the bay, velocities ranged from 55 to 83 fpm (0.279 to 0.422 m/s). Although no further investigation of the site has been conducted at this time, it

was considered a good candidate for inclusion in the study, as an example of strike fighter aircraft painting ventilation.

## **Joint Base Lewis-McChord**

### McChord AFB C-17 Painting Hangar

On Day 1 of the site visit in May of 2013, supply units 4 and 5 (two out of the six supply air handlers in the facility) were not functioning. This was most likely due to a heat-related auto shutoff issue and resulted in a lower-than-normal flow rate in the hangar, particularly in the areas served by these fans. Facility HVAC maintenance personnel were able to restart both of these units on Day 2 of the visit, such that all supply units were operating at normal capacity. Ventilation measurements gathered on Day 1 were significantly different than those gathered on Day 2. Measurements were obtained at various locations and heights around the body of the C-17 aircraft present in the hangar at the time. A large set of measurements was gathered because of the difficulty in determining a single representative air velocity value for comparison with the study's theoretical baseline condition of 100 fpm (0.508 m/s).

Figures 30 through 33 summarize the results of the air flow measurements as contour plots of air velocity magnitude. Note that in these figures, the shape of the nose end of the hangar and the velocity into the exhaust hoods are not shown accurately, and contour lines extending through the airframe should be taken as an artifact of the plotting software. Likewise, velocities far away from the aircraft are also not portrayed accurately because no data were gathered at points more than 20 feet away from the aircraft. These distant velocity values are merely extrapolations of the field of data points closer to the plane.

Figure 30 represents the velocity magnitudes measured on Day 1 at the breathing zone height when working on the leading and trailing edges of the wings, which is about 17 feet above the floor. The technical sergeants who manage the hangar indicated that these areas were among those most often painted. Figure 31 shows the air velocity magnitude on day 1 measured at typical working heights for the upper surfaces of the C-17, i.e. the tops of the wings, fuselage, and tail section. Like the workers would when painting, the researchers used man-lifts to access these sections. Both figures 30 and 31 indicate, on average, air flow significantly lower than the 100 fpm (0.508 m/s) benchmark. There also appears to be more air movement on the starboard (right) side of the aircraft, as expected, given that air handlers 4 and 5 being inoperative delivered less air to the port (left) side of the aircraft.

Figure 32 is similar to the plot in Figure 30 except that it is constructed from data gathered on Day 2 of the site visit, when all air handlers were functioning properly. This is reflected in the higher and more uniform velocities observed, with greater symmetry of velocity contours on either side of the plane. Unfortunately, due to travel constraints, the time-consuming measurements of the upper surface air flows using man-lifts were not repeated on Day 2. Therefore, Figure 33, rather than showing actual Day 2 data for the upper surfaces, shows the Day 1 upper surface contour data (Figure 31) after applying a correction factor derived from the difference between the Day 1 and Day 2 lower-level wing section measurements (Figures 30 and 32). As a result, Figure 33 does not reflect true velocities, but still gives insight into what velocities might be expected above the aircraft on average. Note that the Day 2 measurements seem to indicate that the 100 fpm (0.508 m/s) benchmark is successfully reached or exceeded, on average, at most locations around the aircraft.

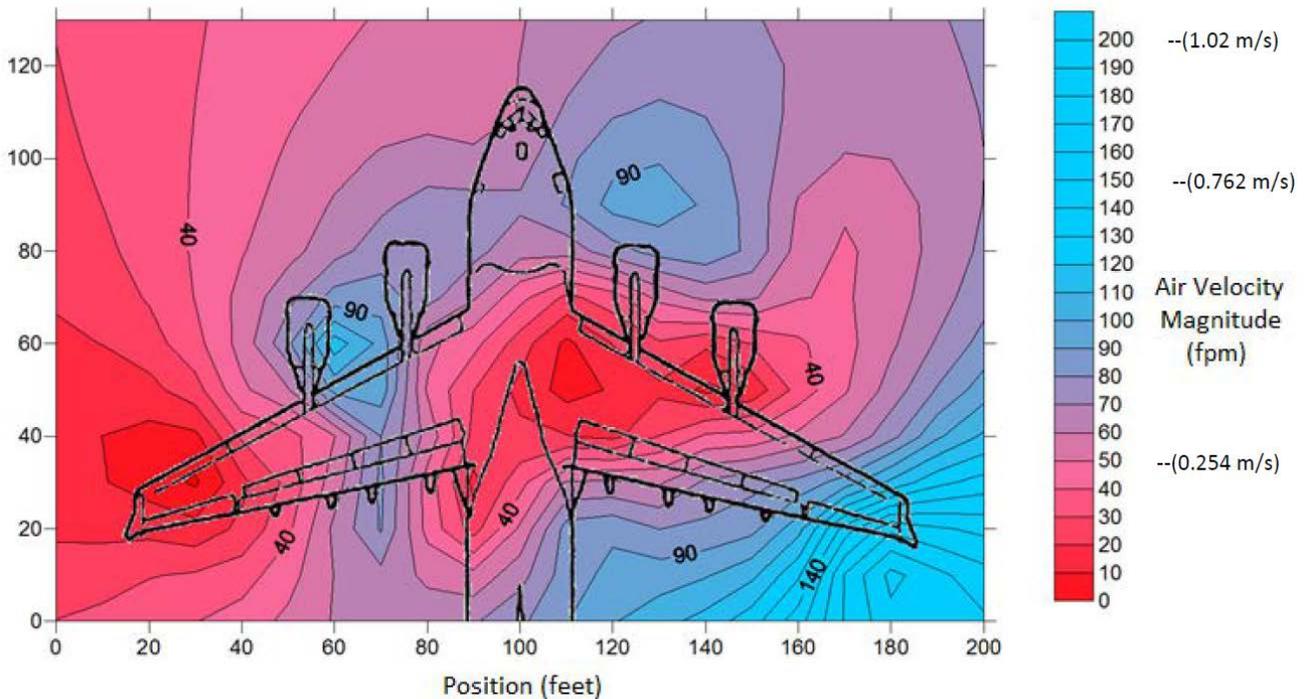


Figure 30. Day 1 contours of velocity magnitude along wing edges at working height, with air handler units 4 and 5 off.

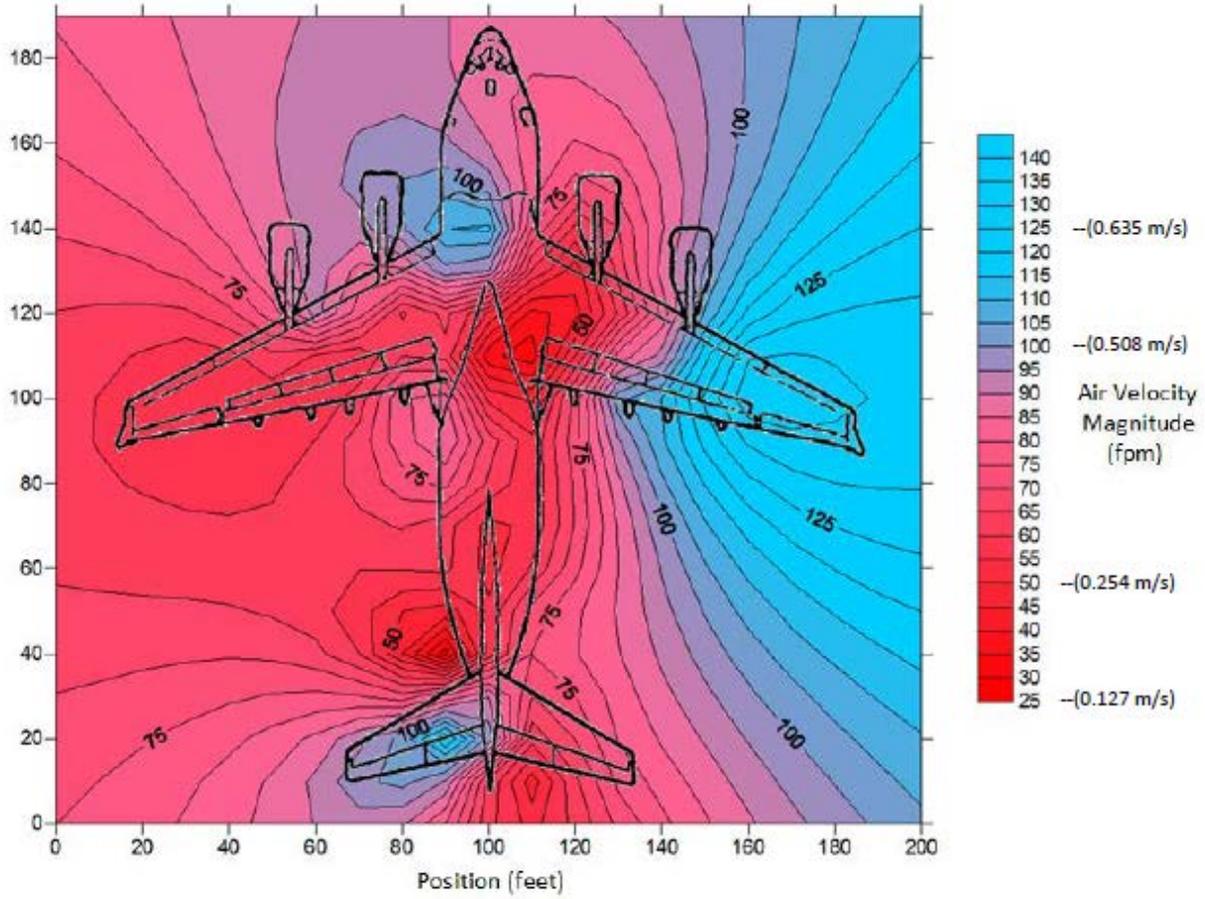


Figure 31. Day 1 contours of velocity magnitude at working height along the upper side of the aircraft, with air handler units 4 and 5 off.

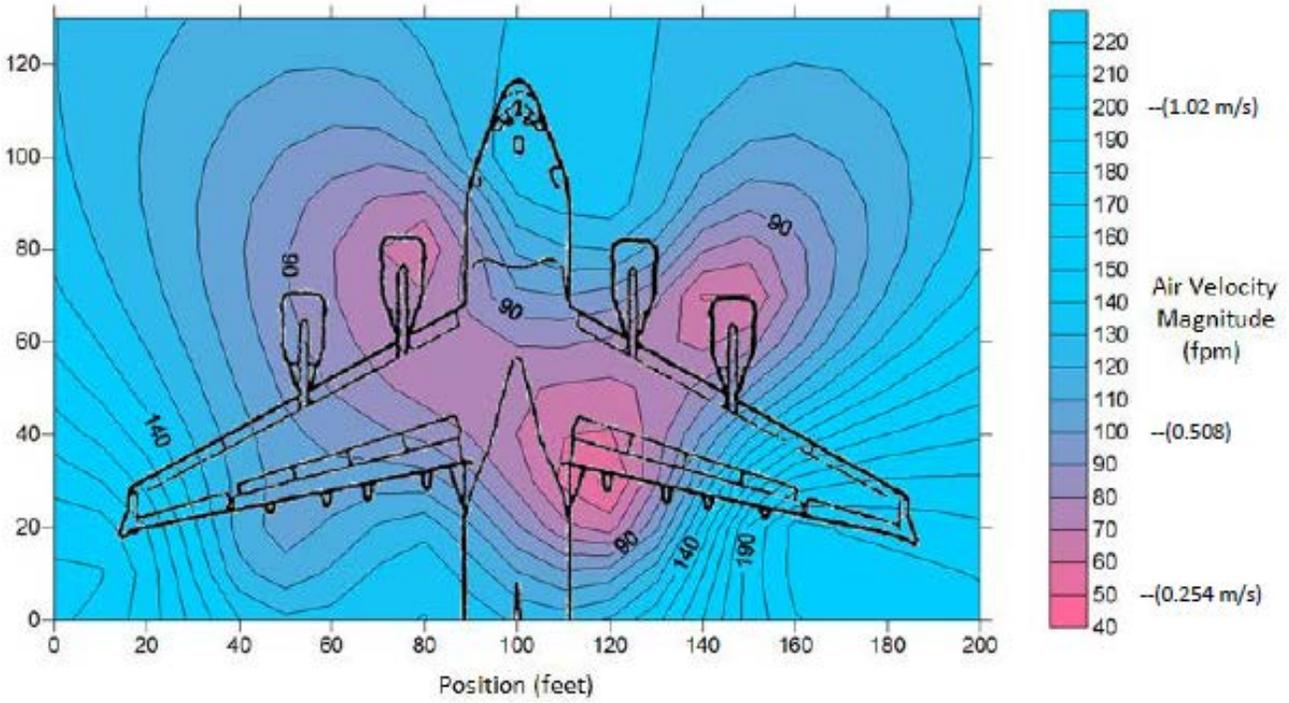


Figure 32. Day 2 contours of velocity magnitude along wing edges at working height, with all air handlers operating normally.

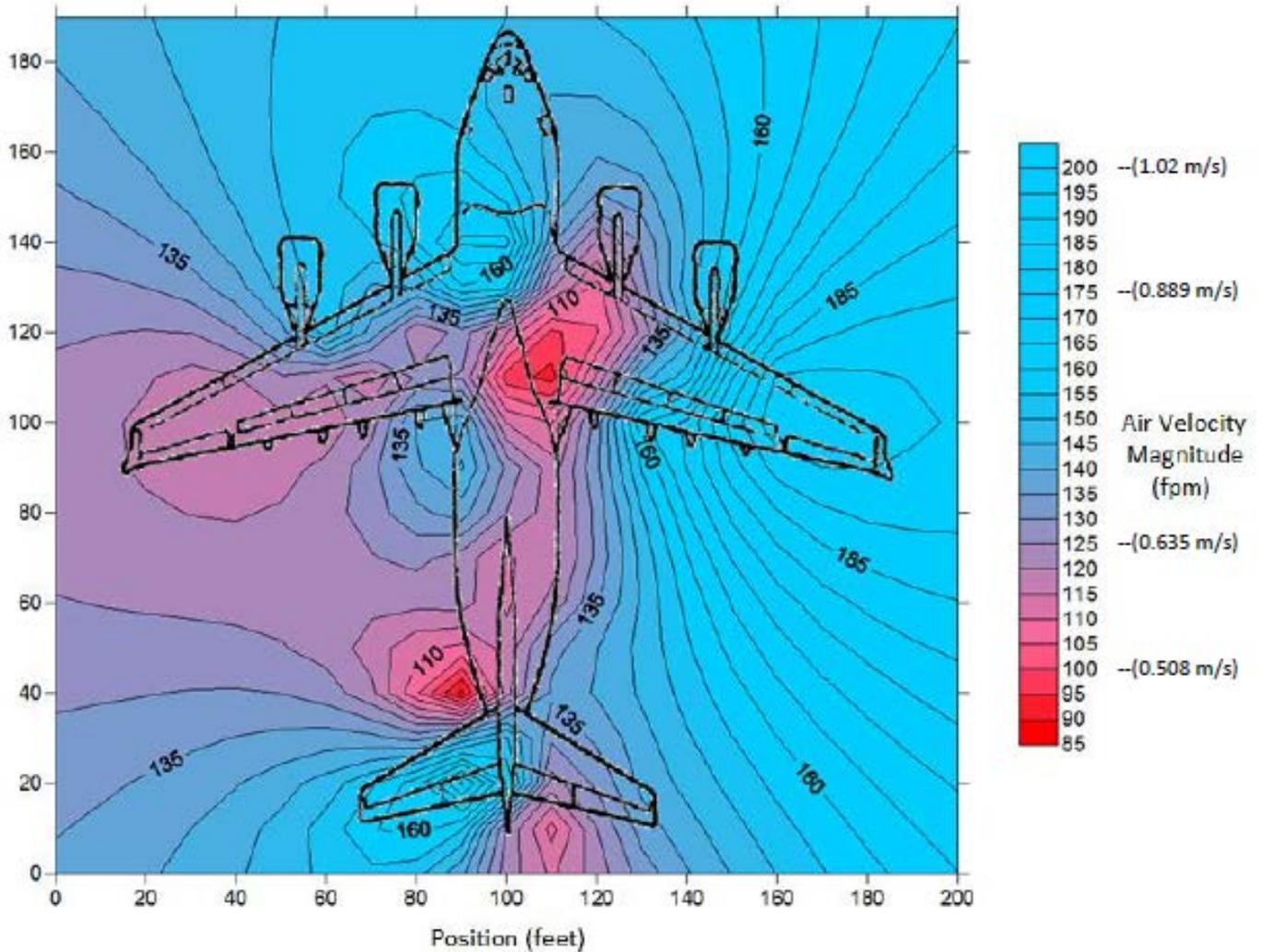


Figure 33. Contours of velocity magnitude at working height along the upper side of the aircraft, with values at full ventilation estimated from the measurements that were made with units 4 and 5 down.

Fort Lewis Helicopter Painting Facility

Some preliminary airflow measurements were obtained during the site visit to this location. Average velocity at the faces of the two supply filter columns was 201 fpm (1.02 m/s), with a range of 0 to 399 fpm (0 to 2.03 m/s). The higher values were measured at the lower half of the floor-to-ceiling columns, nearer to where the supply ducts connect to the column plenums. At the exhaust filter faces, average velocity was 182 fpm (0.925 m/s) and ranged from 23 to 295 fpm (0.117

to 1.50 m/s). Additional measurements were taken at various heights in the midplane of the hangar, halfway between the supply and exhaust filters. Average air velocity along this midplane was 93 fpm (0.472 m/s), and the range was 34 – 259 fpm (0.173 – 1.32 m/s)-- with higher velocities observed at ground level (160 fpm [0.813 m/s] average) and breathing zone height (126 fpm [0.640 m/s] average at 5 foot [1.52 m] height), while lower velocities were seen near the ceiling (56 fpm [0.284 m/s] average, at 18 foot [5.49 m] height). Despite these velocity gradients, the smoke test performed by an Army industrial hygienist showed good directional flow through the work area from supply to exhaust.

## **Discussion**

### **Naval Base Coronado**

The tracer gas experiments and CFD results agreed well for 3/4-flow, but diverged at half-flow (See Figure 18). Because CFD simulations that involve the Reynolds-averaged-Navier-Stokes (RANS) equations in the treatment of turbulence tend to be less accurate at lower Reynolds numbers, when turbulence is present yet not fully developed [Wilcox, 1998b], the CFD results for half-flow should be given less weight than the tracer results. Thus, the CFD result of half-flow being as effective as 3/4-flow should be treated with some circumspection.

Considering both the CFD and tracer experiments, it can be said that the full-flow condition was not more protective than the 3/4-flow condition, as shown in Figures 17 and 18. The 3/4-flow condition can be summarized as producing velocities in the hangar volume that are bracketed by the normalized velocities at the filters, thus a range of 68.9 to 102 fpm, and similarly for full-flow: 99.0 to 136 fpm (0.502 to 0.691 m/s). The mid-bay velocity averages, for 3/4-flow and full-flow, were 73.6 and 104 fpm (0.374 and 0.528 m/s), respectively.

The results of the simulation generally show the limitations of controlling exposure through ventilation alone. If we look at a horizontal slice through the hangar at typical breathing zone height, the relationship of concentration and ventilation rate follows the intuitive idea that more air is better. Figure 14 shows that for this slice ("BZ Height"), while more air is better, it is a situation of diminishing returns. For example, a 33.3% velocity increase from 65.0 fpm to 86.6 fpm (0.330 to 0.440 m/s) leads to only a 14.4% concentration decrease from 92.7 ppm to 79.3 ppm. In some instances, more air velocity increases the concentration, as in the unbalanced case of 108 fpm (0.549 m/s) supply coupled with 65.0 fpm (0.330

m/s) exhaust. Adding more air only at the supply end increased the concentration from 92.7 to 106 ppm, compared to 65.0 fpm (0.330 m/s) balanced at both ends of the hangar.

Perhaps the more important locations to consider are those where the aircraft painters were commonly observed working or where conditions seemed to represent a worst-case scenario. Not only were there diminishing returns for moving more air and a concentration penalty for unbalanced flow, there were also locations where a balanced 65.0 fpm (0.330 m/s) and a balanced 86.6 fpm (0.440 m/s) were approximately equal in controlling exposure. This occurred for the highest exposure location, the sprayer under the starboard wing. Here, the sprayer was exposed to 2212 ppm at 65.0 fpm (0.330 m/s), but 2279 ppm at 86.6 fpm (0.440 m/s). The best summary representation of the effect of ventilation rate is the geometric mean of the concentrations at the worker locations. The pattern in the estimates shown in Figure 14 is clearly that 43.3 is less effective than 65.0 fpm; 65.0 and 86.6 fpm are quite close; and, 108/65.0 is worse than all but 43.3 fpm. The balanced 108 fpm was the most effective velocity at all locations. Balanced 65.0 fpm was the second most effective velocity at the highest exposure locations, the sprayers.

The CFD results in Figure 15 (RNG k- $\epsilon$  turbulence model and convergence criterion of  $10^{-4}$ ) are quite different than those in Figure 14 (standard k- $\epsilon$  turbulence model and convergence criterion of  $10^{-3}$ ). The concentrations in Figure 15 are generally lower than those in Figure 14. A reasonable interpretation is that the model with the lower error tolerance (Figure 15) resolved the steep, near-source concentration gradients more precisely, with less numerical diffusion. In Figure 15, 75 fpm (0.381 m/s) is shown to be more effective than 100 fpm (0.508 m/s) for three of the six locations (including the two highest exposure locations) and less effective or approximately equal for the other three locations. The geometric mean concentration for 75 fpm (0.381 m/s) was higher than for 100 fpm (0.508 m/s). The arithmetic mean concentration was lower for 75 fpm (0.381 m/s) than for 100 fpm (0.508 m/s). This difference between arithmetic and geometric means is due to 75 fpm (0.381 m/s) being more effective at higher concentration levels. While conservation of mass requires higher flow to result in lower concentration, integrating over the entire space, local variations in the flow and concentration fields appear that can deviate significantly from the overall conservation requirement. Which of the CFD results (Figure 14 or Figure 15) best represents real contaminant transport during the refinishing process is difficult to say, definitively. While the results in Figure 15 are more accurate from a numerical point of view, the concentration variability as a function of location and

velocity is larger than what intuition would suggest. There are mixing processes (which reduce concentration variability) in a real work environment, such as a worker's motion while spraying, that were not captured here. It is possible that the increased numerical diffusion from the k-epsilon model (shown in Figure 14) may better represent real mixing processes to some degree.

### Follow-Up Survey

Air velocity measurements gathered during the 2014 follow-up survey show that airflow was within 25 fpm (0.127 m/s) of the 100 fpm (0.508 m/s) criterion at the mid-hangar plane in every one of the surveyed bays. Supply and exhaust flow rates were well-balanced in several bays, especially Bays 1 and 6, but were poorly balanced in Bays 4 and 5. The imbalance in these two bays may be a result of clogged filters. In Bay 5, for instance, heavy paint deposition was observed on the exhaust filters, obstructing the flow of air.

Air sampling in the follow-up survey involved some uncontrolled variables: the surveys were conducted in different bays although with very similar ventilation (Bay 6 versus combined Bays 7 and 8, and Bay 2); samples were collected during the painting of different aircraft (F-18 versus E-2 and C-2); different quantities of paint were used in the operations; and the samples were sometimes collected and analyzed using different methods. Therefore, changes in contaminant concentrations cannot be attributed solely to the ventilation system modification. The isocyanate, hexavalent chromium and total particulate results do not show a consistent relationship between ventilation velocity and contaminant concentration. However, it is clear that any ventilation rate effect is not large compared to other sources of variability.

Considering the exposure data in Table 5, a reasonable interpretation is that airflow of 80.0 fpm (0.406 m/s) is not less protective than airflow of 104 fpm (0.528 m/s). There are specific contaminants and worker positions where one velocity is more protective than the other, according to this data. The bigger picture seems to be that velocity in this range does not make much of a difference. A rigorous statistical test for differences based on airflow velocity is unlikely to detect differences that are statistically significant, because of the very small sample size. To rely on such a test, then, might bias the interpretation toward the "velocity makes no difference" position. Instead, reporting the outcomes as was done here is a best effort at drawing objective conclusions from limited data.

## **Marine Corps Air Station Cherry Point**

A comparison of the modeled concentrations at the breathing zones of individual sprayers reveal that the sprayer located underneath the aircraft, at position #3, received the highest exposures in all cases (see Figures 25-29). The airframe obstructs the flow, resulting in lower velocities in the space between the fuselage and floor. Whereas intuition might predict an acceleration of the flow through this gap, what seems to happen instead is the aircraft is “seen” as a large obstruction and “avoided” by the streamlines. The situation might be improved by focusing additional ventilation under the aircraft, perhaps using local exhaust through flexible ducts or a fan driving flow under the airframe toward the main exhaust. Like the H-53 rotary wing aircraft here, for the F-18 strike fighter aircraft painted at Naval Base Coronado the concentrations were also highest under the fuselage.

The CFD results suggest that a velocity of 100 fpm (0.508 m/s) can be either more effective or less effective than 75 fpm (0.381 m/s) at controlling exposures, depending on workers’ positions in the hangar (Figures 25 and 29). The results are dependent on the extent of convergence of concentration, a scalar variable, well after the velocity and turbulence fields have been determined to a generally accepted convergence level. A larger number of iterations seems to diminish the concentration difference between 75 and 100 fpm (0.381 and 0.508 m/s), and yet maintain the clearly higher concentration at 50 fpm (0.254 m/s). Presumably, accuracy increases with additional iterations. This suggests that a reduction in delivered airflow might be possible without compromising worker health and safety. However, the under-fuselage worker location should be addressed with control measures beyond the main ventilation system. Additional on-site tracer gas and exposure monitoring tests are recommended to investigate this possibility further and confirm these findings.

## **Sioux City Air National Guard Base**

Significantly higher air flow velocities were observed in the Bay 3 painting hangar compared to the Bay 5 painting hangar. Bay 3 average velocities at the filter face were 161 fpm (0.818 m/s) for the supply and 191 fpm (0.970 m/s) for the exhaust, compared to only 112 fpm (0.569 m/s) supply and 78 fpm (0.396 m/s) exhaust in Bay 5. Measurements at each bay midpoint reflected this difference: Bay 3 ranged from 77 to 97 fpm (0.391 to 0.493 m/s), whereas Bay 5 ranged from 55 to 83 fpm (0.279 to 0.422 m/s). Some particularly low velocities at the exhaust filter in bay 5 corresponded to paint-coated areas directly downstream from more active work areas. Bay 3 is already within the acceptable range, and

with some minor adjustments and filter maintenance, it is likely that airflow in Bay 5 could be increased to operate near the 100 fpm (0.508 m/s) benchmark. The results of these preliminary measurements, combined with the configuration of the two hangars that is fairly representative of the normal design of the majority of DOD aircraft painting facilities, suggest that the two Sioux City Air National Guard painting hangars are good candidates for continuing future investigations.

### **Joint Base Lewis-McChord**

Data collected over two days suggest the ventilation system serving the C-17 Corrosion Control Facility is effective at delivering airflow to areas in which workers would normally work. On day 2 of the survey, when all air handlers were operating as expected, there were several small areas underneath the aircraft fuselage and wings where air velocity magnitude dropped to 50-60 fpm (0.254-0.305 m/s), but on average, velocities were equal to or greater than 100 fpm (0.508 m/s). Although no data were gathered along the upper surfaces of the aircraft on day 2, the corrected day 1 data leads to the expectation that most of these upper areas would also experience air flow in excess of 100 fpm (0.508 m/s). The fact that the hangar is able to meet the 100 fpm (0.508 m/s) benchmark makes it a good candidate for additional study. The hangar's large size and its ceiling-mounted-supply configuration set it apart from the other facilities included in the study and are of particular interest for further investigation.

### **Project Data Summary**

Table 6 provides an overview of exposure results for various crossflow ventilation velocities. Exposures were ranked and the results were analyzed non-parametrically, because the three approaches presented—tracer studies, CFD simulations, and real process air sampling—involved different methodologies. Ventilation velocities were ranked 1 to 3 by exposures, from lowest to highest, in each of N trials, and the ranks were summed. Over the 28 trials with three observed ventilation velocities, the rank-sum exposure values were 72, 46.5, and 49.5, for approximately 50, 75, and 100 fpm (0.508 m/s), respectively. Over the eight trials in which real process sampling was performed for only two distinct velocities, the rank-sum exposures were 13 and 11, for nominally 75 and 100 fpm (0.381 and 0.508 m/s). Combining all 36 trials for the moderate and high velocities resulted in ranked exposures of 59.5 and 60.5, respectively. This analysis supports the earlier assertions that, while a velocity near 50 fpm (0.254 m/s) is clearly less protective, no clear effect is observed in the range of 75 to 104 fpm (0.762 to 0.528 m/s).

**Table 6. Sum of ranked outcomes for ventilation velocities**

Trial	N	50-66	75-80	85-104
Tracer I	5	13	7	10
Tracer II	1*	3	1	2
CFD-NBC I	6	18	12	6
CFD-NBC II	6	18	8.5	9.5
CFD-NBC III	5	9	9	12
CFD-MCAS	5	11	9	10
Total	28	72	46.5	49.5
Sampling: HDI monomer mean	2*		3	3
Sampling: HDI oligomer mean	2*		4	2
Sampling: TPM mean	2*		3	3
Sampling: Cr[VI] mean	2*		3	3
Sampling total	8*		13	11
Total	36		59.5	60.5

\*N = number of comparisons of means.

## **Conclusions and Recommendations**

Significant progress was made in the investigation of the relationships among airflow, ventilation configuration, and contaminant exposure in several DoD aircraft painting hangars. The results of extensive CFD modeling, tracer gas experiments, and exposure monitoring in a Naval Base Coronado painting hangar, further supported by additional CFD modeling in another painting facility at Marine Corps Air Station Cherry Point and by ventilation measurements at the Sioux City Air National Guard Base and at Joint Base Lewis McChord, have led to some insights on how to best control exposure through ventilation. The results of the

admittedly incomplete analyses of the four ESTCP sites converge to the following preliminary guidance:

## Conclusions

- Ventilation configuration greatly influences contaminant exposure (as observed qualitatively using smoke releases).
- Within a range of velocities from 75 to 100 fpm (0.508 m/s), ventilation velocity weakly influences contaminant exposure (evaluated quantitatively using air sampling, tracer experiments, and CFD simulation),
- Ventilation system maintenance was an issue in all facilities visited.
  - Some individual fans were down when the system controls were set to full at most facilities.
  - Exhaust filter overloading and supply filter disrepair were common.
  - Pressure imbalances greater than 0.05 in. w.g. were measured during many of the site visits.

## Recommendations

While the primary focus of this project was to demonstrate and validate the concept that lowering the ventilation flow rate would not increase occupational health hazards, we noticed that there could be improvements to the ventilation configuration as well. Our recommendations regarding the ventilation rate and ventilation configuration improvements are listed below:

- The results of this project indicate that a modest decrease in linear air velocity from approximately 100 fpm (0.508 m/s) to the range 75 to 80 fpm is a viable method of maintaining lower airborne contaminant concentrations, while reducing energy costs of ACCPFF. The observations below support this position.
  - Computational fluid dynamics studies of an F-18 and H-53 in separate hangars and tracer studies of the F-18 facility have shown that exposures resulting from 75 fpm (0.381 m/s) and from 100 fpm (0.508 m/s) are generally indistinguishable, while exposures resulting from each are clearly lower than from 50 fpm (0.254 m/s).
    - For spaces that are largely obstructed, such as underneath the fuselage, a main flow velocity of 100 fpm (0.508 m/s) may provide more air movement through these spaces (although this movement will normally be less than 100 fpm (0.508 m/s)).

- Because these spaces are not well ventilated by the bulk airflow through the hangar and have the highest exposures, it may be more effective to provide local exhaust via a flexible duct (elephant trunk) or to impel the air toward the exhaust using a stand-alone fan.
- Depending on factors such as ventilation configuration and hangar geometry, higher air velocity may generate turbulent flow patterns that can disperse contaminants into the breathing zone rather than move them directly to the exhaust.
- Personal exposure monitoring during painting at 104 and 80 fpm (0.528 and 0.406 fpm) has not shown a general increase in exposure for the lower velocity.
  - Exposures for the higher exposed group, i.e., sprayers, were lower for the lower velocity for three out of four materials (F-18).
  - Exposures for the lower exposed group, i.e., helpers or hosemen, were higher for the lower velocity for all four materials (F-18).
  - When C-2 and E-2 results at 80 fpm (0.406 m/s) are combined with F-18 results at 80 fpm (0.406 m/s), the lower velocity had lower exposures in five out of nine artisan-material pairs, although no differences were statistically significant.
  - Variability in the results across various sampling methods has shown the importance of using identical media and analytical techniques when investigating the effect of velocity on concentration.
- Maintaining a balance between supply and exhaust flow rate is important for effective transport of contaminants away from work areas and toward the exhaust.
  - Imbalanced supply and exhaust amounts to excess energy usage, because the degree to which one side of the system outpaces the other adds no contaminant removal benefit. Furthermore, an imbalance reduces ventilation effectiveness by causing (with too much supply) large circulations and additional turbulence in the flow or (with too much exhaust) infiltration of flows near the exhaust that short-circuit the normal flow through the work area.
  - If supply rate significantly exceeds the exhaust rate, exposure control and air pollution permit compliance will be improved by balancing the supply and exhaust. A slight excess of exhaust is preferred to

- maintain negative hangar pressure, perhaps -0.05 in. water (-0.0934 mmHg) gauge, to prevent fugitive emissions to the environment.
- If there is an exhaust deficit, a practical way to balance the system may include replacing exhaust pre-layers more frequently and keeping all exhaust filters at the lower end of the maintenance life, i.e. filter pressure drop. The exhaust velocity and the overall airflow patterns that were intended by design cannot be achieved when exhaust filters are blocked by the accumulation of paint droplets. Flow blockage also results in increased energy costs as the exhaust fan RPM must increase to deliver the required flow across a larger pressure drop.
    - In speaking with managers at the study sites, a common frustration was that the electric bill and the filter maintenance costs are handled by separate administrative entities. Any budgetary incentive to extend filter lifecycles into the range of inefficient system operation should be removed.
  - In future designs, careful matching of supply blower and exhaust fan sizing or linked control, perhaps through variable frequency drives, are system-balancing techniques that are worth considering.
  - While it is recognized that not all configurations are practical for all facilities and aircraft, the following is a ranking of configurations, from most to least effective, for exposure control.
    - Directional flow from nose to tail, created by floor-to-ceiling and wall-to-wall plenums.
      - Design deviations are acceptable only if flow reversals do not occur in the active work area.
    - Directional flow across the airframe, from one side to the other.
      - While the aircraft profile presents a large flow obstruction, the most important feature of effective ventilation is bulk air moving toward the exhaust in an organized manner, without reversals and with a minimum of turbulence.
    - Hybrid of ceiling supply and exhaust near nose and leading edge of wings seemed to work reasonably well for very large aircraft. Switching supply and exhaust in this configuration seems reasonable as well.
    - Directional flow from ceiling to floor or floor to ceiling
      - This configuration is difficult to implement without resorting to a number of individual air terminal devices—diffusers and intakes—that are generally unable to create uniform directional flow.

- If the air terminal devices are located near or arrayed in the pattern of the airframe—a design perhaps conceived with the mistaken concept that air in a free volume will move in a straight line— the situation may be improved by introducing curtains and partitions that channel the flow through the work area.
- The situation that must be avoided is mixing ventilation, which is characterized by circulations, airflow reversals, wide velocity variability, and long contaminant residence times.
  - A common scenario that creates mixing occurs when a large space is served by only a small number of air terminal devices. When supply jets are too far apart, their plumes do not merge into a single bulk of air, and flow reversals are set up between the plumes.
  - Individual exhaust terminals (as compared to a large plenum filter) are very limited in their range of capture because they draw air in from all open directions. The ventilation system should be designed and maintained to encourage flow through the hangar as if it were a very large rectangular duct.
- Any changes in ventilation operation should include provisions to prevent possible safety hazards (e.g., doors blowing open or closed) created by changes in hangar pressure.
- An airborne exposure assessment should be performed after any process changes to further verify worker protection.

### **Potential Future Studies**

- In addition to modeling existing paint finishing hangar ventilation systems, there remains room for continued exploration of innovative design using CFD. Reducing the hangar cross-sectional area to more closely fit each aircraft size and maintain a desired velocity at a lower volumetric flow rate, directing supplying air to the work zones more precisely, and bringing exhaust terminals closer to contaminant sources are examples of possible paths to consider that may reduce worker exposures, while also reducing associated energy costs.
- Real process exposure monitoring at different ventilation velocities was performed during paint refinishing of an F-18 strike fighter aircraft. Similar monitoring of a rotary wing and a larger fixed wing airframe would be logical next steps in the validation of reduced flow. Such direct evidence, if favorable, should reasonably mitigate the implementation risk of any

remaining skepticism among industrial hygienists, in light of the analyses presented in this report.

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