In-Depth Survey Report

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

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DEPARTMENT OF HEALTH AND HUMAN SERVICES
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Survey Dates:	June 16-20, July 21-23, August 2-4, 2009 April 10-14, 2010
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Abbreviations

µm – micrometer
µg/m^3 – micrograms per cubic meter
A_{CS} – Cross-sectional area of the hangar bay
A – Filter area
ACGIH – American Conference of Governmental Industrial Hygienists
AIHA – American Industrial Hygiene Association
ANOVA – Analysis of Variance
ANSI– American National Standards Institute
APF – Assigned Protection Factor
APR – air-purifying respirator
ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers
Ba – barium
BC – boundary condition
BUMED – Navy Bureau of Medicine and Surgery
BZ – breathing zone
CEMB – Chemical Exposure and Monitoring Branch
CFD – computational fluid dynamics
cfm/ft^2 – cubic feet per minute per square foot
CFR – Code of Federal Regulations
CGA – Compressed Gas Association
CNS – Central Nervous System
Cr – chromium
CrVI – hexavalent chromium
Cu – copper
DART – Division of Applied Research and Technology (within NIOSH)
EGBE – Ethylene Glycol Butyl Ether or 2-butoxyethanol
EPHB – Engineering and Physical Hazards Branch (within NIOSH)
fpm – feet per minute
FRCSW – Fleet Readiness Center Southwest
HDI – hexamethylene diisocyanate
HETAB – Hazard Evaluations and Technical Assistance Branch (within NIOSH)
HSD – honestly significant difference (in Tukey's t-test)
in. water gauge – inches of water relative to absolute pressure
LEL – lower explosive limits
LOD – limit of detection
MAK – methyl amyl ketone
MAP – 1-(9-anthracenylmethyl) piperazine
MDI – methylene diphenyl diisocyanate
MEK – methyl ethyl ketone
mg/m^3 – milligrams per cubic meter
MIBK – methyl isobutyl ketone
MIRAN – Miniature Infrared Analyzer
mm Hg – height of a mercury column in millimeters
MSDS – Material Safety Data Sheets

NAB – Naval Amphibious Base
NAVAIR – Naval Air Command
NAVFAC ESC – The Naval Facilities Engineering Service Center
NBC – Naval Base Coronado
NCO – isocyanate functional group
NFPA – National Fire Protection Association
NIOSH – National Institute for Occupational Safety and Health
NMCSD – Naval Medical Center San Diego
OEL – Occupational Exposure Limit
OSHA – Occupational Safety and Health Administration
PBZ – Personal Breathing Zone
PEL – OSHA Permissible Exposure Limits
ppm – parts per million
PVC – polyvinyl chloride
RANS – Reynolds-Averaged Navier-Stokes
REL – NIOSH Recommended Exposure Limit
RPM – revolutions per minute
SF_6 – sulfur hexafluoride
Sn – tin
Sr – strontium
STEL – Short-Term Exposure Limit
Ti – titanium
TLV – ACGIH Threshold Limit Value
TP – Total Particulates
TWA – Time-Weighted Average
V_{CS} – Air velocity measured at the bay cross-section
V – Air velocity measured at a filter
VFD – Variable Frequency Drive
VOCs – Volatile Organic Compounds
WPAFB – Wright-Patterson Air Force Base
XAD – polymeric adsorbent

Abstract

Researchers from the Centers for Disease Control and Prevention/National Institute for Occupational Safety and Health (CDC/NIOSH) investigated the performance of the ventilation system in a Navy aircraft paint finishing hangar, in terms of the efficiency and effectiveness of contaminant removal and worker exposure control. The Naval Facilities Engineering Service Center (NAVFAC ESC) and the Navy Medical Center San Diego (NMCSD), Industrial Hygienists collaborated with NIOSH in the study. The Navy seeks to keep worker exposures to air contaminants, including hexavalent chromium (CrVI), hexamethylene diisocyanate (HDI), methyl isobutyl ketone (MIBK), and others, below levels required by regulatory health and safety standards, while limiting the environmental footprint, i.e. energy use, and operational costs of paint finishing hangar ventilation. The specific operation under study was refinishing F/A-18C/D strike fighter aircraft in Bay 6 of Building 465, at Fleet Readiness Center Southwest, Naval Base Coronado, San Diego, California. Approximately twenty F-18s were processed per year in Bay 6, with each aircraft requiring 5 to 6 days.

In early 2008, a pilot study of the relationship between air velocity and exposure level was performed through computational fluid dynamic (CFD) simulations of a Navy aircraft painting facility. In those initial results, decreasing the ventilation rate by 50%, from 100 fpm to 50 fpm, increased the modeled gas concentration in a worker's breathing zone by 15%. However, during the current and more comprehensive study beginning in 2009, field observations indicated that the ventilation system was unbalanced, thus complicating the flow pattern and the relationship of velocity and concentration. The ventilation system's variable frequency drive (VFD) provided six different operational modes and controlled the system. In full painting mode, the VFD attempted to match the exhaust flow rate to the supply flow rate, so that air and contaminants would flow efficiently from the supply at one end of the bay to the exhaust filters at the other end. The bay was observed to be under positive pressure, meaning there was more supply than exhaust. This was found to be due to the inability of the exhaust to match the supply under higher filter bank pressure drops (as much as 2.5 in water gauge) that are encountered when the filter loading, with particles and paint, is at the moderate or high end of the filter maintenance cycle. To the extent the system is unbalanced toward supply, air inside the hangar (which contains contaminants) is likely emitted through the outside doors and other openings leading to a lower pressure area. In so doing, energy is wasted during moderate and high filter loading and, in some operational modes, heating, and environmental compliance is compromised. Therefore, one goal of this project was to correct the pressure imbalance under all operating conditions (thereby saving energy, improving ventilation efficiency, and reducing air emissions). The testing described in this report evaluated how changes, such as ventilation rates, might affect contaminant concentrations, worker exposures, and pressure levels within the hangar.

Evaluations of the hangar ventilation system were based on a combination of field studies and CFD simulations. Initially, a walk-through survey was conducted June 16-19, 2009, encompassing range-finding air-sampling (for CrVI, HDI, and any other contaminants found on the material safety data sheets) and the gathering of hangar dimensions, geometric details, and ventilation boundary conditions that would be used to set-up the CFD simulations. Next, the current ventilation system performance in terms of contaminant control was evaluated through comprehensive air sampling of all solvent, primer, and topcoat constituents, on July 22 and August 3, 2009 and April 13, 2010. At the same time, CFD simulations of the existing scenario were built and validated using the measurements. CFD was then used to predict concentration vs. air velocity and illustrate the relationship between volumetric flow rate of air (which has a large effect on energy use) and contaminant removal, from both health (contaminant exposure) and safety (fire and explosion) perspectives. Subsequently, a tracer gas study, with no workers present, was conducted April 12 and 14, 2010 to document the change in contaminant concentration resulting from lowering the ventilation rate (from a supply/exhaust velocity of 136/99.0 fpm down to 102/68.9 and 73.4/49.0 fpm) under real-world conditions. These studies led to the following conclusions:

1. Balancing the air supply and exhaust can improve exposure control and air pollution permit compliance. This finding is based on CFD simulations, and is consistent with ventilation standard practice.
2. Tracer gas measurements conducted during unbalanced supply and exhaust settings indicated that 3/4 of the normal supply and exhaust rates provided the lowest concentrations, when compared to full flow (supply = 136 fpm; exhaust = 99.0 fpm) and half-flow (supply = 73.4 fpm; exhaust = 49.0). 3/4-flow was a supply velocity of 102 fpm and an exhaust velocity of 68.9 fpm. 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.
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 -0.1 in. water.
4. Personal sampling of workers during typical aircraft refinishing operations showed that MEK (range: <0.03 to 665 ppm, with a STEL of 300 ppm), MIBK (range: 0.02 to 918 ppm, with a STEL of 75 ppm), isocyanates (range: 6.29 to 34.7 µg/m^3, with an ACGIH TLV of 35 µg/m^3) and hexavalent chromium (range: 145 to 537 µg/m^3, with an OSHA PEL of 5 µg/m^3, an ACGIH TLV of 10 µg/m^3, and a NIOSH REL of 1 µg/m^3) were the only air contaminants that approached or exceeded occupational exposure limits (OELs). The reported ranges were for exposures lasting approximately one hour, whereas the PELs, RELs, and TLVs are for an 8-hour or 10-hour time-weighted average (TWA), and the STEL applies to any 15-minute period. The sprayers have the highest exposures, and they wear air-line respirators, on continuous flow

mode, making their exposures approximately 1000 times lower than concentrations in workplace air.

5. The ventilation system does not adequately address worker exposure and requires supplementing with respiratory protection.
   Area air sampling measurements taken between the process and the exhaust filters indicated that concentrations of methyl isobutyl ketone (MIBK), methyl ethyl ketone (MEK), and all other materials measured in the aircraft refinishing process were less than 1% of any LEL. Thus, explosion from chemical concentrations is not an issue here.

Based on these conclusions, the following recommendations can be made:

1. The supply and exhaust airflow rates should be balanced to reduce exposure risk to workers. The balanced system should maintain the bay under slightly negative pressure (perhaps -0.1 in. water), if prevention of fugitive emissions to the environment is desired.
2. Tracer gas measurements should be performed at balanced ventilation settings to validate the concentration reduction predicted by the CFD simulations.
3. The respiratory protection program should be continued, under existing or feasibly modified ventilation.
4. 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 have a marked effect on operational efficiency.
5. After balancing or any other system modifications, follow-up concentration and velocity sampling should be done to verify ventilation improvements.
6. Measurements 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 area air sampling during this study clearly indicated that an explosion hazard was not present.
7. In addition to correcting existing aircraft painting facility ventilation systems, innovative design should be explored using CFD. Reducing the hangar cross-sectional area to 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 will reduce worker exposures, while also reducing associated energy costs.

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

$$V_{CS} = \left(\frac{A}{A_{CS}}\right)V,$$

where A and V are the face area and face velocity of the supply or exhaust openings.

Introduction

The Centers for Disease Control and Prevention (CDC)/National Institute for Occupational Safety and Health (NIOSH) 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 processes, 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 objective of each of these studies has 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 and techniques. Next, in-depth surveys are conducted to determine both 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 a Navy aircraft refinishing facility ventilation system was evaluated, alongside the appropriateness of the existing respiratory protection program. As the paint used to coat the planes contains hazardous chemicals, exposures must be addressed.

For some perspective, isocyanates are highly reactive, low molecular weight chemicals. They are the leading attributable chemical cause of occupational asthma in the US and many other industrialized countries. Affected workers must leave their jobs to prevent progression of the symptoms. Some of these symptoms include powerful irritation to the mucous membranes of the eyes, 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. However, the most serious case of exposure due to chemical sensitization from the isocyanates can result in severe asthma attacks which are sometimes fatal [NIOSH 1996, 2006].

The potential health effects of exposure to other chemicals in aircraft paints include, but are not limited to, central nervous system (CNS) depression and nasal cancer. These effects are linked to various solvents [Levy B.S. and D.H. Wegman 1988] and hexavalent chromates [NIOSH 2009], respectively. The ventilation system is ideally used to efficiently control the concentration of these contaminants released from the paint and to prevent the concentration from exceeding occupational exposure limits (OELs) set by regulatory and advisory health and safety organizations such as OSHA Permissible Exposure Limits (PELs), American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) and NIOSH Recommended Exposure Limits (RELs) while also limiting releases to the outdoor environment. In the aircraft painting process, however, protection against possible chemical sensitization from isocyanates requires exposure control that is feasible only in combination with a respiratory protection program, because sensitization can occur in some people at a very low dose.

This report evaluates the current ventilation system and the exposures of the aircraft painting workers to air contaminants. It also offers comparisons to other ventilation rates that are achievable with existing equipment or reasonable modifications. The Department of the Navy is motivated to reduce its energy costs and related greenhouse gas emissions, while maintaining a safe and healthy work environment. The interest NIOSH has in evaluating the aircraft painting operations is worker health and safety.

The Department of the Navy spends substantial funds to operate existing large paint hangars, with cross-sectional areas as large as 1,500 ft^2. The annual electricity cost for a hangar building configured into four paint finishing bays for smaller aircraft or two bays for larger aircraft is approximately $200K. OSHA standard, 29 CFR 1910.94 – *Ventilation*, requires that paint booths maintain an air velocity in the booth cross-section of 100 fpm [CFR a]. The Department of Defense (DOD) Unified Facilities Criteria (UFC) also refers to 1910.94, in specifying ventilation requirements [DOD 2004]. However, an OSHA interpretation of 1910.94 prepared for DOD corrosion control (paint) hangars stated that the hangars are paint spray areas and not booths. Recent communication between NIOSH and

OSHA suggested that the large size of the painting hangars leads to the spray area designation (please see Appendix D). The Navy must comply with training and respiratory protection standards and ensure compliance with 29 CFR1910, Subpart Z, which provides PELs for most of the materials involved in this study [CFR b]. The hexavalent chromium standard, 29 CFR 1910.1026, also comes into play. Specifically, part (f)(1)(ii), on painting large aircraft, allows respiratory protection to achieve the PEL (5 µg/m^3), if 8-hr TWA concentrations controlled through other methods do not exceed 25 μg Cr(VI)/m^3, "unless the employer can demonstrate that such controls are not feasible." [CFR c]. Limiting outdoor releases for compliance with the operating permit from the San Diego Air Pollution Control Board adds another requirement to the ventilation system.

Understanding the scientific relationship between air velocity and regulatory compliance is essential for the Navy to fulfill its goals in this area. NMCSD industrial hygienists and NAVFAC ESC engineers assist Fleet Readiness Center Southwest (FRCSW) in meeting Federal and DoD health and safety standards. NAVFAC ESC has the additional motivation of reducing the energy used for paint hangar ventilation, as part of the Navy's environmental sustainability program.

Every large Navy paint facility is currently designed to meet the OSHA paint booth requirement of 100 fpm as a target velocity, although the bay in the current study delivered more than 100 fpm of supply air. The OSHA value was chosen to: (1) prevent explosions, (2) reduce overspray and (3) protect worker health. In Navy aircraft painting operations, items 2 and 3 are addressed also to some extent by modern paint application methods. These include using high-volume low-pressure (HVLP) spray guns, which significantly reduce paint overspray, and the airline respirators worn by the workers when applying primer and paint to protect against volatile organic compounds (VOCs), isocyanates, chromates and other chemical stressors. For some perspective, the ACGIH recommends only 50 fpm for large vehicle paint booths [ACGIH 2010 A].

The investigation included comprehensive personal and area air sampling of the aircraft refinishing process under the existing ventilation conditions observed in the painting bay. Ventilation rates of half, 3/4, and all of the observed rate were evaluated through tracer gas experiments, without workers present. CFD simulations were also performed at various flow rates. The study took place in Building 465, Bay 6, at FRCSW. Four field surveys were conducted between June 2009 and April 2010.

While this study focused on the effect of air velocity, control of exposure to air contaminants cannot be summarized into a single number of feet per minute. The interaction of the flow with the work piece geometry, the workers, and the sources determines how quickly air contaminants, such as solvent vapors and paint overspray, are removed from the breathing zone. Thus, achieving a target velocity does not guarantee adequate exposure control, and local flow characteristics may play a larger role than overall flow rate in determining exposure outcomes.

Personal air sampling for contaminants was performed during unbalanced full flow conditions; tracer gas studies were performed under various unbalanced flow conditions; and, modeling was based mainly on balanced flow rates, but also included a hypothetical unbalanced case. Actual exposures were not determined with the system functioning as designed, i.e. a balanced 100 fpm cross sectional flow. Because the personal sampling was conducted under unbalanced conditions, it is difficult to extrapolate what actual exposures would occur during the process with balanced flow rates. Further study is warranted.

Plant and Process Description

The specific operation under study was 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). 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 airbase 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, which each 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, which paints approximately twenty aircraft per year. A team of seven artisans worked in Bay 6: the foreman, two sprayers, two sprayer helpers or "hosemen," and two workers who would rotate in as a sprayer or hoseman or do various jobs, such as material inventory and equipment preparation. Bay 6 is typical of other bays at FRCSW. During the study, however, only painting of whole aircraft was observed there, probably because that was the operation of interest. Painting individual aircraft parts was observed in other bays. Recent data show the annual production for the hangar that contains Bays 5 and 6 as: (38) F-18, (6) E-2, and (4) CH-53 helicopters.

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. For wheeling in large aircraft (such as the C-130), the supply walls of both bays are opened like a gate, the accordion door is opened and the two bays become one big hangar, served by two identical ventilation systems.

The refinishing group receives the aircraft after it has been abrasive blasted. When the aircraft enters the hangar, it is first sanded until smooth with hand held sanders. Next, the aircraft surfaces are examined for defects. These are potted with epoxy putty, which is sanded down when dry. The next task of the Navy painters (usually civilian employees) is to wipe down the plane with rags soaked in methyl iso-butyl ketone, and it is at this point that the NIOSH air sampling began. During sanding and wipe-down, the ventilation system is running at full capacity, and workers are in full-face air-purifying respirators (APRs) and Tyvek® suits.

When the surfaces are ready for spray painting, certain areas such as the cockpit canopy are covered with paper and masking tape.

Spray painting involves three products: green primer, dark gray paint and light gray paint. Dark gray is sprayed on the top surfaces of the Hornet, and then light gray is sprayed on the bottom. Leading the list of hazardous materials are hexavalent chromium in the primer and hexamethylene diisocyanate in the paints. During application, the sprayers wear supplied air hoods and Tyvek® suits and the hosemen who assist the sprayers with keeping the various lines clear and untangled wear either supplied air hoods or full-face air purifying respirators. Two sprayers and two hosemen work in the bay during coat application, and workers who will be assigned a role in the next process wait near the supply air wall, where contaminant concentrations were undetectable during air sampling. The hangar temperature is usually maintained at 75 ^{o}F. After application of the primer and again after application of both paints, the artisans exit to the outdoors, the bay is brought up to 120 ^{o}F to bake the coatings, and the flow is reduced to 25%.

Detail work follows the spray operations, including stenciling of decals that identify the aircraft as a U.S. Navy or U.S. Marine Corps fighter. The finished plane is then “sold” to the operational group, after a thorough inspection. The entire process typically lasts from five to six days.

Description of Controls and Equipment

Engineering Controls

Bay 6, in Building 465 of Fleet Readiness Center South West (FRCSW) is served by four supply blowers and four exhaust fans, with exhaust fan speed linked to blower function via variable frequency drive (VFD) controllers. These are managed by Siemens, Inc. Two of the supply blowers are equipped with steam heat elements. The design functions of this ventilation system are to maintain a safe and healthy work environment, to control and collect sanding particulate and paint overspray before they enter the ambient, and to maintain the temperature needed for painting operations. Figures 1 and 2 show the configuration of the bay, filters, and aircraft, with a supply wall blowing air toward an exhaust wall at the opposite end of the bay.

The design air velocity target at full capacity is 100 cubic feet per minute per square foot of cross-sectional area, cfm/ft^2 or fpm. This criterion was based on the use of 29 CFR1910.94(c)(6)(i), Table G-10, Minimum Maintained Velocities Into Spray Booths [CFR a], even though the bay seems to fit the OSHA definition of a spray area (which does not have a prescribed air velocity) rather than a spray booth.

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

$$V_{CS} = \left(\frac{A}{A_{CS}}\right)V \text{ ,}$$

where A and V are the face area and face velocity of the supply or exhaust openings. This is a conservative approach, because velocities thus defined will be lower than velocities measured in the empty bay, which would not normally include the slower flow in the boundary layer of walls, floor, and ceiling.

An alternative statement of velocity could have been the speed of the air coming out of the supply filter, which covers most of the supply end wall. CFD simulations showed that the velocity at the filter is a good representation of the velocity just upwind from the nose of the aircraft, which is the velocity specification implied by the OSHA ventilation standard, 1910.94. Then, the stated exhaust velocity can be the actual velocity going into the exhaust filter multiplied by the ratio of exhaust filter area to supply filter area, so that both supply and exhaust stated velocities represent the volumetric flow. Normalization is necessary because the supply and exhaust openings differ in size: A_S = 1274 ft^2 and A_E = 551 ft^2. The various possibilities for defining the bay flow rate show that the issue of what the velocity is or should be cannot be separated from where that velocity occurs.

Personal Protective Equipment

All hangar personnel wore Tyvek® suits. Airline hood respirators were always used by the workers applying the primer and the top coats. The hosemen were observed to wear either airline hood or full-face, air-purifying respirators. Respirators are needed, even with engineering controls present, to protect against hexavalent chromium and chemical sensitization from the isocyanates. The respirators also reduce exposure to volatile organic compounds (VOCs) and other airborne stressors, either gas or aerosol.

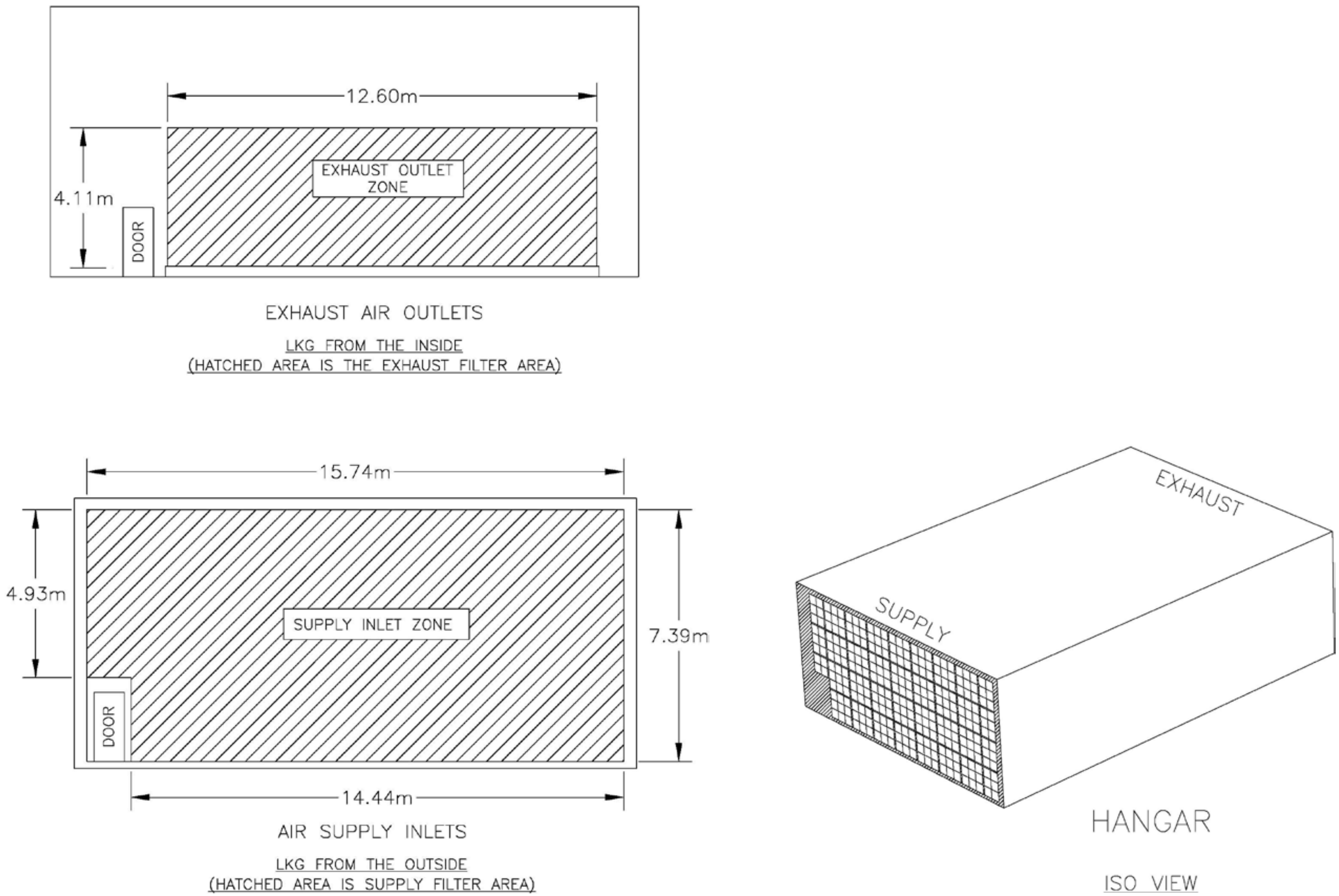


Figure 1. Drawing showing filter area of Bay 6, Building 465, Fleet Readiness Center Southwest, San Diego, CA.

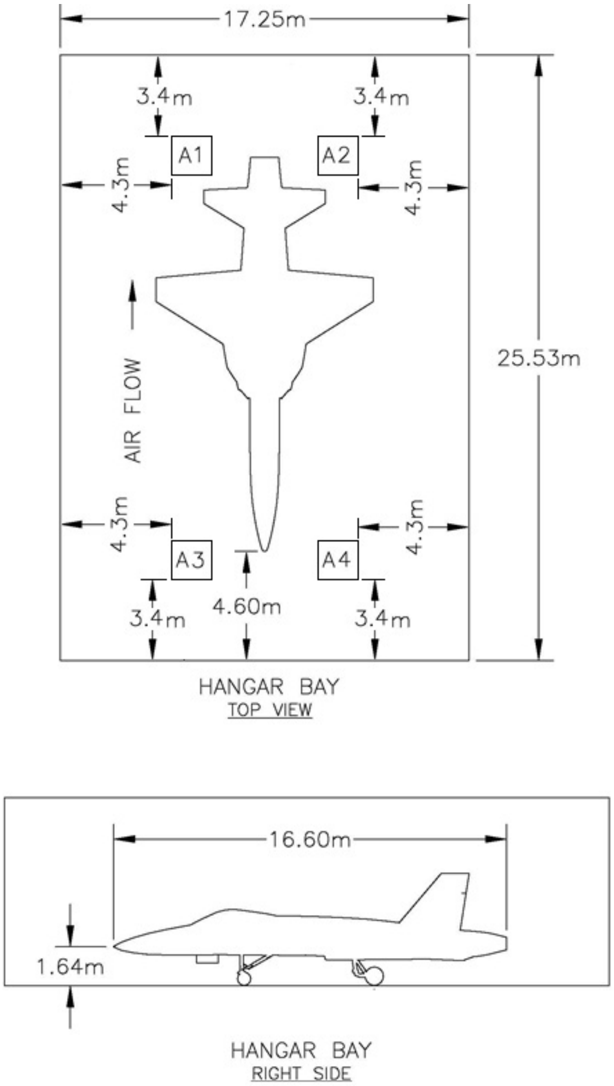


Figure 2. Drawing showing interior of bay, F/A-18C/D Hornet, and area sample locations (A1 – A4). Bay 6, Building 465, Fleet Readiness Center Southwest, San Diego, CA.

Methodology

NIOSH researchers studied the relationship between worker exposure and hangar ventilation in a comprehensive manner. This involved a combination of field studies and CFD simulations. This field study was conducted in accordance with 42 CFR 85a, the NIOSH regulations governing the investigation of places of employment. Initially, a walk-through survey was conducted, encompassing range-finding air-sampling and the gathering of geometric and ventilation boundary condition information for CFD. Next, the current ventilation system performance in terms of contaminant control was evaluated through air sampling. At the same time, CFD simulations of the existing scenario were built and validated using the measurements. CFD was then used to test the relationship of predicted contaminant concentration and air velocity, from both exposure and fire safety points-of-view. Subsequently, a tracer gas study with no workers present was conducted to document the change in contaminant concentration and ventilation rate/energy use resulting from altering the bay ventilation rate.

VENTILATION EVALUATION

The function of the ventilation from a mechanical point-of-view was investigated by a team consisting of a NAVFAC engineer, NMCSD industrial hygienist, and a NIOSH engineer. The equipment consisted of a Shortridge AirData Multimeter, AMD-860 with current calibration certification, a Shortridge VelGrid, two sections of 20-foot tygon tubing, and an extension pole capable of 25 feet in length. Basic operation, i.e. which fans are on or off, was observed by noting the sequence number that the system was set to and by climbing up to the hangar building roof and noting sound and vibration. Secondarily, a computer was sometimes available with software that tracked the performance of the exhaust fans. The air permit from the San Diego County Air Pollution Control Board was inspected on site. The permit requires the exhaust filter pressure drop to be “maintained between 0.5 and 2.25” in. water gauge and that “exhaust fans and exhaust filters…are installed and operating properly."

The pressure drop across the exhaust filter bank was read from the gauge in the control room before the start of each painting cycle. The static differential pressures were also measured across the bay/ambient, bay/control room, and control room/ambient at the beginning of each paint cycle, using a ShortRidge AirData Multimeter. The filter face velocities were measured prior to start of each painting cycle and after final top coat application. All face velocity measurements were taken using the VelGrid attachment to a ShortRidge AirData Multimeter. The supply measurement locations were a grid overlaying the physical grid formed by the filter housing beams, such that the measurements were taken at the centers of these “cells.” See Figures 3 and 4. Similar measurements were taken at the exhaust filter. Also, velocity measurements were taken in a matrix of 16 locations at the bay midpoint between supply and exhaust terminals.

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

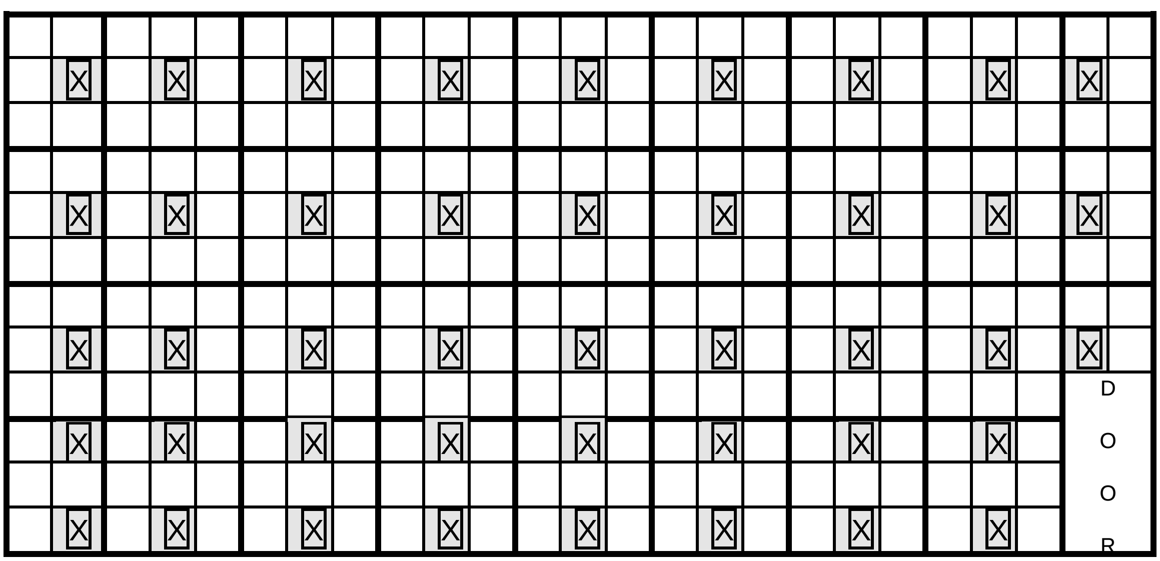


Figure 4. Supply measurement matrix of 43 locations on the filter, viewed from inside the bay

AIR SAMPLING

Air sampling was conducted in Building 465, Bay 6 to evaluate air concentrations of compounds present in paints, primers, and solvents used to spray paint F/A-18C/D Hornet strike fighter aircraft. All sampling occurred under the existing, full-flow ventilation conditions. Sampling was conducted on three separate surveys: July 23, 2009; August 4, 2009; and April 13, 2010. Sampling was conducted in three phases during each survey: wiping the aircraft down using methyl isobutyl ketone; spray painting the aircraft using a chemically cured two component chromate, epoxy polyamide water reducible primer paint (Deft 44-GN-007, Mil-PRF-85582D, Type I, Class C1); and spray painting the aircraft using a chemically-cured, two-component polyurethane topcoat paint in both light and dark gray (light gray: Deft 03-GY-292, Mil-PRF-85285D, Type I, Class H and dark gray: Deft 03-GY-287, Mil-PRF-85285D, Type I, Class H).

Using Material Safety Data Sheets (MSDS) of the paints as a guide, air samples were collected for select volatile organic compounds (VOC), total particulates (TP), hexavalent chromium (CrVI), select metals, nitroethane, and hexamethylene diisocyanate (HDI). The source of CrVI was the epoxy polyamide primer, which contained barium chromate and zinc chromate, in component A. During the aircraft wipe down phase of the spray painting operation, only VOC samples were collected. VOCs, TP, CrVI, select elements, and nitroethane air samples were collected during the primer spray painting phase. VOC, TP, select elements, and HDI air samples were collected during the top coat paint spray painting phase. Both personal breathing zone (PBZ) and area air samples were collected during the three phases of the aircraft painting operation. All workers that were sampled wore disposable Tyvek® coveralls, neoprene gloves, and a Tyvek® hood supplied air respirator. PBZ samples were collected by attaching, to the worker's belt, an air sampling pump connected by tubing to the sample media that were placed on his supplied air hood. Area air samples were collected on tripods at four corners surrounding the F/A-18C/D Hornet, two tripods upwind of the source (aircraft) and two tripods downwind, as shown in Figure 2. The sample media on the tripods were approximately 5 ft above the floor.

The VOCs sampled included: 2-butoxyethanol (EGBE); n-butyl acetate; cumene; ethyl benzene; methyl amyl ketone (MAK); methyl ethyl ketone (MEK); methyl isobutyl ketone (MIBK); toluene;1,2,4-trimethylbenzene; and 1,3,5-trimethylbenzene. These organic compounds were selected to be sampled based on the MSDSs. VOC samples were collected using charcoal tubes (front section 100 mg and back section 50 mg) at air sampling flow rates of 50 ml/min and 200 ml/min. Charcoal tube analysis was done using NIOSH method 1501 with modifications to accommodate methyl ethyl ketone, methyl isobutyl ketone, methyl amyl ketone, and 2-butoxyethanol [NIOSH 1994]. The solvent used to desorb the charcoal tubes was modified from carbon disulfide to 5% n-propanol/95% carbon disulfide solution. Both PBZ and area air samples were collected for VOCs for all three phases of the aircraft spray painting operation.

TP and CrVI air samples were collected on pre-weighed polyvinyl chloride (PVC) filters (37 mm diameter and 5.0 µm pore size) at an air flow rate of 2.0 liter per minute (lpm). TP and CrVI were analyzed according to NIOSH methods 0500 and 7605, respectively [NIOSH 1994]. Both PBZ and area air samples were collected for TP and CrVI during the primer phase of the spray painting operation.

The select metals sampled included barium (Ba), chromium (Cr), copper (Cu), tin (Sn), strontium (Sr), and titanium (Ti). These elements were chosen for analysis based on information derived from the MSDSs. The samples were collected on pre-weighed PVC filters (37 mm diameter and 5.0 µm pore size) at an air flow rate of 2.0 lpm. Total particulates were analyzed according to NIOSH method 0500. Samples were then digested and analyzed for the selected metals according to NIOSH method 7303 [NIOSH 1994]. Metal samples were only collected as area air samples during the primer and topcoat painting phases.

Nitroethane samples were collected using XAD 2 tubes (600 mg front section and 300 mg back section) at an air sampling flow rate of 50 ml/min. Analyses of the nitroethane samples were done according to NIOSH method 2526 [NIOSH 1994]. Nitroethane samples were only collected during the primer phase of the aircraft spray painting operation and only as area air samples.

Air samples collected for HDI were collected on glass fiber filters (37 mm diameter) impregnated with 1-(9-anthracenylmethyl) piperazine (MAP) at an air sampling flow rate of 1.0 lpm. Once the samples were collected, the filters were desorbed in the field in 5 ml solution of acetonitrile with 1 X 10^{-4} M MAP. Analyses for HDI were done according to NIOSH method 5525 [NIOSH 1994] with modifications. In addition to HDI monomer results, isocyanate functional group (NCO) monomer and oligomer results also were provided. Both PBZ and area air samples were collected during the topcoat spray painting phase.

The personal and area sampling was performed only during the specific phases of the refinishing process (wipe-down, priming, painting) rather than over the course of the entire work shift. Because each of the three processes involved different materials, without significant exposures to that material in the other two processes, task-specific sampling was the more efficient method of measuring the various exposures. In cases where approaching or exceeding an 8 or 10-hr OEL was plausible, the TWA was constructed from the task concentrations and their durations, while assuming zero exposure in between operations. The TWAs that exceeded OELs are reported in the Results section and in Appendix A.

The isocyanate samples were analyzed by the Chemical Exposure & Monitoring Branch (CEMB) of NIOSH. All other analyses (gravimetric; organic; vapor, nitroethane; the elements Ba, Cr, Cu, Sn, Sr, and Ti, and CrVI) were done by Bureau Veritas North America (Novi, MI). CEMB and Bureau Veritas are each accredited by the American Industrial Hygiene Association (AIHA).

CFD SIMULATION

Because of the substantial cost and impracticality of ventilation system modifications on a trial basis and because of human subject concerns, proposed design air velocities were simulated using computational fluid dynamics (CFD) to gain performance insights. Performance information is more useful and cost-effective before modifications are made. CFD models were created for both the existing system and the proposed systems using identical techniques. CFD is a numerical method that solves the system of equations that describe fluid behavior, using a computational grid. Applied here, the fluids are air and a contaminant that needs to be controlled. In the model, contaminant with the physical properties of MIBK was emitted, in both vapor and liquid droplet forms, from the hand areas of two simulated workers at commonly observed spraying locations, at a flow rate specified by the spray gun manufacturer. The MIBK vapor was given its documented density of 4.23 kg/m^3, about 3.5 times denser than air, and its documented viscosity of 6.70 x 10^{-6} kg/m-s, which is less than half as viscous as air. The MIBK droplets were given their documented density of 800 kg/m^3 (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 the “air” in the hangar. Turbulence was modeled using the standard Reynolds-averaged Navier–Stokes (RANS) k-ε model. With turbulence intensity and length scale used as boundary conditions, intensity was set at 10 percent and length scale at one meter for the large filter area BCs 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). NIOSH provided solid models representing workers in Tyvek® suits, using Solidworks (Dassault Systemes SolidWorks Corp., Concord MA). The geometry shown in Figure 5 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 site visits. The solution utilized a RANS turbulence model and was steady-state. The iterative convergence criteria were normalized residuals decreasing below 10^{-4} to nearly 10^{-5} in most cases. Solution instability was a persistent problem until the under-relaxation parameters for pressure correction, velocity, and turbulence were set 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.

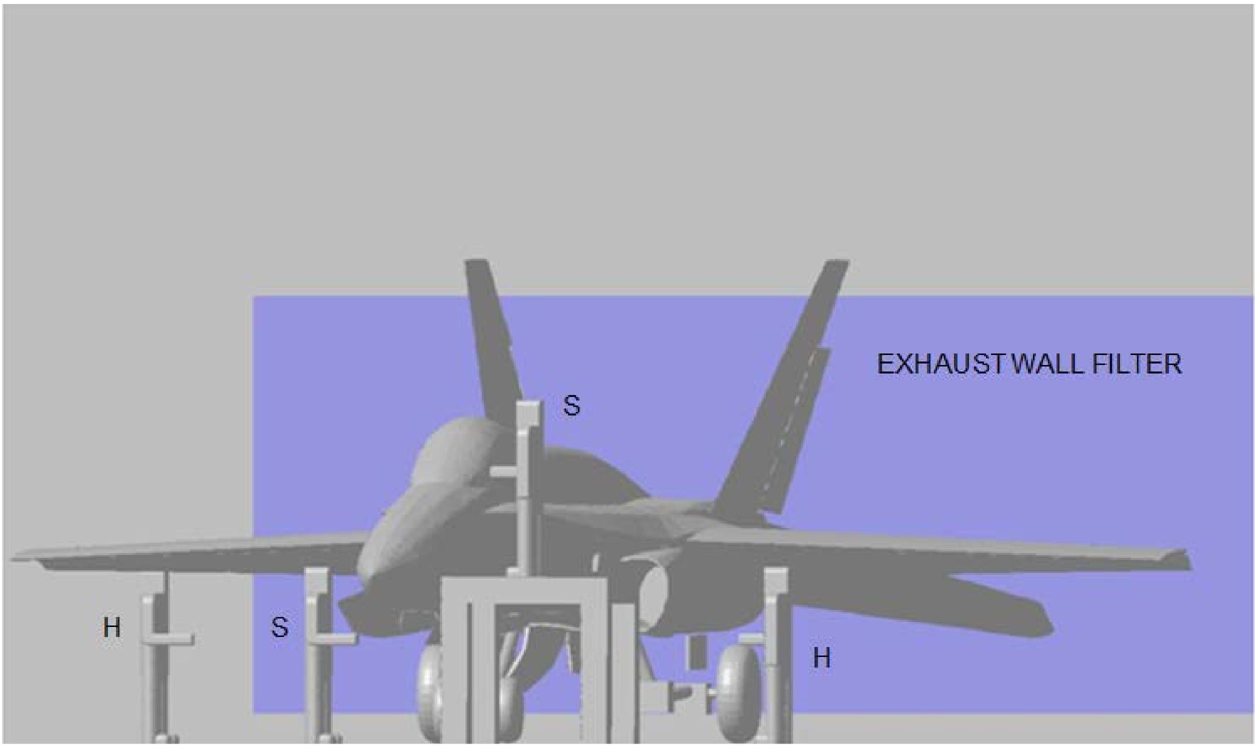


Figure 5. Geometry of simulated workers, exhaust wall filter, and F/A-18C/D Aircraft. Hosemen (H) are further from the aircraft and further downwind than sprayers. The contaminant source is located at the end of the sprayers' (S) right arms. One sprayer is on a scaffold.

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.

This project was originally conceived by the Navy as a CFD comparison of the exposure reduction effectiveness of 100 fpm versus lower rates, such as 75 or 50 fpm. The CFD simulations were designed with these velocities as the supply filter boundary conditions to represent what would be measured in a field inspection. However, the unbalanced condition of the real ventilation in Bay 6 made the theoretical average velocity in the entire bay cross section [$V_{CS} = V_S (A_S / A_{CS})$] a better value, with which to compare CFD, air monitoring, and tracer gas results. V_{CS} and A_{CS} are the cross-sectional velocity and area, and V_S and A_S are the supply filter velocity and area. Therefore, the reported CFD velocities are not just the familiar values of 100 and 75 fpm. Instead, they include 86.6, 65.0, and 43.3 fpm, because the supply filter area is only 86.6% of the cross-sectional area of the bay, or A_S/A_{CS} = (118.4 m^2/136.7 m^2) = 0.866. Table 3 in the Results section lists all air velocities involved in the study.

TRACER GAS

Tracer gas is commonly used to evaluate the performance of a ventilation system. The industrial hygiene literature indicates that tracer gas is an appropriate evaluation method to test the removal efficiency of a hazard even in particulate form. ANSI/ASHRAE Standard 110-1995 states that “fine dust, small enough to be of health significance will be carried along with the hood air currents in a fashion similar to the transport of a gas” [ASHRAE 1995]. In Hemeon’s “Plant and Process Ventilation” [Hemeon, 1999], the author states that “to control small particle motion, one must control the motion of the air in which the small particles are suspended.” The authors in “Risk Assessment of Chemicals” [Leeuwen and Vermeire 2007] describe how “small particles tend to behave like gases.” Probably the most compelling study compared capture efficiencies measured by tracer gas and aerosol tracer techniques and concluded that the transfer of aerosol to a local exhaust system was “nearly identical to that of a gas” for particles with diameters less than 30 µm [Beamer, et al. 1997]. Because local exhaust ventilation involves accelerating flows, it provides more opportunity for particle paths to deviate from air streamlines. The situation in the hangar bay has accelerating particle flow in the form of the paint spray, but the main flow is somewhat uniform in velocity at a relatively small distance from the aircraft surface.

A tracer gas method was used to quantitatively compare the effectiveness of the ventilation system at four different settings: full-flow, 3/4-flow, half-flow, and 1/4-flow. The tracer gas used was 99.5% minimum purity sulfur hexafluoride (SF_6). A dual stage series 200 brass regulator with a CGA 590 inlet was connected to the tracer gas cylinders. The gas was supplied through ¼ in. diameter Teflon® tubing and controlled using a mass flow controller set to 500 ml/min. The mass flow controller was manufactured by Aalborg (model GFC17, Aalborg Instruments and Controls, Inc., Aalborg, Denmark) and had a flow range of 0-1000 ml/min when calibrated to SF_6. Tracer gas was released during three different tracer gas release scenarios each having a different configuration of the source at the release location near the front of the F/A-18C/D Hornet. During the first release scenario, the source configuration was a single source of SF_6 located near the front of the aircraft released at 500 ml/min as shown in Figure 6. During the second and third release scenarios, the source configurations were split into two locations each releasing 250 ml/min of SF_6 as shown in Figure 6.

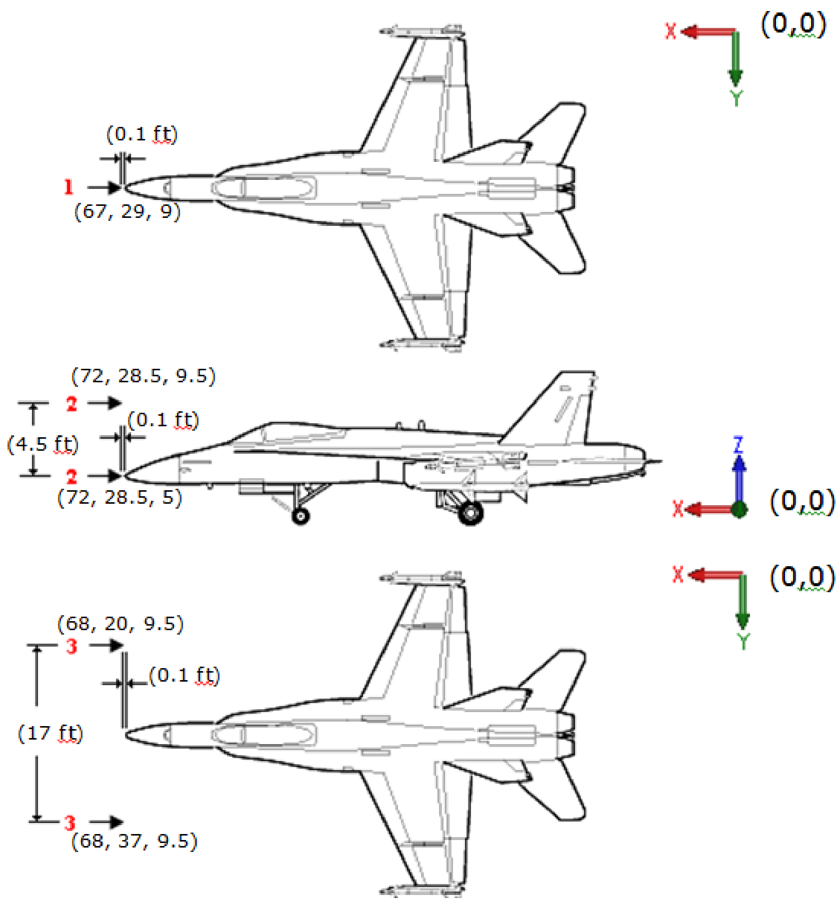


Figure 6: Source locations for the release of SF_6 near the front of the F/A-18C/D Hornet. Source: http://www.boeing.com/defense-space/military/fa18/fa18cd3v.htm

When evaluating the ventilation system, the concentration of the SF_6 was measured using five MIRAN® Sapphire Specific Vapor Analyzers (Thermo Environmental Instruments, 8 West Forge Parkway, Franklin, MA 02038). Each MIRAN® measured SF_6 continuously for 30 minutes at each ventilation setting. The ventilation system was adjusted to achieve room velocities corresponding to approximately 118 fpm, 85.4 fpm, 61.2 fpm, or 30.0 fpm. Tracer gas concentrations of SF_6 were logged to each MIRAN® Sapphire at two-second intervals and later downloaded to a laptop computer. Approximate locations of each MIRAN® Sapphire around the F/A-18C/D Hornet during the first release scenario are shown in Figure 7. Source locations and sample locations for the first source release scenario are provided in Table 1. The origin of the coordinate system is the point where the starboard wall, exhaust wall, and floor intersect, shown schematically in Figure 7.

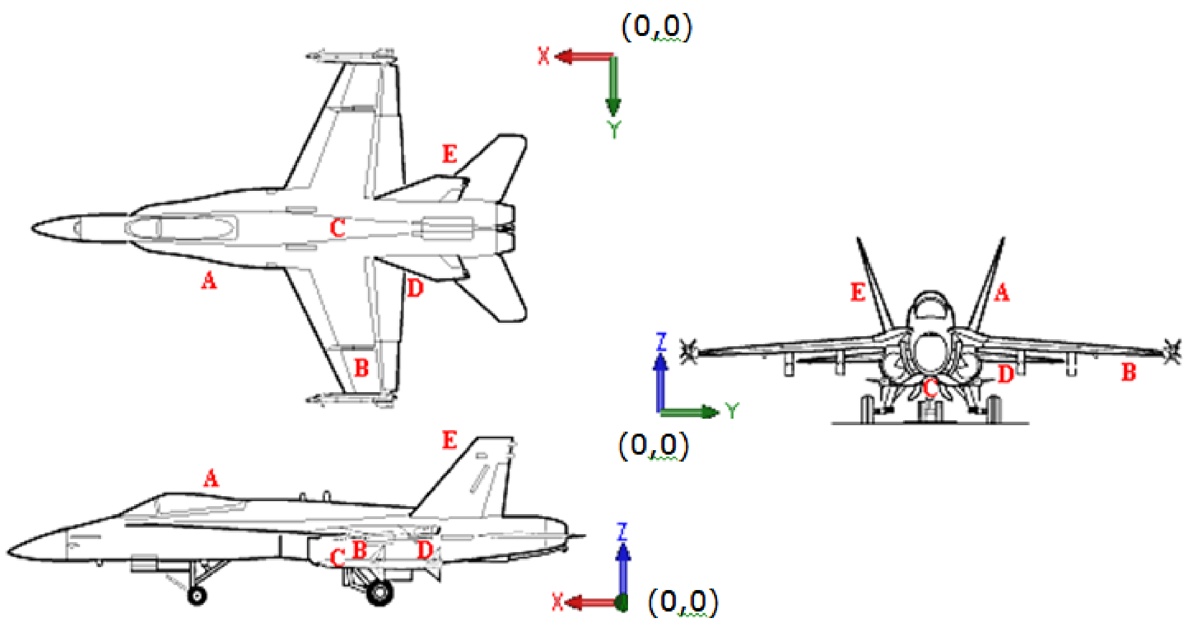


Figure 7: Approximate locations of the five MIRAN® Sapphires around the F/A-18C/D Hornet during the first release scenario. Source: http://www.boeing.com/defense-space/military/fa18/fa18cd3v.htm

Table 1: Source and sample locations for the first source configuration

	X (ft)	Y (ft)	Z (ft)
Source 1:	67	29	9
A	41	34	11
B	31	38	4.75
C	37	29	3
D	24	32	4.75
E	20	21	15

Sample location D was placed on the port side of the aircraft during the first tracer gas source release scenario. This was done since preliminary testing indicated that the ventilation system caused the tracer gas to migrate to the port side of the aircraft when a single source was placed near the nose. Sample location D was placed on the starboard side of the aircraft for the second and third tracer gas release scenarios. Approximate locations of each MIRAN® Sapphire around the F/A-18C/D Hornet during the second and third release scenarios are shown in Figure 8. Source locations and sample locations for the second and third source release scenarios are provided in Table 2.

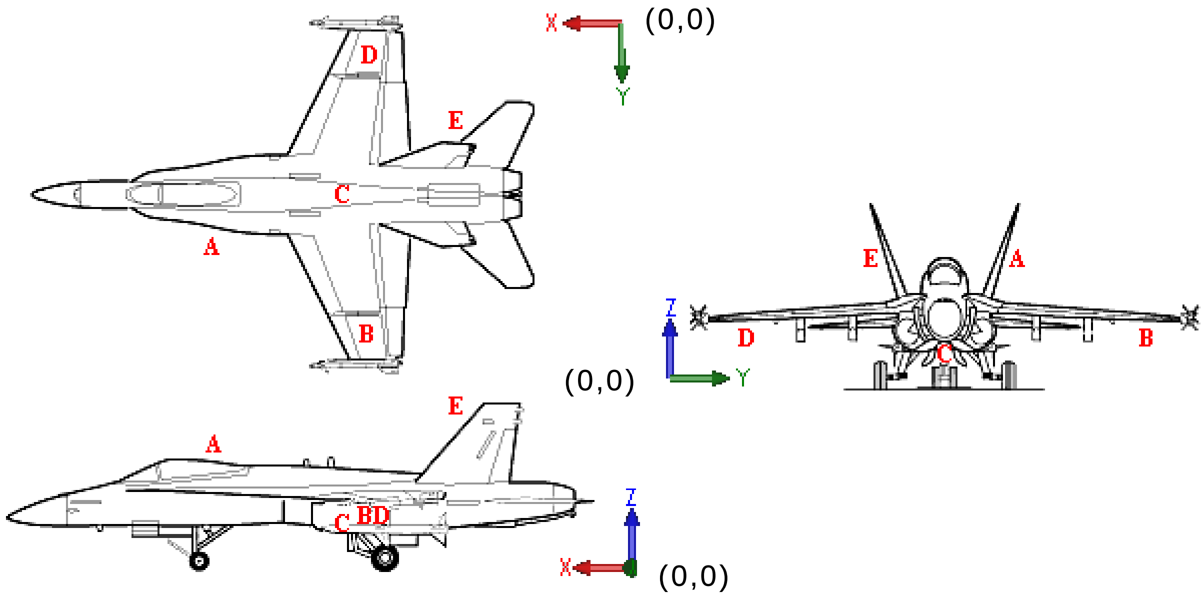


Figure 8: Approximate locations of the five MIRAN® Sapphires around the F/A-18C/D Hornet during the second and third release scenarios. Source: http://www.boeing.com/defense-space/military/fa18/fa18cd3v.htm

Table 2: Source and sample locations for the second and third source configurations

	X (ft)	Y (ft)	Z (ft)
Source 2 Lower:	72	28.5	5
Source 2 Upper:	72	28.5	9.5
Source 3	68	20	9.5
Source 3 Port:	68	37	9.5
A	44	36	17.5
B	32	40	4.75
C	36	29	3
D	31	15	4.75
E	22	18	13.5

Each measurement was recorded for a thirty minute interval. The changeover to a new ventilation rate, including checking the status of the five MIRAN real-time tracer gas monitors and 15 minutes to let the new flow situation reach equilibrium, was observed to require about 30 minutes also.

Evaluation Criteria

OCCUPATIONAL EXPOSURE LIMITS AND HEALTH EFFECTS

As a guide to the evaluation of the hazards posed by workplace exposures, NIOSH investigators use mandatory and recommended OELs when evaluating chemical, physical, and biological agents in the workplace. Generally, OELs suggest levels of exposure to which most workers may be exposed up to 10 hours per day, 40 hours per week for a working lifetime without experiencing adverse health effects. It is, however, important to note that not all workers will be protected from adverse health effects even though their exposures are maintained below these levels. A small percentage may experience adverse health effects because of individual susceptibility, a pre-existing medical condition, and/or hypersensitivity (allergy). In addition, some hazardous substances may act in combination with other workplace exposures, the general environment, or with medications or personal habits of the worker to produce health effects even if the occupational exposures are controlled at the level set by the exposure limit. Combined effects are often not considered in the OEL. Also, some substances are absorbed by direct contact with the skin and mucous membranes, and thus can increase the overall exposure. Finally, OELs may change over the years as new information on the toxic effects of an agent become available.

Most OELs are expressed as a TWA exposure. A TWA exposure refers to the average airborne concentration of a substance during a normal 8- to 10-hour workday. Some substances have recommended STEL or ceiling values which are intended to supplement the TWA where there are recognized toxic effects from higher exposures over the short-term.

In the U.S., OELs have been established by Federal agencies, professional organizations, state and local governments, and other entities. The U.S. Department of Labor OSHA PELs are occupational exposure limits that are legally enforceable in covered workplaces under the Occupational Safety and Health Act. NIOSH recommendations are based on a critical review of the scientific and technical information available on the prevalence of health effects, the existence of safety and health risks, and the adequacy of methods to identify and control hazards [NIOSH 1992]. They have been developed using a weight of evidence approach and formal peer review process. Other OELs that are commonly used and cited in the U.S. include the TLVs® recommended by ACGIH®, a professional organization [ACGIH 2010]. ACGIH TLVs are considered voluntary guidelines for use by industrial hygienists and others trained in this discipline “to assist in the control of health hazards.” WEELs are recommended OELs developed by AIHA, another professional organization. WEELs have been established for some chemicals "when no other legal or authoritative limits exist." [AIHA 2007 a].

OSHA requires an employer to furnish employees a place of employment that is free from recognized hazards that are causing or are likely to cause death or serious physical harm [Occupational Safety and Health Act of 1970, Public Law 91–596, sec. 5(a)(1)]. Thus, employers are required to comply with OSHA PELs. Some hazardous agents do not have PELs, however, and for others, the PELs do not reflect the most current health-based information. Thus, NIOSH investigators encourage employers to consider the other OELs in making risk assessment and risk management decisions to best protect the health of their employees. NIOSH investigators also encourage the use of the traditional hierarchy of controls approach in eliminating or minimizing identified workplace hazards. This includes, in preferential order, the use of: (1) substitution or elimination of the hazardous agent, (2) engineering controls (e.g., local exhaust ventilation, process enclosure, dilution ventilation) (3) administrative controls (e.g., limiting time of exposure, employee training, work practice changes, medical surveillance), and (4) personal protective equipment (e.g., respiratory protection, gloves, eye protection, hearing protection).

SPECIFIC OELs and HEALTH EFFECTS

OELs for the Aircraft Refinishing Process

Exposure criteria with which to compare the air sampling results collected during F/A-18C/D Hornet spray painting operations are listed in the Appendix in Table A-1. Included in Table A-1 are lower explosive limits (LEL), OSHA PELs, NIOSH recommended exposure limits (RELs), and other OELs. The LEL describes the leanest mixture that is still flammable, i.e. the mixture with the smallest fraction of combustible gas.

In February 2006, OSHA issued a comprehensive standard, governing occupational exposures to CrVI. Included in this rule is a new PEL of 5 µg CrVI/m^3 for 8-hr TWA exposures to all CrVI compounds, with an action level of 2.5 µg/m^3. Exceeding the action level for 30 days or more per year triggers certain requirements such as periodic sampling and medical surveillance. The new PEL contains a special provision for exposures during the spray application of chromate-containing paints onto whole aircraft or large aircraft parts. This provision allows compliance with the PEL using personal protective equipment as long as 8-hr TWA concentrations achieved with engineering and work practice controls do not exceed 25 µg CrVI/m^3 [CFR c]. The NIOSH REL for CrVI is a TWA of 1.0 µg/m^3 for an up to 10-hour exposure [NIOSH 2005]. The ACGIH TLV for CrVI depends on water solubility: 50 µg/m^3 (soluble) and 10 µg/m^3 (insoluble), each as an 8-hr. TWA. In the MSDS for the epoxy polyamide primer, the CrVI compounds, barium chromate and zinc chromate, are said to be insoluble in water, making the applicable TLV 10 µg/m^3.

Health Effects of Exposure to Hexamethylene Diisocyanate

Exposure to isocyanates is irritating to the skin, mucous membranes, eyes, and respiratory tract. The most common adverse health outcome associated with isocyanate exposure is asthma due to sensitization; less prevalent are contact dermatitis (both irritant and allergic forms) and hypersensitivity pneumonitis (HP). Contact dermatitis can result in symptoms such as rash, itching, hives, and swelling of the extremities. A worker suspected of having isocyanate-induced asthma/sensitization will exhibit the traditional symptoms of acute airway obstruction, e.g., coughing, wheezing, shortness of breath, tightness in the chest, and nocturnal awakening. An isocyanate-exposed worker may first develop an asthmatic condition (i.e., become sensitized) after a single (acute) exposure, but sensitization usually takes a few months to several years of exposure. The asthmatic reaction may occur minutes after exposure (immediate), several hours after exposure (late), or a combination of both immediate and late components after exposure (dual). The late asthmatic reaction is the most common, occurring in approximately 40% of isocyanate sensitized workers. After sensitization, any exposure, even to levels below an occupational exposure limit or standard, can produce an asthmatic response that may be life threatening. Experience with isocyanates has shown that monomeric, prepolymeric and polyisocyanate species are capable of producing respiratory sensitization in exposed workers [NIOSH 2003].

Currently, the prevalence of isocyanate-induced HP in the worker population is unknown and is considered to be rare when compared to the prevalence rates for isocyanate-induced asthma. Whereas asthma is an obstructive respiratory disease usually affecting the bronchi, HP is a restrictive respiratory disease affecting the lung parenchyma (bronchioles and alveoli). The initial symptoms associated with isocyanate-induced HP are flu-like, including shortness of breath, nonproductive cough, fever, chills, sweats, malaise, and nausea. After the onset of HP, prolonged and/or repeated exposures may lead to an irreversible decline in pulmonary function and lung compliance and to the development of diffuse interstitial fibrosis. Early diagnosis is difficult since many aspects of HP, i.e., the flu-like symptoms and the changes in pulmonary function, are manifestations common to many other respiratory diseases and conditions [NIOSH 2003].

The only effective intervention for workers with isocyanate-induced sensitization (asthma) or HP is cessation of all isocyanate exposure. This can be accomplished by removing the worker from the work environment where isocyanate exposure occurs, or by providing the worker with supplied-air respiratory protection and preventing any dermal exposures [NIOSH 2003]. Moreover, NIOSH guidance for a similar compound, methylene diphenyl diisocyanate (MDI), says that if a medical evaluation determines that a worker is sensitized, the worker must not be allowed to return to a job where MDI is used [NIOSH 2006].

Health Effects of Exposure to Hexavalent Chromium

An increased risk of lung cancer has been demonstrated in workers exposed to hexavalent chromium (CrVI) compounds [NIOSH 2009]. Other adverse health effects associated with CrVI exposure include dermal irritation, skin ulceration, allergic contact dermatitis, occupational asthma, nasal irritation and ulceration, perforated nasal septa, rhinitis, nosebleed, respiratory irritation, nasal cancer, sinus cancer, eye irritation and damage, perforated eardrums, kidney damage, liver damage, pulmonary congestion and edema, epigastric pain, and erosion and discoloration of the teeth [ATSDR 2008; NIOSH 2009]. Only the inhalation route was the subject of personal sampling in the current study.

Results

SUMMARY of AIR VELOCITIES

During personal air sampling under the existing ventilation conditions, two sets of velocity measurements were performed, using the filter face traverses described in the Methods section. The supply rate at full capacity was measured to be higher than 100 fpm, with an average of 136 fpm and a range of 106 to 167 fpm (N = 2 x 43 measurements). The exhaust rate was measured to be near 100 fpm, depending on flow resistance due to exhaust filter loading, with an average of 99.0 fpm and a range of 31.1 to 134 fpm (N = 2 x 24 measurements). The wide range of exhaust velocities seemed to be caused by the pattern of filter loading with paint overspray. Also, one set of cross-sectional velocity measurements was taken at the hangar midpoint, with the aircraft present, and the spatial average velocity was 104 fpm, with a range of 45 to 152 fpm (N = 20).

In addition to the full-flow condition, tracer gas experiments took place under the 3/4, half, and 1/4-flow rates. One set of supply (N = 43), midpoint (N=20), and exhaust (N = 24) velocity measurements were performed each at 3/4 and half-flows. Table 3 summarizes the average air velocities for the air sampling, CFD, and tracer gas portions of the study. The range of measured values is reported underneath the mean. The observation that the exhaust filter velocity range includes higher velocities for half-flow than for 3/4-flow may have been due to the half-flow condition being measured before a painting process and the 3/4-flow condition being measured afterwards, when the filter was more loaded. Another possible explanation is that two fans operating (half-flow) created a flow pattern in the plenum that resulted in higher velocities at certain filter face locations than did three fans operating (3/4-flow). Velocities were not measured for the 1/4-flow condition.

Table 3. Measured (Average) and Modeled Air Velocities

Test Type	Measured or Modeled?	Fraction of Current Flow Rate	Supply Velocity [range] (fpm)	Mid-hangar Velocity [range] (fpm)	Exhaust Velocity [range] (fpm)	Balanced?
Air Sampling	Measured	Full-flow	136 [106, 167]	104 [31.1,134]	99.0 [45, 152]	No
CFD Simulations	Modeled		43.3	44.0	43.3	Yes
			65.5	65.9	65.5	Yes
			75.0	76.2	75.0	Yes
			86.6	87.9	86.6	Yes
			100	102	100	Yes
			108	65.9	65.5	No
			108	110	108	Yes
Tracer Experiment	Measured	Half-flow	73.4 [54.6, 107]	71.8 [50.0, 103]	49.0 [34.5, 124]	No
		3/4-flow	102 [82.3, 126]	73.6 [43.0, 99.0]	68.9 [24.0, 96.3]	No
		Full-flow	136 [106, 167]	104 [31.1,134]	99.0 [45, 152]	No

AIR SAMPLING

Air sampling results from the three surveys of spray painting F/A-18C/D Hornet strike fighter aircraft were tabulated and summarized into the three phases: aircraft wipe down, primer spray painting, and topcoat spray painting. During all three processes, the ventilation system was at full-flow. Summary statistics included the number of samples and the arithmetic mean. For those mean results for which there were results less than the limit of detection (LOD), the LOD divided by the square root of 2 was used to determine the mean [Hornung and Reed 1990].

Aircraft Wipe Down

Prior to spray painting the aircraft with primer, the aircraft is wiped down with MIBK. Workers used MIBK soaked rags and wiped down the surface to prep it for spray painting. The aircraft wipe down took approximately 30 minutes. Two PBZ samples for VOCs were collected during the operation. On the four tripods surrounding the aircraft, two samples for VOCs were collected: one at an air sampling flow rate of 50 ml/min and one at 200 ml/min. Results for the three surveys are shown in Table A-2 and summarized in Table A-3. Detectable concentrations of EGBE, MEK, MIBK, 1, 2, 4-trimethylbenzene, 1, 3, 5-trimethylbenzene, and toluene were measured in these samples. During the 30 minutes of wipe down, the mean MEK and MIBK concentrations for the workers performing this task were 145 ppm (ACGIH STEL = 300 ppm, NIOSH STEL = 300 ppm) and 190 ppm (ACGIH STEL = 75 ppm, NIOSH STEL = 75 ppm), respectively. Thus, the STEL for MIBK was exceeded during wipe-down. One of the six personal samples showed concentrations of 665 ppm for MEK and 918 ppm for MIBK, which are at least an order of magnitude higher than the other five samples. While these values were retained in the calculation of the means, it is possible they were anomalies. In any case, the exposure was adequately controlled by air-purifying respirators.

None of the 8- or 10-hr TWA OELs were exceeded, since the 30-minute duration of this task was by far the largest MEK or MIBK exposure of the day. For workers in the sprayer job classification for the remainder of the day, the MEK 8-hr TWA was 9.47 ppm (REL = 200 ppm, PEL = 200 ppm, TLV = 200 ppm). The MIBK 8-hr TWA was approximately 12.0 ppm (REL = 50 ppm, PEL = 100 ppm, TLV = 20 ppm). Assuming the helper job classification for the rest of the shift, the MEK and MIBK TWAs were 8.44 ppm and 11.1 ppm, respectively. All PBZ calculations are based on the average concentration of six samples.

During wipe-down, mean area air sample results for tripod #1 for MEK and MIBK were 3.90 and 5.43 ppm, respectively. For tripod #2 the results for MEK and MIBK were 1.55 and 2.12 ppm, respectively. These two tripod samples were located downwind from the aircraft. Mean area air sample results for tripod #3 for MEK and MIBK were 0.38 and 0.50 ppm, respectively. For tripod #4, the results were 0.07 and 0.13 ppm. These two tripod samples were located upwind from the aircraft.

Aircraft Primer Painting

Four workers were sampled for VOCs, TP, and CrVI during the spray painting of the aircraft with primer. Two of the workers were spray painters and the other two were helpers for the spray painters. It took between 30 and 50 minutes to spray paint an aircraft with primer. In addition to VOCs, TP, and CrVI, metals and nitroethane were also collected on the four tripods.

The VOC results for samples collected during the primer spray painting phase are tabulated in Table A-4 and summarized in Table A-5. All VOCs except ethyl benzene were detected during the primer spray painting, although methyl amyl ketone and n-butyl acetate each only had one detectable result. Mean PBZ sample results for EGBE, MEK, and MIBK for the spray painters were 2.58, 12.2, and 7.63 ppm, respectively. Mean PBZ sample results for EGBE, MEK, and MIBK for the helpers were 0.58, 0.20, and 0.52 ppm, respectively.

As 8-hr TWAs, the EGBE exposure for sprayers was 0.220 ppm and for helpers was 0.0557 ppm (REL = 5 ppm, PEL = 50 ppm). Note that the MEK and MIBK full-shift TWAs were already reported in the Wipe-down section. The mean concentrations for EGBE, MEK, and MIBK at tripod #1 were 1.48, 0.23, and 0.59 ppm, respectively. The mean concentrations for EGBE, MEK, and MIBK at tripod #2 were 0.58, 0.22, and 0.54 ppm, respectively. The mean concentrations for EGBE, MEK, and MIBK at tripod #3 were 0.33, 0.47, and 0.42 ppm, respectively. The mean concentrations for EGBE, MEK, and MIBK at tripod #4 were 0.18, <0.08, and <0.06 ppm, respectively. All the EGBE, MEK, and MIBK results were well below the OELs, including STELs during primer spraying.

The TP and CrVI sample results during primer spray painting are shown in Table A-6 and summarized in Table A-7. The PBZ sample results for the spray painters during primer application, which had a duration of approximately one hr., were 19872 $\mu g/m^3$ for TP and 537 $\mu g/m^3$ for CrVI. For the helpers, the results were 4883 $\mu g/m^3$ for TP and 145 $\mu g/m^3$ for CrVI.

As 8-hr TWAs, the sprayer and helper exposures for TP were 4,170 and 946 $\mu g/m^3$ (TLV = 10,000 $\mu g/m^3$, PEL = 15,000 $\mu g/m^3$). Because TP was measured using a PVC filter, closed-face cassette and not an inhalable particulate sampler, comparison to the TLV (which refers to the inhalable fraction) carries the uncertainty of size selection difference between the two methods. While this uncertainty was probably not enough to have changed the conclusion that the TP TLV was not exceeded, this has not been shown definitively. What is certain is that the PEL was not exceeded. The sprayer and helper CrVI TWAs were 41.6 and 10.4 $\mu g/m^3$ (TLV = 10 $\mu g/m^3$, REL = 1 $\mu g/m^3$, PEL = 5 $\mu g/m^3$). Thus, the NIOSH REL and the OSHA PEL were exceeded for both the sprayer and helper job groups. The helper exposure, however, was below 25 $\mu g/m^3$, which means reducing the exposure below the PEL of 5 $\mu g/m^3$, using the respiratory protection program, complied with the OSHA chromium standard. Reducing the *sprayer* exposure through engineering controls must still be accomplished to come into compliance using respirators.

The mean results for TP and CrVI for the two tripods downwind from the aircraft, tripod #1 and tripod #2, were 5826 and 186 µg/m^3 for #1 and 2142 and 59.8 µg/m^3 for #2. The mean results for TP and CrVI for the two tripods upwind from the aircraft, tripod #3 and tripod #4, were <688 and 0.32 µg/m^3 for #3 and <778 and 0.90 µg/m^3 for #4.

Sample results for TP and select metals collected on the four tripods during primer application are listed in Table A-8 and summarized in Table A-9. Ba, Cr, Cu, and Sr were detectable in these samples. One sample collected, on tripod #1, had a trace concentration of Sn. The mean concentrations for TP, Ba, Cr, Cu, and Sr on tripod #1 for the three different sampling dates were 6248, 768, 288, 0.95, and 3.95 µg/m^3, respectively The mean concentrations for TP, Ba, Cr, Cu, and Sr on tripod #2 were 2514, 293, 111, 0.65, and 1.47 µg/m^3, respectively. The mean concentrations for TP, Ba, Cr, Cu, and Sr on tripod #3 were 576, 0.59, <3.53, <0.68, and <0.26 µg/m^3, respectively. The mean concentrations for TP, Ba, Cr, Cu, and Sr on tripod #4 were <775, 1.94, 3.77, 3.65, and <0.30 µg/m^3, respectively.

Sample results for nitroethane collected on the four tripods during primer spray painting are shown in Table A-10 and summarized in Table A-11. Only trace amounts of nitroethane were measured. The mean nitroethane concentration on tripods #1, #2, #3, and #4 were 0.94, 0.32, <0.13, and 0.14 ppm, respectively.

<u>Aircraft Topcoat Painting</u>

During each of the three surveys, four workers were sampled for VOCs and HDI during the spray painting of the aircraft with light and dark gray topcoat paint. Two of the workers were spray painters and the other two were helpers for the spray painters. Thus, each job group was sampled six times. It took between 75 and 100 minutes to spray paint an F/A-18C/D with the topcoat. In addition to VOCs and HDI, metals were also collected on the four tripods.

The VOC results for samples collected during the topcoat spray painting phase are tabulated in Table A-12 and summarized in Table A-13. All VOCs except cumene were detected during the topcoat spray painting. Mean PBZ sample results for MAK, MEK, MIBK, and n-butyl acetate for the sprayers were 9.43, 1.67, 3.01, and 4.44 ppm, respectively. Mean PBZ sample results for MAK, MEK, MIBK, and n-butyl acetate for the helpers were 2.31, 1.06, 1.40, and 1.25 ppm, respectively.

As 8-hr TWAs, the sprayers had exposures to MAK and n-butyl acetate of 1.71 and 0.808 ppm, respectively. The helpers' TWAs were 0.397 ppm for MAK and 0.232 ppm for n-butyl acetate. These exposures are well below the OELs. These are, for MAK: REL = 100 ppm and PEL = 100 ppm, and for n-butyl acetate: REL = 150 ppm and PEL = 150 ppm. As noted earlier, the MEK and MIBK TWAs were reported in the Wipe-down section.

The mean concentrations for MAK, MEK, MIBK and n-butyl acetate at tripod #1 were 2.52, 0.49, 0.57, and 1.33 ppm, respectively. The mean concentrations for MAK, MEK, MIBK, and n-butyl acetate at tripod #2 were 4.12, 0.07, 0.14, and 1.84 ppm, respectively. The mean concentrations for MAK, MEK, MIBK, and n-butyl acetate at tripod #3 were <0.01, <0.01, <0.01, and <0.01 ppm, respectively. The mean concentrations for MAK, MEK, MIBK, and n-butyl acetate at tripod #4 were <0.01, 0.03, 0.05, and <0.01 ppm, respectively.

The HDI monomer, NCO monomer, and NCO oligomer sample results collected during topcoat spray painting are shown in Table A-14 and summarized in Table A-15. The PBZ sample results for the spray painters during topcoat application for HDI and NCO monomer and NCO oligomer were 34.7 $\mu g/m^3$, 17.4 $\mu g/m^3$, and 290 $\mu g/m^3$, respectively. The PBZ sample results for the helpers during topcoat application for HDI and NCO monomer and NCO oligomer were 6.29 $\mu g/m^3$, 3.09 $\mu g/m^3$, and 82.0 $\mu g/m^3$, respectively. The HDI 8-hr TWAs were 6.30 $\mu g/m^3$ for the sprayers and 1.08 $\mu g/m^3$ for the helpers (REL = 35 $\mu g/m^3$, TLV = 35 $\mu g/m^3$). As the NCO monomer, the sprayer and helper TWAs were 3.15 and 0.531 $\mu g/m^3$, respectively. The NCO oligomer had TWAs of 52.5 $\mu g/m^3$ for the sprayers and 14.0 $\mu g/m^3$ for the helpers. The NCO group does not have OELs at this time.

The mean results HDI monomer, NCO monomer, and NCO oligomer for the two tripods downwind from the aircraft (tripod #1 and tripod #2) were 5.30, 7.57 and 98.7 $\mu g/m^3$ for #1 and 9.34, 3.44 and 79.2 $\mu g/m^3$ for #2. The mean results HDI monomer, NCO monomer, and NCO oligomer for the two tripods upwind from the aircraft tripod #3 and tripod #4 were <0.41, <0.23 and <1.20 $\mu g/m^3$ for #3 and <0.40, <0.23, and <1.34 $\mu g/m^3$ for #4.

Sample results for TP and select metals collected on the four tripods during topcoat application are listed in Table A-16 and summarized in Table A-17. The metal detected during topcoat application was Ba, Cu, Sr, and Ti. The mean concentrations for TP, Ba, Cu, Sr, and Ti on tripod #1 for the three different sampling dates were 3451, 0.31, 0.20, 0.15, and 50.5 $\mu g/m^3$, respectively The mean concentrations for TP, Ba, Cu, Sr, and Ti on tripod #2 were 3866, <0.13, 0.26, 0.11, and 51.4 $\mu g/m^3$, respectively. The mean concentrations for TP, Ba, Cu, Sr, and Ti on tripod #3 were <236, <0.12, 0.18, <0.10, and <1.30 $\mu g/m^3$, respectively. The mean concentrations for TP, Ba, Cu, Sr, and Ti on tripod #4 were <241, <0.12, 0.17, <0.10, and <1.24 $\mu g/m^3$, respectively.

CFD SIMULATION

Examination of Figure 9 shows that the two least effective rates are 43.3 fpm and the unbalanced 108 fpm supply – 65.0 fpm exhaust scenario. These rank first and second, 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 9 also shows the similarity of 65.0 fpm and 86.6 fpm, especially at critical worker locations. In the difficult to ventilate area under the landing gear hatch, the 65.0 and 86.6 fpm 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, at the two sprayer locations (which represent the highest exposures) 65.0 fpm has lower concentrations than 86.6 fpm: 738 ppm and 2212 ppm vs. 857 ppm and 2279 ppm. The lowest concentrations occurred at the balanced 108 fpm rate.

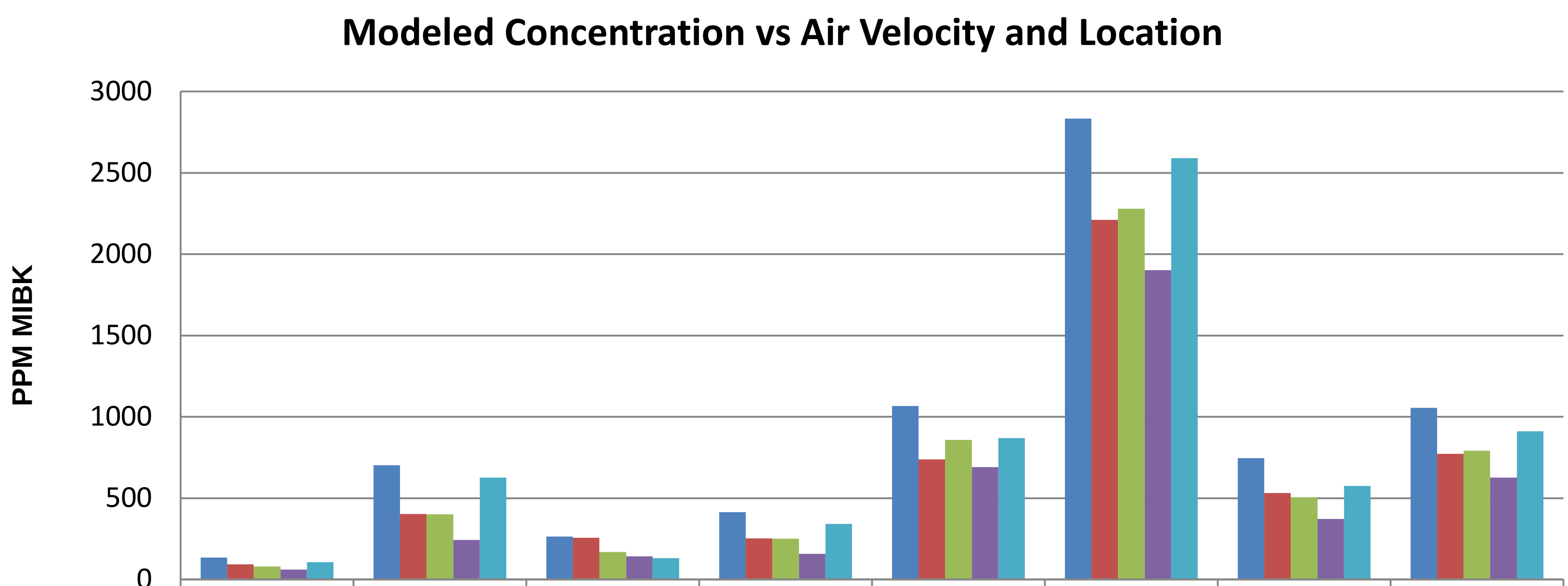
Recently completed CFD simulations (Figure 10) using what is generally considered a more accurate turbulence model (RNG k-epsilon) and a much more time-consuming convergence criterion (10^{-4}) show that 75 fpm produces lower concentrations than 100 fpm at the locations where the concentrations are highest. Although the CFD results are closer to being log-normally distributed than to being normally distributed, Figure 10 includes the arithmetic mean, because the geometric mean seemed overly influenced by the concentrations that were very close to zero. Worth noting is that these recent CFD 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 model with lower error tolerance resolved the steep, near-source concentration gradients more precisely, with less numerical diffusion.

Considering again the unbalanced 108/65.0 fpm 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 and the exhaust 99.0 fpm, taken as the average of traverses before and after painting. Lower velocities were chosen for the CFD model, because 136 fpm is enough greater than the current Navy design velocity of 100 fpm to seem impractical for this project. All air velocities in the current study are listed in Table 3.

The inability of the exhaust to keep pace with the supply is due to the pressure drop across the exhaust wall filter bank. The pressure observed during this flow measurement was 1.67 in. water gauge. The filter material is not replaced until the pressure drop reaches 2.5 in. water gauge, and the exhaust velocity decreases as filter resistance increases. The clean filter bank, without any accumulated material, has a pressure drop of approximately 0.50 in. water 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.

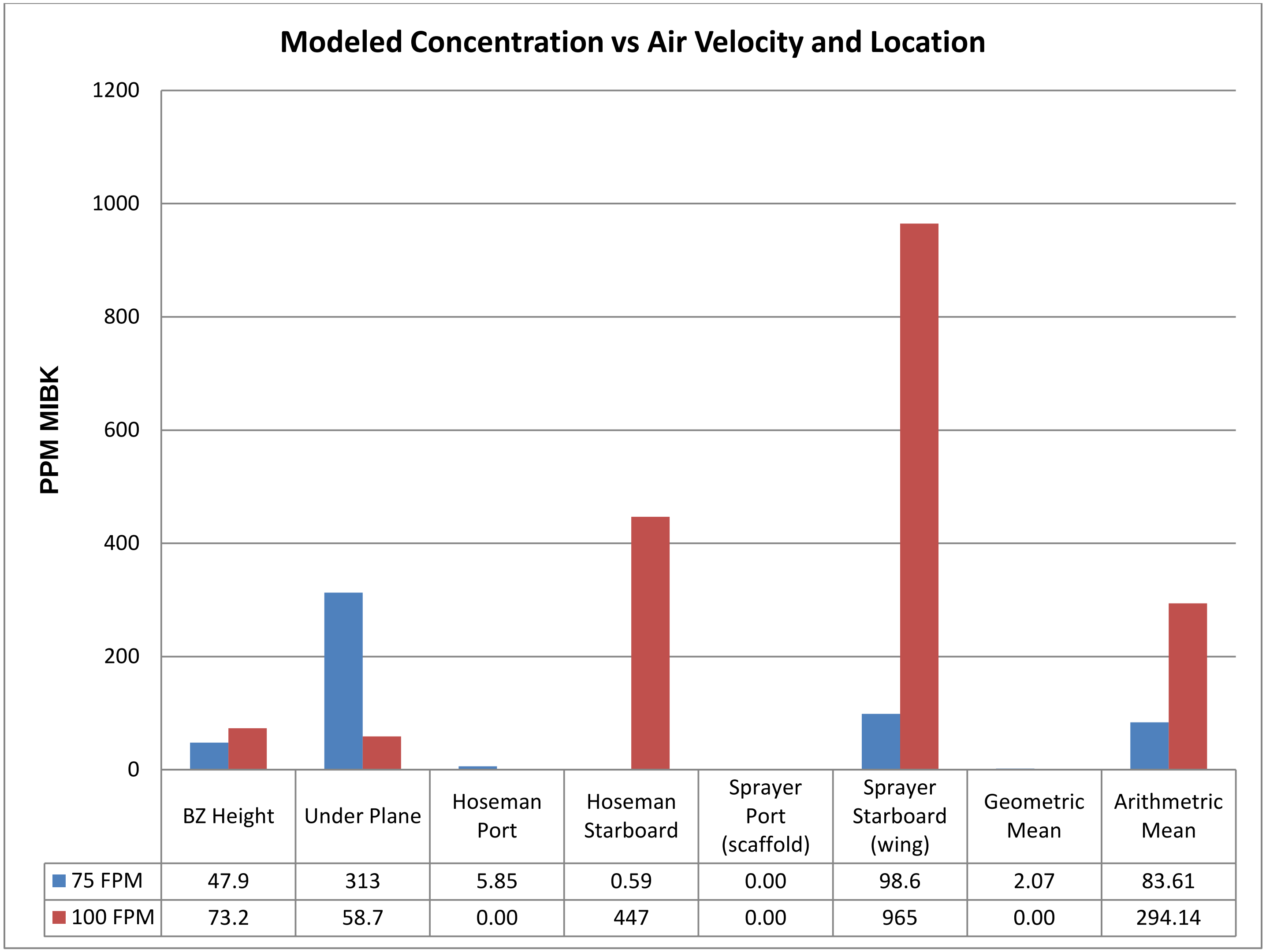
In the dispersion of 10µm MIBK droplets shown by Figure 11, the effect of supply-exhaust balancing is evident in the narrower, tighter pattern of particle paths. The top image (unbalanced) shows a more diffuse jumble of paths, while in the bottom image (balanced), the paths are more convective, although still not linear. In the figure, red particles are launched by the port-side sprayer and green by the starboard-side sprayer.

Additional CFD-generated graphics are found in Appendix B. In Figure B-1, the balanced case shows less contaminant dispersion in the direction lateral to the main flow. The path-lines of Figure B-2 convey effects of flow imbalance, with short-circuiting from the supply air filter to the exit door, along with a wider distribution of air age.



	BZ Height	Under Plane	Hoseman Port	Hoseman Starboard	Sprayer Port (scaffold)	Sprayer Starboard (wing)	Geometric Mean	Arithmetic Mean
43.3 FPM	133.7	702	264	413	1066	2833	746	1056
65 FPM	92.7	402	257	253	738	2212	532	772
86.6 FPM	79.3	401	168	251	857	2279	506	791
108 FPM	61	243	143	157	691	1902	372	627
108/65 FPM	106	627	131	342	869	2590	576	912

Figure 9. Concentrations of a gas with the properties of MIBK calculated using CFD, for various air velocities and observed worker locations. 108 / 65 fpm indicates the unbalanced condition of 108 fpm of supply and 65 fpm of exhaust.



	BZ Height	Under Plane	Hoseman Port	Hoseman Starboard	Sprayer Port (scaffold)	Sprayer Starboard (wing)	Geometric Mean	Arithmetic Mean
75 FPM	47.9	313	5.85	0.59	0.00	98.6	2.07	83.61
100 FPM	73.2	58.7	0.00	447	0.00	965	0.00	294.14

Figure 10. CFD results at 75 fpm and 100 fpm using the RNG k-epsilon turbulence model and a convergence criterion of 10^{-4} for the normalized residuals.

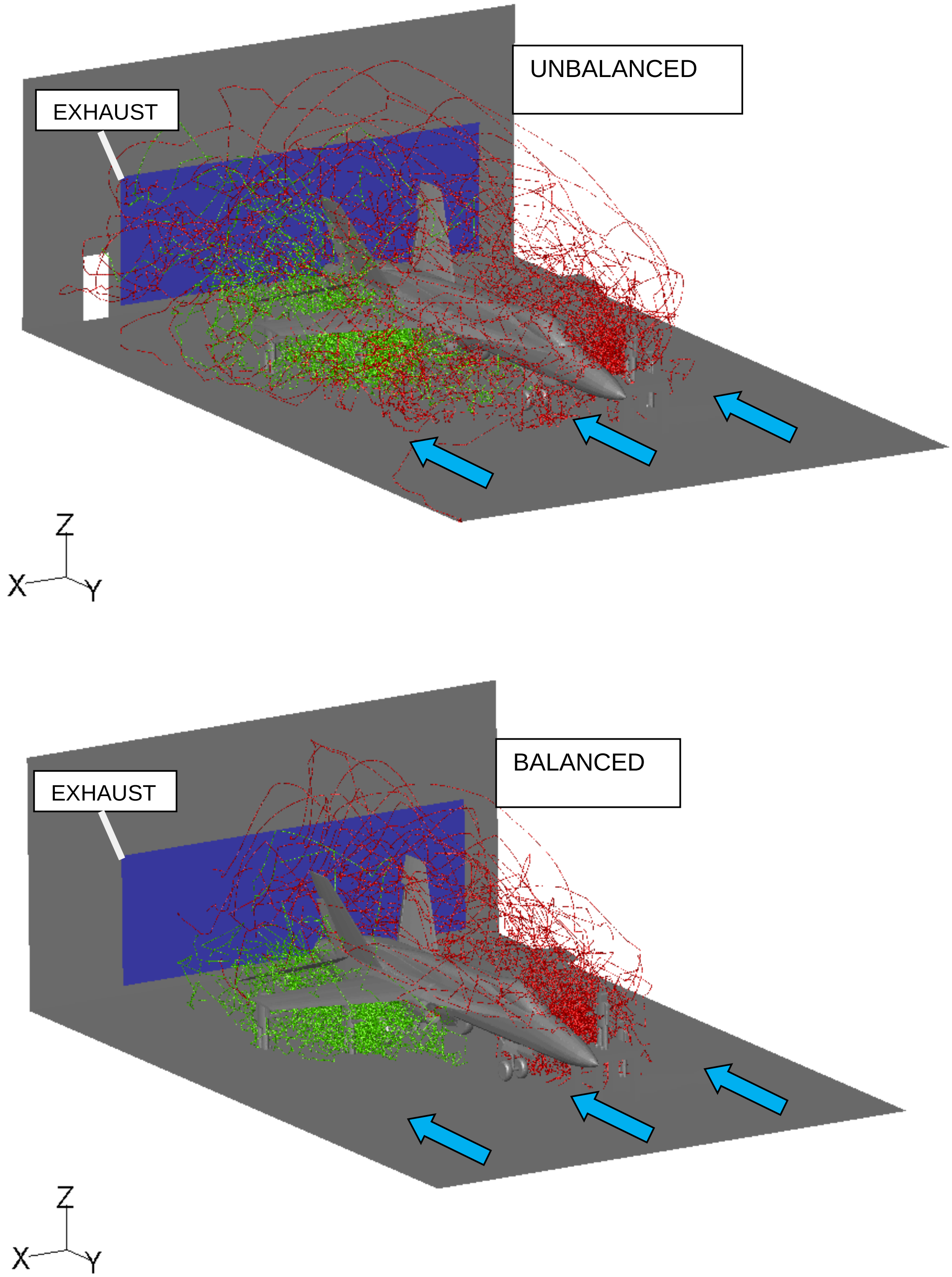


Figure 11. Particle tracks for the unbalanced 108 fpm supply – 65.0 fpm exhaust case (top image) and the balanced 65.0 fpm case (bottom image). The balanced case shows less particle dispersion.

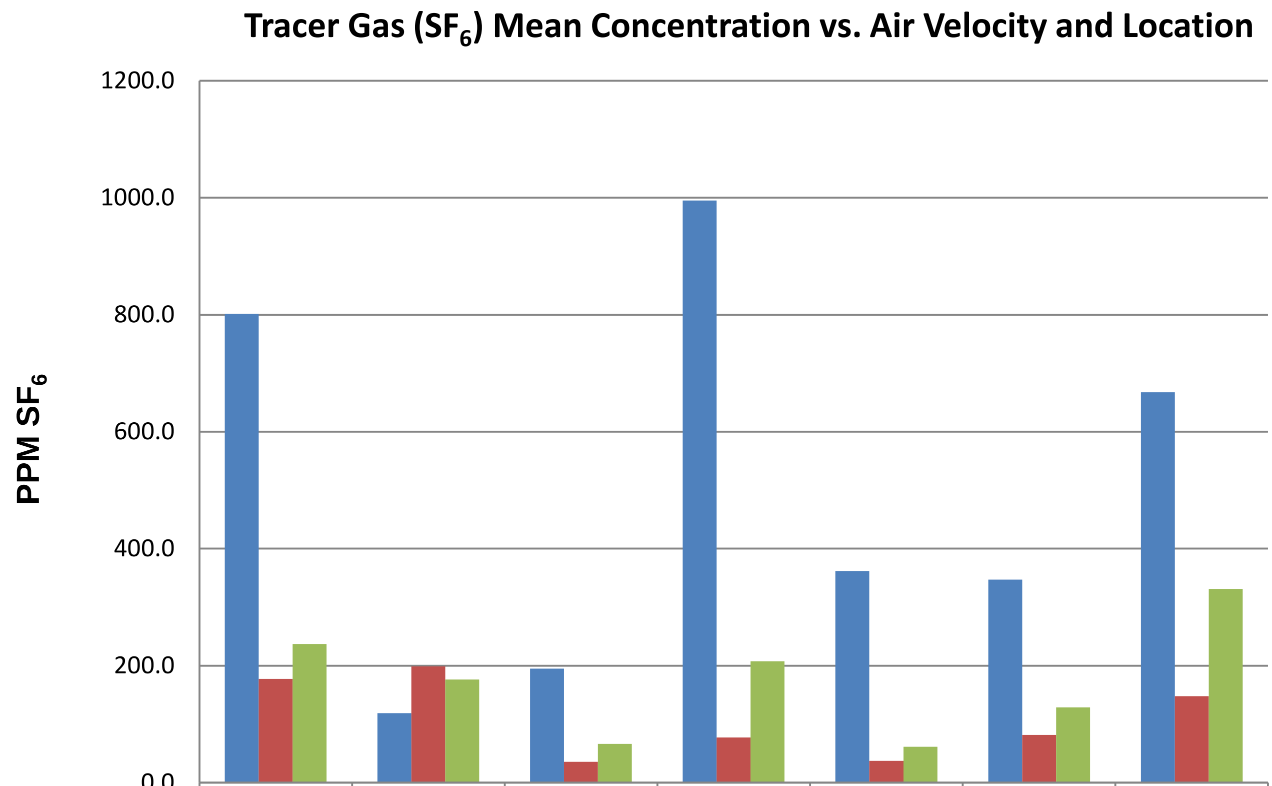
TRACER GAS

The concentrations of sulfur hexafluoride (SF_6) 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 concentration at half-flow was higher than for 3/4-flow, with statistical significance (95% confidence intervals did not overlap). 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 concentration. In this unbalanced condition of 102 fpm of supply and 68.9 fpm of exhaust, the velocity measured at the hangar midpoint (i.e. the cross-section that includes the aircraft) was 73.6 fpm. The tracer gas results can be found in Figure 12 and Table 4, with additional data in Appendix C.

There were 45 data series. Each data series contained 800-900 data points. Mixed models with the repeated measures option were used to analyze the data. When all data points for the 45 series were included for analysis, the calculations could not finish after 24 hours. For that reason, subset data series were created for every fifth, tenth, fifteenth and twentieth observations. Geometric means based on these subset data series were calculated. The results were similar – the similarity of these geometric means indicated that these time series data points were stationary. Mixed models with these subsets of data series were then analyzed. However, the mathematical calculation of some of the model parameters was non-estimable. Therefore, no multiple comparison for air velocities could be performed.

The Analysis of Variance procedure (ANOVA) was then used to analyze the data. At first, the means of log-transformed data points for each series were calculated. There were 45 log means (45 data series). The 1/4 flow rate was excluded. Three variables were used as the main effects for the models: flow rate, location and configuration. Statistically significant difference based on the ANOVA F-test was found among velocities ($p=0.035$). However, pair–wise multiple comparison could not further distinguish the differences.

From inspection of graphs of the data series, one MIRAN instrument returned results that differed from the others because of brief concentration fluctuations down to zero. This MIRAN is referred to as “HETAB” because of the NIOSH branch that owns this particular instrument. Because the HETAB location series looked potentially problematic, the ANOVA was repeated with HETAB series excluded. Again, the three variables used as the main effects for the models were: air velocity, location and configuration. As shown in Table 4, a statistically significant difference based on the ANOVA F-test was found among velocity ($p=0.019$). This time, however, the follow-up multiple comparison based on Tukey’s studentized range test identified a statistically significant difference between half-flow and 3/4-flow, as stated earlier. Half-flow has a statistically significant higher concentration than the concentration of 3/4-flow. No statistically significant difference was found between half and full-flow or 3/4 and full-flow.



	Under Plane	Under Starboard Wing	Starboard Rudder	Port Side of Canopy	Under Port Wing	Overall Geometric Mean	Overall Arithmetic Mean
HALF-FLOW (73.4 FPM/49.0 FPM)	801.6	118.7	195.1	995.5	361.9	347.4	667.3
3/4-FLOW (102 FPM/68.9 FPM)	177.5	198.8	35.7	77.3	37.6	81.8	148.0
FULL-FLOW (136 FPM/99.0 FPM)	236.9	176.3	66.6	207.7	61.2	128.7	331.3

Figure 12. Time-averaged concentrations of SF_6 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 4. Tukey's studentized range (HSD) test for tracer gas log mean concentration. Comparisons significant at the 0.05 level are indicated by *.**

Velocity Comparison	Difference Between Tracer Gas Log Means	Simultaneous 95% Confidence Limits		
half vs full	1.3644	-0.2762	3.0051	
half vs 3/4	1.9612	0.1350	3.7875	***
3/4 vs full	-0.5968	-2.3908	1.1971	

Discussion

AIR SAMPLING

Based on air sampling results from the three surveys, the following compounds are the main focus for evaluation, because they had the highest exposure risk: methyl ethyl ketone (MEK) and methyl iso-butyl ketone (MIBK) during the wipe down phase; total particulate (TP), hexavalent chromium (CrVI), 2-butoxyethanol (EGBE), MEK and MIBK during the primer spray painting phase; and methyl amyl ketone (MAK), MIBK, and hexamethylene diisocyanate (HDI) during the topcoat spray painting phase. All air sampling was performed at the full-flow ventilation condition and during the typical processes of F/A-18C/D aircraft refinishing.

Wipe-down

The OSHA PEL, NIOSH REL, and ACGIH TLV for MEK are all a time-weighted average (TWA) of 200 ppm. There are also NIOSH and ACGIH short-term exposure limits (STELs) for MEK of 300 ppm. The OSHA PEL for MIBK is a TWA of 100 ppm, while the NIOSH REL is 50 ppm and the ACGIH TLV is 20 ppm. There are also NIOSH and ACGIH STELs for MIBK of 75 ppm. In Table A-2, the MEK average is 145 ppm and the MIBK average is 190 ppm.

The 8-hr TWAs were calculated using the concentrations and durations for the wipe-down phase and the other two processes, primer and topcoat. For MEK and MIBK, respectively, these full-shift averages were 9.47 and 12.0 ppm for wipe-down workers who became primer and topcoat sprayers later in the shift and 8.44 and 11.1 ppm, for workers for helped the sprayers, after wipe-down.

The MEK OELs (REL = 200 ppm, PEL = 200 ppm, TLV = 200 ppm, STEL = 300 ppm) were not exceeded. With the MIBK OELs of PEL = 100 ppm, REL = 50 ppm, TLV = 20 ppm, and STEL = 75 ppm, the short-term exposure limit for MIBK was exceeded, as the concentration of 190 ppm during wipe-down is 2.53 times greater than the STEL of 75 ppm.

If the MIBK exposure had persisted for a full eight-hour shift, the PEL and the REL would have been exceeded. Instead, during the 30 to 45 minutes of the wipe-down operation, a fraction of the full-shift limit occurred. The 8-hr TWAs were below the OELs. The actual exposures were lower than measured concentrations, since workers were wearing full-face air-purifying respirators (APRs), which have an assigned protection factor (APF) of 50 [OSHA 2009]. The respirators were fitted with organic vapor cartridges.

<u>Spraying of Primer</u>

The average of six total particulate (TP) samples of workers spraying the primer on the F/A-18C/D Hornet showed a concentration of 19.9 mg/m^3 and a duration of 37 min. Since the PEL for TP is an eight-hour TWA of 15 mg/m^3 and the TP exposure lasted less than an hour, this limit was not exceeded during primer application. However, the 8-hr TWA must also include the contribution from exposure to the topcoat aerosol. Unfortunately, the TP exposure during topcoat application was not measured for the breathing zone, but was measured for the area samples. The breathing zone concentration for topcoat application was estimated, then, using the area concentration and the ratio of the breathing zone and area concentrations for the primer application, as follows:

$$\mathrm{PBZ_T} = \mathrm{A_T}\left(\frac{PBZ_P}{A_P}\right).$$

Directly measuring the PBZ concentration during topcoat application would have been more accurate. However, the fact that the primer aerosol and the topcoat aerosol were generated by the same spray equipment makes it somewhat reasonable that the ratio of breathing zone to area concentrations will be similar for both processes (performed by the same workers, on the same aircraft, and on the same day). The full shift TWAs calculated in this manner were 4.17 mg/m^3 for sprayers and 0.946 mg/m^3 for helpers. Even with the uncertainty in this estimate, it is not plausible that the PEL of 15 mg/m^3 or the TLV of 10 mg/m^3 were exceeded. There is no REL established for TP.

The PEL and REL for CrVI are a TWA of 5 and 1 µg/m^3, respectively. The PEL for EGBE is a TWA of 50 ppm, while the REL is a TWA of 5 ppm. The 8-hr EGBE TWA for the sprayers, 0.220 ppm, is well below the occupational limit. CrVI is a very different situation, with a concentration range of 0.320 µg/m^3 for an upwind area sample to 537 µg/m^3 for a sprayer. The latter is clearly above the OSHA PEL of 5 µg/m^3, even for an exposure that lasts only 37 minutes. Indeed, the 8-hr TWAs were 41.6 µg/m^3 for the sprayers and 10.4 µg/m^3 for the helpers. Furthermore, the 25 µg/m^3 level required by 1910.1026(f)(1)(ii) was not achieved at full ventilation capacity (136 fpm, supply/99.0 fpm, exhaust), even though this exceeds the 100 fpm required by 29 CFR 1910.94 for paint booths. The sprayers are in supplied-air hoods, which have an APF of 1000. Thus, the current ventilation system adheres to the 100 fpm criterion, but cannot adequately control CrVI exposure, without adding the protection of the supplied-air hoods.

Whether OSHA would require 100 fpm for this operation is not a settled matter at this time. OSHA distinguishes work areas for spray finishing as follows [CFR d]:

> 1910.107(a)(2) ***Spraying area***. Any area in which dangerous quantities of flammable vapors or mists, or combustible residues, dusts, or deposits are present due to the operation of spraying processes.
>
> 1910.107(a)(3) ***Spray booth***. A power-ventilated structure provided to enclose or accommodate a spraying operation to confine and limit the escape of spray, vapor, and residue, and to safely conduct or direct them to an exhaust system.

Appendix D contains correspondence between the Navy and OSHA that defines corrosion control bays as spraying areas rather than spray booths, and spray areas are not regulated by 1910.94, making the 100 fpm requirement found in Table G-10 not directly applicable. The definition turns, however, on painting something as large as an aircraft being incidental to how the space is generally used. When the Navy re-examined the level of painting activity in the bays, they asked OSHA for clarification of the spray area definition, and OSHA referred to NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*, and 29 CFR 1910 Subpart Z, *Toxic and Hazardous Substances*, as their priorities. According to OSHA, if these priorities were met, a violation of Table G-10 of 1910.94 would be considered, at most, *de minimus*.

What is still unclear is the effect on overall compliance of exceeding PELs in Subpart Z, given that the respiratory protection program is needed to control exposures. The hexavalent chromium standard, 1910.1026, provides some answers:

> *Where painting of aircraft or large aircraft parts is performed in the aerospace industry, the employer shall use engineering and work practice controls to reduce and maintain employee exposure to chromium (VI) to or below 25 µg/m^3 unless the employer can demonstrate that such controls are not feasible. The employer shall supplement such engineering and work practice controls with the use of respiratory protection that complies with the requirements of paragraph (g) of this section to achieve the PEL.*

If the 25 µg/m^3 criterion was not met, a logical approach by OSHA might be to require 100 fpm, their “gold standard” for control. However, the 25 µg/m^3 criterion was not met by this ventilation system delivering approximately 100 fpm to the bay midpoint. It is also not clear that 100 fpm is the most effective velocity.

The sprayer helpers or hosemen are responsible for managing the various airlines and paint hoses for the sprayers and are farther from the source. These workers wear full-face APRs with an APF of 50. Based on the APF, the concentration of CrVI inside the respirator (the concentration that was breathed) can be estimated as 0.145 mg/m^3/50 = 0.0029 mg/m^3 or 2.9 times greater than the NIOSH REL of 0.001 mg/m^3. However, the typical task duration (observed in the three surveys to be from 45 min. to one hr.) was short enough for the exposure to stay below the 10-hr. TWA NIOSH REL.

Spraying of Paint

The PEL and REL for MAK is a TWA of 100 ppm. There is no PEL established for HDI. The REL for HDI is a TWA of 0.035 mg/m^3. NIOSH also established a ceiling for HDI of 0.140 mg/m^3 for a 10 minute period.

The highest concentrations of HDI were found in the samples of the sprayers, with an average across this group of approximately 40 µg/m^3 or 0.040 mg/m^3. Thus, the REL was not exceeded, with an exposure duration of approximately 100 minutes. More precisely, the 8-hr TWA was 6.30 µg/m^3 or 0.00630 mg/m^3. However, it is difficult to comment on the highest ten-minute average that occurred within that sample time, relative to the NIOSH ten-minute ceiling. It is clear nonetheless that both the sprayers and the hosemen were adequately protected with their supplied-air hoods (APF = 1000) and full-face APRs (APF = 50), respectively, along with ventilation as the primary control measure.

Air Sampling Summary

Concerning effectiveness of the control measures in place, the ventilation system by itself is not able to control exposures below OELs for all materials sampled in the processes. The combination of the ventilation system and the respiratory protection program is needed to achieve the required exposure reduction. The situation that comes closest to exceeding an occupational limit is the hosemen wearing APRs during primer application. Respiratory protection carries a heavy exposure reduction burden, with the CrVI concentration being more than 100 times greater than the NIOSH REL concentration and the protection factor taken as 50 [NIOSH 1997]. The duration (less than 100 minutes) of the exposure will keep the situation within the limit, but not by a comfortable margin, as the mean CrVI 8-hr

TWA for hosemen was 10.4 µg/m^3. Applying the theoretical protection factor reduces the TWA to 0.208 µg/m^3, for the average helper, or 20.8% of the REL. If the protection factor of 50 is applied to the maximum sampled value of 17.6 µg/m^3, the 8-hr TWA becomes 0.352 µg/m^3. Furthermore, if the six hosemen samples are fitted to a log-normal distribution, the 95th percentile would be 0.398 µg/m^3, or 39.8% of the REL.

Respiratory Protection Program

Respirators should be selected based upon the concentration of interest and the assigned protection factor (APF) of the respirator. An APF is defined as a measure of the minimum anticipated workplace level of respiratory protection that would be provided by a properly functioning respirator or class of respirators to a percentage of properly fitted and trained users. The respirators in use in Bay 6 of Building 465 were supplied-air hoods and full-face air-purifying respirators (APRs). These have APFs of 1,000 and 50, respectively. Respirators have been appropriately selected for the specific work tasks observed during the aircraft refinishing operation, in light of the means, ranges, and 95th percentiles in the sampling results, although the hosemens' exposure to CrVI during priming is worthy of continued vigilance. For respirators to be worn by employees, an appropriate respiratory protection program must be utilized and be in accordance with OSHA regulation 29 CFR 1910.134 [CFR e]. From interviews with the aircraft painters and the NBC industrial hygiene staff, the program in place seems to adhere to the OSHA standard.

Evaluation of Explosion Hazard

None of the materials used in the wipe-down, priming, or painting processes presented a fire or explosion hazard at the concentrations generated. Concentrations of MEK and MIBK, out of all the compounds, came closest to their lower explosive limits (LEL), but even these remained two orders of magnitude (100-fold) below their LEL. The ANSI/AIHA American National Standard—Spray Finishing Operations (Z9.3) and the National Fire Protection Association Standard for Spray Application Using Flammable or Combustible Materials specify that ventilation control concentrations to less than 25% of the lower flammable limit [NFPA 2007, AIHA 2007 b]. Because area samples taken near the exhaust filter, downstream of all sources, were well below the guideline, it can be deduced that concentrations in the exhaust ducting were also below this guideline. Paint overspray that has accumulated on exhaust filter material could be a source of MIBK, but with a vapor pressure of only 16 mm Hg (at 68 ºF), i.e. 2% of atmospheric pressure, concentrations in the filter plenum and ducting would be very near the levels in hangar air downstream of the painting operations and below 25% of the LEL. Nevertheless, air sampling should be performed in the exhaust ducts, in the case of any process or ventilation change.

CFD SIMULATION

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 9 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 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 supply coupled with 65.0 fpm exhaust. Adding more air only at the supply end increased the concentration from 92.7 to 106 ppm, compared to 65.0 fpm balanced at both ends of the hangar.

The more meaningful locations to consider are those where the aircraft painters were commonly observed working or where conditions seemed to represent a worst case. 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 and a balanced 86.6 fpm 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, but 2279 ppm at 86.6 fpm. The best summary representation of the effect of ventilation rate is the geometric mean of the concentrations at the worker locations. These were 746, 532, 506, 372, and 576 ppm for 43.3, 65.0, 86.6, 108, and unbalanced 108/65.0 fpm, respectively. The pattern in these estimates is clear 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. 65.0 fpm was the second most effective velocity at the highest exposure locations, the sprayers.

The CFD results in Figure 9 (standard k-ε turbulence model and convergence criterion of 10^{-3}) are quite different than those in Figure 10 (RNG k-ε turbulence model and convergence criterion of 10^{-4}). The concentrations in Figure 10 are generally lower than those in Figure 9. A reasonable interpretation is that the model with the lower error tolerance (Figure 10) resolved the steep, near-source concentration gradients more precisely, with less numerical diffusion. In Figure 10, 75 fpm is shown to be more effective than 100 fpm 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 was higher than for 100 fpm. The arithmetic mean concentration was lower for 75 fpm than for 100 fpm. This difference between arithmetic and geometric means is due to 75 fpm being more effective at higher concentration levels.

Which of the CFD results (Figure 9 or Figure 10) best represents real contaminant transport during the refinishing process is difficult to say, definitively. While the results in Figure 10 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 in the Figure 9 results represents real mixing processes to some degree.

It is important to realize that the air velocity, at any given flow rate, varies by location. The strongest example is that the flow underneath the fuselage actually goes in the opposite direction from the main flow. While 100 fpm or another rate can be achieved as a spatial average, the air velocity near the aircraft or near the workers will deviate from the average. This variability leads naturally to the question of where to measure to test whether the target velocity has been achieved. For example, a velocity of 75 fpm, delivered as the cross-sectional average for the bay when empty, achieves different velocities at different locations, ranging from -91.5 fpm near the forward landing gear to 128 fpm at the breathing zone of the sprayer on the scaffold, according to the CFD simulation. The flow reversal underneath the aircraft is shown in Figure 13.

A local flow reversal is an area where air moves against the direction of the main flow. Since air contaminants are thereby carried away from the exhaust, their residence time is increased, which can lead to higher exposures. As the CFD results indicate the area under the fuselage contains a reversal, a design improvement should be considered that keeps the air underneath the aircraft moving, in a bulk sense, toward the exhaust. Before an engineering control is designed to address the reversal, the flow should be observed with a smoke test. This is especially true because scaffolding has recently been put in place (after data was collected and analyzed for the current study) to prevent falls, and the flow near the aircraft may have changed.

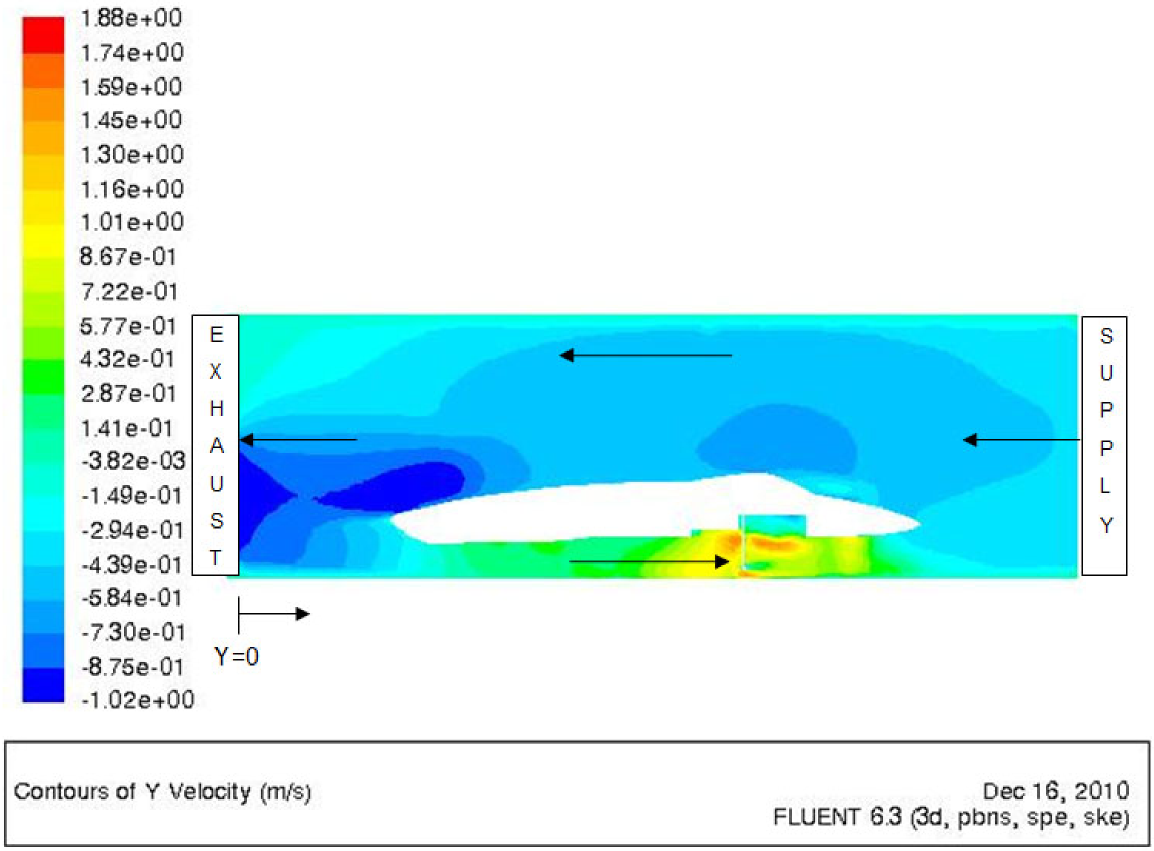


Figure 13. Color map of air velocity in the aircraft/bay centerplane, with schematic arrows. The origin is at the exhaust wall on the left, so flow from supply to exhaust (right to left) is negative. The zero velocity contour is colored blue-green. Velocity from supply to exhaust increases with deepening blue color. Reverse flow, under the aircraft, starts in the green contour and increases into the yellow and red. The scale is given by Fluent CFD software in m/s. The range in fpm is -201 at the exhaust filter to +370 fpm in small turbulent regions around the front landing gear well.

TRACER GAS

It is important first to note that the design air velocity of 100 fpm differs from what is actually delivered in the aircraft painting bay. The full ventilation condition is not 100 fpm, but instead averaged 136 fpm for the supply and 99.0 fpm for the exhaust, while the pressure drop across the exhaust filter increased from 1.33 in. water gauge to 1.67 in. water gauge from the start to the end of painting. Interestingly, the velocity measured at the bay midpoint (i.e. the cross-section that includes the aircraft) was 104 fpm, which is close to the design rate of 100 fpm.

The full flow condition is designated “Cycle 1” in the control room. The 3/4 flow corresponded to 102 fpm (supply), 73.6 fpm (midpoint), and 68.9 fpm (exhaust), and the half-flow produced 73.4 fpm (supply), 71.8 fpm (midpoint), and 49.0 fpm (exhaust). Secondly, all tracer gas experiments occurred under unbalanced conditions, because the full flow condition is unbalanced, and to reduce the flow rate required shutting down blowers and fans in supply/exhaust pairs. Thus, the imbalance was unfortunately maintained. One must look at the CFD results of the previous section to discern the independent effects of flow rate and flow imbalance. Therefore, a supply/exhaust imbalance of 108 fpm/65 fpm is shown to be less effective than both a balanced 108 fpm and a balanced 65 fpm.

Looking at the means of all five measurement locations by velocity (half-flow = 343 ppm; 3/4- flow = 82.7 ppm; full-flow = 130 ppm), the largest difference and the only statistically significant difference in tracer gas concentration among the velocities occurred between half and 3/4-flows. Although not statistically significant, the concentration created by full flow was higher than for 3/4 but lower than for half-flow. A statistically significant difference in concentration between half and 3/4-flows, where the midpoint velocities differed only slightly in 71.8 vs. 73.6 fpm, shows the importance of flow pattern and the incompleteness of average measured velocity as an engineering control description.

Conclusions and Recommendations

The three methods of investigation and analysis were comprehensive air sampling at full flow, computational fluid dynamics simulation at various flow velocities, and tracer gas experimentation at full flow and also at reduced flows that were realizable with the existing ventilation system. In the control of potentially hazardous exposures during refinishing of F/A-18C/D Hornet aircraft, the three separate analyses converge to the following ideas.

First, the supply blowers in Bay 6 of Building 465 are delivering air at 136 fpm at the full flow setting, Cycle #1. This exceeds the typical Navy design air velocity of 100 fpm, and creates an imbalance by delivering more air than the exhaust system can pull. This imbalance amounts to excess energy usage and reduces ventilation effectiveness by causing large circulations and additional turbulence in the flow. In the CFD simulations, an unbalanced flow of 108 fpm of supply and 65.5 fpm of exhaust was less effective than a balanced flow of 65.5 fpm. Full flow (136 fpm of supply and 99.0 fpm of exhaust) was not statistically significantly different than the 3/4 flow (102 fpm of supply and 68.9 fpm of exhaust) in the unbalanced tracer gas experiments. These two findings together suggest that balancing the flow has a larger effect than the velocity of the flow, in the velocity ranges that were investigated. The resistance of the exhaust filter bank determines whether the exhaust fans can match the supply flow. An additional layer of felt-like material that was not part of the original ventilation design was observed on top of the pre-filter, i.e. a pre-pre-filter called a “pre-layer.” The purpose of this inexpensive extra layer is to protect the downstream filter material from being loaded with sanding particulate and paint droplets, thereby reducing the frequency (cost) of filter replacement. However, the exhaust velocity and the overall airflow pattern in the bay that were intended in the design cannot be achieved with the extra flow blockage, especially when the pre-layer becomes loaded (which happens at some point during the process of refinishing each aircraft). Also, energy costs increase as the exhaust fans must work harder to try to deliver the required flow.

Second, the 100 fpm ventilation rate required by OSHA for “spray booths” would not adequately control exposures in this operation, without the additional reduction provided by the respiratory protection program. Recall from the Discussion section that OSHA regards this facility as a “spray area,” which does not have a specific air velocity requirement. With CrVI concentrations during primer application 100 times greater than the OSHA PEL concentration, however, engineering controls are clearly needed. Because ventilation that adheres to 29 CFR 1910.94 (100 fpm) and is balanced would still need to be supplemented with appropriate respirators, the level of protection that engineering controls must deliver is probably best defined by the aircraft painting section of the OSHA hexavalent chromium standard. In other words, controlling CrVI concentrations below 25 $\mu g/m^3$, as an 8-hr TWA, is probably a more applicable performance metric than maintaining an air velocity of 100 fpm. That having been said, it should also be noted that a balanced flow of 100 fpm has not been tried for this operation, in terms of personal monitoring or tracer gas experiments. It is possible that this condition would be more effective than any of the trials conducted thus far. The CFD results, however, do not clearly indicate a most effective balanced velocity among 75.0, 86.6, 100, or 108 fpm.

The sprayer helpers or hosemen wearing air-purifying respirators (APRs) rather than air-supply hoods during primer application is of some concern. The full-face APR provides an assigned protection factor (APF) of only 50. The resulting hexavalent chromium (CrVI) exposure is below the NIOSH REL, but not by a comfortable margin of safety, as the 95th percentile exposure, assuming the APF, was 39.8% of the REL (1 µg/m^3). Using these data and routine regulatory-required protocol sampling, NMCSD should evaluate and consider whether the sprayer helpers should wear supplied air hoods, just as the sprayers currently do. As a work practice recommendation already made by NMCSD, the helpers should avoid being downwind of the sprayers or the spray plume. Ideally, they should stay behind the sprayers, opposite the spray direction.

During painting, the possibility of isocyanate exposure exceeding the NIOSH ten-minute ceiling of 0.140 mg/m^3 provides another reason for respirator use. Regulation of isocyanate exposure is somewhat uncertain territory, because the toxicology of chemical sensitization and occupational asthma varies according to individual susceptibility. Thus, a cautious approach is suggested. Additionally, the respiratory protection program should remain in place to protect the aircraft painters from the significant exposures to MEK and MIBK that occur during these operations.

Third, while the combination of existing ventilation practices and appropriate use of supplied-air hoods and full-face air-purifying respirators are needed to control exposures, the previous two findings suggest that both the effectiveness and the efficiency of the ventilation system at this facility can be improved by balancing supply and exhaust flows. Specifically, the following are recommended:

- Balance the supply velocity with the current exhaust capacity, which was measured to be near 100 fpm, depending on exhaust filter pressure drop. Exposure control and air pollution permit compliance will be improved by balancing the supply and exhaust.
  - A practical way to balance the supply and exhaust velocity may include replacing the exhaust pre-layer more frequently and keeping all exhaust filters at the lower end of the maintenance life, i.e. filter pressure drop. The replacement schedule should be planned as a joint effort among FRCSW, NMCSD, and NAVFAC. Lowering the filter replacement Δp from 2.5 in. water to 2.0 in. water is a good step toward system balance.
  - In future designs, lower capacity supply blowers or lower RPM operation are system balancing techniques worth considering.
- Ensure that a pressure imbalance in the bay does not create the safety hazard of pedestrian doors blowing open (from positive gauge pressure) or slamming shut (from negative gauge pressure).

  - Because the cross-sectional area of the bay is very large (137 m^2) compared to the pedestrian doors (6 m^2), an imbalance of only -0.2 in. water, for example, will force a flow of several hundred fpm into the bay, through the partially open pedestrian door on the supply filter wall, as a worker is leaving or entering.
  - This door slamming shut would create a pinch-point hazard.
  - One suggestion that arose from discussions with NMCSD industrial hygienists is a significantly stronger door spring that would dampen pressure-driven opening or closing velocity.
  - Any intervention must comply with life safety standards associated with means of egress components.
- An airborne exposure assessment should be performed again after any process change.

Purely from a research perspective, lowering the supply and exhaust further, from 100 to 75 fpm, is likely to have the following effects, based on the tracer gas study (unbalanced conditions) and the CFD simulations (balanced and unbalanced). The exposures of hosemen may increase slightly. The exposures of sprayers, who have the highest exposures, may decrease slightly. Compared to the current full-flow but unbalanced situation, a balanced 100 fpm may be an improvement, as may a balanced 75 fpm. CFD simulation results that became available very recently suggest that 75 fpm provides an advantageous balance between rate of contaminant removal and induced turbulence, which makes it a good candidate for further evaluation. However, reducing the number of blowers to half (73.4 fpm of supply) is a large change in the current process and should not be done without further scientific justification. The tracer study results indicate that half-flow in the bay is clearly less effective than 3/4-flow. Interestingly, half-flow was not statistically significantly less effective than the current ventilation function, full unbalanced flow. Concerning risk of explosion, concentrations would be maintained below 25% of any applicable LEL at half, 3/4, or full-flow.

Because the system was unbalanced during the tracer gas trials, there is uncertainty in how the ventilation should be reported. The supply rate was higher than the exhaust rate. In this report, the average of the supply and exhaust rates is cited. However, the air velocity at the hangar midpoint was also measured. At the midpoint, the full flow condition delivered 104 fpm; 3/4 flow delivered 73.6 fpm; and half-flow delivered 71.7 fpm. The results did not show statistically significant differences in measured tracer gas concentrations between 3/4 and full-flows. The midpoint velocity of 71.7 fpm was considered less protective than either 73.6 or 104 fpm, because half-flow resulted in statistically significantly higher tracer gas concentrations. The large difference in effectiveness between two nearly equal average cross-sectional velocities, 73.6 fpm and 71.7 fpm, may be due to a difference in flow pattern (related to imbalance) between the 3/4 and half-flows or may be attributed to uncertainty in the midpoint velocity measurements. This finding points to the importance of further field studies. Therefore, it is recommended that more field studies be conducted under balanced conditions.

The applicability of the present study to other Navy painting facilities depends on similarity to the bays in Building 465 and the aircraft involved. However, if the supply rate exceeds the exhaust rate significantly, it is safe to say that balancing the supply rate with the exhaust rate (a slight excess of exhaust is preferred for containment) would improve the ventilation effectiveness in any design that involves supply air directed toward an exhaust terminal. Inspection of a different facility or class of facilities should reveal some ideas about how to proceed. The tools and intuition developed by the present study, especially CFD, would allow any future studies of different designs to proceed quickly and efficiently.

Consideration of previous NIOSH research on a somewhat similar operation may be helpful. A NIOSH Hazard Control document and a related NIOSH report (available on the OSHA website) for autobody repair shops specifies a velocity of 80 fpm, as a spatial average with a minimum of 60 fpm, flowing around the car in a downdraft paint booth [NIOSH 1996, Heitbrink 1998]. These documents also recommend HVLP spray guns (like the ones used in Navy painting operations) and a respiratory protection program to complete the chromium and isocyanate control matrix. It is worth noting that a velocity of 80 fpm, in the accelerated flow around the car body, will be driven by a velocity lower than 80 fpm in the open cross-section above the vehicle. While the OSHA ventilation standard, 29 CFR 1910.94, does not distinguish between cross-draft and downdraft configurations, differences in ventilation configuration (and therefore flow pattern) will influence control effectiveness.

CFD would be a useful tool for innovating aircraft paint hangar design, so that attempts to fulfill the twin goals of ventilation effectiveness and efficiency are not limited to changes in flow rate. Reducing the cross-sectional area of a painting hangar to create higher velocities at lower flow rates, directing supply air to the work zones more precisely, and bringing exhaust terminals closer to contaminant sources are examples of possible paths to consider. CFD allows the virtual prototyping of this process, so that a good design concept is chosen prior to the expense of building or modifying facilities. Subsequently, tracer gas studies in the new or modified building can provide information on ventilation effectiveness before any workers are present. Proceeding in this manner will maximize the benefit of engineering controls and minimize the occupational health and safety risk.

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[CFR e] Code of Federal Regulations, Part 1910: *Occupational Safety and Health*

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Appendix A. Air Sampling under Full Flow Conditions (supply = 136 fpm, exhaust = 99 fpm)

Table A-1. Evaluation Criteria for Air Sampling Results Collected during Spray Painting
Fleet Readiness Center Southwest, Naval Base Coronado Specialty Coatings, Building 465, Bay6 San Diego, CA

Compound	Cas #	Lower Explosive Limit (%)	OSHA Permissible Exposure Limit	NIOSH Recommended Exposure Limit	Other Exposure Limits
Total particulate not otherwise regulated	NA	NA	TWA 15 mg/m^3	NA	ACGIH TLV TWA 10 mg/m3 (using an **inhalable** particulate sampler)
Hexavalent chromium	7440-47-3	NA	TWA 0.005 mg/m^3	TWA 0.001 mg/m^3	ACGIH TLV TWA 0.010 mg/m^3 (insoluble)
Barium	7440-39-3	NA	NA	NA	ACGIH TLV TWA 0.5 mg/m^3
Chromium	7440-47-3	NA	TWA 0.5 mg/m^3	TWA 0.5 mg/m^3	NIOSH IDLH 250 mg/m^3
Copper	7440-50-8	NA	TWA 1 mg/m^3	TWA 1 mg/m^3	NIOSH IDLH 100 mg/m^3
Strontium	7440-24-6	NA	NA	NA	NA
Tin	7440-31-5	NA	TWA 2 mg/m^3	TWA 2 mg/m^3	NIOSH IDLH 100 mg/m^3
Titanium	7440-32-6	NA	NA	NA	NA
Nitroethane	79-24-3	3.4	TWA 100 ppm	TWA 100 ppm	NIOSH IDLH 1000 ppm
1,2,4-Trimethylbenzene	95-63-6	0.9	NA	TWA 25 ppm	ACGIH TLV TWA 25 ppm; EU TWA 20 ppm; NIOSH IDLH 1000 ppm
1,3,5-Trimethylbenzene	108-67-8	0.9	NA	TWA 25 ppm	ACGIH TLV TWA 25 ppm; NIOSH IDLH 1000 ppm
2-butoxyethanol	111-76-2	1.1	TWA 50 ppm	TWA 5 ppm	NIOSH IDLH 700 ppm
Cumene	98-82-8	0.9	TWA 50 ppm	TWA 50 ppm	NIOSH IDLH 900 ppm
Ethyl benzene	100-41-4	1.2	TWA 100 ppm	TWA 100 ppm	NIOSH STEL 125 ppm; NIOSH IDLH 800 ppm
Methyl n-amyl ketone	110-43-0	1.1	TWA 100 ppm	TWA 100 ppm	NIOSH IDLH 800 ppm
Methyl ethyl ketone	78-93-3	1.4	TWA 200 ppm	TWA 200 ppm	NIOSH STEL 300 ppm; NIOSH IDLH 3000 ppm
Methyl isobutyl ketone	108-10-1	1.4	TWA 100 ppm	TWA 50 ppm	NIOSH STEL 75 ppm; NIOSH IDLH 500 ppm
n-Butyl acetate	123-86-4	1.7	TWA 150 ppm	TWA 150 ppm	NIOSH STEL 200 ppm; NIOSH IDLH 1700 ppm
Toluene	108-88-3	1.1	TWA 200 ppm	TWA 200 ppm	ACGIH TLV & EU TWA 50 ppm; OSHA Ceiling 300 ppm; OSHA 10 min. Max. peak 500 ppm; NIOSH STEL 150 ppm; NIOSH IDLH 500 ppm
Hexamethylene diisocyanate	822-06-0	0.9	NA	TWA 0.035 mg/m^3	NIOSH Ceiling 0.140 mg/m^3 (10 min.); NIOSH REL 0.035 mg/m^3; ACGIH TLV TWA 0.035 mg/m^3

NA = none
available

% = percent

CAS # = Chemical Abstracts Service registry number

OSHA = Occupational Safety and Health Administration

NIOSH = National Institute for Occupational Safety and Health

mg/m^3 = milligrams of analyte per cubic meter of
air

ppm = parts analyte per million parts air

TWA = time-weighted average

STEL = short term exposure limit (15 minute)

ACGIH TLV = American Conference of Governmental Industrial Hygienist Threshold Limit Value [ACGIH 2001].

IDLH = Immediately Dangerous to Life or Health

EU = European Union

Table A-2
Select Volatile Organic Compounds Air Concentrations during F/A-18C/D Hornet Wipe Down
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Sample Date	Work Activity or Sample Location	Sample Type	Sample Time	Air Sample Volume (m^3)	1, 2, 4-Trimethylbenzene Conc. (ppm)	1, 3, 5-Trimethylbenzene Conc. (ppm)	2-Butoxyethanol Conc. (ppm)	Cumene Conc. (ppm)	Ethyl benzene Conc. (ppm)	Methyl Amyl Ketone Conc. (ppm)	Methyl Ethyl Ketone Conc. (ppm)	Methyl Isobutyl Ketone Conc. (ppm)	N-Butyl Acetate (ppm)	Toluene Conc. (ppm)
7/23/2009	Wipe Down Worker A	P	25	0.0050	<0.02	<0.02	<0.04	<0.02	<0.02	<0.04	62.6	63.0	<0.03	0.03
7/23/2009	Wipe Down Worker B	P	25	0.0051	<0.02	<0.02	<0.04	<0.02	<0.02	<0.04	31.9	47.9	<0.03	0.02
7/23/2009	Tripod #1	A	25	0.0012	<0.07	<0.07	<0.02	<0.08	<0.07	<0.17	6.57	14.4	<0.14	0.11
7/23/2009	Tripod #1	A	25	0.0050	<0.02	<0.02	<0.04	<0.02	<0.02	<0.04	<0.03	0.02	<0.03	0.02
7/23/2009	Tripod #2	A	30	0.0015	<0.06	<0.06	<0.14	<0.07	<0.06	<0.15	0.80	1.50	<0.11	<0.04
7/23/2009	Tripod #2	A	30	0.0060	<0.01	<0.01	<0.03	<0.02	<0.02	<0.04	0.85	1.83	<0.03	0.02
7/23/2009	Tripod #3	A	32	0.0016	<0.05	<0.05	<0.13	<0.06	<0.06	<0.13	<0.08	<0.07	<0.10	<0.03
7/23/2009	Tripod #3	A	32	0.0064	<0.01	<0.01	<0.03	<0.02	<0.1	<0.03	0.69	1.75	<0.03	0.01
7/23/2009	Tripod #4	A	31	0.0016	<0.05	<0.05	<0.13	<0.06	<0.06	<0.13	0.17	0.22	<0.11	<0.03
7/23/2009	Tripod #4	A	31	0.0062	<0.01	<0.01	<0.03	<0.02	<0.01	<0.03	0.10	0.23	<0.03	0.02
8/4/2009	Wipe Down Worker A	P	28	0.0057	<0.01	<0.01	<0.04	<0.02	<0.02	<0.04	71.0	76.7	<0.03	<0.01
8/4/2009	Wipe Down Worker B	P	25	0.0051	0.03	0.02	<0.04	<0.02	<0.02	<0.04	665	918	<0.03	0.25
8/4/2009	Tripod #1	A	25	0.0012	<0.07	<0.07	<0.17	<0.08	<0.07	<0.17	6.31	7.11	<0.14	<0.04
8/4/2009	Tripod #1	A	25	0.0052	<0.02	<0.02	<0.04	<0.02	<0.02	<0.04	6.46	6.98	<0.03	<0.01
8/4/2009	Tripod #2	A	27	0.0014	<0.06	<0.06	<0.15	<0.07	<0.07	<0.16	4.13	4.37	<0.12	<0.04
8/4/2009	Tripod #2	A	27	0.0055	<0.01	<0.01	<0.04	<0.02	<0.02	<0.04	4.42	5.75	<0.03	<0.01
8/4/2009	Tripod #3	A	29	0.0015	0.59	0.19	0.52	<0.07	<0.06	<0.15	<0.08	<0.07	<0.11	<0.04
8/4/2009	Tripod #3	A	29	0.0059	<0.01	<0.01	<0.03	<0.02	<0.02	<0.04	1.43	1.03	<0.03	<0.01
8/4/2009	Tripod #4	A	27	0.0014	<0.06	<0.06	<0.15	<0.07	<0.07	<0.16	<0.03	<0.07	<0.12	<0.04
8/4/2009	Tripod #4	A	27	0.0054	<0.02	<0.02	0.18	<0.02	<0.02	<0.04	<0.03	0.08	<0.03	<0.01

Table A-2
Select Volatile Organic Compounds Air Concentrations during F/A-18C/D Hornet Wipe Down
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Sample Date	Work Activity or Sample Location	Sample Type	Sample Time	Air Sample Volume (m^3)	1, 2, 4-Trimethylbenzene Conc. (ppm)	1, 3, 5-Trimethylbenzene Conc. (ppm)	2-Butoxyethanol Conc. (ppm)	Cumene Conc. (ppm)	Ethyl benzene Conc. (ppm)	Methyl Amyl Ketone Conc. (ppm)	Methyl Ethyl Ketone Conc. (ppm)	Methyl Isobutyl Ketone Conc. (ppm)	N-Butyl Acetate (ppm)	Toluene Conc. (ppm)
4/13/2010	Wipe Down Worker A	P	26	0.0052	<0.04	<0.04	0.05	<0.04	<0.04	<0.03	22.1	20.1	<0.04	<0.05
4/13/2010	Wipe Down Worker B	P	35	0.0070	<0.03	<0.03	0.19	<0.03	0.08	<0.02	16.0	14.3	<0.03	0.08
4/13/2010	Tripod #1	A	46	0.0023	<0.08	<0.08	<0.08	<0.08	<0.09	<0.07	1.91	2.01	<0.08	<0.10
4/13/2010	Tripod #1	A	46	0.0092	<0.02	<0.02	0.02	<0.02	<0.02	<0.02	2.13	2.04	<0.02	<0.03
4/13/2010	Tripod #2	A	46	0.0023	<0.08	<0.08	<0.08	<0.08	<0.09	<0.07	1.22	1.38	<0.08	<0.10
4/13/2010	Tripod #2	A	48	0.0096	<0.02	<0.02	0.04	<0.02	<0.02	<0.02	1.24	1.46	<0.02	<0.03
4/13/2010	Tripod #3	A	41	0.0020	<0.09	<0.09	<0.09	<0.09	<0.10	<0.08	<0.13	<0.10	<0.09	<0.12
4/13/2010	Tripod #3	A	41	0.0082	<0.02	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.04	<0.02	<0.03
4/13/2010	Tripod #4	A	46	0.0023	<0.08	<0.08	<0.08	<0.08	<0.09	<0.07	<0.12	<0.08	<0.08	<0.10
4/13/2010	Tripod #4	A	47	0.0094	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.04	0.10	<0.02	<0.03

YELLOW HIGHLIGHT = STEL Exceeded.

Table A-3
Summary of Select Volatile Organic Compounds Air Concentrations during F/A-18C/D Hornet Wipe Down
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Work Activity or Sample Location	Sample Type	Number of Samples	1, 2, 4-Trimethylbenzene Conc. (ppm)	1, 3, 5-Trimethylbenzene Conc. (ppm)	2-Butoxyethanol Conc. (ppm)	Cumene Conc. (ppm)	Ethyl benzene Conc. (ppm)	Methyl Amyl Ketone Conc. (ppm)	Methyl Ethyl Ketone Conc. (ppm)	Methyl Isobutyl Ketone Conc. (ppm)	N-Butyl Acetate (ppm)	Toluene Conc. (ppm)
Wipe Down Worker	P	6	0.02	0.02	0.06	<0.03	0.03	<0.04	145	190	<0.03	0.07
Tripod #1	A	6	<0.05	<0.05	0.04	<0.05	<0.05	<0.05	3.90	5.43	<0.05	0.04
Tripod #2	A	6	<0.05	<0.05	0.06	<0.05	<0.05	<0.05	1.55	2.12	<0.05	0.03
Tripod #3	A	6	0.12	0.05	0.12	<0.05	<0.05	<0.05	0.38	0.50	<0.05	0.03
Tripod #4	A	6	<0.05	<0.05	0.08	<0.05	<0.05	<0.05	0.07	0.13	<0.05	0.03

YELLOW HIGHLIGHT = STEL Exceeded.

Table A-4
Select Volatile Organic Compounds Air Concentrations during F/A-18C/D Hornet Primer Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Sample Date	Work Activity or Sample Location	Sample Type	Sample Time	Air Sample Volume (m^3)	1, 2, 4-Trimethylbenzene Conc. (ppm)	1, 3, 5-Trimethylbenzene Conc. (ppm)	2-Butoxyethanol Conc. (ppm)	Cumene Conc. (ppm)	Ethyl benzene Conc. (ppm)	Methyl Amyl Ketone Conc. (ppm)	Methyl Ethyl Ketone Conc. (ppm)	Methyl Isobutyl Ketone Conc. (ppm)	N-Butyl Acetate (ppm)	Toluene Conc. (ppm)
7/23/2009	Primer Helper A	P	39	0.0103	0.16	0.05	0.39	<0.01	<0.01	<0.02	0.35	1.15	<0.02	0.03
7/23/2009	Primer Helper B	P	51	0.0100	0.30	0.08	0.64	0.01	<0.01	<0.02	0.23	0.57	<0.02	<0.01
7/23/2009	Primer Sprayer A	P	49	0.0095	1.30	0.39	2.90	0.07	<0.01	<0.02	0.68	2.05	<0.02	0.04
7/23/2009	Primer Sprayer B	P	47	0.0079	0.79	0.21	1.48	0.04	<0.01	<0.03	0.23	0.57	<0.02	0.02
7/23/2009	Tripod #1	A	50	0.0025	1.07	0.32	2.26	0.06	<0.04	<0.09	0.45	1.58	<0.07	<0.02
7/23/2009	Tripod #1	A	50	0.0101	1.09	0.30	2.47	0.05	<0.02	<0.02	0.25	0.73	<0.02	0.03
7/23/2009	Tripod #2	A	49	0.0024	0.17	0.06	0.65	<0.04	<0.04	<0.09	0.84	2.53	<0.07	0.14
7/23/2009	Tripod #2	A	49	0.0098	0.18	0.05	0.51	<0.01	<0.01	0.02	0.13	0.50	<0.02	0.01
8/4/2009	Primer Helper A	P	27	0.0055	0.23	0.08	<0.04	<0.02	<0.02	<0.04	0.10	0.26	<0.03	<0.01
8/4/2009	Primer Helper B	P	29	0.0059	0.34	0.11	0.27	0.02	<0.02	<0.04	0.22	0.66	<0.03	<0.01
8/4/2009	Primer Sprayer A	P	29	0.0061	1.58	0.47	2.46	0.08	<0.02	<0.04	<0.02	0.25	<0.03	0.04
8/4/2009	Primer Sprayer B	P	33	0.0067	1.37	0.40	1.82	0.08	<0.01	<0.03	0.08	0.30	<0.03	0.05
8/4/2009	Tripod #1	A	39	0.0019	<0.04	<0.04	<0.11	<0.05	<0.05	<0.11	<0.10	<0.05	<0.09	<0.03
8/4/2009	Tripod #1	A	39	0.0082	0.42	0.13	0.68	0.02	<0.01	<0.03	<0.03	0.05	<0.02	<0.01
8/4/2009	Tripod #2	A	40	0.0021	0.45	0.16	0.66	<0.05	<0.04	<0.10	<0.07	0.05	<0.08	<0.03
8/4/2009	Tripod #2	A	40	0.0082	0.45	0.13	0.73	0.02	<0.01	<0.03	0.05	0.07	<0.02	<0.01
8/4/2009	Tripod #3	A	34	0.0017	<0.05	<0.05	0.6	<0.06	<0.05	<0.12	0.94	0.75	<0.10	<0.03
8/4/2009	Tripod #3	A	34	0.0069	<0.01	<0.01	<0.03	<0.01	<0.01	<0.03	<0.02	<0.01	<0.02	<0.01
8/4/2009	Tripod #4	A	27	0.0014	<0.06	<0.06	<0.15	<0.07	<0.07	<0.16	<0.11	<0.07	<0.12	<0.04
8/4/2009	Tripod #4	A	27	0.0054	<0.02	<0.02	<0.04	<0.02	<0.02	<0.04	<0.03	<0.02	<0.03	<0.01

Table A-4
Select Volatile Organic Compounds Air Concentrations during F/A-18C/D Hornet Primer Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Sample Date	Work Activity or Sample Location	Sample Type	Sample Time	Air Sample Volume (m^3)	1, 2, 4-Trimethylbenzene Conc. (ppm)	1, 3, 5-Trimethylbenzene Conc. (ppm)	2-Butoxyethanol Conc. (ppm)	Cumene Conc. (ppm)	Ethyl benzene Conc. (ppm)	Methyl Amyl Ketone Conc. (ppm)	Methyl Ethyl Ketone Conc. (ppm)	Methyl Isobutyl Ketone Conc. (ppm)	N-Butyl Acetate (ppm)	Toluene Conc. (ppm)
4/13/2010	Primer Helper A	P	33	0.0066	0.76	0.24	1.34	<0.03	<0.03	<0.03	0.28	0.48	1.36	<0.04
4/13/2010	Primer Helper B	P	27	0.0054	0.56	0.18	0.84	<0.03	<0.04	<0.03	<0.05	0.04	<0.03	<0.04
4/13/2010	Primer Sprayer A	P	29	0.0058	1.43	0.45	3.09	0.05	<0.04	0.04	70.0	42.0	<0.03	<0.04
4/13/2010	Primer Sprayer B	P	36	0.0072	1.78	0.56	3.73	0.06	<0.03	<0.02	0.61	0.61	<0.03	<0.03
4/13/2010	Tripod #1	A	34	0.0017	0.29	<0.11	0.50	<0.11	<0.12	<0.10	<0.16	<0.11	<0.11	<0.14
4/13/2010	Tripod #1	A	34	0.0068	0.98	0.30	2.94	<0.03	<0.03	<0.03	0.49	0.50	<0.03	<0.04
4/13/2010	Tripod #2	A	34	0.0017	0.30	<0.11	0.49	<0.11	<0.12	<0.10	<0.16	<0.11	<0.11	<0.14
4/13/2010	Tripod #2	A	34	0.0067	0.33	0.11	0.46	<0.03	<0.03	<0.03	<0.04	<0.03	<0.03	<0.04
4/13/2010	Tripod #3	A	34	0.0017	<0.11	<0.11	<0.11	<0.11	<0.12	<0.10	0.36	0.45	<0.11	<0.14
4/13/2010	Tripod #3	A	34	0.0068	0.05	<0.03	0.06	<0.03	<0.03	<0.03	0.55	0.47	<0.03	<0.04
4/13/2010	Tripod #4	A	34	0.0017	0.14	0.08	0.13	<0.11	<0.12	<0.10	<0.16	<0.11	<0.11	<0.14
4/13/2010	Tripod #4	A	34	0.0068	0.16	0.05	0.23	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.04

Table A-5
Summary of Select Volatile Organic Compounds Air Concentrations during F/A-18C/D Hornet Primer Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Work Activity or Sample Location	Sample Type	Number of Samples	1, 2, 4-Trimethylbenzene Conc. (ppm)	1, 3, 5-Trimethylbenzene Conc. (ppm)	2-Butoxyethanol Conc. (ppm)	Cumene Conc. (ppm)	Ethyl benzene Conc. (ppm)	Methyl Amyl Ketone Conc. (ppm)	Methyl Ethyl Ketone Conc. (ppm)	Methyl Isobutyl Ketone Conc. (ppm)	N-Butyl Acetate (ppm)	Toluene Conc. (ppm)
Primer Sprayer	P	6	1.38	0.41	2.58	0.06	<0.02	0.03	12.2	7.63	<0.03	0.02
Primer Helper	P	6	0.39	0.12	0.58	0.01	<0.02	<0.03	0.20	0.52	0.24	0.02
Tripod #1	A	6	0.65	0.19	1.48	0.04	<0.05	0.01	0.23	0.59	<0.06	0.03
Tripod #2	A	6	0.31	0.10	0.58	0.02	<0.05	0.04	0.22	0.54	<0.06	0.04
Tripod #3	A	4	0.03	<0.02	0.33	<0.05	<0.05	<0.07	0.47	0.42	<0.06	<0.06
Tripod #4	A	4	0.15	0.05	0.18	<0.06	<0.05	<0.07	<0.08	<0.06	<0.06	<0.06

Table A-6
Total Particulate and Hexavalent Chromium Air Concentrations during F/A-18C/D Hornet Primer Painting Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings, Building 465, Bay6, San Diego, CA

Sample Date	Work Activity or Sample Location	Sample Type	Sample Time	Air Sample Volume (m^3)	Total Particulate Conc. ($\mu g/m^3$)	Hexavalent Chromium Conc. ($\mu g/m^3$)	Hexavalent Chromium 8-hr TWA ($\mu g/m^3$)
7/23/2009	Primer Helper A	P	39	0.0790	1393	36.7	2.98
7/23/2009	Primer Helper B	P	51	0.1033	2807	72.6	7.71
7/23/2009	Primer Sprayer A	P	49	0.1000	18994	540	55.13
7/23/2009	Primer Sprayer B	P	47	0.0953	7028	220	21.54
7/23/2009	Tripod #1	A	50	0.0995	11055	342	35.63
7/23/2009	Tripod #2	A	49	0.0846	<709	13.0	1.33
7/23/2009	Tripod #3	A	60	0.1221	<491	0.25	0.03
7/23/2009	Tripod #4	A	57	0.1181	<508	0.25	0.03
8/4/2009	Primer Helper A	P	27	0.0543	6257	166	9.34
8/4/2009	Primer Helper B	P	29	0.0583	4799	130	7.85
8/4/2009	Primer Sprayer A	P	29	0.0589	22088	578	34.92
8/4/2009	Primer Sprayer B	P	33	0.0667	22502	615	42.28
8/4/2009	Tripod #1	A	39	0.0836	2991	87.3	7.09
8/4/2009	Tripod #2	A	40	0.0830	3976	102	8.50
8/4/2009	Tripod #3	A	34	0.0680	<822	<0.29	<0.021
8/4/2009	Tripod #4	A	27	0.0545	<1100	<0.37	<0.021
4/13/2010	Primer Helper A	P	30	0.0578	8389	281	17.56
4/13/2010	Primer Helper B	P	27	0.0531	5650	183	10.29
4/13/2010	Primer Sprayer A	P	30	0.0606	22499	623	38.94
4/13/2010	Primer Sprayer B	P	33	0.0651	26123	645	44.34
4/13/2010	Tripod #1	A	34	0.0670	3432	128	9.07
4/13/2010	Tripod #2	A	34	0.0666	1950	64.5	4.57
4/13/2010	Tripod #3	A	34	0.0667	<750	0.50	0.04

YELLOW HIGHLIGHT = PEL Exceeded. RED HIGHLIGHT = Aircraft Painting Control Limit Exceeded.

Table A-7
Summary of Total Particulate and Hexavalent Chromium Air Concentrations during F/A-18C/D Hornet Primer Painting Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Work Activity or Sample Location	Sample Type	Number of Samples	Total Particulate Conc. (µg/m^3)	Hexavalent Chromium Conc. (µg/m^3)	Hexavalent Chromium 8-hr TWA (µg/m^3)
Paint Sprayer	P	6	19872	537	41.2
Paint Helper	P	6	4883	145	10.2
Tripod #1	A	3	5826	186	15.9
Tripod #2	A	3	2142	59.8	5.11
Tripod #3	A	3	<688	0.32	0.028
Tripod #4	A	3	<778	0.90	0.079

YELLOW HIGHLIGHT = PEL Exceeded. RED HIGHLIGHT = Aircraft Painting PEL Exceeded.

Table A-8
Select Metals Air Concentrations during F/A-18C/D Hornet Primer Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Work Activity or Sample Location	Sample Type	Sample Time	Air Sample Volume (m^3)	Particulate Conc. ($\mu g/m^3$)	Barium Conc. ($\mu g/m^3$)	Chromium Conc. ($\mu g/m^3$)	Copper Conc. ($\mu g/m^3$)	Strontium Conc. ($\mu g/m^3$)	Tin Conc. ($\mu g/m^3$)	Titanium Conc. ($\mu g/m^3$)
Tripod #1	A	50	0.0992	9882	1210	434	1.71	6.55	<6.05	<4.03
Tripod #2	A	49	0.0973	1233	144	50.0	<0.72	0.76	<6.17	<4.11
Tripod #3	A	60	0.1238	<485	0.43	<3.23	<0.57	<0.24	<4.85	<3.23
Tripod #4	A	57	0.1165	<515	0.28	<343	<0.60	<0.26	<5.15	<3.43
Tripod #1	A	39	0.0812	5175	579	222	<0.86	3.08	<7.39	<4.93
Tripod #2	A	40	0.0786	5088	572	216	<0.89	3.05	<7.63	<5.09
Tripod #3	A	34	0.0675	<889	0.68	<5.92	<1.04	<0.44	<8.89	<5.92
Tripod #4	A	27	0.0557	<1075	<0.54	<7.18	10.2	<0.54	<10.8	<7.18
Tripod #1	A	34	0.0678	3688	516	207	0.53	2.21	6.49	<0.44
Tripod #2	A	34	0.0672	1221	164	65.5	0.82	0.61	<5.88	<0.44
Tripod #3	A	34	0.0667	756	0.65	<1.45	<0.44	<0.09	<5.88	<0.44
Tripod #4	A	34	0.0689	<735	5.15	3.82	<0.44	<0.09	<5.88	<0.44

Table A-9
Summary of Select Metals Air Concentrations during F/A-18C/D Hornet Primer Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Work Activity or Sample Location	Sample Type	Number of Samples	Particulate Conc. (µg/m^3)	Barium Conc. (µg/m^3)	Chromium Conc. (µg/m^3)	Copper Conc. (µg/m^3)	Strontium Conc. (µg/m^3)	Tin Conc. (µg/m^3)	Titanium Conc. (µg/m^3)
Tripod #1	A	3	6248	768	288	0.95	3.95	5.33	<2.39
Tripod #2	A	3	2514	293	111	0.65	1.47	<6.56	<3.21
Tripod #3	A	3	576	0.59	<3.53	<0.68	<0.26	<6.54	<3.20
Tripod #4	A	3	<775	1.94	3.77	3.65	<0.30	<7.28	<3.68

Table A-10
Nitroethane Air Concentrations during F/A-18C/D Hornet Primer Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Sample Date	Work Activity or Sample Location	Sample Type	Sample Time	Air Sample Volume (m^3)	Nitroethane Conc. (ppm)
7/23/2009	Tripod #1	A	50	0.0023	1.95
7/23/2009	Tripod #2	A	49	0.0019	<0.11
7/23/2009	Tripod #3	A	60	0.0030	<0.11
7/23/2009	Tripod #4	A	57	0.0028	<0.11
8/4/2009	Tripod #1	A	39	0.0020	<0.16
8/4/2009	Tripod #2	A	40	0.0020	0.38
8/4/2009	Tripod #3	A	34	0.0019	<0.17
8/4/2009	Tripod #4	A	27	0.0013	<0.26
4/13/2010	Tripod #1	A	34	0.0017	0.77
4/13/2010	Tripod #2	A	34	0.0017	0.51
4/13/2010	Tripod #3	A	34	0.0017	<0.10
4/13/2010	Tripod #4	A	34	0.0017	0.16

Table A-11
Summary of Nitroethane Air Concentrations during F/A-18C/D Hornet Primer Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Work Activity or Sample Location	Sample Type	Number of Samples	Nitroethane Conc. (ppm)
Tripod #1	A	3	0.94
Tripod #2	A	3	0.32
Tripod #3	A	3	<0.13
Tripod #4	A	3	0.14

Table A-12
Select Volatile Organic Compounds Air Concentrations during F/A-18C/D Hornet Topcoat Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado, Specialty Coatings Building 465, Bay6, San Diego, CA

Sample Date	Work Activity or Sample Location	Sample Type	Sample Time	Air Sample Volume (m^3)	1, 2, 4-Trimethylbenzene Conc. (ppm)	1, 3, 5-Trimethylbenzene Conc. (ppm)	2-Butoxyethanol Conc. (ppm)	Cumene Conc. (ppm)	Ethyl benzene Conc. (ppm)	Methyl Amyl Ketone Conc. (ppm)	Methyl Ethyl Ketone Conc. (ppm)	Methyl Isobutyl Ketone Conc. (ppm)	N-Butyl Acetate (ppm)	Toluene Conc. (ppm)
7/23/2009	Paint Helper A	P	102	0.0206	0.03	0.71	0.06	<0.004	0.04	2.50	0.28	0.96	1.74	0.01
7/23/2009	Paint Helper B	P	96	0.0193	0.01	0.34	0.06	<0.01	0.02	1.22	0.44	0.54	0.64	0.01
7/23/2009	Paint Sprayer A	P	95	0.0192	0.08	1.81	0.07	<0.01	0.10	8.61	5.67	8.03	4.62	0.02
7/23/2009	Paint Sprayer B	P	102	0.0208	0.07	1.86	0.08	<0.002	0.09	7.52	0.51	1.53	4.05	0.03
7/23/2009	Tripod #1	A	105	0.0052	0.03	1.02	<0.04	<0.02	0.03	2.84	0.07	0.14	1.90	<0.01
7/23/2009	Tripod #1	A	105	0.0211	0.05	1.15	0.06	<0.01	0.04	3.75	0.08	0.16	2.19	0.01
7/23/2009	Tripod #2	A	114	0.0056	<0.01	0.32	<0.04	<0.02	<0.02	0.95	0.03	0.08	0.68	<0.01
7/23/2009	Tripod #2	A	114	0.0228	0.01	0.31	0.04	<0.004	0.01	0.92	0.002	0.05	0.66	0.004
8/4/2009	Paint Helper A	P	83	0.0174	0.01	0.18	<0.01	<0.01	<0.01	0.65	1.02	1.15	0.44	<0.003
8/4/2009	Paint Helper B	P	78	0.0159	0.04	0.82	<0.01	<0.01	0.04	3.36	1.82	2.67	1.88	<0.01
8/4/2009	Paint Sprayer A	P	82	0.0187	0.08	1.92	0.07	<0.01	0.10	8.69	1.51	1.76	2.90	0.02
8/4/2009	Paint Sprayer B	P	90	0.0183	0.12	2.66	<0.01	<0.01	0.14	11.7	1.39	5.41	5.62	0.02
8/4/2009	Tripod #1	A	93	0.0046	0.04	0.66	<0.05	<0.02	<0.02	2.33	0.58	0.43	1.1	<0.01
8/4/2009	Tripod #1	A	93	0.0195	0.03	0.59	<0.01	<0.01	0.03	2.08	0.28	0.36	1.01	0.02
8/4/2009	Tripod #2	A	91	0.0047	0.11	2.81	<0.04	<0.02	0.09	10	0.05	0.16	4.38	<0.01
8/4/2009	Tripod #2	A	91	0.0186	0.09	2.3	0.05	<0.01	0.07	9.09	0.05	0.11	3.73	0.02
8/4/2009	Tripod #3	A	97	0.0049	<0.02	<0.02	<0.04	<0.02	<0.02	<0.04	<0.03	<0.02	<0.03	<0.01
8/4/2009	Tripod #3	A	97	0.0198	<0.004	<0.004	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.003
8/4/2009	Tripod #4	A	98	0.0049	<0.02	<0.02	<0.04	<0.02	<0.02	<0.04	<0.03	<0.02	<0.03	<0.01
8/4/2009	Tripod #4	A	98	0.0196	<0.004	<0.004	<0.01	<0.01	<0.01	<0.01	0.02	0.04	<0.01	<0.003

Table A-12
Select Volatile Organic Compounds Air Concentrations during F/A-18C/D Hornet Topcoat Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado, Specialty Coatings Building 465, Bay6, San Diego, CA

Sample Date	Work Activity or Sample Location	Sample Type	Sample Time	Air Sample Volume (m^3)	1, 2, 4-Trimethylbenzene Conc. (ppm)	1, 3, 5-Trimethylbenzene Conc. (ppm)	2-Butoxyethanol Conc. (ppm)	Cumene Conc. (ppm)	Ethyl benzene Conc. (ppm)	Methyl Amyl Ketone Conc. (ppm)	Methyl Ethyl Ketone Conc. (ppm)	Methyl Isobutyl Ketone Conc. (ppm)	N-Butyl Acetate (ppm)	Toluene Conc. (ppm)
4/13/2010	Paint Helper A	P	64	0.0108	0.03	0.62	0.11	<0.02	0.05	2.77	1.57	1.69	1.21	<0.02
4/13/2010	Paint Helper B	P	66	0.0133	0.03	0.73	0.10	<0.02	0.05	3.38	1.22	1.41	1.58	<0.02
4/13/2010	Paint Sprayer A	P	78	0.0157	0.10	2.20	0.18	<0.02	0.16	11.5	0.76	1.00	5.23	<0.02
4/13/2010	Paint Sprayer B	P	75	0.015	0.08	1.63	0.17	<0.02	0.14	8.56	0.16	0.31	4.21	<0.02
4/13/2010	Tripod #1	A	135	0.0068	<0.03	0.42	0.05	<0.03	<0.03	1.83	0.85	1.05	0.84	<0.04
4/13/2010	Tripod #1	A	135	0.0271	0.02	0.49	0.07	<0.01	0.03	2.29	1.05	1.26	0.93	<0.01
4/13/2010	Tripod #2	A	135	0.0068	<0.03	0.39	0.05	<0.03	<0.03	1.78	0.14	0.22	0.78	<0.04
4/13/2010	Tripod #2	A	135	0.0269	0.02	0.48	0.06	<0.01	0.02	1.99	0.14	0.19	0.78	<0.01
4/13/2010	Tripod #3	A	135	0.0067	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.04	<0.03	<0.03	<0.04
4/13/2010	Tripod #3	A	135	0.027	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
4/13/2010	Tripod #4	A	135	0.0069	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.04	<0.03	<0.03	<0.04
4/13/2010	Tripod #4	A	135	0.0274	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.06	0.11	<0.01	<0.01

Table A-13
Summary of Select Volatile Organic Compounds Air Concentrations during F/A-18C/D Hornet Topcoat Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Work Activity or Sample Location	Sample Type	Number of Samples	1, 2, 4-Trimethylbenzene Conc. (ppm)	1, 3, 5-Trimethylbenzene Conc. (ppm)	2-Butoxyethanol Conc. (ppm)	Cumene Conc. (ppm)	Ethyl benzene Conc. (ppm)	Methyl Amyl Ketone Conc. (ppm)	Methyl Ethyl Ketone Conc. (ppm)	Methyl Isobutyl Ketone Conc. (ppm)	N-Butyl Acetate (ppm)	Toluene Conc. (ppm)
Paint Sprayer	P	6	0.08	2.01	0.10	<0.01	0.12	9.43	1.67	3.01	4.44	0.02
Paint Helper	P	6	0.03	0.57	0.06	<0.01	0.03	2.31	1.06	1.40	1.25	0.01
Tripod #1	A	6	0.03	0.72	0.04	<0.01	0.03	2.52	0.49	0.57	1.33	0.01
Tripod #2	A	6	0.04	1.10	0.04	<0.01	0.04	4.12	0.07	0.14	1.84	0.01
Tripod #3	A	4	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Tripod #4	A	4	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	0.03	0.05	<0.01	<0.01

Table A-14
Hexamethylene Diisocyanate Monomer, Isocyanate Functional Group Monomer, and Isocyanate Functional Group Oligomer
Air Concentrations during F/A-18C/D Hornet Topcoat Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Sample Date	Work Activity or Sample Location	Sample Type	Sample Time	Air Sample Volume (m^3)	Hexamethylene Diisocyanate Monomer Conc. (µg/m3)	Isocyanate Functional Group Monomer Conc. (µg/m3)	Isocyanate Functional Group Oligomer Conc. (µg/m3)
7/23/2009	Paint Helper A	P	102	0.1154	11.3	5.26	130
7/23/2009	Paint Helper B	P	96	0.0993	4.54	2.26	44.8
7/23/2009	Paint Sprayer A	P	95	0.0904	27.3	13.7	180
7/23/2009	Paint Sprayer B	P	102	0.1036	29.1	14.6	198
7/23/2009	Tripod #1	A	105	0.1067	8.97	4.48	147
7/23/2009	Tripod #2	A	114	0.1160	2.59	1.29	36.5
8/4/2009	Paint Helper A	P	83	0.0839	1.93	0.97	27.6
8/4/2009	Paint Helper B	P	75	0.0759	<1.32	<0.79	<5.26
8/4/2009	Paint Sprayer A	P	95	0.0953	39.6	19.8	281
8/4/2009	Paint Sprayer B	P	90	0.0911	26.9	13.4	238
8/4/2009	Tripod #1	A	93	0.0948	3.67	1.84	46.0
8/4/2009	Tripod #2	A	91	0.0934	14.2	7.11	119
8/4/2009	Tripod #3	A	97	0.0950	<0.53	<0.32	<2.11
8/4/2009	Tripod #4	A	98	0.1015	<0.49	<0.30	<1.97
4/13/2010	Paint Helper A	P	66	0.0628	10.8	5.40	133
4/13/2010	Paint Helper B	P	54	0.0546	8.21	4.10	153
4/13/2010	Paint Sprayer A	P	78	0.0830	35.9	18.0	356
4/13/2010	Paint Sprayer B	P	75	0.0754	49.6	24.8	484
4/13/2010	Tripod #1	A	135	0.1327	3.27	16.4	103
4/13/2010	Tripod #2	A	135	0.1316	3.83	1.91	82.1
4/13/2010	Tripod #3	A	135	0.1405	<0.28	<0.14	<0.28
4/13/2010	Tripod #4	A	137	0.1344	<0.30	<0.15	<0.30
4/13/2010	Tripod #1	A*	135	0.1346	11.0	19.1	142
4/13/2010	Tripod #2	A*	135	0.1374	11.2	19.1	139
4/13/2010	Tripod #3	A*	135	0.1344	<0.60	<0.30	0.61
4/13/2010	Tripod #4	A*	137	0.1391	<0.58	<0.29	<0.58

* Impinger Sample

Table A-15
Summary* of Hexamethylene Diisocyanate Monomer, Isocyanate Functional Group Monomer, and Isocyanate Functional Group Oligomer Air Concentrations during F/A-18C/D Hornet Topcoat Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Work Activity or Sample Location	Sample Type	Number of Samples	Hexamethylene Diisocyanate Monomer Conc. (µg/m3)	Isocyanate Functional Group Monomer Conc. (µg/m3)	Isocyanate Functional Group Oligomer Conc. (µg/m3)
Paint Sprayer	P	6	34.7	17.4	290
Paint Helper	P	6	6.29	3.09	82.0
Tripod #1	A	6	5.30	7.57	98.7
Tripod #2	A	6	9.34	3.44	79.2
Tripod #3	A	4	<0.41	<0.23	<1.20
Tripod #4	A	4	<0.40	<0.23	<1.34

*Impinger samples were excluded from summary averages.

Table A-16
Select Metals Air Concentrations during F/A-18C/D Hornet Topcoat Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Sample Date	Work Activity or Sample Location	Sample Type	Sample Time	Air Sample Volume (m^3)	Particulate Conc. ($\mu g/m^3$)	Barium Conc. ($\mu g/m^3$)	Chromium Conc. ($\mu g/m^3$)	Copper Conc. ($\mu g/m^3$)	Strontium Conc. ($\mu g/m^3$)	Tin Conc. ($\mu g/m^3$)	Titanium Conc. ($\mu g/m^3$)
7/23/2009	Tripod #1	A	105	0.2083	5762	0.32	<1.9	<0.34	0.33	<2.9	35
7/23/2009	Tripod #2	A	114	0.1968	2388	<0.15	<2.0	<0.36	<0.15	<3.0	21
7/23/2009	Tripod #3	A	113	0.23	<261	<0.13	<1.7	<0.30	<0.13	<2.6	<1.7
7/23/2009	Tripod #4	A	118	0.2444	<245	<0.12	<1.6	<0.29	<0.12	<2.5	<1.6
8/4/2009	Tripod #1	A	93	0.1993	1655	<0.15	<2.01	<0.35	<3.0	<3.0	16.6
8/4/2009	Tripod #2	A	91	0.1888	6885	<0.16	<2.12	0.49	<3.2	<3.2	58.3
8/4/2009	Tripod #3	A	97	0.194	<309	<0.15	<2.06	<0.36	<3.1	<3.1	<2.1
8/4/2009	Tripod #4	A	98	0.2023	<297	<0.15	<1.98	<0.35	<3.0	<3.0	<2.0
4/13/2010	Tripod #1	A	135	0.2691	2935	<0.07	<0.37	0.12	<0.02	<1.50	100
4/13/2010	Tripod #2	A	135	0.2668	2324	<0.07	<0.37	0.04	<0.02	<1.50	75
4/13/2010	Tripod #3	A	135	0.2731	<183	<0.07	<0.37	<0.11	<0.02	<1.50	<0.11
4/13/2010	Tripod #4	A	137	0.2776	<180	<0.07	<0.37	0.07	<0.02	<1.50	<0.11

Table A-17
Summary of Select Metals Air Concentrations during F/A-18C/D Hornet Topcoat Paint Spraying
Fleet Readiness Center Southwest, Naval Base Coronado
Specialty Coatings
Building 465, Bay6
San Diego, CA

Work Activity or Sample Location	Sample Type	Number of Samples	Particulate Conc. ($\mu g/m^3$)	Barium Conc. ($\mu g/m^3$)	Chromium Conc. ($\mu g/m^3$)	Copper Conc. ($\mu g/m^3$)	Strontium Conc. ($\mu g/m^3$)	Tin Conc. ($\mu g/m^3$)	Titanium Conc. ($\mu g/m^3$)
Tripod #1	A	3	3451	0.31	<1.43	0.20	0.15	<2.47	50.5
Tripod #2	A	3	3866	<0.13	<1.50	0.26	0.11	<2.57	51.4
Tripod #3	A	3	<236	<0.12	<1.38	0.18	<0.10	<2.40	<1.30
Tripod #4	A	3	<241	<0.12	<1.32	0.17	<0.10	<2.33	<1.24

Appendix B. CFD Simulation

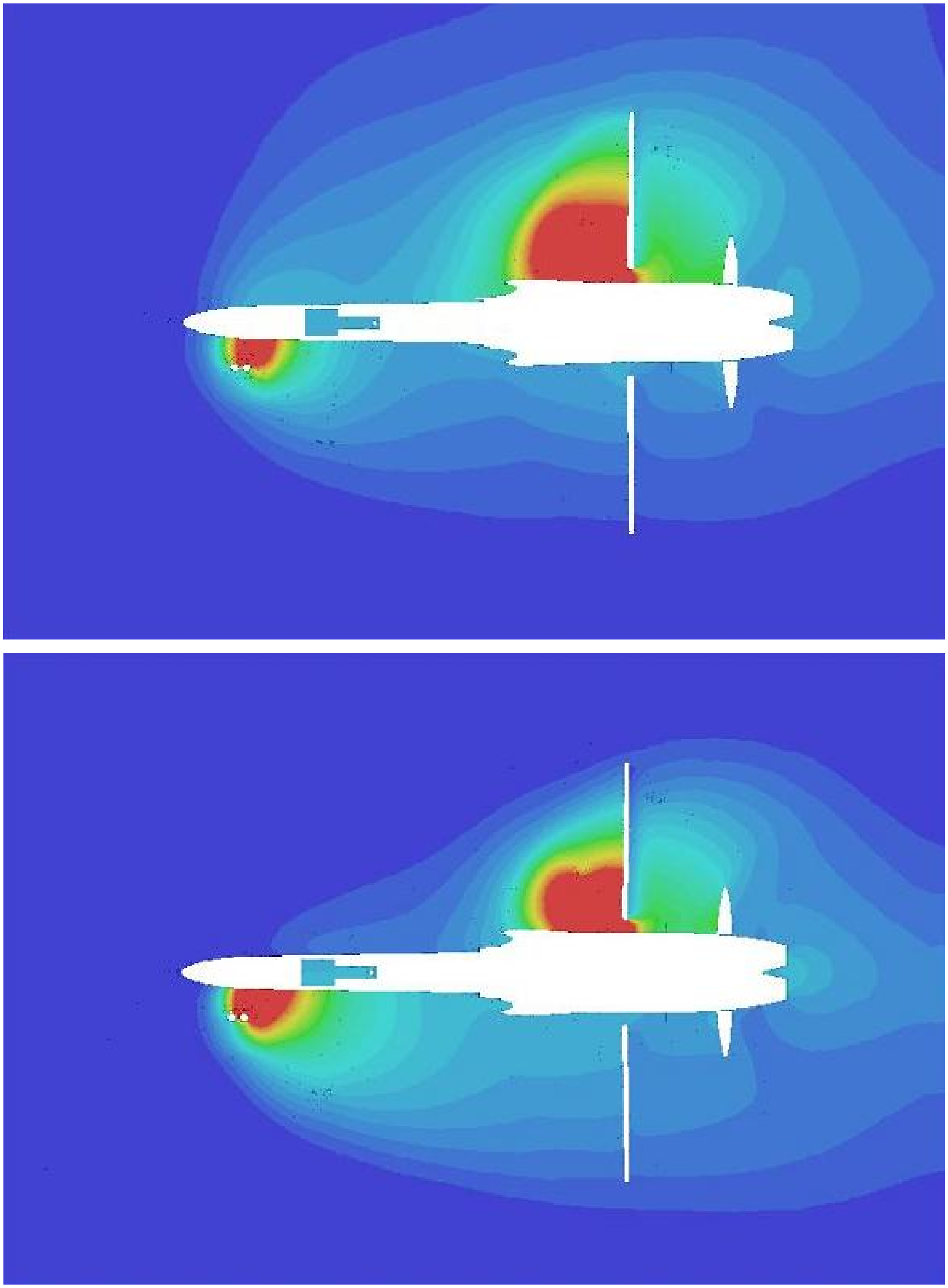


Figure B-1. Contours of MIBK concentration at breathing zone height for the unbalanced 108 fpm supply-65.0 fpm exhaust (top image) and the balanced 65.0 fpm (bottom image) cases.

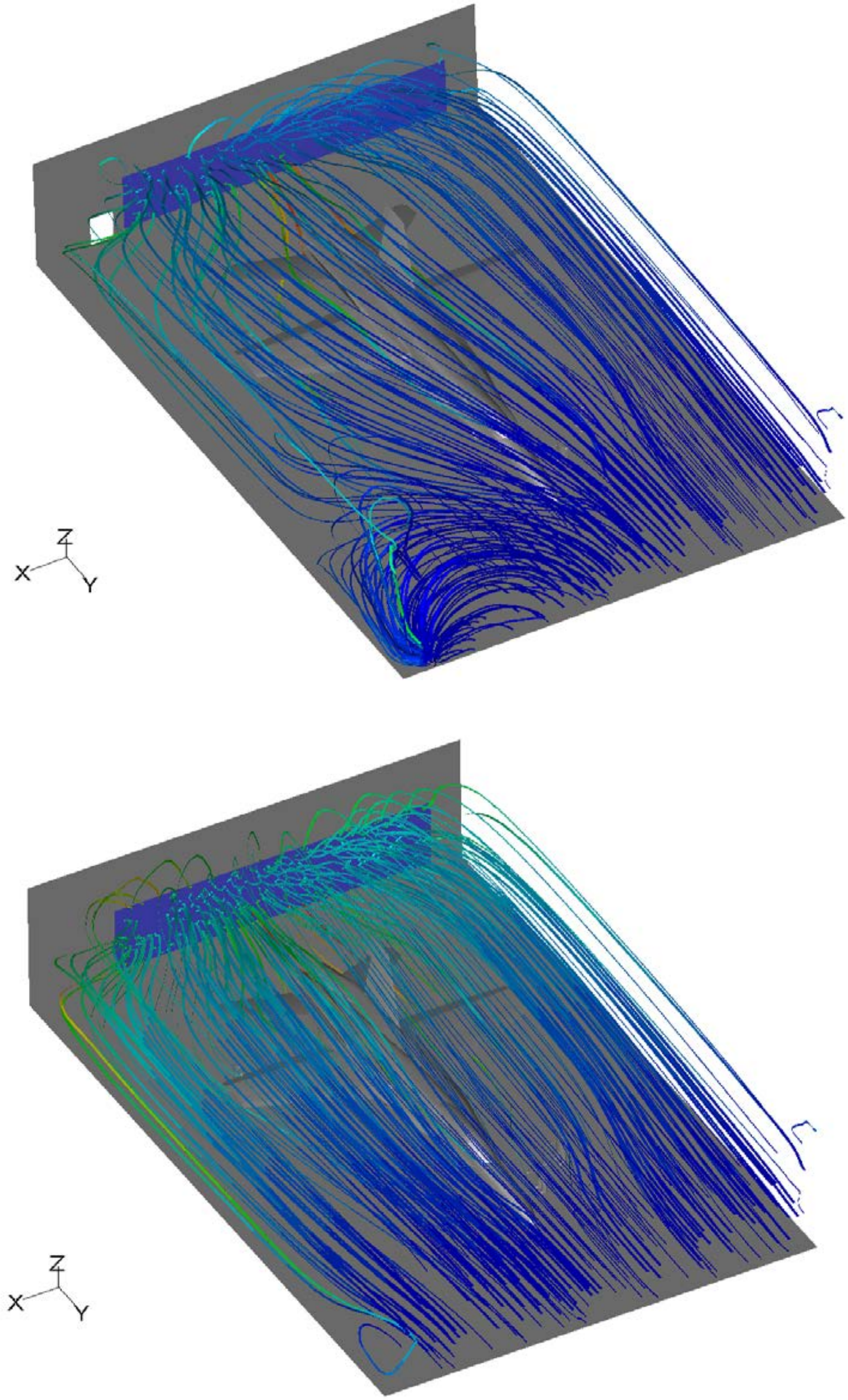


Figure B-2. Visualized flow lines colored by residence time for the unbalanced 108 fpm supply-65.0 fpm exhaust case (top image) and the balanced 65.0 fpm case (bottom image).

Appendix C. Tracer Gas Experiments

DATA SUBSET 5 (MEANS CALCULATED USING EVERY 5th VALUE OF TIME SERIES)

Obs	Source Configuration	Flow Rate (%)	Measurement Location	Data Series	Log Conc. Mean	n	Log Conc Std Dev
1	Horizontal	50	ECTB	HorECTB50	6.54892	174	0.33081
2	Horizontal	50	HETAB	HorHETAB50	5.47361	180	1.05953
3	Horizontal	50	S00245	HorS0024550	5.63942	174	0.57950
4	Horizontal	50	S00262	HorS0026250	6.45370	173	1.12750
5	Horizontal	50	S00427	HorS0042750	5.81443	174	0.68841
6	Horizontal	75	ECTB	HorECTB75	4.72167	174	0.30636
7	Horizontal	75	HETAB	HorHETAB75	5.51685	180	1.72737
8	Horizontal	75	S00245	HorS0024575	4.35093	173	0.04532
9	Horizontal	75	S00262	HorS0026275	4.77668	173	0.10610
10	Horizontal	75	S00427	HorS0042775	6.23390	174	1.50820
11	Horizontal	100	ECTB	HorECTB100	5.80602	174	0.48180
12	Horizontal	100	HETAB	HorHETAB100	5.81779	180	0.64220
13	Horizontal	100	S00245	HorS00245100	4.72233	173	0.31938
14	Horizontal	100	S00262	HorS00262100	6.56572	173	0.97186
15	Horizontal	100	S00427	HorS00427100	5.35936	174	1.13180
16	Single	50	ECTB	SinECTB50	.	0	.
17	Single	50	HETAB	SinHETAB50	4.00872	180	1.80321
18	Single	50	S00245	SinS0024550	4.93860	173	1.57162
19	Single	50	S00262	SinS0026250	8.33995	173	0.47144
20	Single	50	S00427	SinS0042750	4.91313	174	1.73421
21	Single	100	ECTB	SinECTB100	4.98348	172	0.59702
22	Single	100	HETAB	SinHETAB100	5.73999	180	1.62059
23	Single	100	S00245	SinS00245100	4.07581	173	0.68723
24	Single	100	S00262	SinS00262100	4.87191	173	0.76424
25	Single	100	S00427	SinS00427100	0.34550	174	0.80343
26	Vertical	25	ECTB	VerECTB25	8.19056	174	0.38333
27	Vertical	25	HETAB	VerHETAB25	3.79076	180	1.42815
28	Vertical	25	S00245	VerS0024525	5.90536	173	0.65046
29	Vertical	25	S00262	VerS0026225	6.65354	173	0.65549
30	Vertical	25	S00427	VerS0042725	3.72123	174	0.47888
31	Vertical	50	ECTB	VerECTB50	6.81557	174	0.36962
32	Vertical	50	HETAB	VerHETAB50	4.67952	180	0.97346
33	Vertical	50	S00245	VerS0024550	5.24973	173	0.52579
34	Vertical	50	S00262	VerS0026250	5.91794	173	0.92078
35	Vertical	50	S00427	VerS0042750	6.93905	174	0.52185
36	Vertical	75	ECTB	VerECTB75	5.64857	30	0.44104

37	Vertical	75	HETAB	VerHETAB75	5.15941	180	1.12387
38	Vertical	75	S00245	VerS0024575	2.79496	173	0.62659
39	Vertical	75	S00262	VerS0026275	3.91727	173	0.14531
40	Vertical	75	S00427	VerS0042775	1.03621	174	1.62256
41	Vertical	100	ECTB	VerECTB100	5.61478	174	0.29673
42	Vertical	100	HETAB	VerHETAB100	4.06232	180	1.14940
43	Vertical	100	S00245	VerS00245100	3.80137	173	0.12034
44	Vertical	100	S00262	VerS00262100	4.56821	173	0.12925
45	Vertical	100	S00427	VerS00427100	6.64100	174	0.37724

DATA SUBSET 5 SUMMARY

Obs	Flow Rate (%)	Log Conc Mean	n	Log Conc Std Dev
1	25	5.65229	5	1.91727
2	50	5.83802	14	1.11597
3	75	4.41564	10	1.53173
4	100	4.86504	15	1.52031

Obs	Flow Rate (%)	Conc Geo Mean (ppm)	n	Conc Geo Std Dev (ppm)
1	25	284.94	5	6.80
2	50	343.10	14	3.05
3	75	82.74	10	4.63
4	100	129.68	15	4.57

DATA SUBSET 10 (MEANS CALCULATED USING EVERY 10th VALUE OF TIME SERIES)

Obs	Source Configuration	Flow Rate (%)	Measurement Location	Data Series	Log Conc. Mean	n	Log Conc Std Dev
1	Horizontal	50	ECTB	HorECTB50	6.54778	87	0.32460
2	Horizontal	50	HETAB	HorHETAB50	5.45389	90	1.11255
3	Horizontal	50	S00245	HorS0024550	5.64973	87	0.56977
4	Horizontal	50	S00262	HorS0026250	6.46665	86	1.16213
5	Horizontal	50	S00427	HorS0042750	5.82814	87	0.69578
6	Horizontal	75	ECTB	HorECTB75	4.72885	87	0.30381
7	Horizontal	75	HETAB	HorHETAB75	5.53671	90	1.70538
8	Horizontal	75	S00245	HorS0024575	4.35039	86	0.04358
9	Horizontal	75	S00262	HorS0026275	4.77367	86	0.09492
10	Horizontal	75	S00427	HorS0042775	6.24732	87	1.50093
11	Horizontal	100	ECTB	HorECTB100	5.84250	87	0.46034
12	Horizontal	100	HETAB	HorHETAB100	5.77806	90	0.66834
13	Horizontal	100	S00245	HorS00245100	4.73107	86	0.31784
14	Horizontal	100	S00262	HorS00262100	6.54524	86	0.96359

15	Horizontal	100	S00427	HorS00427100	5.34066	87	1.13533
16	Single	50	ECTB	SinECTB50	.	0	.
17	Single	50	HETAB	SinHETAB50	4.04181	90	1.74863
18	Single	50	S00245	SinS0024550	4.95697	86	1.55788
19	Single	50	S00262	SinS0026250	8.33427	86	0.47354
20	Single	50	S00427	SinS0042750	4.86709	87	1.71237
21	Single	100	ECTB	SinECTB100	4.99208	86	0.60728
22	Single	100	HETAB	SinHETAB100	5.65594	90	1.72955
23	Single	100	S00245	SinS00245100	4.08290	86	0.69044
24	Single	100	S00262	SinS00262100	4.87299	86	0.75189
25	Single	100	S00427	SinS00427100	0.34662	87	0.79677
26	Vertical	25	ECTB	VerECTB25	8.18654	87	0.39131
27	Vertical	25	HETAB	VerHETAB25	3.76980	90	1.42420
28	Vertical	25	S00245	VerS0024525	5.91487	86	0.65186
29	Vertical	25	S00262	VerS0026225	6.66947	86	0.67608
30	Vertical	25	S00427	VerS0042725	3.72569	87	0.51992
31	Vertical	50	ECTB	VerECTB50	6.81565	87	0.35832
32	Vertical	50	HETAB	VerHETAB50	4.73945	90	0.94038
33	Vertical	50	S00245	VerS0024550	5.26171	86	0.53391
34	Vertical	50	S00262	VerS0026250	5.90951	86	0.92478
35	Vertical	50	S00427	VerS0042750	6.94895	87	0.53867
36	Vertical	75	ECTB	VerECTB75	5.67514	15	0.43407
37	Vertical	75	HETAB	VerHETAB75	5.11599	90	1.25628
38	Vertical	75	S00245	VerS0024575	2.78473	86	0.60273
39	Vertical	75	S00262	VerS0026275	3.91997	86	0.14514
40	Vertical	75	S00427	VerS0042775	1.01940	87	1.62911
41	Vertical	100	ECTB	VerECTB100	5.61047	87	0.30173
42	Vertical	100	HETAB	VerHETAB100	3.88636	90	1.39834
43	Vertical	100	S00245	VerS00245100	3.80044	86	0.12003
44	Vertical	100	S00262	VerS00262100	4.56918	86	0.13362
45	Vertical	100	S00427	VerS00427100	6.65290	87	0.38630

DATA SUBSET 10 SUMMARY

Obs	Flow Rate (%)	Log Conc Mean	n	Log Conc Std Dev
1	25	5.65328	5	1.92234
2	50	5.84440	14	1.10913
3	75	4.41521	10	1.54054
4	100	4.84716	15	1.52250

Obs	Flow Rate (%)	Conc Geo Mean (ppm)	n	Conc Geo Std Dev (ppm)
1	25	285.22	5	6.84
2	50	345.30	14	3.03
3	75	82.70	10	4.67
4	100	127.38	15	4.58

DATA SUBSET 20 (MEANS CALCULATED USING EVERY 20th VALUE OF TIME SERIES)

Obs	Source Configuration	Flow Rate (%)	Measurement Location	Data Series	Log Conc. Mean	n	Log Conc Std Dev
1	Horizontal	50	ECTB	HorECTB50	6.57205	43	0.28956
2	Horizontal	50	HETAB	HorHETAB50	5.48837	45	0.92643
3	Horizontal	50	S00245	HorS0024550	5.62240	43	0.57856
4	Horizontal	50	S00262	HorS0026250	6.45932	43	1.18334
5	Horizontal	50	S00427	HorS0042750	5.85195	43	0.64836
6	Horizontal	75	ECTB	HorECTB75	4.69242	43	0.24193
7	Horizontal	75	HETAB	HorHETAB75	5.55387	45	1.78078
8	Horizontal	75	S00245	HorS0024575	4.34932	43	0.04078
9	Horizontal	75	S00262	HorS0026275	4.76556	43	0.04777
10	Horizontal	75	S00427	HorS0042775	6.25148	43	1.46714
11	Horizontal	100	ECTB	HorECTB100	5.85321	43	0.42454
12	Horizontal	100	HETAB	HorHETAB100	5.83786	45	0.60928
13	Horizontal	100	S00245	HorS00245100	4.71391	43	0.27560
14	Horizontal	100	S00262	HorS00262100	6.53427	43	0.99483
15	Horizontal	100	S00427	HorS00427100	5.37285	43	1.08980
16	Single	50	ECTB	SinECTB50	.	0	.
17	Single	50	HETAB	SinHETAB50	3.79453	45	1.85851
18	Single	50	S00245	SinS0024550	4.82999	43	1.54637
19	Single	50	S00262	SinS0026250	8.32831	43	0.49734
20	Single	50	S00427	SinS0042750	4.97570	43	1.58883
21	Single	100	ECTB	SinECTB100	4.91258	43	0.57392
22	Single	100	HETAB	SinHETAB100	5.55834	45	1.65612
23	Single	100	S00245	SinS00245100	4.05069	43	0.65582
24	Single	100	S00262	SinS00262100	4.87164	43	0.74942
25	Single	100	S00427	SinS00427100	0.35208	43	0.78966
26	Vertical	25	ECTB	VerECTB25	8.21497	43	0.23508
27	Vertical	25	HETAB	VerHETAB25	3.96052	45	1.01079
28	Vertical	25	S00245	VerS0024525	5.96380	43	0.66998
29	Vertical	25	S00262	VerS0026225	6.65996	43	0.72415

30	Vertical	25	S00427	VerS0042725	3.72586	43	0.49375
31	Vertical	50	ECTB	VerECTB50	6.84557	43	0.33417
32	Vertical	50	HETAB	VerHETAB50	4.71398	45	0.92726
33	Vertical	50	S00245	VerS0024550	5.25063	43	0.50892
34	Vertical	50	S00262	VerS0026250	5.89185	43	0.91140
35	Vertical	50	S00427	VerS0042750	6.93421	43	0.55863
36	Vertical	75	ECTB	VerECTB75	5.64886	7	0.35174
37	Vertical	75	HETAB	VerHETAB75	5.07732	45	1.28778
38	Vertical	75	S00245	VerS0024575	2.74322	43	0.49108
39	Vertical	75	S00262	VerS0026275	3.91990	43	0.14451
40	Vertical	75	S00427	VerS0042775	1.05703	43	1.71636
41	Vertical	100	ECTB	VerECTB100	5.62403	43	0.31087
42	Vertical	100	HETAB	VerHETAB100	3.94654	45	1.40694
43	Vertical	100	S00245	VerS00245100	3.80629	43	0.12142
44	Vertical	100	S00262	VerS00262100	4.56465	43	0.11509
45	Vertical	100	S00427	VerS00427100	6.66968	43	0.43157

DATA SUBSET 20 SUMMARY

Obs	Flow Rate (%)	Log Conc Mean	n	Log Conc Std Dev
1	25	5.70502	5	1.88674
2	50	5.82563	14	1.14545
3	75	4.40590	10	1.53297
4	100	4.84457	15	1.52091

Obs	Flow Rate (%)	Conc Geo Mean (ppm)	n	Conc Geo Std Dev (ppm)
1	25	300.37	5	6.60
2	50	338.88	14	3.14
3	75	81.93	10	4.63
4	100	127.05	15	4.58

FULL DATA SET

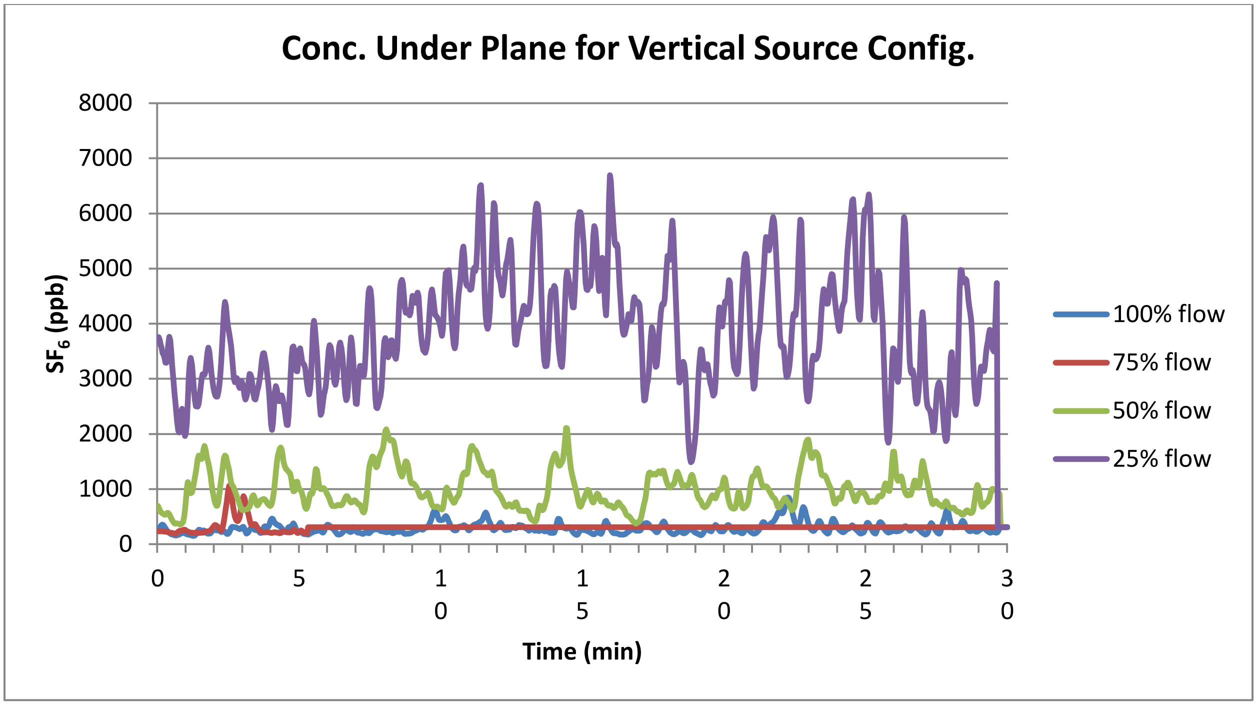
Obs	Source Configuration	Flow Rate (%)	Measurement Location	Log Conc. Mean	n	Log Conc Std Dev
1	Horizontal	50	ECTB	6.55284	871	0.32719
2	Horizontal	50	HETAB	5.47237	1801	1.05283
3	Horizontal	50	S00245	5.63738	870	0.57544

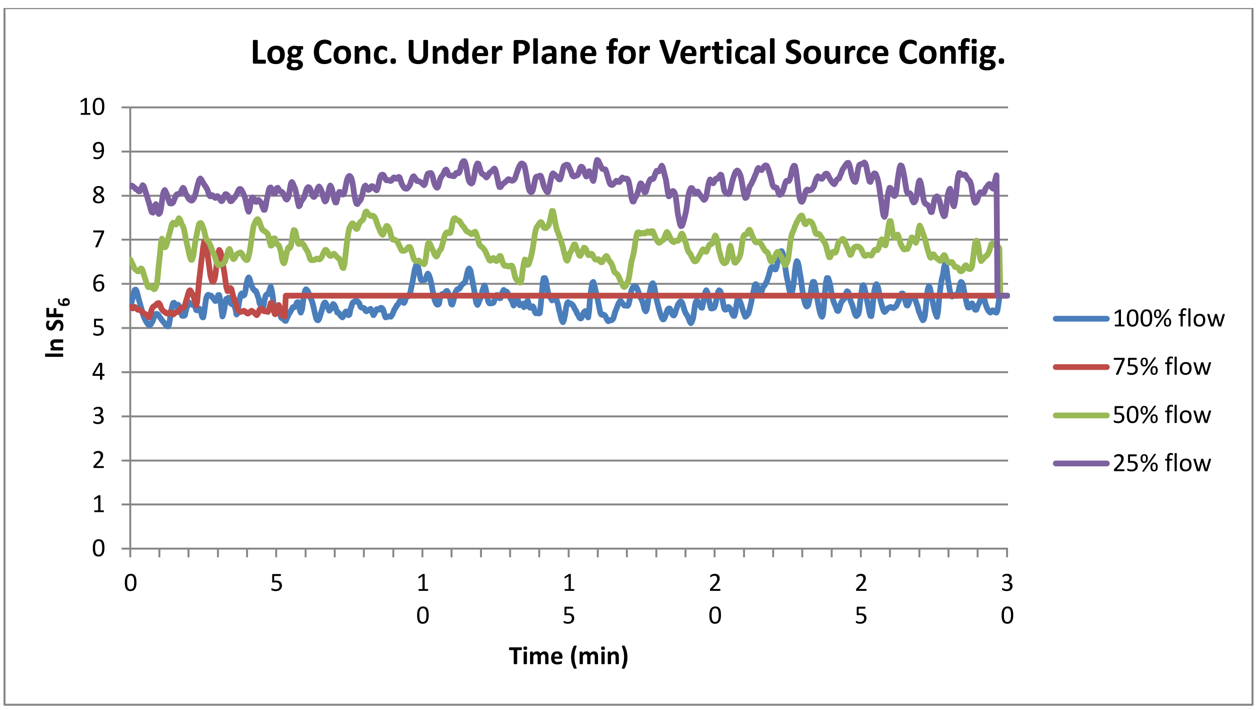
4	Horizontal	50	S00262	6.45381	868	1.12110
5	Horizontal	50	S00427	5.81350	871	0.68829
6	Horizontal	75	ECTB	4.72141	871	0.30072
7	Horizontal	75	HETAB	5.42532	1801	1.85484
8	Horizontal	75	S00245	4.35188	868	0.04694
9	Horizontal	75	S00262	4.77776	868	0.10663
10	Horizontal	75	S00427	6.22510	871	1.50960
11	Horizontal	100	ECTB	5.80826	871	0.48051
12	Horizontal	100	HETAB	5.79156	1801	0.73099
13	Horizontal	100	S00245	4.72060	868	0.32219
14	Horizontal	100	S00262	6.56543	868	0.96716
15	Horizontal	100	S00427	5.36732	871	1.13092
16	Single	50	ECTB	.	0	.
17	Single	50	HETAB	4.11756	1801	1.66128
18	Single	50	S00245	4.93644	868	1.56779
19	Single	50	S00262	8.34072	869	0.47020
20	Single	50	S00427	4.92082	871	1.72774
21	Single	100	ECTB	4.98137	863	0.59901
22	Single	100	HETAB	5.75639	1801	1.58154
23	Single	100	S00245	4.07358	868	0.68735
24	Single	100	S00262	4.87333	869	0.76039
25	Single	100	S00427	0.33450	871	0.79850
26	Vertical	25	ECTB	8.18928	871	0.39039
27	Vertical	25	HETAB	3.90806	1801	1.29423
28	Vertical	25	S00245	5.90679	868	0.65182
29	Vertical	25	S00262	6.65551	868	0.64894
30	Vertical	25	S00427	3.72128	871	0.48139
31	Vertical	50	ECTB	6.82031	871	0.36628
32	Vertical	50	HETAB	4.73876	1801	0.86693
33	Vertical	50	S00245	5.24622	869	0.52158
34	Vertical	50	S00262	5.91524	868	0.91852
35	Vertical	50	S00427	6.93993	871	0.52014
36	Vertical	75	ECTB	5.63676	154	0.42936
37	Vertical	75	HETAB	5.15964	1801	1.10990
38	Vertical	75	S00245	2.79578	868	0.61669
39	Vertical	75	S00262	3.91769	869	0.14439
40	Vertical	75	S00427	1.03068	871	1.61262
41	Vertical	100	ECTB	5.61322	871	0.29527
42	Vertical	100	HETAB	3.96788	1801	1.21283
43	Vertical	100	S00245	3.80051	869	0.12159
44	Vertical	100	S00262	4.56915	868	0.13468
45	Vertical	100	S00427	6.64020	870	0.37690

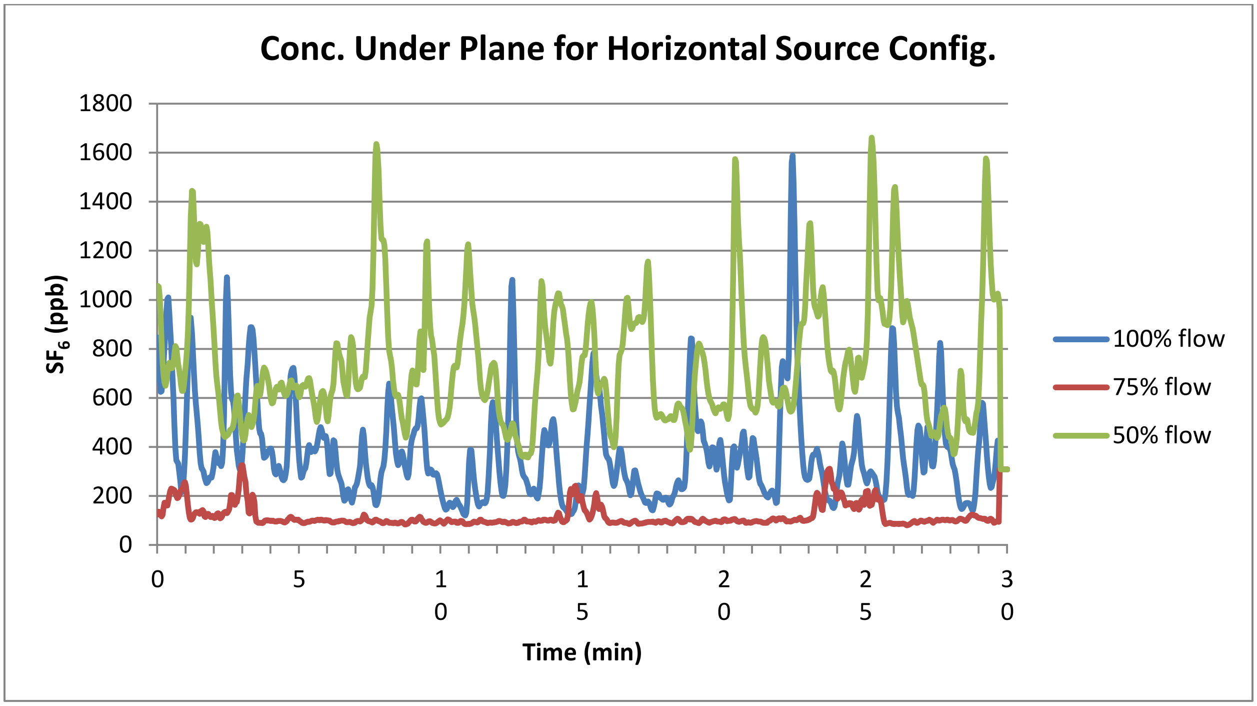
FULL DATA SUMMARY

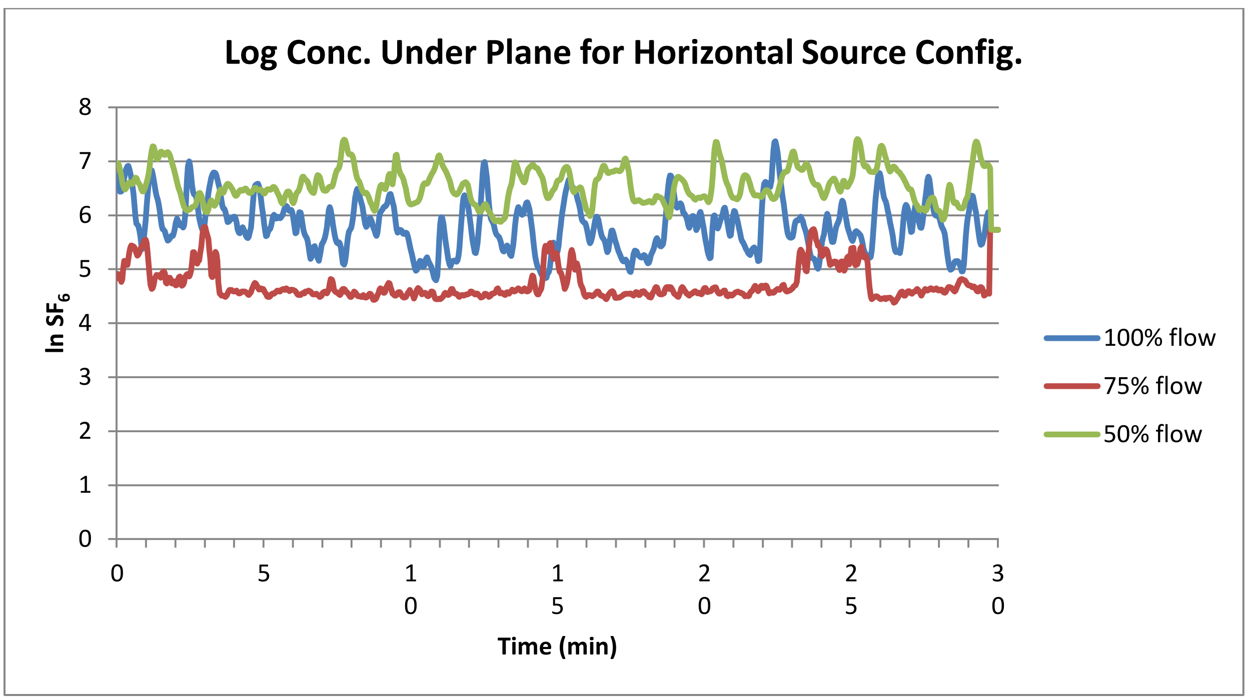
Obs	Flow Rate (%)	Log Conc Mean	n	Log Conc Std Dev
1	25	5.67618	5	1.88917
2	50	5.85042	14	1.09838
3	75	4.40420	10	1.52372
4	100	4.85755	15	1.52617

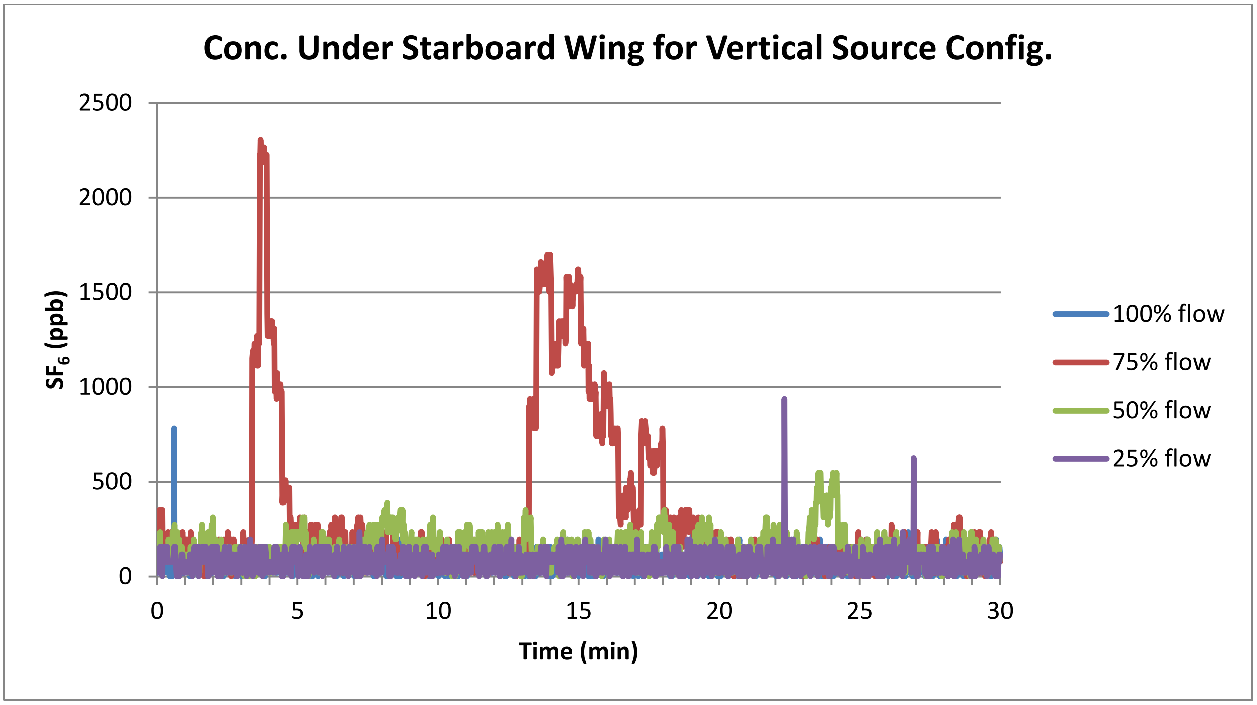
Obs	Flow Rate (%)	Conc Geo Mean (ppm)	n	Conc Geo Std Dev (ppm)
1	25	291.83	5	6.61
2	50	347.38	14	3.00
3	75	81.79	10	4.59
4	100	128.71	15	4.60

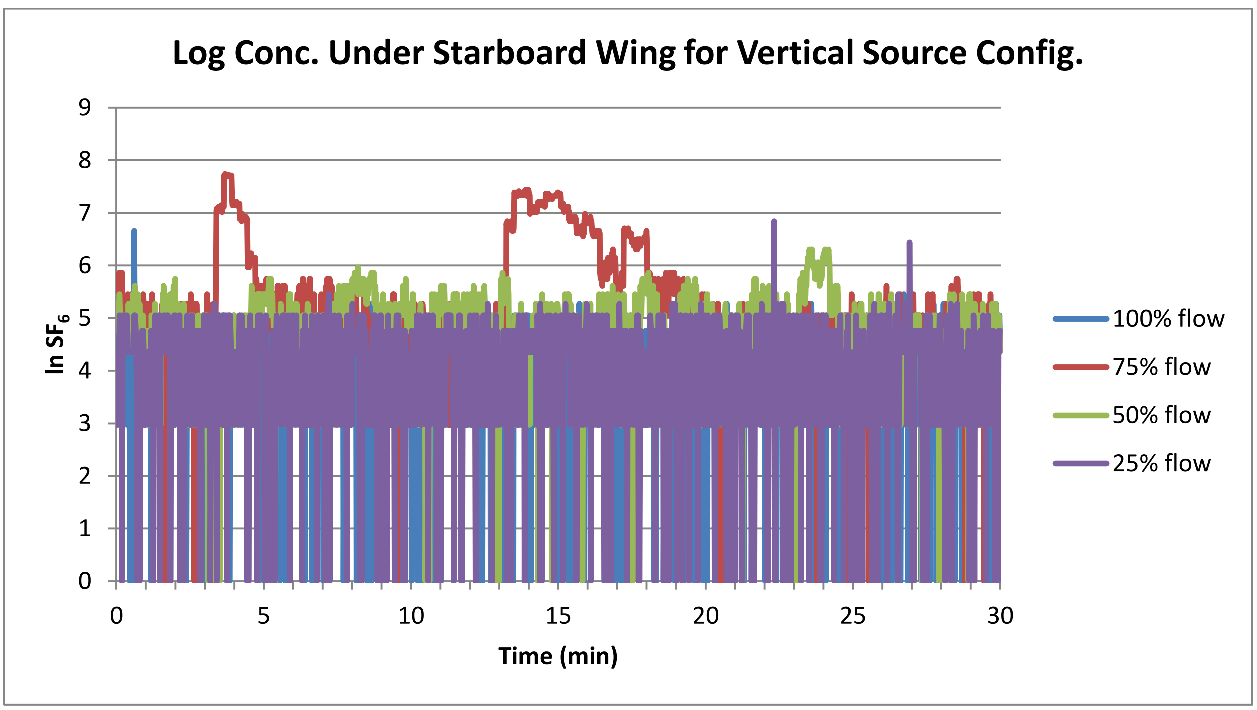

Conc. Under Plane for Vertical Source Config.
SF6 (ppb)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
30
Time (min)
100% flow
75% flow
50% flow
25% flow

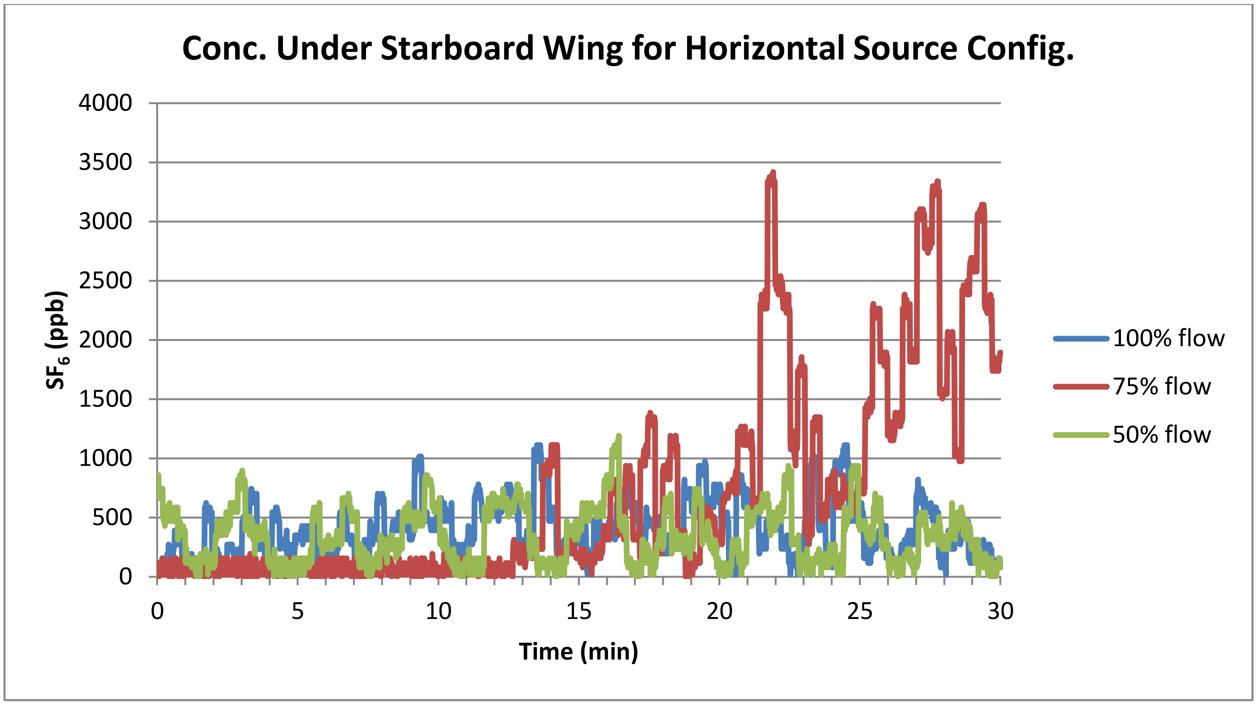

Log Conc. Under Plane for Vertical Source Config.
ln SF6
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
20
25
30
Time (min)
100% flow
75% flow
50% flow
25% flow

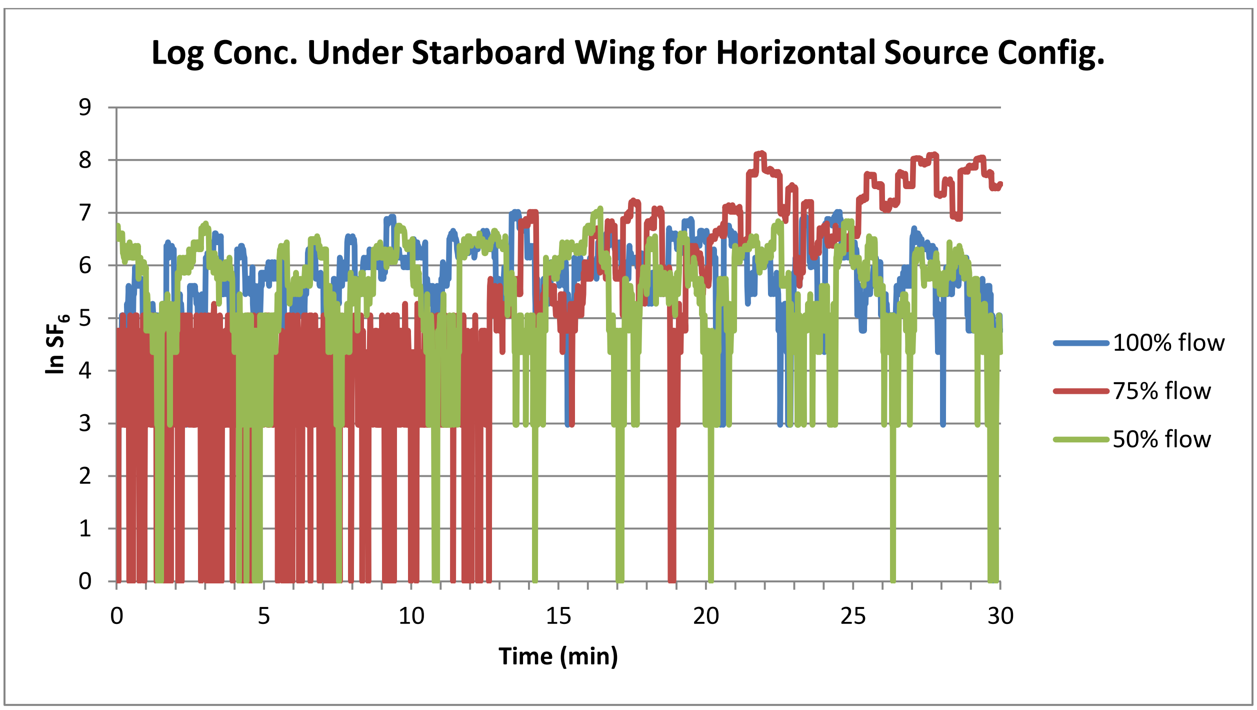

Conc. Under Plane for Horizontal Source Config.
SF6 (ppb)
1800
1600
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
Time (min)
100% flow
75% flow
50% flow

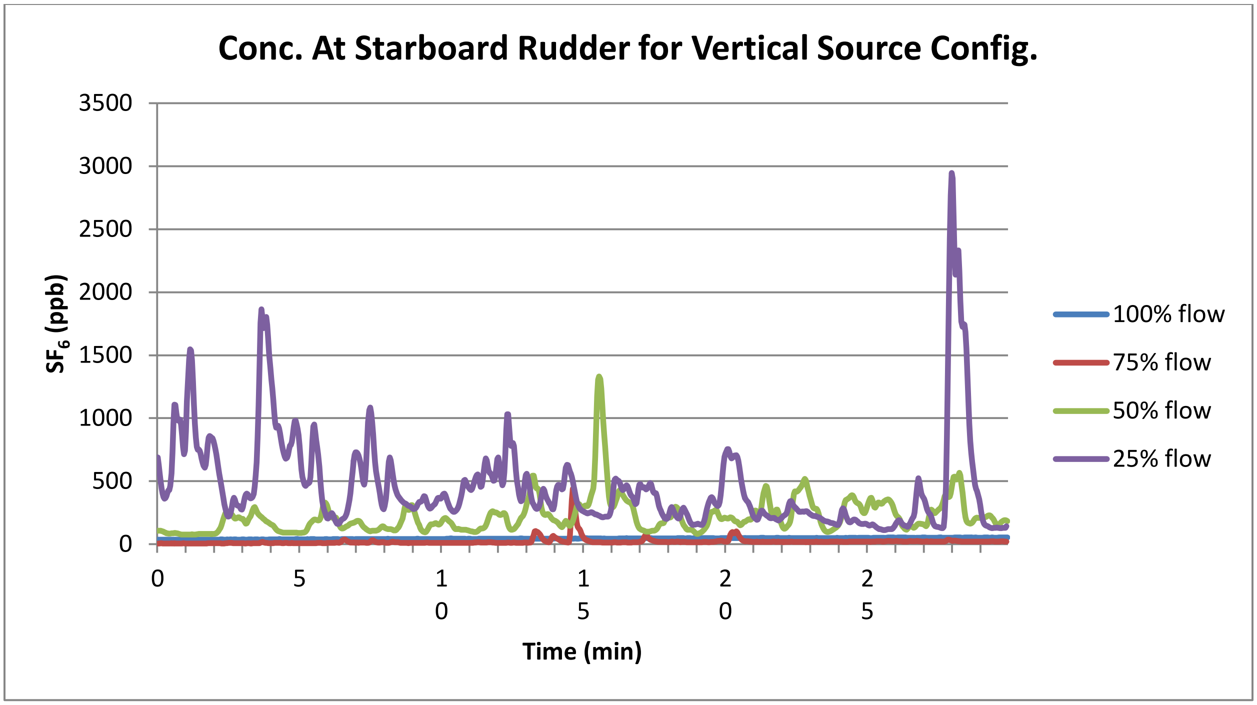

Log Conc. Under Plane for Horizontal Source Config.
ln SF6
8
7
6
5
4
3
2
1
0
0
5
10
15
20
25
30
Time (min)
100% flow
75% flow
50% flow

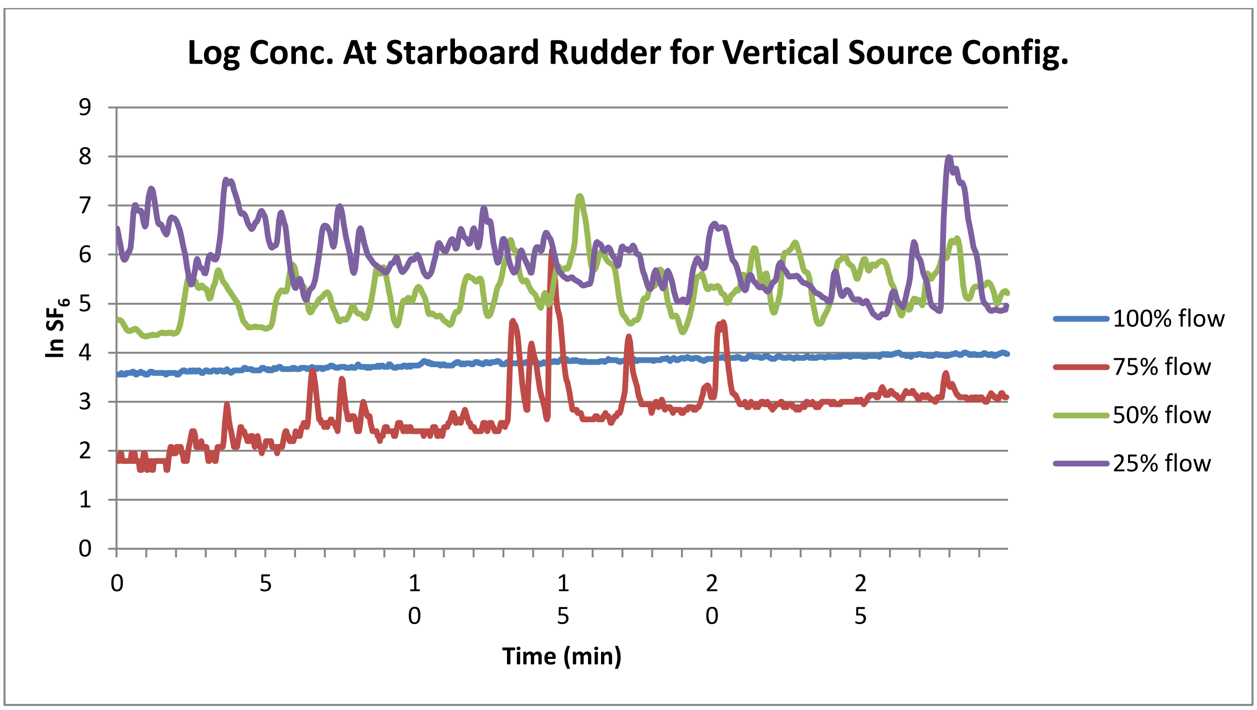

Conc. Under Starboard Wing for Vertical Source Config.
SF6 (ppb)
Time (min)
100% flow
75% flow
50% flow
25% flow
0
500
1000
1500
2000
2500
0
5
10
15
20
25
30

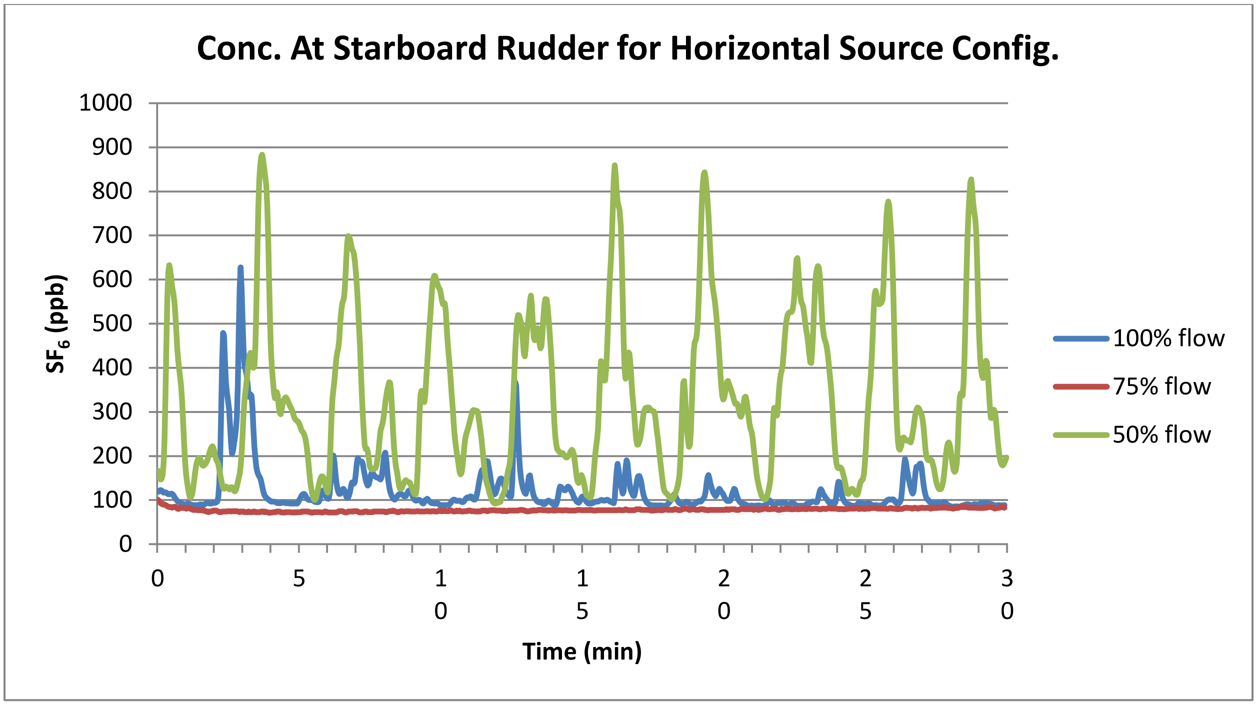

Log Conc. Under Starboard Wing for Vertical Source Config.
ln SF6
Time (min)
100% flow
75% flow
50% flow
25% flow
0
1
2
3
4
5
6
7
8
9
0
5
10
15
20
25
30

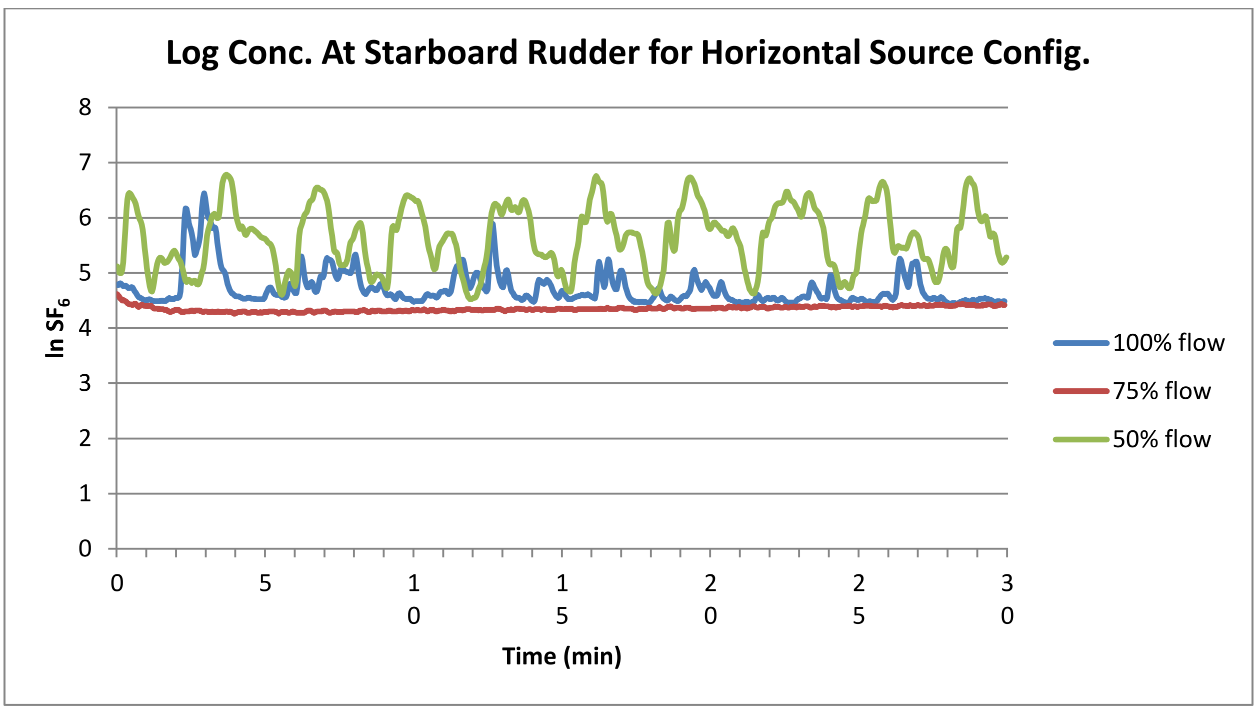

Conc. Under Starboard Wing for Horizontal Source Config.
SF6 (ppb)
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
Time (min)
100% flow
75% flow
50% flow

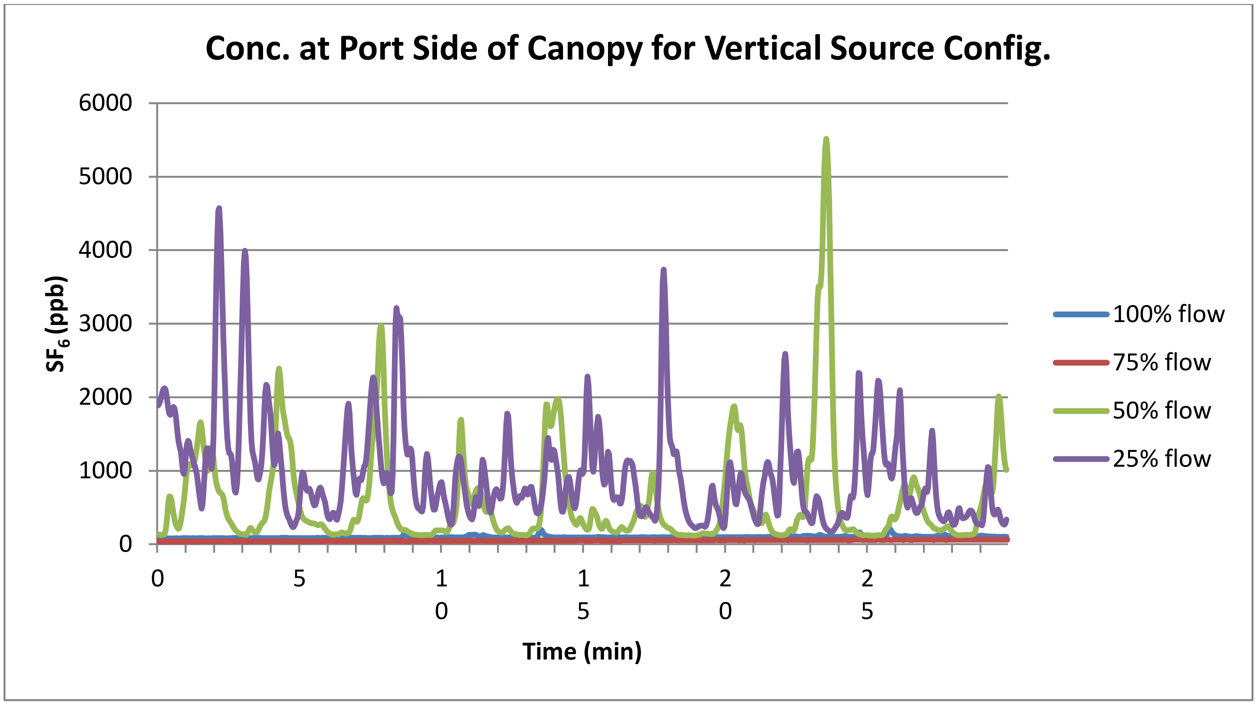

Log Conc. Under Starboard Wing for Horizontal Source Config.
ln SF6
9
8
7
6
5
4
3
2
1
0
0
5
10
15
20
25
30
Time (min)
100% flow
75% flow
50% flow

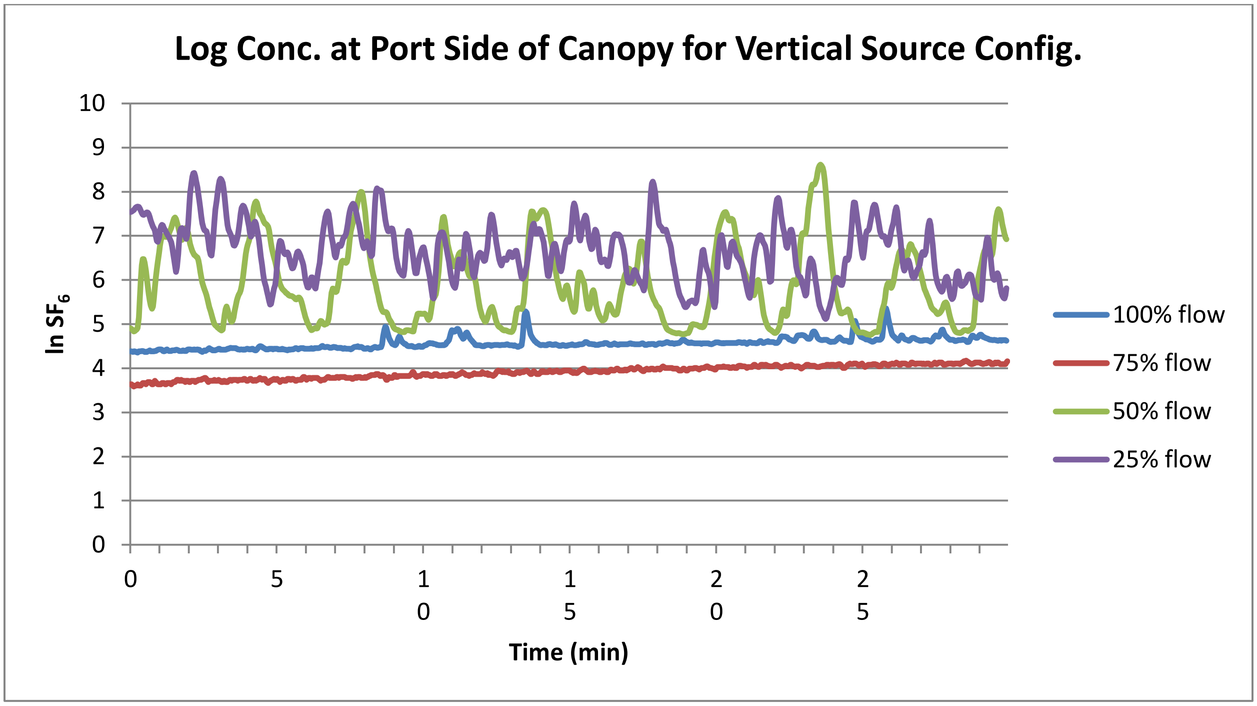

Conc. At Starboard Rudder for Vertical Source Config.
3500
3000
2500
2000
1500
1000
500
0
SF_6 (ppb)
0
5
1
0
1
5
2
0
2
5
Time (min)
100% flow
75% flow
50% flow
25% flow

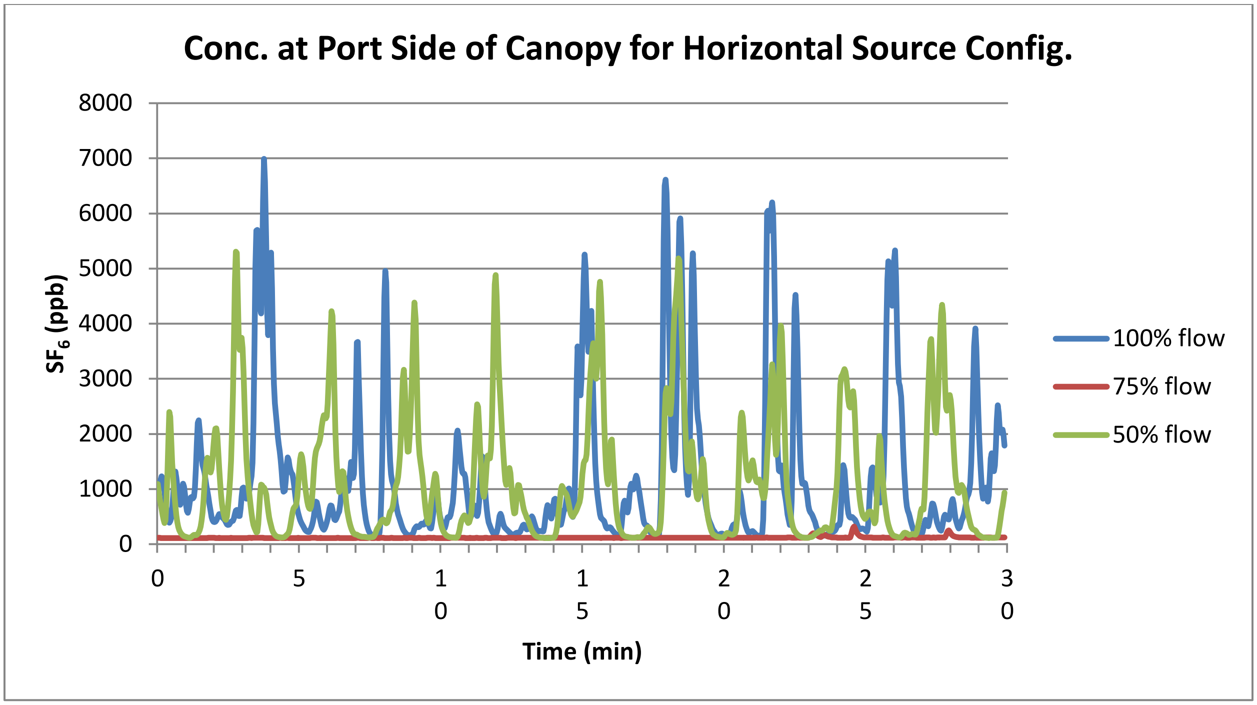

Log Conc. At Starboard Rudder for Vertical Source Config.
9
8
7
6
5
4
3
2
1
0
ln SF_6
0
5
1
0
1
5
2
0
2
5
Time (min)
100% flow
75% flow
50% flow
25% flow

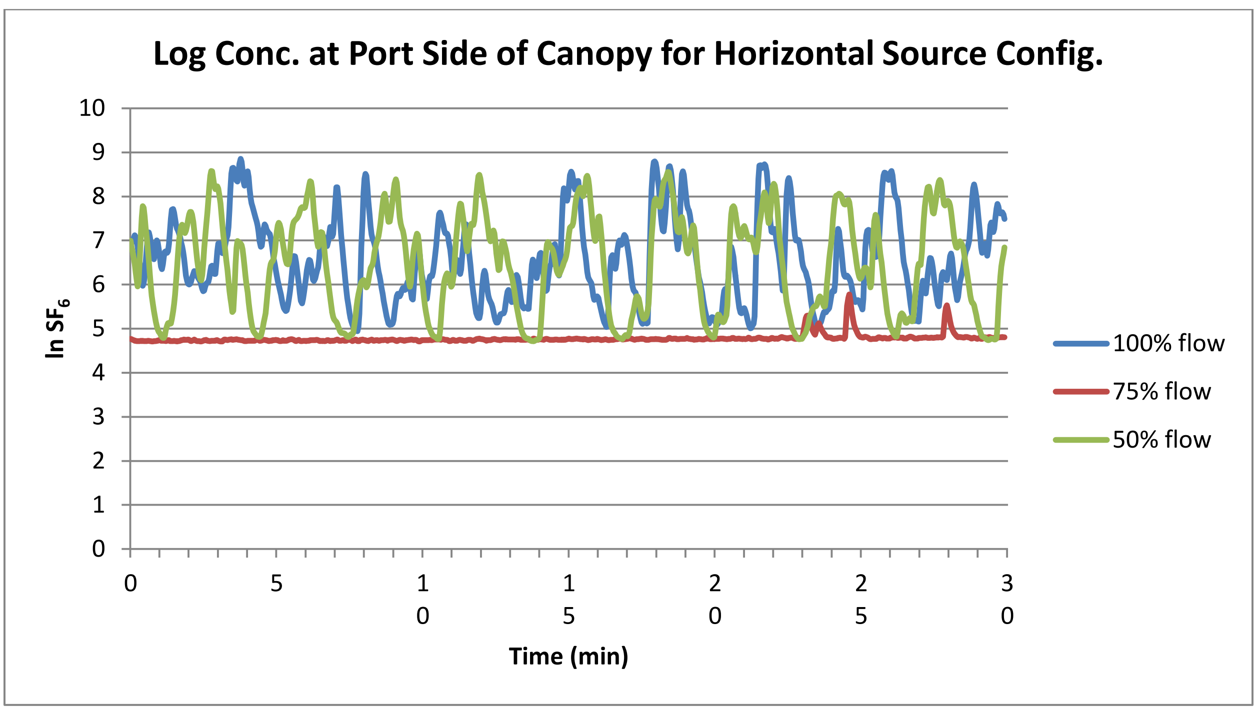

Conc. At Starboard Rudder for Horizontal Source Config.
SF6 (ppb)
1000
900
800
700
600
500
400
300
200
100
0
0
5
1
0
1
5
2
0
2
5
3
0
Time (min)
100% flow
75% flow
50% flow

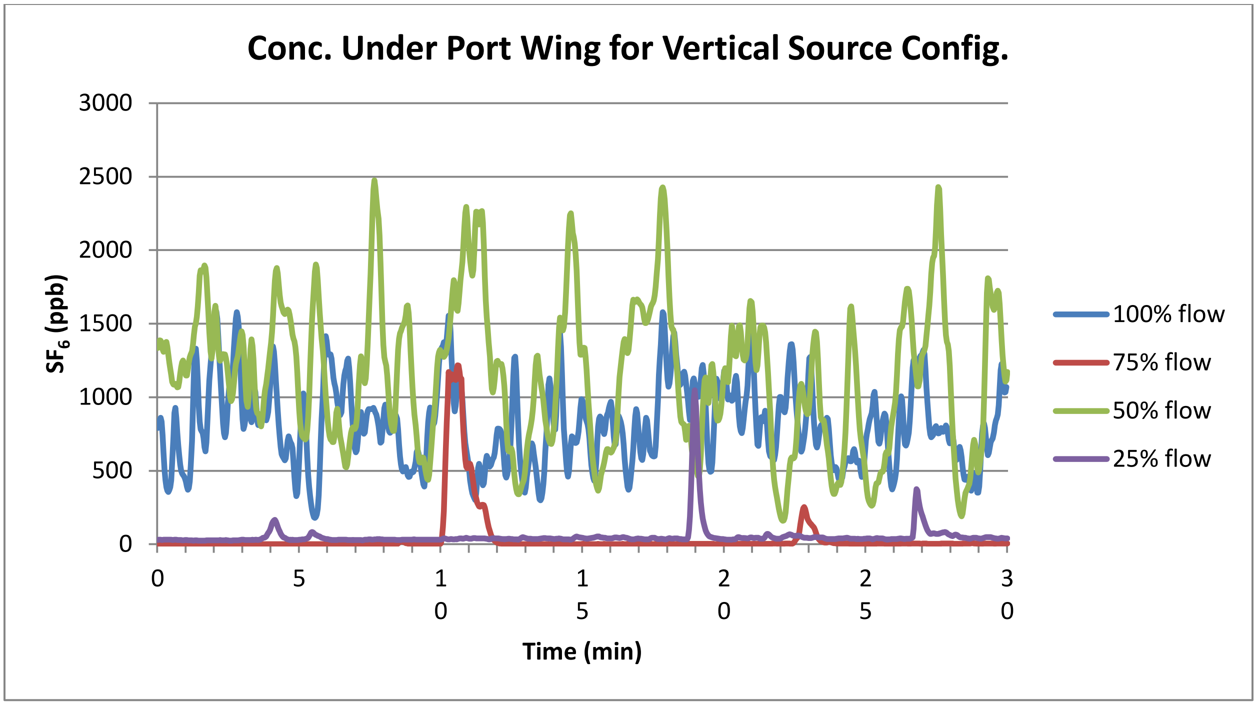

Log Conc. At Starboard Rudder for Horizontal Source Config.
ln SF6
8
7
6
5
4
3
2
1
0
0
5
1
0
1
5
2
0
2
5
3
0
Time (min)
100% flow
75% flow
50% flow

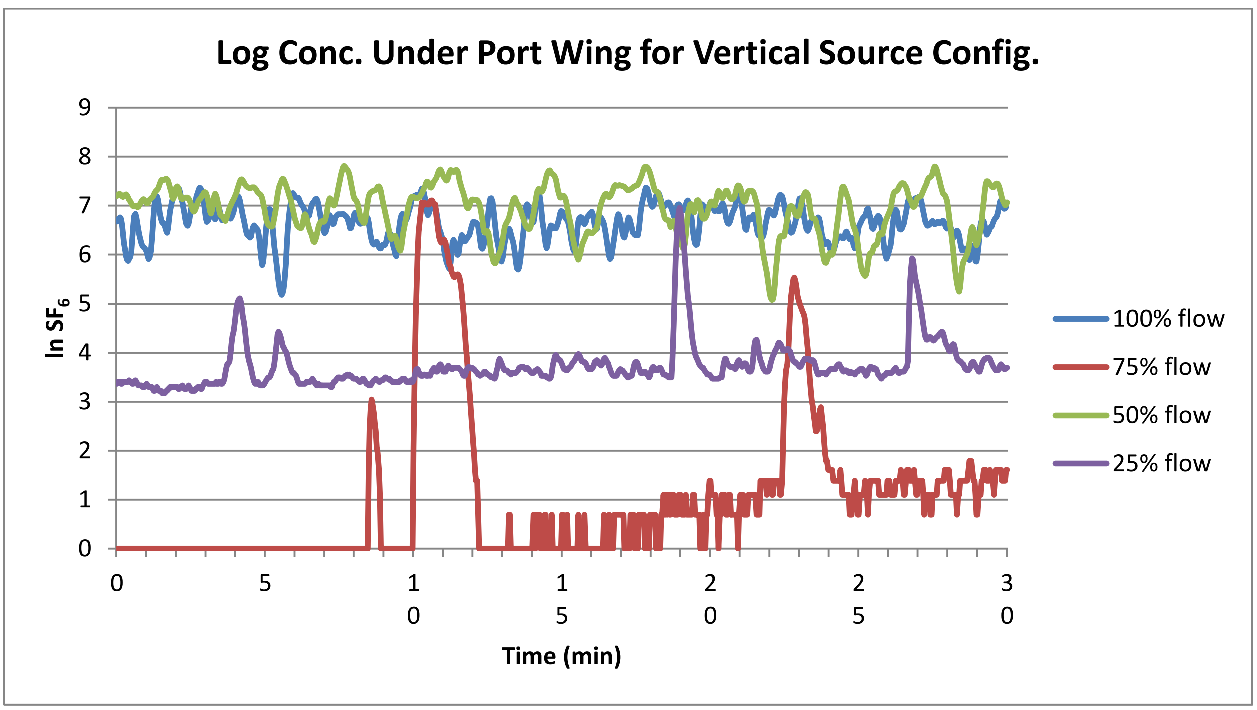

Conc. at Port Side of Canopy for Vertical Source Config.
6000
5000
4000
3000
2000
1000
0
SF_6 (ppb)
0
5
1 0
1 5
2 0
2 5
Time (min)
100% flow
75% flow
50% flow
25% flow

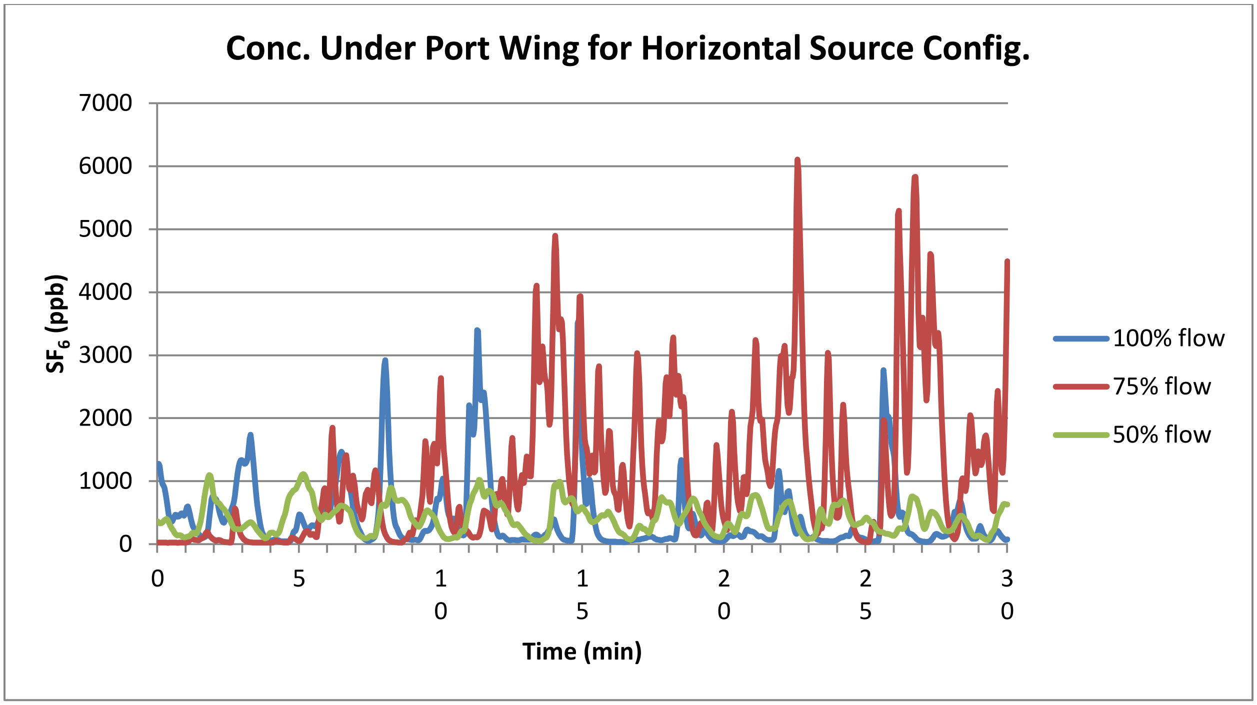

Log Conc. at Port Side of Canopy for Vertical Source Config.
10
9
8
7
6
5
4
3
2
1
0
ln SF_6
0
5
1 0
1 5
2 0
2 5
Time (min)
100% flow
75% flow
50% flow
25% flow

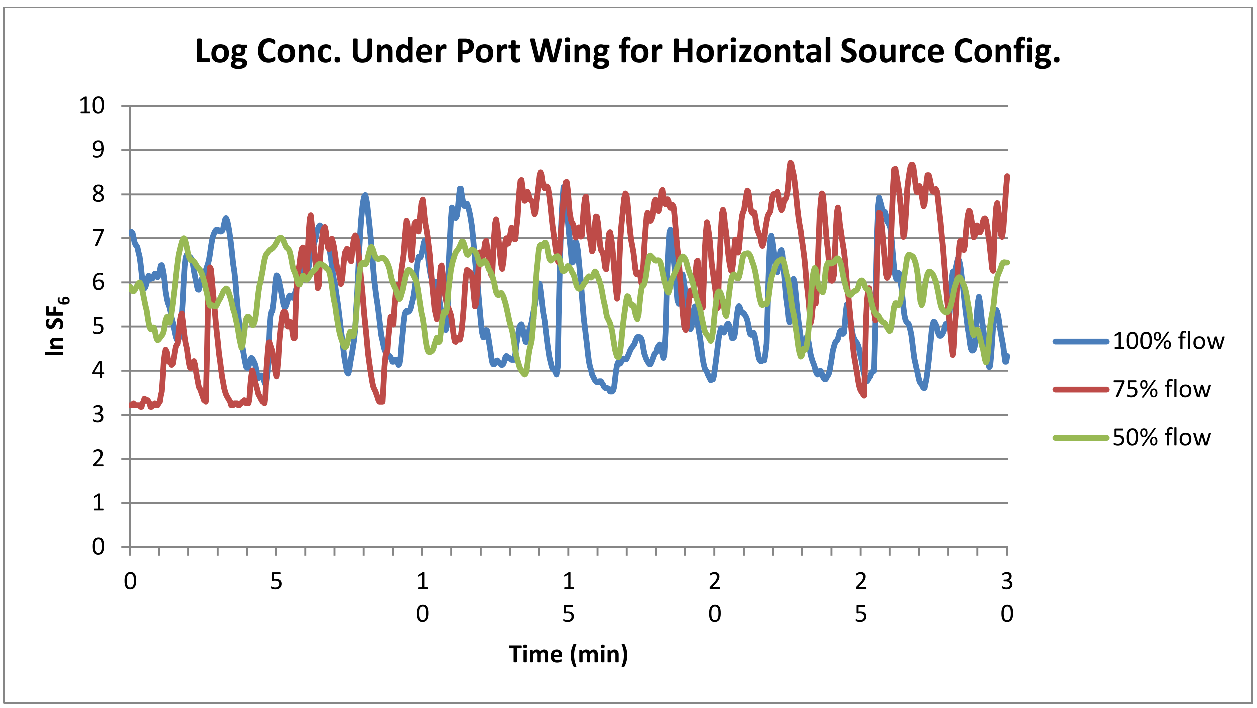

Conc. at Port Side of Canopy for Horizontal Source Config.
SF6 (ppb)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
5
1
0
1
5
2
0
2
5
3
0
Time (min)
100% flow
75% flow
50% flow


Log Conc. at Port Side of Canopy for Horizontal Source Config.
ln SF6
10
9
8
7
6
5
4
3
2
1
0
0
5
1
0
1
5
2
0
2
5
3
0
Time (min)
100% flow
75% flow
50% flow


Conc. Under Port Wing for Vertical Source Config.
SF$_6$ (ppb)
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
Time (min)
100% flow
75% flow
50% flow
25% flow


Log Conc. Under Port Wing for Vertical Source Config.
ln SF$_6$
9
8
7
6
5
4
3
2
1
0
0
5
10
15
20
25
30
Time (min)
100% flow
75% flow
50% flow
25% flow


Conc. Under Port Wing for Horizontal Source Config.
SF6 (ppb)
7000
6000
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
30
Time (min)
100% flow
75% flow
50% flow


Log Conc. Under Port Wing for Horizontal Source Config.
ln SF6
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
20
25
30
Time (min)
100% flow
75% flow
50% flow

Appendix D. Letters Related to Airflow Requirements for Corrosion Control Hangars

From: Kanth, Sanji - OSHA [mailto:Kanth.Sanji@dol.gov]
Sent: Wednesday, May 11, 2011 1:12 PM
To: Earnest, G. Scott (CDC/NIOSH/DART)
Cc: McGowan, Larry - OSHA; Buchanan, Art - OSHA; Haloftis, Alcmene - OSHA
Subject: RE: aircraft spray painting questions

Hello Earnest:

My responses are given below. As I mentioned to you, this is not an OSHA Policy, but are my thoughts on the subject. The policy responses come from the Director of Directorate Enforcement Programs.

Can the company reduce airflows from approx 100 fpm to 75 fpm and still comply with OSHA standards? i.e. 1910.107,
1910.94, 1910.1026 or others

The provisions requiring 100 fpm apply to Spray booths and not to Spray Areas. The aircraft hangars are considered as Spray Areas – see attached letter dated April 8, 1997, addressed to Ms. Elsie L. Munsell of the Department of Navy. In your situation, the provisions contained in 1910.107(d)(4) would apply, which requires the ventilation to be adequate to remove flammable vapors and mists to a safe location. The concentrations of vapors and mists shall not exceed 25 % of Lower Flammable Limits (LFL) in the exhaust stream of the ventilation system of the aircraft hangars. For the Chromium (VI) standard, 1910.1026, paragraph (f)(1)(ii) provides a unique exception for the painting of aircraft or large aircraft parts. For these operations, employee exposures shall be reduced to 25 ug/m3 or less using engineering and work practice controls. Respiratory protection shall then be used to achieve the PEL. The term “aircraft or large aircraft parts” refers to the interior or exterior of assembled aircraft, and to wings, tail sections, control surfaces (e.g., rudders, elevators, and ailerons), or comparably sized aircraft parts.

Is a ventilated aircraft hangar of this size considered to be a spray booth or a spray area? Also, does the frequency of
Aircraft painting in the hangar impact whether it is considered a spray booth or spray area? (I think the answers to these questions
relate to the appropriate air velocities).

Aircraft hangars are considered to be Spray areas. Elise’s response elaborates on why aircraft hangars are considered to be spray areas.

Do you have any OSHA documents/interpretations that I can reference in a draft NIOSH report that would help to
answer these issues? I am hoping to get an answer to this early next week if possible.

Please see attached [1997 correspondence between Elise Munsell and John Plummer.]

Please let me know if you have any questions.

Thanks.

Sanji Kanth, PE
202-693-2135

From: Earnest, G. Scott (CDC/NIOSH/DART) [mailto:gse0@cdc.gov]
Sent: Friday, May 06, 2011 2:55 PM
To: Kanth, Sanji - OSHA
Cc: Earnest, G. Scott (CDC/NIOSH/DART)
Subject: aircraft spray painting questions

Hi Sanji,

It was nice to talk with you this morning. As I mentioned, I am involved in some work related
To spray painting of large aircraft in a ventilated hangar. The spray paint contains Cr6, and the spray
painters are wearing supplied air respirators. The hangar has dimensions of approx 7 meters x 16 meters
X 25 meters with supply air on one side and exhaust air on the other. The current ventilation rates in the hangar
are a little over 100 fpm. I do not think there is a significant fire/explosion hazard at this facility.

The issue is that the company would like to reduce the air velocities below 100 fpm to possibly around 75 fpm to
reduce energy costs. They think the exposures levels at 75 fpm are going to be similar to exposures at
100 fpm and have data to support this.

The main questions are:

Can the company reduce airflows from approx 100 fpm to 75 fpm and still comply with OSHA standards? i.e. 1910.107,
1910.94, 1910.1026 or others

Is a ventilated aircraft hangar of this size considered to be a spray booth or a spray area? Also, does the frequency of
Aircraft painting in the hangar impact whether it is considered a spray booth or spray area? (I think the answers to these questions
relate to the appropriate air velocities).

Do you have any OSHA documents/interpretations that I can reference in a draft NIOSH report that would help to answer these issues? I am hoping to get an answer to this early next week if possible.

Thanks for any help you can provide.

-Scott

G. Scott Earnest, Ph.D., P.E., C.S.P.
CAPT, USPHS
Branch Chief
Engineering and Physical Hazards Branch
Division of Applied Research and Technology
National Institute for Occupational Safety and Health
Ph: 513-841-4539
Fax: 513-841-4506
GEarnest@cdc.gov

DATE: May 13, 1999

MEMORANDUM

To: Ron Cain, Office of Federal Agency Programs, Occupational Safety and Health Administration, Washington, DC 20210

Via: John Plummer, Director, Office of Federal Agency Programs, Occupational Safety and Health Administration, Washington, DC 20210

From: Kathleen M. Paulson, P.E.

Naval Facilities Engineering Service Center

Naval Occupational Safety and Health - Air (ESC 425),

1100 23rd Avenue,

Port Hueneme, CA 93043-4370

Commercial:(805) 982-4984, DSN: 551-4984, FAX:(805) 982-1409

Internet: paulsonkm@nfesc.navy.mil

Web Page: http://www.nfesc.navy.mil/enviro/esc425/NoshArBr.htm

Subj: Industrial Ventilation Flow Rates in Aircraft Hangars

We appreciate your offer to revisit the OSHA standard interpretation you provided to the Department of the Navy, Office if the Assistant Secretary, (Installations and Environment) regarding spray painting in aircraft hangars. See Enclosures (1) and (2). When we tried to apply the interpretation that you provided to us dated April 8, 1997, we discovered discrepancies in our characterization of the processes performed in Navy Final Finish and Corrosion Control Hangars. Enclosure (3) defines the operations performed in each of the various level hangars.

Our questions are:

1. What is your definition of a production spray finishing operation?
2. How do you characterize the five operational levels of hangars discussed in Enclosure 3?
3. What airflow rate criteria is required for each of the five levels?
4. If 100 cubic feet per minute per square foot of cross-sectional area is required for any of the five operational levels, please define the term cross-sectional area. Is it:
   a) Area of the exhaust filter bank?

b) Area of the exhaust filter bank?
c) Air envelope around the plane, which excludes the "empty" area where there will be no aircraft parts?
d) Full opening of the hangar, for instance the approximate side of the hangar door opening plus about 5 feet on the top and sides of the hangar reserved for maneuverability?
e) Full opening of the hangar including open space for roof trusses?

Naval Facilities Engineering Command (NAVFAC) assigned the NAVOSH Air Branch of NFESC to revise Military Handbook 1003/17, Industrial Ventilation Systems. The handbook defines engineering design criteria for use by all components of the Department of Defense. We are adding a new chapter to the MIL-HDBK discussing the criteria for spray painting in aircraft hangars. We are having difficulties applying the interpretation to our criteria. To add to the urgency, NAVFAC is also in the process of designing several new aircraft hangars. Reducing the flow rate from 100 cubic feet per minute per square foot of cross-sectional area will provide a significant reduction in equipment first costs and annual operating costs.

Our position is - Aircraft hangars should not be designed for 100 cubic feet per minute per square foot of cross-sectional area due to the size of the space and the dilution effect. Regardless of the flow rate, not all the paint overspray will reach the filters and we acknowledge some will drop to the floor. This is particularly true for the portion of the aircraft farthest from the exhaust filter bank. Paint spray criteria in the ACGIH Industrial Ventilation Manual permits airflow in large spaces as low as 50 cubic feet per minute per square foot of cross-sectional area. Both the NFPA 33 and the ANSI Z9.3 consensus standards require a sufficient ventilation rate to prevent vapor build-up by requiring airflow to keep the vapor less than 25% of the LEL. Airflow calculations based on LEL are typically 10-25% of the rates required for health protection. Enclosure (4) reiterates our understanding of the pertinent regulations.

Our experience shows that even in spray painting operations using flow rates of 100 cubic feet per minute per square foot of cross-sectional area, some employee's occupational exposure exceeds the PEL for certain paints and paint components. Therefore, our employees use respiratory protection when painting in hangars.

Thank you for continuing to consider our concern. Based on our phone conversation today, I understand that you are also working on this issue with the US Air Force. Could you direct us to their point of contact? Our contacts are Kappy Paulson and Mr. Trinh Do (805) 982-4886.

U.S. Department of Labor

Occupational Safety and Health Administration
Washington, D.C. 20210

Reply to the Attention of:

JUL 1 1999

MEMORANDUM FOR: KATHLEEN M. PAULSON, P.E.
NAVOSH Air Branch
Naval Facilities Engineering Service Center

Richard Fairfax

FROM: RICHARD FAIRFAX, Director
Directorate of Compliance Programs

SUBJECT: NFESC e-mail dated May 13, 1999

This memorandum is in response to your email of May 13, 1999 and confirms subsequent e-mail correspondence between you and Ron Cain of my staff.

OSHA considers the Department of Defense corrosion control hangars described in the NFESC memo dated May 13, 1999 as "spray areas." As such, the spray areas must comply with the requirements of NFPA 33, 1995 edition for "Spray Application Using Flammable or Combustible Materials," and with subpart Z of 29 CFR 1910 for hazardous substances. Non-compliance with table G-10 in 29 CFR 1910.94 will be considered *de minimis* by OSHA as long as the above requirements are met.

Should you require further assistance in this or any other matter, feel free to contact John Plummer or Ron Cain of my staff at 202-693-2122.

Standard Interpretations - Table of Contents

• **Standard Number:** 1910.94(c); 1910.107; 1910.38; 1910.39

April 8, 1997

Ms. Elsie L. Munsell
Deputy Assistant Secretary of the Navy
(Environment and Safety)
Department of the Navy
1000 Navy Pentagon
Washington, D.C. 20350-1000

Dear Ms. Munsell:

This is in response to your letter of March 14 requesting an interpretation of the Occupational Safety and Health Administration (OSHA) standard for the airflow rate required for a spray painting area.

29 CFR 1910.94(c) and 29 CFR 1910.107 both apply to spray areas. These sections are currently under revision and will be combined into one area of 29 CFR 1910.107. There is no specific flow rate mentioned in either standard for spray areas, OSHA uses National Fire Protection Association Publication, NFPA 33, 1995 edition, (copy enclosed) Spray Application Using Flammable or Combustible Materials, paragraph 5-2, which requires that "each spray area be provided with mechanical ventilation that is capable of confining and removing vapors and mists to a safe location and is capable of confining and controlling combustible residues, dusts, and deposits. The concentration of vapors and mists in the exhaust stream of the ventilation system shall not exceed 25% of the lower flammable limit." This means that the airflow may be variable depending on the job being performed. This also means that under the circumstances that you have described, OSHA considers these corrosion-control hangars to be spray areas as opposed to spray booths. The determining factor in this decision is that other work is also performed in the area and painting is incidental to the specific area that is being treated (wing, rudder, etc.), and not the entire aircraft on a repetitive basis.

The employees must also be fully trained in the hazards to which they are exposed and in the emergency action and fire protection plans required by 29 CFR 1910.38 [and 1910.39], in personal protective equipment as required in 29 CFR 1910 Subpart I and also in the health requirements listed in 29 CFR 1910 Subpart Z.

Should you have further questions, please contact [the Office of General Industry Enforcement at (202) 693-1850].

Thank you for your continued interest in occupational safety and health.

Sincerely,

John E. Plummer, Director
Office of Federal Agency Programs

Enclosure

March 14, 1997

MEMORANDUM FOR: DIRECTOR, FEDERAL AGENCY PROGRAMS, OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION

Subj: INTERPRETATION OF OSHA STANDARD

This is to request an interpretation of the Occupational Safety and Health Administration (OSHA) standard for the airflow rate required in a spray painting area. We are building several new aircraft corrosion-control hangars throughout the United States and need a standard design criteria for the ventilation systems.

Our questions are: (1) What OSHA standard applies for spray painting in a corrosion control hangar, 29 CFR 1910.94 or 29 CFR 1910.107? (2) What is the minimum required maintained ventilation velocity?

Spray painting performed in the hangars will be primarily spot maintenance, but large areas of the aircraft could occasionally be painted. We consider the painting area a spray area rather than a spray room or booth. Spray areas appear to be covered under 29 CFR 1910.107, which does not specify a minimum design airflow rate.

In Industrial Ventilation, A Manual of Recommended Practice, 22nd edition the American Conference of Governmental Industrial Hygienists (ACGIH) allows the designer to use a design flow rate of 75 cfm/ft(2) for very large, deep booths, see VS-75-01. Additionally, VS-75-04 allows the designer to further reduce the airflow rate to 50 cfm/ft(2) when the cross-sectional area in a drive-through booth is greater than 150 ft(2). The ACGIH guidelines and consensus standards criteria are typically recommended when there is no OSHA criteria addressing a particular problem.

The hangar designers will perform the necessary calculations to ensure the airflow rate will keep the hangar atmosphere below 25% of the lower explosive limit.

My point of contact for further information on this matter is Commander Carol Pickerel, USN, Special Assistant for Occupational Health at (703) 614-1276.

ELSIE L. MUNSELL
Deputy Assistant Secretary of the Navy
(Environment & Safety)

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