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MODELING & VERIFYING AIRCRAFT PAINT HANGAR AIRFLOW TO REDUCE GREEN HOUSE GAS AND ENERGY USAGE WHILE PROTECTING OCCUPATIONAL HEALTH

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14. ABSTRACT
Aircraft paint contains toxic chemicals, such as iso-cyanates and hexavalent chromates, and ventilation and other protective measures are necessary to prevent exposure of workers that paint aircraft. Computational fluid dynamics (CFD) modeling was used in conjunction with on-site tracer gas experiments to assess air flow conditions in the hangar and to investigate design alternatives. The project determined that a reduction in delivered airflow might not increase contaminant exposure. This report provides a summary of results from the site visits and discusses areas of potential future research.

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ACRONYMS

62 AW	62nd Airlift Wing
ACCPFF	Aircraft Corrosion Control and Paint Finishing Facility
ACGIH	American Conference of Governmental Industrial Hygienists
ACS	Cross-sectional Area
BTU	British Thermal Unit
CDC	Centers for Disease Control and Prevention
CFD	Computational Fluid Dynamic
CFR	Code of Federal Regulation
Cr	Chromium
CrVI	Hexavalent Chromium
DoD	Department of Defense
EPHB	Engineering and Physical Hazards Branch
ESTCP	Environmental Security Technology Certification Program
FPM	Feet per Minute
FRCSW	Fleet Readiness Center Southwest
GHG	Greenhouse Gases
HDI	Hexamethylene diisocyanate
HVAC	Heating, Ventilation and Air Conditioning
HVLP	High-volume low pressure
JBLM	Joint Base Lewis-McChord
kWh	Kilowatt Hour
MAK	Methyl n-amyl ketone
MCAS	Marine Corps Air Station
MEK	Methyl ethyl ketone
MIBK	Methyl-isobutyl ketone
MIBK	Methyl isobutyl ketone
MUC	Maximum Use Concentration
NASNI	Naval Air Station North Island
NAVFAC ESC	Naval Facilities Engineering Service Center
NBC	Naval Base Coronado
NESDI	Navy Environmental Sustainability Development to Integration
NIOSH	National Institute for Occupational Safety and Health
NMCSD	Navy Medical Center San Diego
OEL	Occupational Exposure Limit
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
PETTT	Productivity Enhancement, Technology Transfer and Training
QDR	Quadrennial Defense Review
RANS	the Reynolds-averaged-Navier-Stokes
REL	Recommended Exposure Limit
RNG	Renormalization group
RPM	Revolutions per minute
SRM	Safety, Reliability and Maintainability
TLV	Threshold Limit Value

VFD	Variable Frequency Drive
VOC	Volatile Organic Compound

EXECUTIVE SUMMARY

Aircraft painting can be a hazardous process. Therefore, ventilation and other protective measures are necessary to prevent exposure of workers to toxic chemicals, such as iso-cyanates and hexavalent chromates, which are contained in the paints. In 2008, researchers from the Centers for Disease Control and Prevention/National Institute for Occupational Health and Safety (CDC/NIOSH) began work on a collaborative project with the U.S. Navy to evaluate ventilation in a Navy aircraft painting hangar at Naval Base Coronado as part of the Navy Environmental Sustainability Development to Integration (NESDI) program. Computational fluid dynamics (CFD) modeling was used in conjunction with on-site tracer gas experiments to assess air flow conditions in the hangar and to investigate design alternatives. The project determined that a reduction in delivered airflow might not increase contaminant exposure. By decreasing air flow from 100 feet per minute (fpm) to 75 fpm, electricity consumption would be significantly reduced, which would subsequently reduce greenhouse gas emissions. The counterintuitive finding that a modest decrease in airflow velocity did not increase exposure resulted in an interest in expanding the project to encompass more sites around the U.S. with support from the Environmental Security Technology Certification Program (ESTCP).

Three additional sites were chosen for study inclusion: Marine Corps Air Station Cherry Point, Sioux City Air National Guard Base, and Joint Base Lewis-McChord. A four-step process of site assessment, CFD analysis, tracer gas validation, and exposure testing was planned for the assessment of each site. However, work on this ESTCP hangar ventilation project was terminated by ESTCP in February 2014. The demonstration sites that were originally proposed decided against hosting the demonstrations due to potential Occupational Safety and Health Administration (OSHA) non-compliance concerns that could surface, though unrelated to this project. Because the project team could not find demonstration sites (paint hangars across the Department of Defense declined to host the demonstrations), ESTCP decided to end the project.

Through February 2014, the four-step assessment protocol had been completed for the Naval Base Coronado site. The other three sites remained at various stages of the site assessment process. Initial site visits suggested that these locations are good candidates for additional investigation. Continuing research and the implementation of more efficient ventilation systems at these locations could yield significant benefits in the form of energy cost savings and better worker protection. Site visits determined that ventilation configuration and the design of aircraft corrosion control and paint finishing facilities (ACCPFF) significantly affect contaminant control performance. Ventilation system maintenance was an issue in all facilities visited. From this study and previous studies, it was seen that ventilation configuration is more effective at influencing contaminant exposure than the ventilation rate. This report provides a summary of results from the site visits and discusses areas of potential future research.

The results of this incomplete study are consistent with the findings of the NESDI project. Analyses completed to date indicate that a modest decrease in linear air velocity from approximately 100 fpm to the range 75 to 80 fpm is a viable method of maintaining occupational health and safety, while reducing energy costs and carbon emissions associated with ACCPFF. As part of this project, the intent was to obtain a letter of interpretation from OSHA based on study results. Because the project was not completed, a letter was not obtained from OSHA and the regulatory situation remains unclear.

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1.0 INTRODUCTION

1.1 Background

1.1.1 Background for Control Technology Studies

The National Institute for Occupational Safety and Health (NIOSH) is an agency within the Centers for Disease Control and Prevention (CDC), and 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 research and education programs separate from the standard setting and enforcement functions carried out by the Occupational Safety and Health Administration (OSHA) in the Department of Labor. An important area of NIOSH research deals with methods for controlling occupational exposure to potential chemical and physical hazards. The Engineering and Physical Hazards Branch (EPHB) of the Division of Applied Research and Technology has been given the lead within NIOSH to study the engineering aspects of health hazard prevention and control.

Since 1976, EPHB has conducted a number of assessments of health hazard control technology on the basis of industry, common industrial process, 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 (Baron and Bennett 2002, Heitbrink and Bennett 2006, NIOSH 1980a, NIOSH 1980b, NIOSH 1989, NIOSH 1996, NIOSH 2006, NIOSH 2007, NIOSH 2009a). 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 prior studies are designed with a number of steps or phases. Initially, a series of walk-through surveys are conducted to select plants or processes with effective and potentially transferable control concepts. Next, in-depth surveys are conducted to determine the control parameters and the effectiveness of these controls. The reports from these in-depth surveys are then used as a basis for preparing technical reports and journal articles on effective hazard control measures. Ultimately, the information from these research activities builds the database of publicly available information on hazard control techniques for use by health professionals who are responsible for preventing occupational illness and injury.

The study described in this report was conducted to gain a better understanding of worker exposure to the hazardous chemicals contained in paints and to propose methods of control that will protect the workers from these hazards. Controlling or eliminating exposures to occupational hazards is the fundamental method of protecting workers. Traditionally, a hierarchy of controls will be used as a means of determining how to implement feasible and effective control solutions for this study. One representation of this hierarchy can be summarized as follows:

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

In this project, the effectiveness and efficiency of ventilation systems in several aircraft corrosion control and paint finishing facilities (ACCPFF) were evaluated, alongside the appropriateness of the existing respiratory protection program. Exposure must be addressed because the paint used to coat the planes contains hazardous chemicals.

1.1.2 Background for this Study

Workers in ACCPFF are exposed to a variety of hazardous chemicals. Aircraft paints commonly contain hexavalent chromates and various organic solvents which have been linked to nasal cancer [NIOSH 2009b] and central nervous system depression [Levy B.S. and D.H. Wegman 1988], respectively. They also contain isocyanates, which are the leading attributable chemical cause of occupational asthma in the US and many other industrialized countries. Symptoms of isocyanate exposure 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. The most serious cases of exposure due to chemical sensitization from isocyanates can result in severe asthma attacks which are sometimes fatal [NIOSH 1996, 2006].

Worker exposure control is of utmost importance in aircraft painting operations. Proper ventilation of ACCPFF is necessary to achieve required exposure control limits. Regulatory and advisory occupational exposure limits (OELs) include OSHA Permissible Exposure Limits (PELs), American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs), and NIOSH Recommended Exposure Limits (RELs). In addition to controlling worker exposure, ventilation systems must also comply with requirements for the release of contaminants to the outdoor environment.

OSHA standard, 29 CFR 1910.94 – *Ventilation*, requires that paint booths maintain an air velocity in the booth cross-section of 100 feet per minute (fpm) [CFR a]. This design criterion is based on empirical data gathered in the 1950s. At that time, the first goal of painting ventilation was explosion protection. However, the explosion risks, along with other worker health risks, have been reduced in more recent years by modern paint application methods. These include the use of high-volume low-pressure (HVLP) spray guns, which significantly reduce paint overspray. In addition, workers now wear airline respirators when applying primer and paint, and these respirators help control exposure to volatile organic compounds (VOCs), isocyanates, chromates and other chemical stressors. Furthermore, high-VOC paints are no longer used. For perspective, the ACGIH recommends only 50 fpm for large vehicle paint booths [ACGIH 2010].

A recent OSHA interpretation of 29 CFR 1910.94 acknowledges that aircraft painting hangars are classified as “spray areas” rather than spray booths. OSHA provides no flow-rate guidelines for spray areas, so this classification effectively exempts aircraft painting hangars from the 100 fpm target of 29 CFR 1910.94. Because large painting hangars are not bound by the 100 fpm regulation, it is permissible to explore the concept of reduction of delivered airflow, and the corresponding ventilation costs, in facilities that were originally designed to meet the 100 fpm target for spray booths, as long as worker safety is not compromised and outdoor releases comply with facility operating permits. However, the OSHA PELs apply to painting processes, regardless of the applicability of the spray booth ventilation specification. This set of confusing and contradictory circumstances calls for a better understanding of what ventilation rate is most effective.

In 2008, researchers from CDC/NIOSH began work with then Naval Facilities Engineering Service Center (NAVFAC ESC) engineers and Navy Medical Center San Diego (NMCSD) industrial hygienists on a collaborative project to evaluate ventilation in a Navy aircraft painting hangar as part of the Navy Environmental Sustainability Development to Integration (NESDI) program. (NAVFAC ESC is now Naval Facilities Engineering and Expeditionary Warfare Center as of 2012). The goal of this project was to keep worker exposures to air contaminants, including hexavalent chromium (CrVI), hexamethylene diisocyanate (HDI), methyl-isobutyl ketone (MIBK), and others, at or below concentrations that meet regulatory health and safety standards, while limiting the environmental footprint (i.e., energy use, and operational costs of paint hangar ventilation). The NESDI study was conducted in a hangar at Naval Base Coronado (NBC) in San Diego, California. NBC operates two painting buildings, numbered 464 and 465, which contain a total of eight painting bays designed for refinishing Navy F/A-18C/D Hornet strike fighter aircraft. Each of these bays uses between $4,000 and $5,000 of electricity per month. The annual electricity cost for buildings 464 and 465 normally exceeds $400,000. Over 90% of the electricity is used by the supply and exhaust fans, which are designed to meet the 100 fpm airflow standard specified by OSHA.

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

The finding of the NESDI project—that worker protection could be maintained, or possibly improved, while also reducing the energy requirements of painting ventilation—led to an interest from the Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) to build upon that project to include other aircraft painting operations. Whereas four sites were chosen for the ESTCP study, only three had been visited at the time the project was canceled. Since a relationship already existed with NBC because of the NESDI project, this site was visited as a follow-up that would provide useful close-out information for the ESTCP project. ESTCP decided to cancel the project due to concerns over an implementation risk while in an atmosphere of increased budget pressure. The implementation risk was created by concerns expressed by some members of the DoD industrial hygiene community about the project's goals. Because industrial ventilation is vital to controlling airborne hazards in painting environments, industrial hygienists are committed to this resource and intuit that less of a good thing is less protective. The manner in which airflow that is too fast can actually increase exposure is a subtle point, understood by experts in the ventilation engineering specialty of industrial hygiene. Even for these professionals, however, optimal ventilation velocity is a research area that has not fully settled as standard practice. Furthermore, within all branches of engineering, numerical modeling such as computational fluid dynamics has become a standard tool. Industrial hygienists have not developed a comfort level with this technology's predictions and design guidance, especially when it diverges from their gut instincts.

1.2 Objective of the Demonstration

The objectives of this project were to demonstrate and validate new engineering airflow design criteria for DoD aircraft corrosion control and paint finishing hangar operations, and to demonstrate and validate that that the current practice of using the ventilation rate 100 feet per (fpm) minute is ineffective. The primary objective of the project was to compare the currently regulated flow rate of 100 fpm through the hangar cross-section to a lowered airflow rate. The comparison was to be accomplished by both on-site testing and CFD modeling. The real process testing would provide the final verification and validation of performance the system. Prior to that, unmanned tracer experiments and CFD simulations would provide predictive information for the behavior of airflow and contaminants in the hangar. The scientific, data-driven, and advanced engineering argument would support the reduction of airflow rates in hangars, while maintaining occupational safety and health and quality control.

With technical support from NIOSH, NESDI sponsored a CFD and tracer gas study for a single paint hangar and aircraft type. Results showed that a maintained air velocity of 75 fpm may be as effective as the current criterion of 100 fpm. The study is described in NIOSH reports EPHB-329-12a and EPHB-329-12b, "*Experimental and Numerical Research on the Performance of Exposure Control Measures for Aircraft Painting Operations,*" "Parts I and II," respectively.

However, because the project ended prematurely, the CFD modeling was conducted for only two sites, while walk-through evaluations and ventilation measurements were conducted at five sites during the selection process. The expectation was that four sites would be selected for inclusion in the full study. The final four study sites had not been selected at the time of cancellation.

1.3 Regulatory Drivers

Important legislation, regulations, and policies that are impacted by work performed on this project include, but are not limited to:

1. Occupational Safety and Health Act (29 CFR1910) addresses occupational safety and health protections for artisans working in the paint hangars. The primary objective of this study is

to produce scientific evidence that shows it is possible for DoD facilities to maintain safety and health standards while reducing the energy demands of industrial paint hangars and meet federal energy policy and regulations.

2. Executive Order 13423 of January 24, 2007 “Strengthening Federal Environmental, Energy, and Transportation Management”

   Sec. 2. Goals for Agencies. In implementing the policy set forth in section 1 of this order, the head of each agency shall: (a) improve energy efficiency and reduce greenhouse gas emissions of the agency, through reduction of energy intensity by (i) 3 percent annually through the end of fiscal year 2015, or (ii) 30 percent by the end of fiscal year 2015, relative to the baseline of the agency’s energy use in fiscal year 2003;

3. Executive Order 13514 of October 5, 2009 “Federal Leadership in Environmental, Energy, and Economic Performance”. This executive order supplements Executive Order 13423 by reaffirming the Federal energy performance goals and setting a strategy for greenhouse gas reduction.

   Section 1. Policy. In order to create a clean energy economy that will increase our Nation's prosperity, promote energy security, protect the interests of taxpayers, and safeguard the health of our environment, the Federal Government must lead by example. It is therefore the policy of the United States that Federal agencies shall increase energy efficiency; measure, report, and reduce their greenhouse gas emissions from direct and indirect activities; conserve and protect water resources through efficiency, reuse, and stormwater management; eliminate waste, recycle, and prevent pollution; leverage agency acquisitions to foster markets for sustainable technologies and environmentally preferable materials, products, and services; design, construct, maintain, and operate high performance sustainable buildings in sustainable locations; strengthen the vitality and livability of the communities in which Federal facilities are located; and inform Federal employees about and involve them in the achievement of these goals.

   A potential benefit of reducing the energy demand of aircraft paint hangars is the reduction in greenhouse gases associated with the use of the energy that can be saved by reducing flow below the current guideline of 100 fpm.

4. Energy Policy Act of 2005 set the stage for the goal of a 20 percent reduction in energy intensity for Federal buildings by 2015 based on a 2003 baseline. This act specifically states that laboratory and industrial building must comply with energy reduction goals.

   This project specifically targets industrial facilities that have a significant potential for energy reduction. Typically, facility managers target the administrative facilities that present a much easier and known facility upgrade. ACCPFF are not typically one of the first facilities targeted for energy reduction studies due to the complexity of operations.

5. Energy Independence and Security Act of 2007 adopts the energy intensity goals of Executive Order 13423 setting agency goals to a 30 percent reduction in energy intensity by 2015.

   Reducing the volumetric airflow below 100 fpm in these large paint hangars will significantly reduce fan energy demands and cooling and heating loads to maintain the air at the process temperature and humidity. This objective will provide a significant benefit to the DoD and the agency goal of meeting a 30 percent reduction by 2015.

6. UFC 4-211-02, Aircraft Corrosion Control and Paint Facilities list specific criteria for the design of Navy and Marine Corps aircraft corrosion control and paint hangars. This Unified Facility Criteria applies to Air Force facilities as well except where noted in the UFC.

   Successful scientific evidence showing a decrease in flow can reduce energy intensity and maintain worker safety will allow the team to submit an update for this UFC.

2.0 TECHNOLOGY DESCRIPTION

2.1 Technology Overview

The intent of this project was to demonstrate and validate a new engineering airflow design criteria for DoD aircraft paint hangar operations. By comparing the OSHA standard flow rate through horizontal flow hangars to a lowered airflow using real time measurement of air flow and then capturing the information in a CFD modeling, scientific data would be developed to support the reduction of airflow rates in hangars while maintaining occupational safety and health.

Multiple facility configurations and aircraft types must be investigated to determine whether this finding is robust and can be generalized to other configurations. Additionally, capturing real world performance of the hangars and using the CFD model as a simulation of aircraft paint hangars will pave the way for more innovative designs that reduce energy use while still protecting worker health and safety. Moreover, the performance of facilities in the proposed study, in terms of the current criterion, were evaluated for issues such as unbalanced supply and exhaust rates, air distribution, bay pressurization, appropriate permit operation requirements, and system over-design, all of which may be sources of inefficiency and wasted energy.

The project provides the scientific basis to change the engineering design criteria for aircraft paint hangars by using both on site verification of the system performance and exposure monitoring with CFD modeling to characterize contaminant concentration experienced by spray painters during typical painting operations. Evolutions of solvent vapors during wipe down and primer/topcoat spray application at two or more reduced flow rates were simulated using ventilation and process conditions measured during baseline field studies.

In addition, the project evaluated the importance of *where* airflow was delivered and measured. Effectiveness of ventilation depended on moving air in the right places. Accuracy of ventilation characterization required an understanding of where velocities should be measured. A required flow rate that is a single number does not address the flow physics that involves transitionally turbulent flow around obstructions, e.g., the aircraft and along surfaces. The velocity varies in time and in space. It is the local flow that determines the effectiveness of the ventilation system for that location, which occasionally is the location of an artisan spraying hazardous material.

To expand the study to cover all DoD corrosion control and paint finishing hangars and to convince OSHA regulators that the reduced flow rate concept applied to all horizontal-flow hangars, additional validation and verification of the model for differently-sized fixed and rotary winged aircraft in different hangars was necessary. The data captured on site and the CFD modeling would indicate if the lower flow rate could be used for downdraft conditions. Inputs included detailed aircraft and hangar geometry, hangar airflows, worker locations, paint gun flow patterns and paint constituents. CFD outputs included local air contaminant concentration and air velocity at all points in the hangar. CFD model selected outputs would be verified on site. It is important to note that CFD modeling be performed in tandem with onsite testing as a means of easily exporting the findings to other facilities and as a means to provide verification of the performance. Unfortunately, on-site testing could not be conducted because the project ended prematurely. The ultimate goal was to provide a scientific basis for engineering design criteria that will reduce the cross-sectional airflow velocity in aircraft paint hangars. Reduced cross-sectional velocity translates into energy reduction and lower greenhouse gases (GHGs).

The removal of overspray droplets and solvent vapor using ventilation involves two simple canonical flows: flow through a pipe and flow around a bluff body, see Figures 1 and 2. An empty hangar with end-to-end ventilation is essentially a pipe or duct with a large cross-sectional area. The aircraft, corrosion control artisans, and equipment are bluff bodies obstructing the flow and creating turbulence. The contaminant sources are located near these bluff bodies, and the contaminant dispersion depends on the local flow. In the case of duct flow, a higher flow rate of clean air will reduce the downstream contaminant concentration, i.e., classical dynamic dilution. However, higher flow rates increase turbulence, which in turn enhances contaminant dispersion in all directions, including toward the artisan's breathing zone.

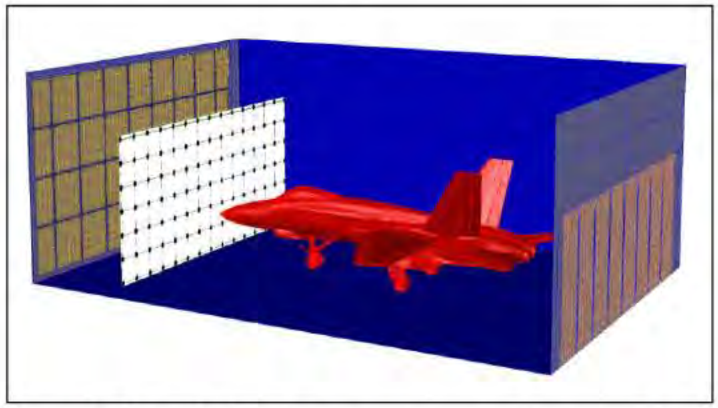


Figure 1: Pre-obstruction measurement area grid location.

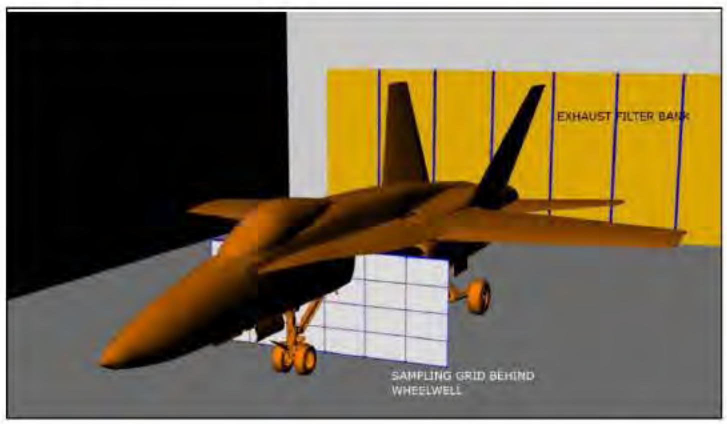


Figure 2: Wheel well velocity measurement area grid location.

The flow situation during aircraft painting operations is a complex combination of these two simple flows, and it is unclear what the ideal flow rate is for providing maximum worker protection. Figure 3 is a CFD snapshot showing mean particle paths from a spray application where the paint spray plume generally moves toward the exhaust, without entering the breathing zone. It may be the case as suggested in the NIOSH report, that a flow rate lower than 100 fpm, which certainly saves energy, also provides better protection to workers near contaminant sources, where the highest concentrations are generally found.

CFD is the right tool to predict contaminant concentrations at any location within the hangar, under any ventilation condition of interest. It has the advantages of easily altered ventilation rates and a complete lack of hazard. Additionally, comprehensive personal monitoring and tracer gas experiments provide real-world data to answer exposure questions directly and to compare with CFD for model validation. Personal monitoring for hexavalent chromium, elemental chromium, total particulate, hexamethylene di-isocyanate, methyl isobutyl ketone, Methyl n-Amyl Ketone and methyl ethyl ketone provides a scientific basis for comparison to occupational exposure limits.

Chronological Summary: Research on the exposure effect of lowering ventilation air velocity in the aircraft paint finishing environment began at NIOSH in 2008 with a pilot project funded by NESDI coordinated through NAVFAC EXWC. The surprisingly positive results motivated further work at NIOSH and NAVFAC EXWC in this area. The CFD technology that facilitated the research has been used at NIOSH since 1998, with particular emphasis on the effect of turbulence in bluff body flows and wakes on contaminant transport in non-stream-wise directions.

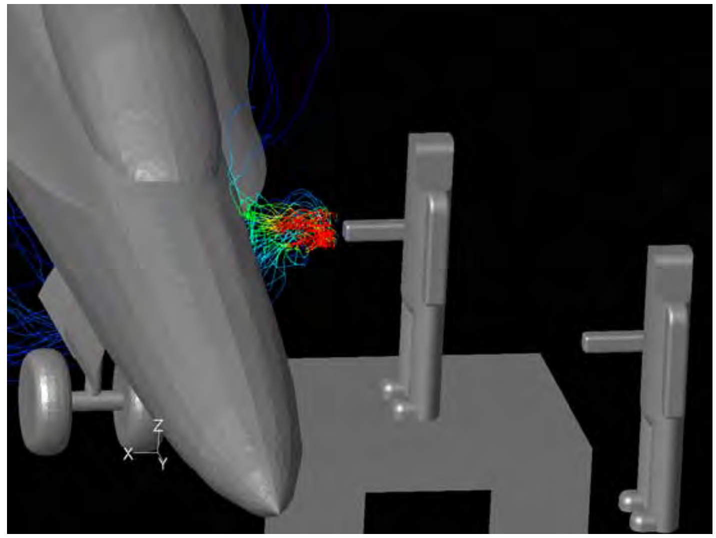


Figure 3: Paths of methyl isobutyl ketone droplets, colored by concentration, at 3/4 flow.

Anecdotal Observations: Computational fluid dynamics has also been used to understand how air contaminants, such as virus-containing droplets, can be transported from a contagious passenger in aircraft cabins. The critical difficulty is accurately modeling the turbulence in the cabin airflow. It is this turbulence that carries particles over a distance of several seat rows, even though the cabin ventilation system is designed to maintain the flow perpendicular to the aisles, where the supply air typically enters underneath the luggage compartment and exhausts near the floor at the cabin wall, to contain contaminants within one seat row.

One of the researchers for the aircraft painting ventilation project, James Bennett of NIOSH, appeared on Good Morning America, being interviewed by Lisa Stark, during the H1N1 influenza outbreak of 2008. He described research on the extent of exposure of passengers at various row distances from a contagious passenger, who may be generating droplets by coughing, sneezing, talking, or even breathing. The interest in this kind of information ebbs and flows, according to the presence of a potentially dangerous pathogen that may be transmitted by air.

2.2 Advantages and Limitations of the Technology

2.2.1 Performance Advantages

The primary performance benefit from reducing airflow from the current criteria is significantly decreased energy consumption by fan motors. Existing motors fitted with controllers can be operated at reduced RPMs. As an example, modern VFD controllers were installed in recent years in the Paint Complex at NBC, as part of the base's energy management initiative. In some situations where control is limited to basic on/off switching, individual fans can be powered down if the plenum can maintain properly uniform flow and if the desired pressure balance can be maintained. New ventilation specification and procurement can occur at a reduced volumetric capacity. These reductions in the use and size of equipment directly relate to energy intensity reductions. Another positive savings from the reduction in airflow is the reduced cooling and heating demand of the intake air. Most aircraft paints require a specific climate when being applied. Maintaining a specific temperature and humidity for such a large volume of air requires significant energy input.

Understanding the behavior of the contaminants that are being transported by this airflow will help prove that lower airflow rates are not only safe for the immediate works, but can significantly reduce energy intensity. The expectation for this project is to have at least a 35% reduction in energy intensity, kWh/ft^2, in hangars where the airflow rate can be reduced to 75 fpm.

2.2.2 Cost Advantages

Cost advantages by reducing the flow of air in ACCPFF corrosion control include lower systems costs, less energy demand, and smaller facilities. By demonstrating that reduced airflow across ACCPFF can meet both health and safety requirements and product quality control, future designs for new construction or major renovation will benefit from lower system costs. Reduced system size and the corresponding lower energy demand will ultimately lead to lower facility energy requirements which will directly affect O&M. A system with a reduced energy footprint also has the potential to lower the design, construction, and maintenance costs of the total system and facility.

2.2.3 Performance Limitations

The premise of this project is to create a balanced ventilation system (supply and exhaust rates equal, except for small negative gauge pressure to contain contaminants) for removing contaminants using ideal flow velocities. This effort results in a highly optimized system that will require regular maintenance to ensure the continuity of the performance boost. Fewer fans or smaller fan sizes in large hangars will require modestly greater start-up time to reach and maintain the facility at a specific painting temperature. The concern is that any benefit derived from reducing the fan sizes will be negated by an increased requirement in maintaining that specific facility climate, although moving less outside air through the tempered indoor space will often reduce the heating or cooling requirement. Another limitation is that hangars can have very specific configurations based on the type of airframe being maintained. The airframe itself impacts significantly the airflow in the hangar space. The variability in designed airflow patterns or airframe type can also impact system performance.

2.2.4 Cost Limitations

Considerations that could limit any cost advantage include, increased time and energy costs to provide climate control to large hangar spaces, costs associated with corrosion control hangar re-design, costs related to failure to meet indoor air quality compliance requirements, and the upfront cost to rebalance the system to provide a balanced system. Airflow in some of the larger hangars is designed to specifically target painting operations around the airframe. A reduction in total airflow might require a longer period of time to maintain a specific climate in the corrosion control hangar. Findings that suggest that reducing the airflow is beneficial will result in maintenance activities considering using the reduced flow rates which in turn will increase their short term costs to redesign and balance the system. Lastly is the potential for air quality compliance violations as a result of the failure of a finely balanced system going without maintenance. Air quality violations have the potential for significant fines and costs associated with remediation.

2.2.5 Social Acceptance

OSHA managers and industrial hygienists have been reluctant to consider reductions in the design airflow across corrosion control hangars. Validated scientific evidence should help support the case for reduced airflow, provided worker health is not impacted.

3.0 PERFORMANCE OBJECTIVES

The performance objectives are listed in Section 3.1, Table 1. They were used to create a baseline energy profile, measure airflow in the ACCPFF, determine the energy performance, and evaluate the effect of the reduced airflow on the concentrations of the contaminants.

3.1 SUMMARY OF PERFORMANCE OBJECTIVES

Table 1: Performance Objectives.

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
Energy Usage			
1. Electric Motor Energy (Fan Power)[1]	Energy Intensity (kWh/ft^2)	Meter readings of energy used by exhaust and supply fans during wipe down and paint process.	35 percent or greater reduction in energy during painting process from baseline airflow compared an optimized airflow. Reduction or increase[2] in energy use (during painting process) from existing baseline airflow when compared to system adjusted to test baseline condition. Baseline could be < or>100 cfm.
2. Thermal energy	Energy Intensity (kWh/ft2) or million BTU	Meter readings of chiller or thermal energy used for heating hangar space	20 percent reduction in energy usage during painting process from baseline airflow.
System			
3. System Reliability	Percent reliable	Operational and maintenance logs	Greater than 99% reliable
Indoor Air Environment			
4. Hangar bay environment during painting process	Temperature (^{0}F)	Temperature and relative humidity near aircraft. Taken just prior to start of paint cycle.	Air temperature within ± 5 ^{0}F of process requirement.
	Relative humidity (percent)		Relative humidity within ±5 percent relative humidity R.H. of process requirement.
Green House Gas Indicators			
5. Direct Greenhouse Gas Emissions	Direct fossil fuel GHG emissions (metric tons)	Estimated (calculated) release of GHG based on source of energy	35 percent or greater reduction compared to *ideal baseline* airflow when compared to the optimal flow rate[2]

[1] 100 percent outdoor air Assumes minimal infiltration and heat transfer through hangar bay walls and ceiling when compared to tempered air mass being supplied during painting process

[2] Data will be used to either add or subtract from percent energy reduction determined from row one data This will allow evaluation at facilities that are not currently running at 100 $\frac{cfm}{ft^2}$ For instance, a facility running at 60 $\frac{cfm}{ft^2}$ would not be in compliance and may need to be corrected to 100 $\frac{cfm}{ft^2}$ as the baseline For this example, there would be an increase in energy in both the baseline and the proposed test condition of ~75 $\frac{cfm}{ft^2}$ A few recently designed USAF hangars are intentionally designed for less than 100 $\frac{cfm}{ft^2}$ The team will decide with ESTCP staff if they will or will not be included as a demonstration site and if we will establish a baseline or only evaluate the existing condition

Performance Objective	Metric	Data Requirements	Success Criteria
System Economics			
6. System Economics: Existing System	$	Dollar costs (equipment, maintenance and energy costs)	10 percent reduction (Note: If the facility is not properly operating, this is likely to increase with a balanced system)
7. System Economics: New System	$	Dollar costs	20 percent reduction in ventilating equipment costs
8. Design footprint for NEW facility	Square foot	Typical Design	5 percent reduction of mechanical room
Occupational Safety and Health[3]			
9. Sampling for air contaminants at workers breathing zone and specified area samples.	TLV (ppm or mg/m^3)	Chromium (Cr)	Identify the capture velocity with the lowest exposure, defined as statistically significant change in mean or 95th %-tile TWAs, at the 90% confidence level.
		Hexavalent chromium (CrVI)	
		Methyl isobutyl ketone (MIBK) Methyl ethyl ketone (MEK)	
		Methyl n-amyl ketone (MAK)	
		Hexamethylene diisocyanate (HDI)[4]	
10. Sampling for LEL in General Area	LEL	Methyl isobutyl ketone (MIBK)	Less than 25 percent of LEL
		Methyl ethyl ketone (MEK)	
		Methyl n-amyl ketone (MAK)	
11. Sampling for particle deposition on the floor surface	TWA/PEL/TWA or TLV/TWA (ppm or mg/m^3)	Chromium (Cr)	Identify the capture velocity with the lowest exposure, defined as statistically significant change in mean or 95th %-tile TWAs, at the 90% confidence level.
		Total particulate not otherwise regulated	
	μg/100 cm^2	Chromium (Cr)	Identify the capture velocity with the lowest exposure, defined as statistically significant change in mean or 95th percentile wipe samples, at the 90% confidence level.
		Hexavalent chromium (CrVI)	
		Total particulate not otherwise regulated	
12. Outdoor re-entrainment of air contaminants	Concentration comparison (ppm) at 75 and 100 fpm	Tracer gas and/or solvent concentration	Concentration at the reduced velocity not exceeding that at the baseline or "as-is" velocity, measured as the mean and the 95th percentile, evaluated for statistical significance at the 90% confidence level.
Qualitative Performance Objectives			
1. Regulatory clarification via OSHA and DoD policy	Scientific evidence	Letter to OSHA suggesting an interpretation of the Ventilation Standard, using project outcomes as guidance	A letter of interpretation from OSHA that clarifies ventilation requirements, feasibility, and occupational exposures in the affected DoD facilities

Performance Objective	Metric	Data Requirements	Success Criteria
2. Scalability & transfer-ability across DoD	Scientific evidence	Exposures are not jeopardized	Accepted for inclusion in UFC
3. Scalability & transfer-ability across all DoD	Scientific evidence	Exposures are not jeopardized	Accepted for inclusion in ACGIH IV Manual

[3] Permissible Exposure Limits (PELs) are the legal occupational exposure limits (OEL) under OSHA regulations. As such, they were developed by rulemaking and subject to the political process. The Threshold Limit Values (TLVs) are professional guidelines developed by the American Conference of Industrial Hygienists (ACGIH). TLVs are viewed as "state of the art" and TLVs tend to be more stringent than PELs. NIOSH's Recommended Exposure Limits (RELs) are based solely on scientific basis for "no human effect" and tend to be more stringent than PELs and TLVs. None of these Occupational Exposure Limits are a clear line between safe and unsafe exposures.

[4] There is no PEL for Hexamethylene diisocyanate. Therefore, the NIOSH REL and ACGIH TLV will be used.

3.2 PERFORMANCE OBJECTIVES DESCRIPTIONS

The complexity and interest in the performance corrosion controls hangars evaluated for this project involve a number of scientific and engineering disciplines. These stakeholders each have specific requirements that are inherently different, yet are equally important in measurement of the ventilation performance. In particular we have broken down the objectives into functional areas that each stakeholder will find important from this demonstration.

Quantitative success criteria

1. Electrical motor intensity for supply and exhaust fans during wipe down and application of paint.

   Purpose: To determine change in electrical energy use during wipe down through complete painting process in the corrosion control facility at the optimum velocity.
   Metric: Exhaust and Supply Fan Electrical Energy Intensity (kWh/ft^2)
   Data: kWh of energy use per paint cycle and hangar bay floor area.
   Analytical Methodology: Direct comparison of the current flow rate and the optimized flow rate which are then normalized to the arithmetic mean time for completing the painting process.
   Success Criteria: 20 percent or greater reduction in energy use from the baseline. This rate would tie into the EPACT 2005, EISA 2007, and the Guiding Principles for High Performance Sustainable Buildings that the DoD is in the process of conforming.

2. Thermal energy intensity during the wipe down and application of paint.

   Purpose: To determine change in thermal energy use during the paint process such as the reduction in use of steam for heating the space.
   Metric: Cooling or heating energy intensity (kWh/ft^2 or MBTU/ft^2)
   Data: kWh or BTU of thermal energy use per paint cycle and hangar bay floor area.
   Analytical Methodology: Direct comparison of the current flow rate and the optimized flow rate which are then normalized to the arithmetic mean time for completing the painting process.

Success Criteria: 20 percent or greater reduction in energy use from the baseline. This rate would tie into the EPACT 2005, EISA 2007, and the Guiding Principles for High Performance Sustainable Buildings that the DoD is in the process of conforming.

3. System reliability during painting process.

   Purpose: To determine the reliability of variable frequency drive fans during painting operations.
   Metric: percent reliability
   Data: Maintenance and operational logs of the system
   Analytical Methodology: Evaluate maintenance and operational logs of the fan units to determine reliability based on total number of days and days operational
   Success Criteria: VFD fans should be 99% reliable.

4. Hangar bay environment during painting process.

   Purpose: To verify that hangar air quality stays within allowed parameters of the painting process at various airflow rates.
   Metric: Hangar bay air temperature and relative humidity
   Data: Temperature (^{o}F) and relative humidity (percent) at five locations around envelope of the plane.
   Analytical Methodology: Meter error tolerance shall be factored in to recorded value of temperature and humidity.
   Success Criteria: No one reading shall vary more than ±5 percent of the process requirement.

5. Direct greenhouse gas emissions

   Purpose: Calculate reduction in greenhouse gas emissions as a result of reduced fan loads on the corrosion control hangar.
   Metric: Direct fossil fuel GHG emissions (metric tons)
   Data: Expected GHGs emitted based on energy readings
   Analytical Methodology: Estimated using the Emissions & Generation Resource Integrated Database (eGRID) U.S. annual non-base load CO2 output emission rate to convert reductions of kilowatt-hours into avoided units of carbon dioxide emissions. Then using the accounting methodology in the Federal Greenhouse Gas Accounting and Reporting Guidance Technical Support Document, October 2010.
   Success Criteria: 20 percent or greater reduction compared to current baseline airflow. This rate would tie into the EPACT 2005, EISA 2007, and the Guiding Principles for High Performance Sustainable Buildings that the DoD is in the process of conforming.

6. Systems Economics: Existing System

   Purpose: To determine the potential savings of the operation of a corrosion control hangar given an upgrade to the existing ventilation system or energy source. It is anticipated that some ventilation systems have not operated at their design flow rates. The system would need to be upgraded to comply with health and safety requirements.
   Metric: Dollar value
   Data: Metered energy kWh
   Analytical Methodology: Cost benefit analysis
   Success Criteria: 10 percent reduction in operating costs

7. Systems Economics – New system

   Purpose: To determine the potential savings of the operation of a corrosion control hangar given the installation of a new system. Assuming a reduction in flow rate is acceptable, new corrosion control hangars could be designed to the lower rate which in turn would lower the total facility cost.
   Metric: Dollar value
   Data: Metered energy kWh
   Analytical Methodology: Cost benefit analysis
   Success Criteria: 20 percent reduction in operating costs

8. Design footprint for new facility

   Purpose: Findings from the project lead to new design specifications when creating new paint hangars. Ideally, the reduced volume will reduce overall cost and to some extent less footprint due to a smaller ventilation system required.
   Design drawings and specifications or templates
   Success Criteria: 5 percent reduction of mechanical room

9. Sampling for contaminants at workers breathing zone and specified area samples.

   Purpose: To determine the concentrations of controlled chemicals at the normal and reduced flow rate.
   Metric: 8-hr and process duration TWA exposures, Permissible Exposure Limit (PEL)/Threshold limit value (TLV) (ppm or mg/m3)
   Data: Concentrations of:
   - Chromium (Cr)
   - Hexavalent chromium (CrVI)
   - Methyl isobutyl ketone (MIBK)
   - Methyl ethyl ketone (MEK)
   - Methyl n-amyl ketone (MAK)
   - Hexamethylene diisocyanate (HDI)

   Analytical Methodology: Personal sampling devices and laboratory analysis
   Success Criteria: Personal exposure at the reduced velocity less than or not exceeding that at the baseline or "as-is" velocity, measured as the mean and the 95th percentile, with statistical significance at the 90% confidence level.

10. Sampling for Lower Explosive Limit (LEL) in the general area

   Purpose: To determine the concentrations of chemicals that have a potential to cause explosions
   Metric: Lower Explosive Limit (LEL)
   Data: Concentrations of:
   - Methyl isobutyl ketone (MIBK)
   - Methyl ethyl ketone (MEK)

- Methyl n-amyl ketone (MAK)

Analytical Methodology: General area sampling devices and laboratory analysis
Success Criteria: Less than 25 percent of LEL

11. Sampling for particle deposition on the floor surface

Purpose: To determine the concentrations of controlled chemicals at the normal and reduced flow rate.
Metric: Surface wipe samples, measured in µg/100 cm^2
Data: Concentrations of:
- Chromium (Cr)
- Hexavalent chromium (CrVI)
- Total Particulate

Analytical Methodology: Surface sampling media/template and laboratory analysis
Success Criteria: Contamination at the reduced velocity less than or not exceeding that at the baseline or "as-is" velocity, measured as the mean and the 95^{th} percentile, evaluated for statistical significance at the 90% confidence level.

12. Outdoor re-entrainment of air contaminants

Purpose: To determine whether a reduction in hangar air velocity causes or adds to contaminated air from exhaust stacks re-entering the facility through supply intakes.

Metric: Comparison of supply air concentrations at tested air flow rates.

Data: During tracer gas experiments inside the hangars, concentrations will also be measured, outdoors, at the supply intakes. If concentrations are not detectable, due to outdoor dilution for example, MEK and MIBK concentrations will be measured at the supply intakes, during aircraft wipe-down operations.

Analytical Methodology: infrared analyzer and/or laboratory analysis
Success Criteria: Concentration at the reduced velocity not exceeding that at the baseline or "as-is" velocity, measured as the mean and the 95^{th} percentile, evaluated for statistical significance at the 90% confidence level.

Qualitative success criteria:

1. Regulatory clarification for occupational health and safety across DoD

   Purpose: To contribute to the fund of knowledge among DoD industrial hygiene professionals, such that desired paint hangar ventilation velocities are generally agreed upon.
   Metric, data and analysis: Scientific evidence generated during this project to show ventilation and exposure relationships.
   Success Criteria: Issuance by OSHA of a letter of interpretation, concerning aircraft paint finishing and corrosion control hangars.

2. Scalability & transfer-ability across DoD

   Purpose: The ability to use the findings and methods at other DoD corrosion prevention paint hangars.
   Metric, data and analysis: Scientific evidence generated during this project to show exposure limits.
   Success Criteria: The acceptance of the recommendation for the lower flow rate of 75 fpm as an acceptable standard in the current UFC.

3. Scalability & transfer-ability across DoD

   Purpose: The ability to use the findings and methods at other DoD corrosion prevention paint hangars.
   Metric, data and analysis: Scientific evidence generated during this project to show exposure limits.
   Success Criteria: Accepted for inclusion in ACGIH IV Manual as an accepted method for corrosion prevention paint hangars.

4.0 FACILITY/SITE DESCRIPTION

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

4.1 Facility/Site Location and Operation

4.1.1 Naval Base Coronado

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

The refinishing of whole aircraft is performed in Buildings 464 and 465, 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 (shown in Figure 4), where approximately twenty aircraft are painted per year. Refinishing of strike fighter aircraft takes place in one bay of a large two-bay hangar. One entire bay wall is a door to the outside that swings open for moving aircraft in and out. This door contains the supply plenum and filter. Supply air flows from this end of the bay to the exhaust filter on the opposing wall. An accordion door separates the two bays when only one bay is required. To accommodate larger aircraft (such as the C-2), the supply walls of both bays are opened like a gate, the accordion door is retracted and the two bays become one big hangar, served by two identical ventilation systems.

Bay 6, in Building 465 of FRCSW, is served by four supply blowers and four exhaust fans, with exhaust fan speed served by VFD controllers. Two of the supply blowers are equipped with steam heat elements. The design functions of this ventilation system are to maintain a safe and healthy work environment, to control and contain sanding particulate and paint overspray, and to maintain the temperature required for painting operations. Figures 5 and 6 show the configuration of the bay, filters, and aircraft, with a supply wall blowing air toward an exhaust wall at the opposite end of the bay.

Figure 4: Photo of the refinishing of an F-18 aircraft in Bay 6 of Building 465 at Naval Base Coronado.

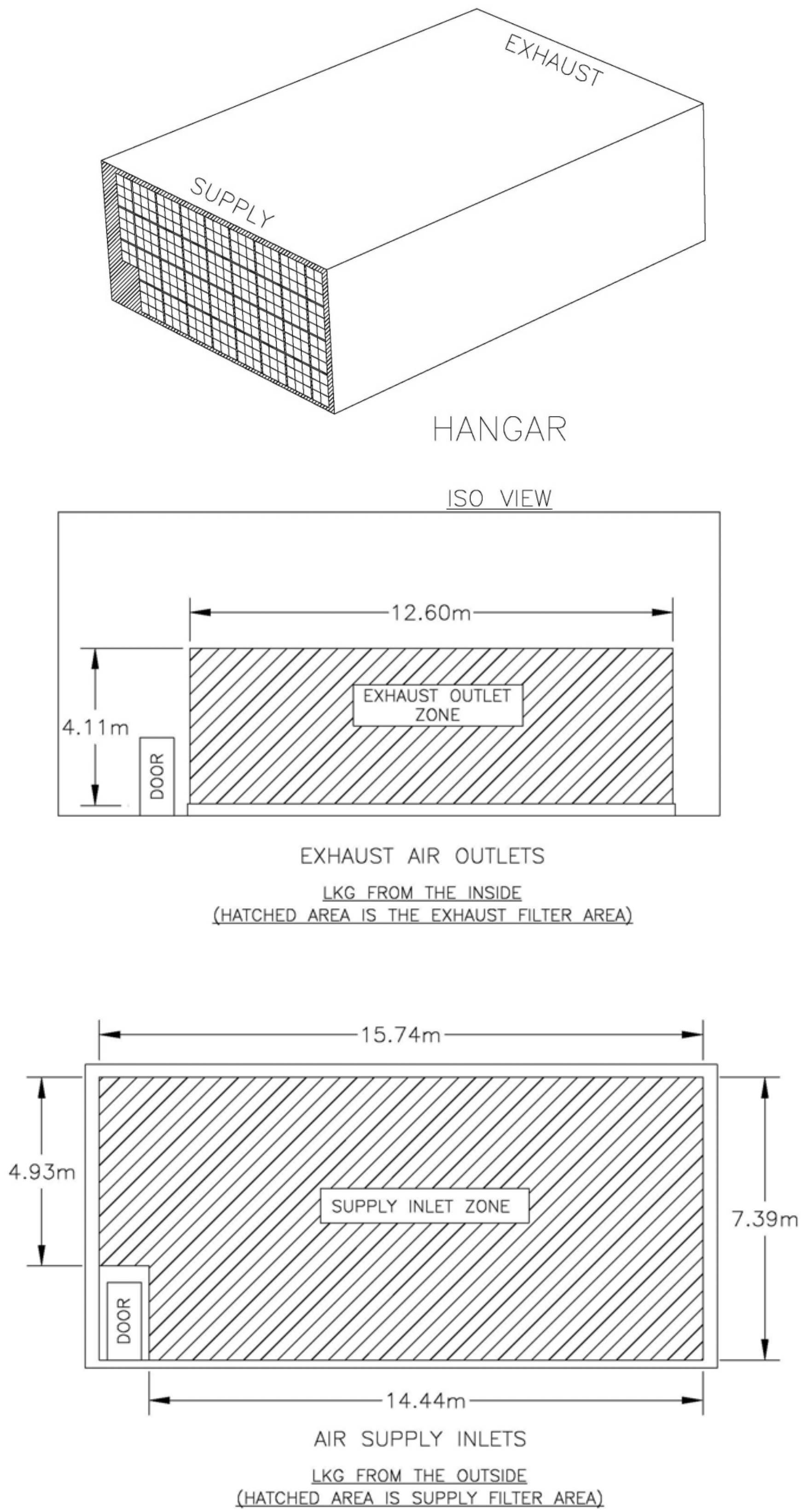


Figure 5: Drawing showing the filter area of the aircraft painting bay.

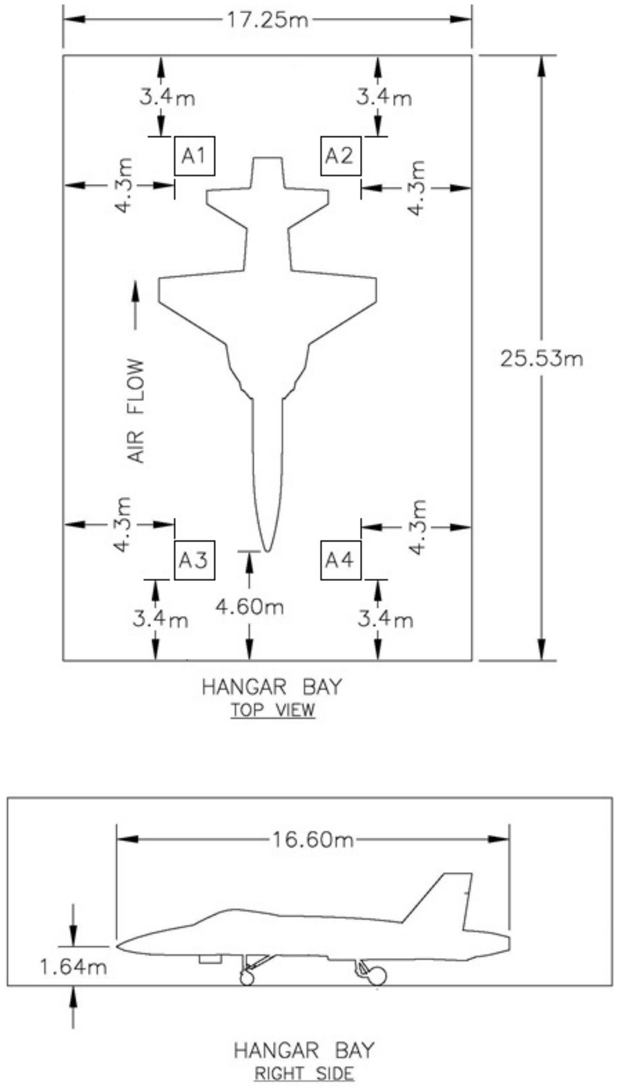


Figure 6: Drawing showing interior of bay, F/A-18C/D Hornet, and area sample locations (A1 – A4).

4.1.2 Marine Corps Air Station Cherry Point

Marine Corps Air Station Cherry Point is home to the 2nd Marine Aircraft Wing. Fleet Readiness Center East (FRC East) operates two aircraft painting hangars at Cherry Point: one cross-draft hangar with one large bay and one downdraft hangar which can be broken up into 4 smaller bays. These hangars commonly service MH-53, AH-1, V-22, and CH-46 rotary-wing aircraft, as well as the AV-8 Harrier fixed-wing aircraft. Based on discussions with FRC East and a site visit it was decided that only the cross draft paint hangar would be evaluated during this study, as modern paint hangars are typically designed to the cross draft specification.

During the initial walkthrough of the cross flow hangar (Figure 7), the team observed that only 2 out of 4 supply fans and 6 out of 8 exhaust fans were operational. Maintenance and repair of the system was discussed with site engineers, and funding for the extensive repairs needed was identified as a large issue.

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

Figure 7: View of the MCAS Cherry Point Helicopter Painting Hangar.

4.1.3 Sioux City Air National Guard Base

The Sioux Gateway Airport hosts the 185th Air Refueling Wing of the Iowa Air National Guard. It is also home to the Iowa Air National Guard Paint Facility. This facility handles the painting of a variety of fixed and rotary-wing aircraft, such as the A-10 Thunderbolt, the F-15 Eagle, the F-16 Fighting Falcon, and the UH-60 Blackhawk. The facility has painted more than 500 aircraft since it opened in 2000. The paint facility consists of two hangars, designated Bay 3 and Bay 5 (Figure 8).

Bay 3 Paint Hangar

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

Bay 5 Paint Hangar

- Dimensions: (paint bay inside hangar building): L = 76'-79' (staggered, sliding, supply filter panels), W = 64', H (middle) = 25', H (sides) = 17'.
- 2 supply fans
- 3 Exhaust fans
- Preliminary airflow measurements inside the bay were 55-83 fpm
- Measurements at the filters: supply ~112 fpm, exhaust ~78 fpm(perhaps at a paint-clogged area)

Paint schedule:

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

Paints used:

- AKZO NOBEL Flat Grey ECM-F-6118, 6270,6176,6251, 6320, 6375, 7038 (black)
- AKZO NOBEL Epoxy primer (2 hr) 10P8-11; Epoxy Primer High Solids 10P20-13
- CARC paints: Sherwin Williams Black F93B506; Green F93G505; paint catalyst V93V502
- Paint gun is HVLP.

Energy and Ventilation Systems:

- There is a facility-wide energy meter. Installing sub-meters for the air handling units would assist painting related energy assessments.
- Outside air is heated in the air handling unit using natural gas and then distributed to the larger building envelope that contains Bays 3 and 5. Supply air enters Bay 3 through the open sliding door opposite the exhaust wall filter bank. Supply air enters Bay 5 through ceiling slot diffusers at the large sliding door through which aircraft enter. Covering the opposite wall is the exhaust filter bank.
- During periods when the air handling units are not moving air through and maintaining temperature in the facility, there are additional blower heaters to keep temperatures stable for paint curing.

Figure 8: Interior of Bay 5 of the Iowa Air National Guard Paint Facility.

4.1.4 Joint Base Lewis-McChord

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

4.1.4.1 McChord AFB C-17 Painting Hangar

Hangar building 1160 on JBLM, designated a Corrosion Control Facility (CCF), was chosen as a study site. The main production in this facility is paint finishing of C-17 Globemaster aircraft flown by the 62 AW. The building and ventilation system appear purpose-built and thoughtfully designed for painting the C-17. The ventilation system design is a hybrid of ceiling supply units and end-wall exhaust hoods. The 182 supply openings are arrayed in a pattern that focuses supply air on the aircraft. The eight exhaust hoods are positioned near the aircraft—about 25 feet from the leading edges of the wings and nose (Figures 9 and 10). The ventilation system is modern and utilizes variable frequency drive (VFD) controllers. However, the current system has only a small number of settings that can be selected by the operators.

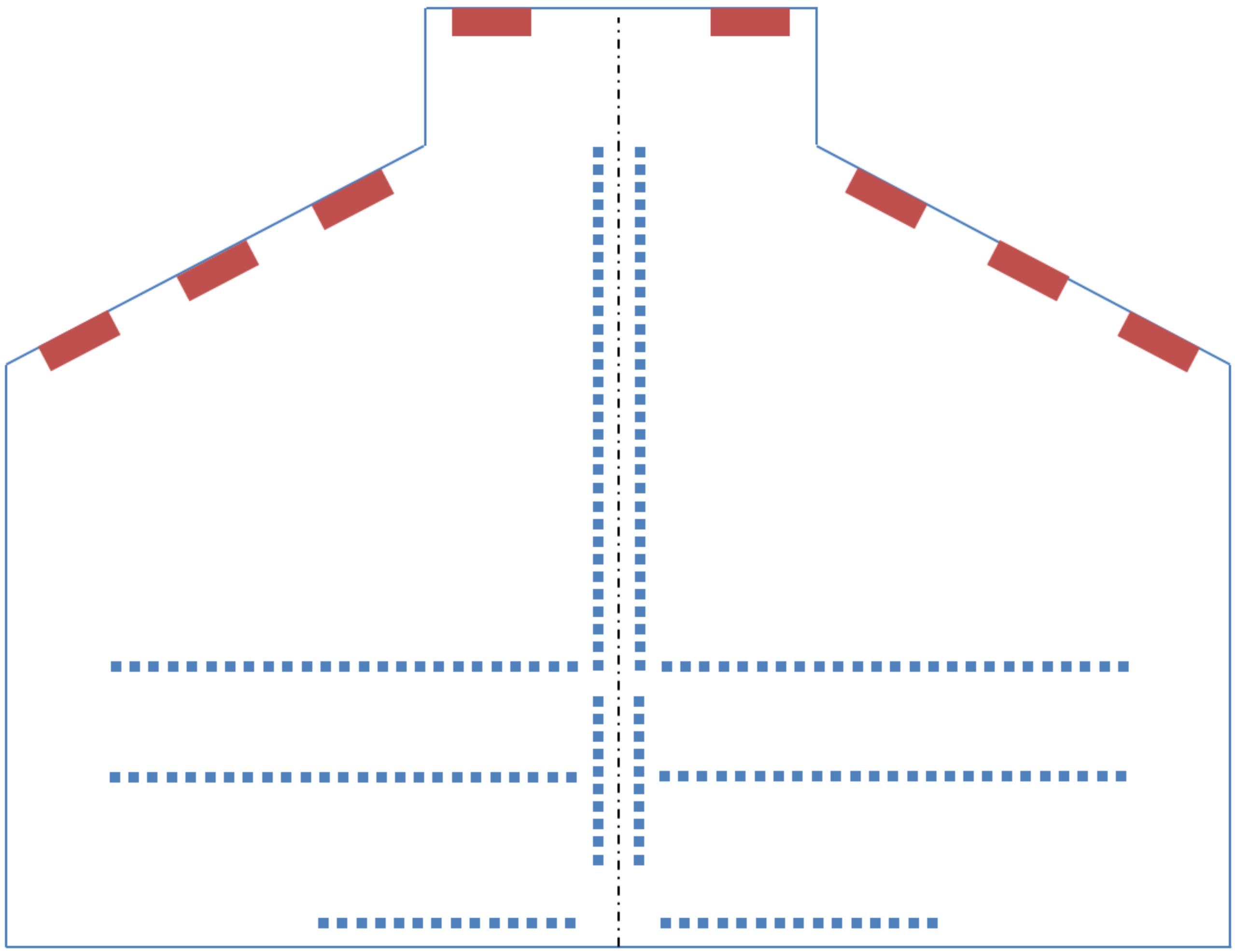


Figure 9: JBLM hangar Building 1160 ventilation system schematic (top view). Ceiling-mounted supply openings are drawn in blue, while the end-wall exhaust hoods are drawn in red.

Figure 10: Photo of the JBLM corrosion control hangar. The eight large exhaust hoods are visible along the back wall, and the arrays of small square supply inlets can be seen on the ceiling.

4.1.4.2 Fort Lewis Helicopter Painting Hangar

A second possible study site at JBLM was also visited: a helicopter painting facility which regularly handles the refinishing of UH-60 Blackhawk and OH-58 Kiowa aircraft. The hangar bay is 61 feet long, 30 feet wide, and 20 feet high. Air is supplied and exhausted through floor-to-ceiling filter banks embedded in columns at each of the four corners of the hangar. The two columns on either side of the hangar bay door serve as exhaust, while the two columns on the opposite side of the hangar serve as supply (see Figures 11 and 12).

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

Figure 11: The Fort Lewis helicopter painting hangar. The exhaust filter columns can be seen on either side of the hangar door.

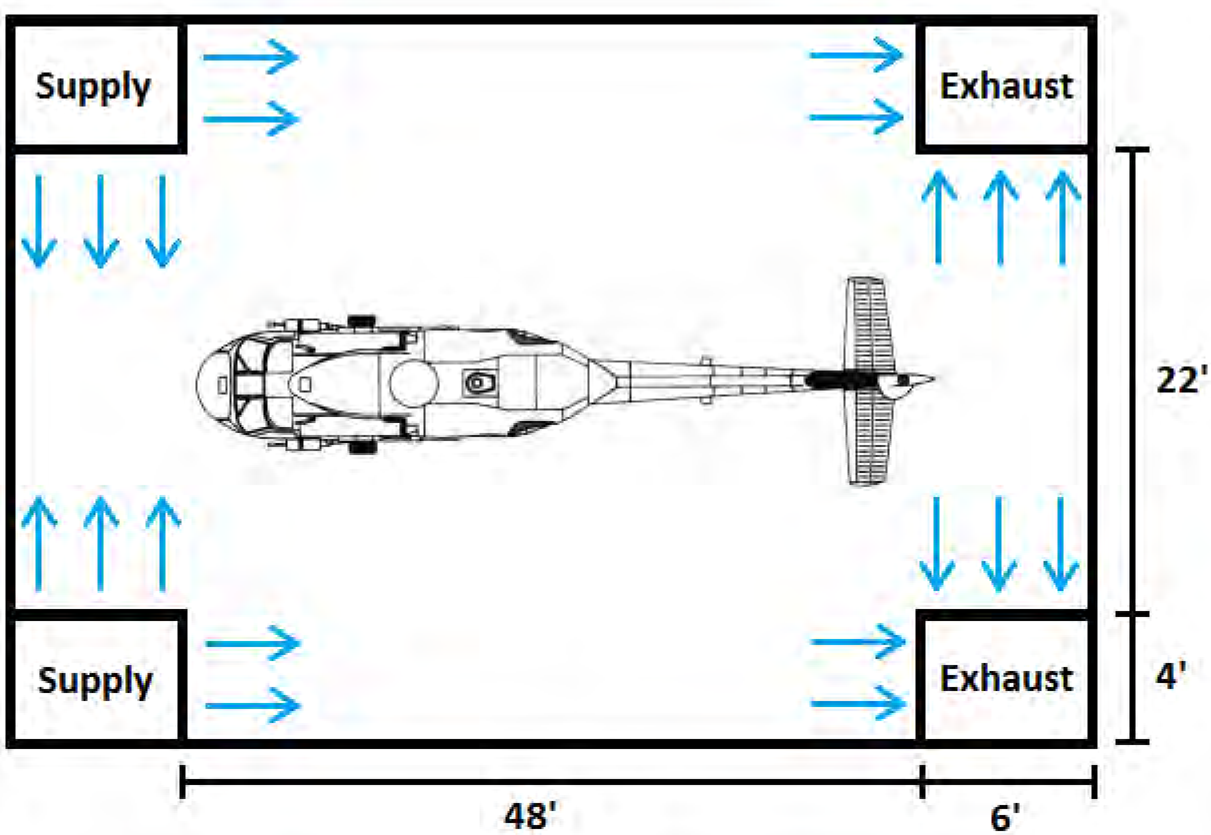


Figure 12: Overhead schematic of the Fort Lewis helicopter painting hangar.

4.2 Facility/Site Conditions

See Section 4.1 for the site conditions of each location that was visited.

5.0 TEST DESIGN

Prior to cancellation, the ESTCP project utilized a four-step analysis process for each site, with one site-visit at each step. The steps used at each selected site were site assessment, CFD analysis, tracer study and exposure monitoring. A description of each step is listed below.

1. The first site visit would be to assess the site for appropriateness. The site would be assessed based on a number of criteria, such as condition of the hangar, type of ventilation system, adjustability of ventilation system, ability to monitor energy use, and coordination depth with facility personnel. Study inclusion required that a site be willing to participate, that it had the ability to achieve the ventilation criterion of approximately 100 fpm, as an average across the hangar cross-section adjacent and upwind of the aircraft, and that it would be modifiable in the sense of reducing the characteristic air velocity by approximately 25 fpm. Sites would be rejected if they were slated for renovation, if they displayed poor operation and maintenance, if they used water wash filtration systems, or if they were otherwise not representative of DoD painting hangars in general. Alternatively, a site with well-functioning ventilation at approximately 75 fpm that could be brought to 100 fpm would also be a good candidate. Airflow measurements for all sites were made using a Shortridge Instruments Airdata Multimeter ADM-860C, with a VelGrid probe.
2. If the site was deemed appropriate for further study, a second site visit would be made in order to assess energy usage on the site and characterize the hangar for CFD simulation. This would include measuring the dimensions of the hangar, gathering information on the ventilation configuration, and obtaining flow rate measurements. If possible, baseline exposure monitoring would also be conducted during standard painting operations. This site visit would be followed by a period of extensive CFD modeling of the existing system to assess the effects of alternative ventilation configurations and lower flow rates.
3. After CFD modeling, a third site visit would take place to conduct tracer gas testing in the hangar. A tracer gas, such as sulfur hexafluoride, would be released in the hangar-- with no people inside-- at the normal supply/exhaust flow rate and at lower flow rates, and concentrations would be measured at various locations. Numerical simulation data would then be compared to the tracer gas results in order to assess the accuracy of CFD predictions.
4. Finally, a fourth site visit would be made for the purpose of assessing worker exposure at reduced flow rate configurations.

This four-step process of site assessment, CFD analysis, tracer gas validation, and exposure testing, has been successfully completed for the Naval Base Coronado site. As of the cancellation of the project, the other three sites remain at various stages of the process (Table 2).

Table 2: Status of Sites.

	Naval Base Coronado*	Cherry Point Marine Corps. Air Station	Air National Guard Base Sioux City	Joint Base Lewis McChord
Site assessment	X	X	X	X
Vent/CFD analysis	X	X	V	V
Tracer validation	X			
Exposure monitoring	X			

*** Some activities at NBC were part of the NESDI project. Others were part of the ESTCP project.**
V = Ventilation testing completed only
X = Completed

5.1 Baseline Characterization

The most comprehensive characterization of an aircraft paint finishing technology baseline occurred prior to the ESTCP project. In early 2008, preliminary CFD simulations were performed to model the relationship between air velocity and worker exposure levels in a Navy aircraft painting hangar. Air velocities of 100 and 50 fpm were compared for roughly approximate aircraft, worker, and source representations. The results showed only a small increase in exposure at 50 vs 100 fpm. With promising test-of-concept results in hand, NAVFAC initiated a project that received funding from NESDI. A walk-through survey was conducted June 16-19, 2009, in a hangar at Naval Air Station North Island (NAS NI). Personal and area air sampling (for CrVI, HDI, and any other contaminants found on the material safety data sheets) was performed, and hangar dimensions, geometric details, and ventilation boundary conditions were collected to set-up high-fidelity CFD simulations. Next, the ventilation system's ability to control air contaminants was evaluated through comprehensive personal and area air sampling of all solvent, primer, and topcoat constituents, on July 22 and August 3, 2009 and April 13, 2010. Three visits were needed to monitor three painting processes (typically spaced days or weeks apart), which provided statistical characterization of exposures. CFD simulations were performed and validated based on the ventilation settings available at the time of the 2009-2010 field studies. An initial tracer gas study was conducted April 12 and 14, 2010 to evaluate the performance of the hangar ventilation system under a number of supply/exhaust ventilation settings.

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

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

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

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

1. The system was unbalanced with supply at 136 fpm and exhaust at 99.0 fpm. Balancing the air supply and exhaust could improve exposure control, consistent with ventilation standard practice.
2. From tracer gas measurements, 3/4 of the normal supply and exhaust rates provided the lowest concentrations, when compared to full flow (supply = 136 fpm; 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, at measurement locations that had been observed during painting.
3. CFD simulations showed a large increase in contaminant concentration at typical worker locations, when the supply rate exceeded the exhaust rate, compared to when the supply and

exhaust rates were equal. "Balancing," as in item 1, means maintaining a very small negative pressure, perhaps approximately -0.05 in. water.

4. Based on personal sampling of workers during typical aircraft refinishing operations, the ventilation system did not adequately control worker exposure to below OELs and required with the use of respiratory protection, as was already being done.
5. Because all materials measured in the aircraft refinishing process were less than 1% of any LEL, explosion from chemical concentrations was not an issue.
6. Additional tracer gas and CFD simulations were needed to fill the following information gaps:
    a. Tracer gas studies were performed only on the system in the unbalanced state. Additional tracer studies are needed under balanced conditions.
    b. CFD simulations were performed under balanced ventilation boundary conditions and under a hypothetical positive pressure scenario, rather than the measured unbalanced boundary conditions. Additional CFD simulations are needed that use the measured supply and exhaust velocities.

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

Setting 1: 1/4 supply (43.3) and 2/4 exhaust (49)
Setting 2: 2/4 supply (73) and 3/4 exhaust (65)
Setting 3: 2/4 supply (73) and 4/4 exhaust (99)
Setting 4: 3/4 supply (108) and 4/4 exhaust (99)

Tracer gas experiments were conducted over two nights, while normal hangar operations continued during the daytime. Results from each night were reported separately because the source and measurement locations and exhaust filter pressure drop could not be held precisely constant between nights.

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

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

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

Conclusions

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

Recommendations

1. Achieving balanced flow (perhaps -0.04 ±0.002 in. water gauge, if prevention of fugitive emissions to the environment is desired [ACGIH 2013]) through capital improvements at the site should be considered, based on ventilation standard practice.
2. After balancing or any other system modifications, follow-up tracer gas testing, process air sampling, and velocity sampling should be done to verify ventilation improvements.
3. Correcting the pressure imbalance should include replacing appropriate exhaust filters, pre-filters, or pre-layers during moderate or high filter loading to reduce pressure drop and save energy. The filter pressure drop value at which filters will be replaced should be recommended by NAVFAC ESC and the filter manufacturer. Balancing the system and improving system maintenance will improve operational efficiency.
4. Measurements of the concentration of flammable or explosive materials in air should be made directly in the exhaust stream to demonstrate compliance with NFPA 33: “Standard for Spray Application Using Flammable or Combustible Materials 2011,” if any significant changes are made to the existing ventilation system or settings. The current study did not include this specific measurement, because no flammable materials were used in the tracer studies and because previous area air sampling during aircraft painting under the existing ventilation indicated that an explosion hazard was not present.
5. In addition to correcting existing paint finishing hangar ventilation systems, innovative design should be explored using CFD. Reducing the hangar cross-sectional area to more closely fit each aircraft size and maintain a desired velocity at a lower flow rate, directing supply air to the work zones more precisely, and bringing exhaust terminals closer to contaminant sources are examples

of possible paths to consider that may reduce worker exposures, while also reducing associated energy costs.

6. Any changes in ventilation operation should include provisions to prevent possible safety hazards (doors blowing open or closed) created by changes in hangar pressure.

5.2 Design and Layout of Technology and Components

Computational fluid dynamics applied to exposure assessment and ventilation evaluation is an innovative technology. CFD is a numerical method that solves the system of equations that describe fluid behavior by using a computational grid. CFD is essential in this study due to its ability to model and anticipate the results of a wide range of ventilation modifications prior to potentially costly implementation that is generally impractical on a trial basis. Performance information is more useful and cost-effective before modifications are made. As of project cancellation, CFD modeling has been conducted for only two of the four ESTCP sites: NBC and Marine Corps Air Station (MCAS) Cherry Point.

5.2.1 Naval Base Coronado

CFD simulations for the NBC hangar were performed for a variety of ventilation settings representing both balanced and unbalanced flow rates. Balanced flow rates of 43.3, 65, 75, 86.6, 100, and 108 fpm were modeled along with unbalanced flow rates of 73/49, 108/65, and 139/99 fpm supply/exhaust velocities. The unbalanced rates were representative of conditions which would result from turning off certain fans in the existing ventilation equipment to reduce air flow, while the balanced conditions would require more extensive modifications to equalize supply and exhaust rates.
In the model, a contaminant with the physical properties of methyl isobutyl ketone (MIBK) was emitted, in both vapor and liquid droplet forms, from the hand areas of two simulated workers placed at commonly observed spraying locations, at a flow rate specified by the spray gun manufacturer. For the model, the MIBK vapor density was 4.23 kg/m^3, about 3.5 times denser than air, and its viscosity was 6.70×10^{-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 “air” in the hangar. Turbulence was modeled using the form of the Reynolds-averaged Navier–Stokes (RANS) k-ε model that incorporates renormalization group theory (RNG). With turbulence intensity and length scale used as boundary conditions, intensity was set at 10 percent, and length scale was set at one meter for the large filter area and one tenth of a meter for the sprayers. Between grid points, variables such as contaminant concentration were interpolated using the first-order upwind scheme.

A nine-million cell mesh file of an F/A-18C/D Hornet was provided by NAVFAC ESC, working with the User Productivity Enhancement, Technology Transfer and Training (PETTT) Program. The mesh was generated using Gridgen software (Pointwise, Inc., Fort Worth TX). The geometry is shown in Figure 13. NIOSH provided solid models representing workers in Tyvek® suits (Figure 14), using Solidworks. The geometry and mesh were imported by NIOSH into the CFD solver and post-processor, Fluent 6.3 (ANSYS, Inc., Canonsburg PA). Remaining model inputs were based on building and ventilation measurements taken during the site visits. The solution utilized a RANS turbulence model and was steady-state. Solution instability was addressed by setting the under-relaxation parameters for pressure correction, velocity, and turbulence very low, at 0.2 or even 0.1. For this reason, a second order discretization was not attempted, and the reported results come from the first order upwind scheme.

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

The CFD simulations were each run for 38,000 iterations and used the RNG k-ε turbulence model. Residual convergence levels were below 10^{-4}, except in the case of species ($<10^{-5}$) and eddy dissipation rate (slightly greater than 10^{-4}). The "stiffness" or resistance to decreases in error of the eddy dissipation rate equation is typical of indoor airflow CFD simulations. The species concentration never reached a steady-state but seemed to reach stability, with regular fluctuations in a consistent, limited range. The constant and large number of iterations (38,000) was used as the ultimate convergence requirement to ensure that comparisons among the three flow conditions were free of convergence errors, or that at least the convergence error was very small and similar for all flow conditions, which would still allow a reasonably accurate comparison.

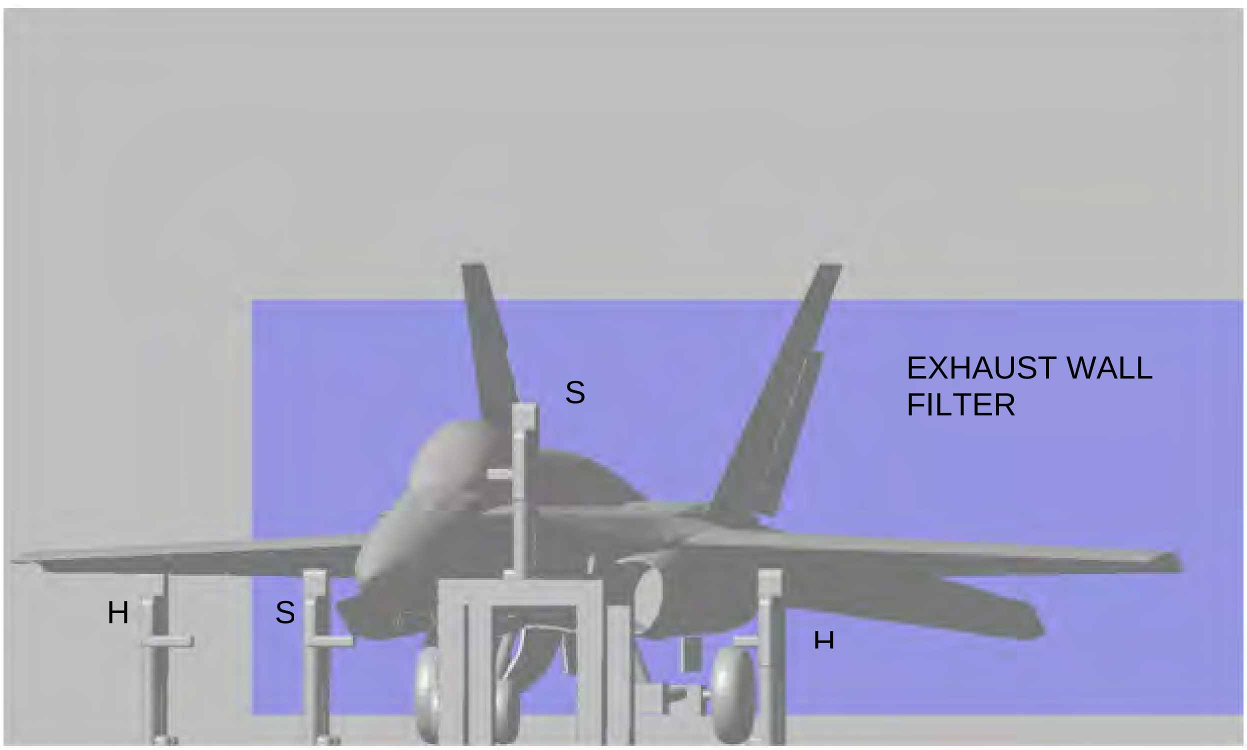


Figure 13: Geometry of workers, exhaust wall filter, and F/A-18C/D Aircraft. Hose men (H) are further from the aircraft and further downwind than sprayers. The contaminant source is located at the end of the sprayers' (S) right arms. One sprayer is on a scaffold.

5.2.2 Marine Corps Air Station Cherry Point

The modeling for MCAS Cherry Point was conducted in collaboration with Zhongquan Zheng, Zhenglun Wei, and Anpeng He at the University of Kansas, with similar methods to those used by NIOSH for the NBC site. The Kansas team was brought in to provide an independent CFD perspective. Measurements made during a NIOSH site visit were used to construct a three-dimensional mesh of the hangar (Figure 15). Geometry of an MH-53 helicopter, the most frequently-painted aircraft type, was provided by MCAS engineers in the form of an ANSYS Design Modeler file. This file was developed into a computational mesh, after inserting the geometry for five workers (Figures 15 and 16). The worker geometry is identical to what was used in the NBC simulations and represents a person of average height wearing a Tyvek® suit, as might be expected during regular painting operations**.** Three of the workers were made to represent sprayers, and two were made to represent helpers. The arms of the three sprayers served as contaminant injection points, with an injection velocity of 10 m/s, based on spray gun specifications.

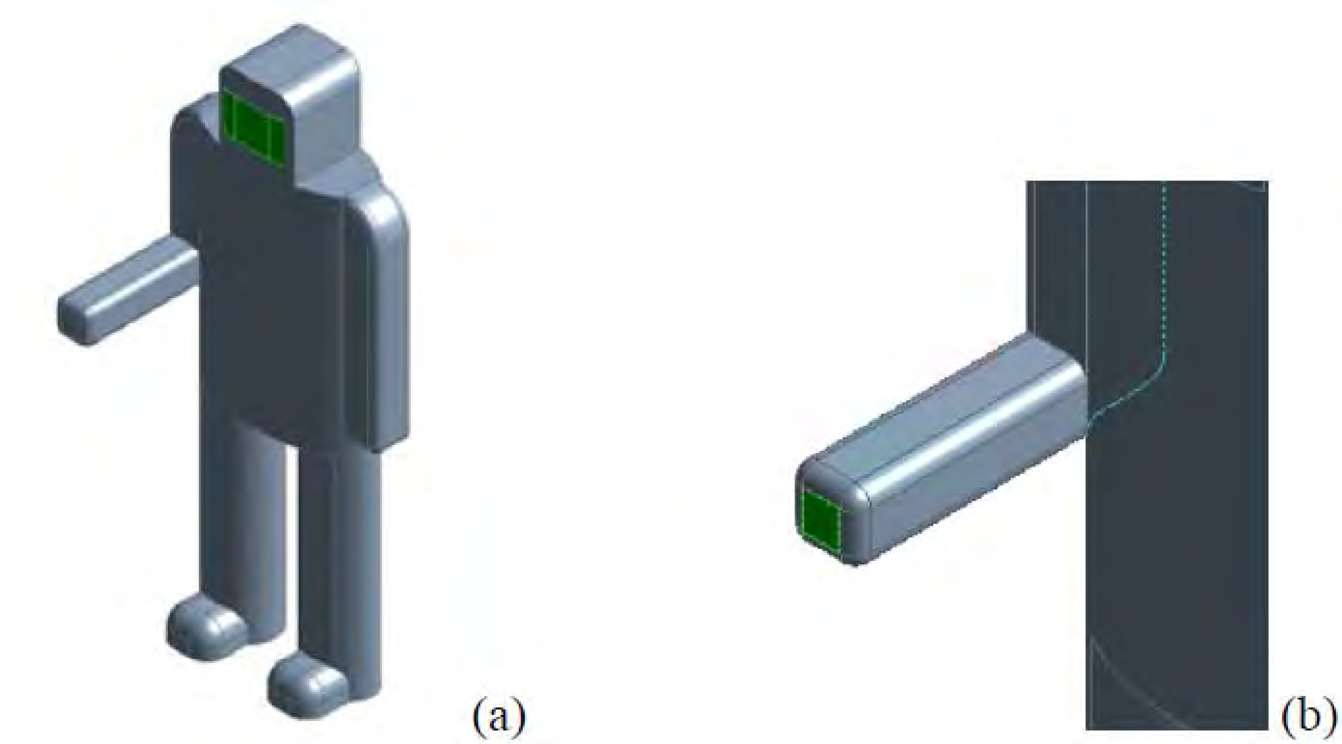


Figure 14: (a) Full worker geometry, with face region highlighted. (b) Close-up of worker arm, with injection region highlighted.

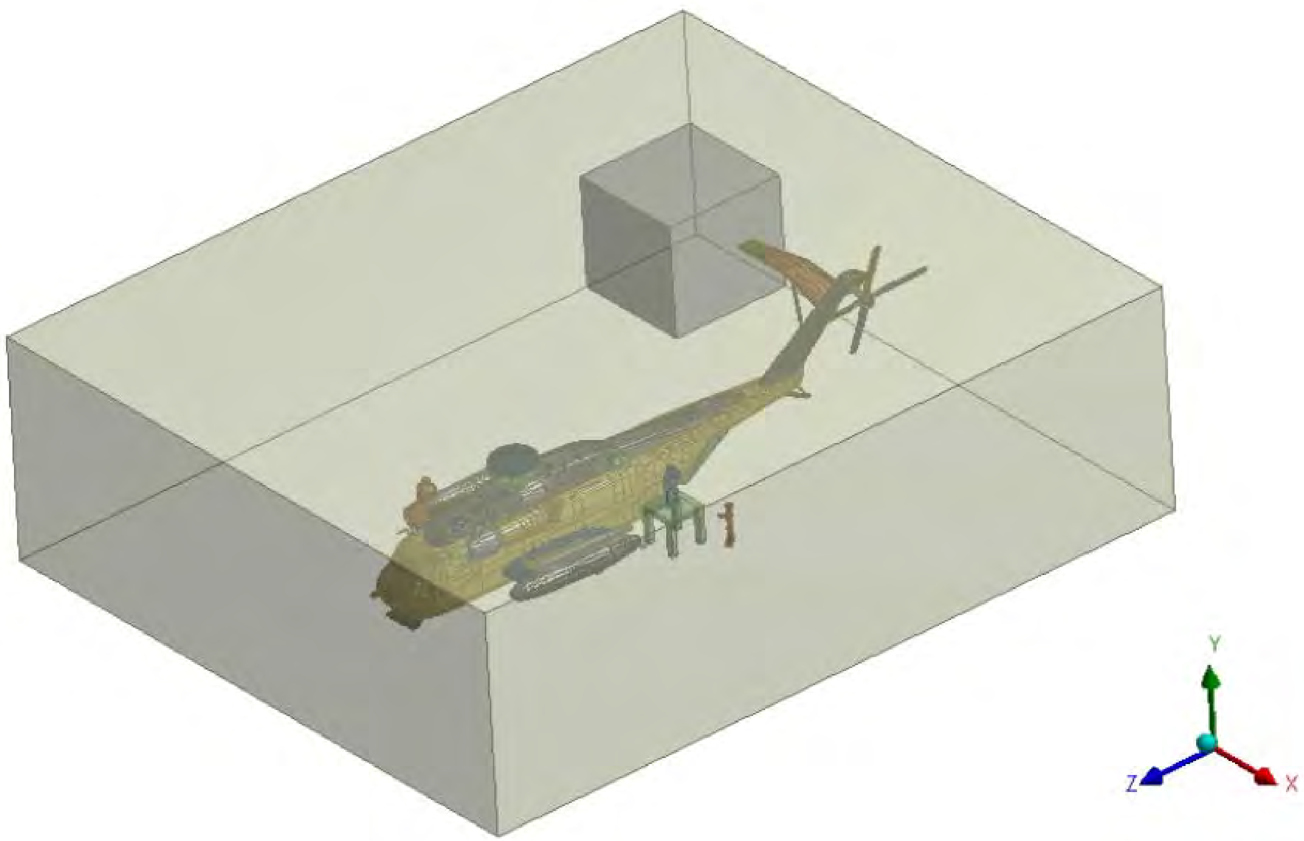


Figure 15: Overview of MCAS Cherry Point Hangar Geometry.

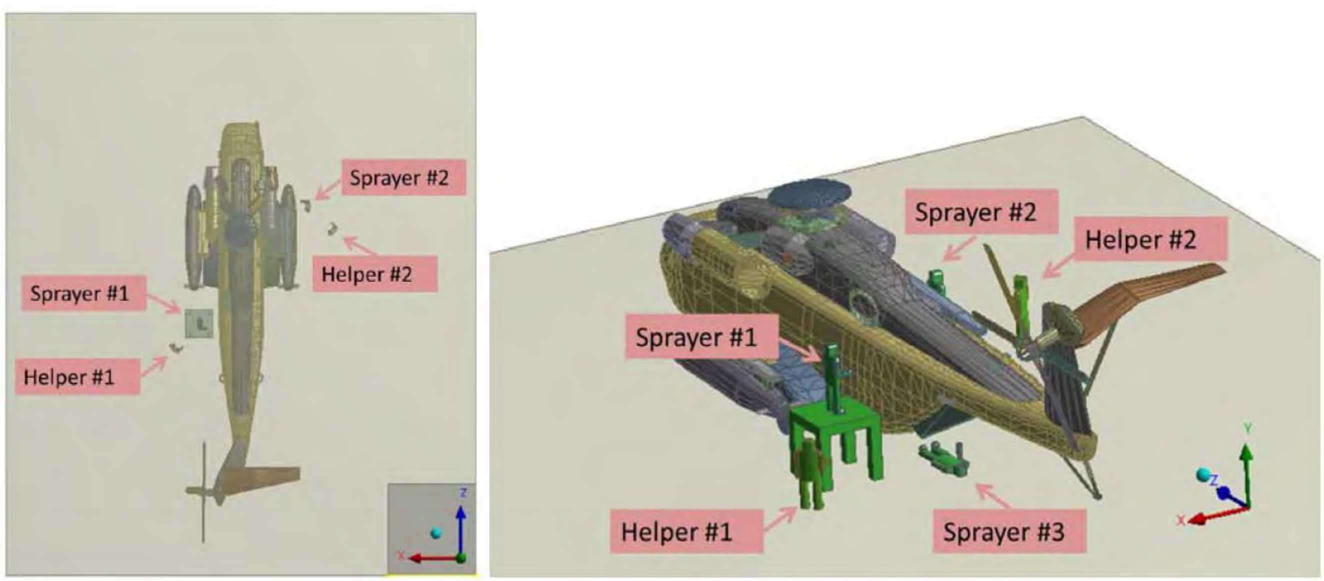


Figure 16: Overhead and isometric views of worker positions relative to MH-53 helicopter geometry.

5.3 Operational Testing

Tracer Gas Experiments (prior to ESTCP project)

During April 10-14 of 2010 and March 13-16 of 2011tracer gas experiments were conducted from 1500 to 2300 hr. at Naval Base Coronado, in a corrosion control hangar at Naval Air Station North Island, using sulfur hexafluoride (SF_6). The concentrations of 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 concentrations, at the five monitoring locations, was higher for half-flow than for 3/4-flow, with statistical significance (95% confidence intervals did not overlap, as shown in Figure 20 and Table 5). 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.

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

Air velocity measurements were collected in Bays 1 and 4 of Building 464 and in Bays 5-8 of Building 465 at NBC. The supply and exhaust filter banks in these bays are smaller than the cross-sectional area of the hangar. Thus, for ease of comparison, the exhaust measurements taken at the supply and exhaust filters were normalized to the area of the hangar cross-section. Mean normalized air velocity was 108 fpm at the supply banks, 83.9 fpm at the exhausts, and 94.2 fpm in the middle of the bays, halfway between the supply and exhaust filter banks. In Bay 6, which was the only bay investigated during the initial site visit, the supply/exhaust balance was significantly improved, with 114 fpm at the supply and 109 fpm at the exhaust, compared to 136 fpm supply and 99 fpm exhaust observed during the initial site study (Tables 3 and 4).

Table 3: Summarized Air Velocity Data.
Supply and exhaust values are normalized to the cross-sectional area of the hangar bays. No mid-hangar measurements were gathered in Bay 1 because there was no aircraft in the bay.

	Aircraft	Supply mean (range)	Mid-hangar mean (range)	Exhaust mean (range)
Bay 1	no aircraft	91.5 (71-126)		94.1 (30-115)
Bay 4	F-18	93.6 (41-137)	113 (51-257)	57.0 (19-105)
Bay 5	H-53	133 (44-249)	82.0 (50-140)	65.0 (19-109)
Bay 6	H-60	114 (97-137)	114 (84-148)	109 (66-136)
Bay 7	E-2	114 (39-159)	83.5 (41-114)	96.2 (67-118)
Bay 8	E-2	106 (96-118)	78.8 (54-100)	82.3 (10-129)

Table 4: Comparison of Mean Air Velocity Data Gathered in Bay 6.
During the initial survey to measurements obtained during 2014 follow-up survey, after ventilation was modified to reduce flow imbalance.

Location	Measured Velocity (fpm)		Velocity Normalized to Cross Section Area (fpm)	
	Initial Survey	Post-modification	Initial Survey	Post-modification
Supply	157 (122-193)	132 (112-158)	136 (106-167)	114 (97-137)
Mid-Hangar	104 (45-152)	114 (84-148)	104 (45-152)	114 (84-148)
Exhaust	264 (83-358)	290 (177-362)	99 (31.1-134)	109 (66-136)

5.4 Sampling Protocol

Personal Exposure Monitoring (within ESTCP project)

Air sampling to determine isocyanate concentration was conducted in Bays 7 and 8, which were in a combined configuration to provide room for a single E-2 aircraft. Samples were analyzed using OSHA methods 18 and 42 with modifications. Mean HDI monomer concentration was 1.34 µg/m^3, compared to 9.41 µg/m^3 during the initial survey. Mean HDI oligomer concentration was 122 µg/m^3, compared to 92.1 µg/m^3 during the initial survey. Air samples were also collected during a parts painting process. Mean HDI concentration during parts painting was 2.0 µg/m^3 and mean HDI oligomer concentration was 46.3 µg/m^3 (Table 6).

For the sprayers, total particulate matter exposure averaged 19.9 mg/m^3 during the baseline survey and dropped to 14.1 mg/m^3 after the ventilation system had been modified (balanced and lowered). The hexavalent chromium exposure dropped from 537 to 364 µg/m^3. For the helpers, the exposures increased after ventilation modification, with total particulate matter going from 4.88 to 5.89 mg/m^3 and hexavalent chromium increasing from 149 to 172 µg/m^3. Only a single sprayer and a single helper were available for sampling during the follow-up survey, and these values were within the measured range of the baseline samples. Rows highlighted in green indicate that ventilation modifications may have lowered exposures, while yellow highlight indicates exposures may have increased.

Airflow measuring devices and sampling pumps were factory calibrated within the manufacturers recommended schedules. All sampling pumps were pre and post calibrated in the BUMED industrial hygiene laboratory on base at NASNI. Samples were analyzed by Bureau Veritas North America, an AIHA certified laboratory. QC analyses on all samples were performed and documented by the Chemical Exposure Monitoring Branch of NIOSH.

5.5 Sampling Results

5.5.1 Naval Base Coronado

Figures 17 and 18 summarize the results of CFD modeling for the NBC hangar, by showing the steady-state converged concentrations at observed worker locations and the arithmetic and geometric means over these locations. Examination of Figure 17 shows that the two least effective rates are 43.3 fpm and the unbalanced 108 fpm supply–65 fpm exhaust scenario, denoted 108/65 in the figure i.e. the unbalanced condition has two different flow rates. These rank first and second highest, respectively, by concentration level at four out of five locations in the solution field. The main pattern is also seen in the spatial average of the entire hangar at a level of the typical standing breathing zone (BZ height) and in the mean of the probe locations. While the BZ height calculation reflects the rate of removal from the whole space, the specific probe locations were chosen based on observations of where workers are located during the process and includes perceived worst case zones.

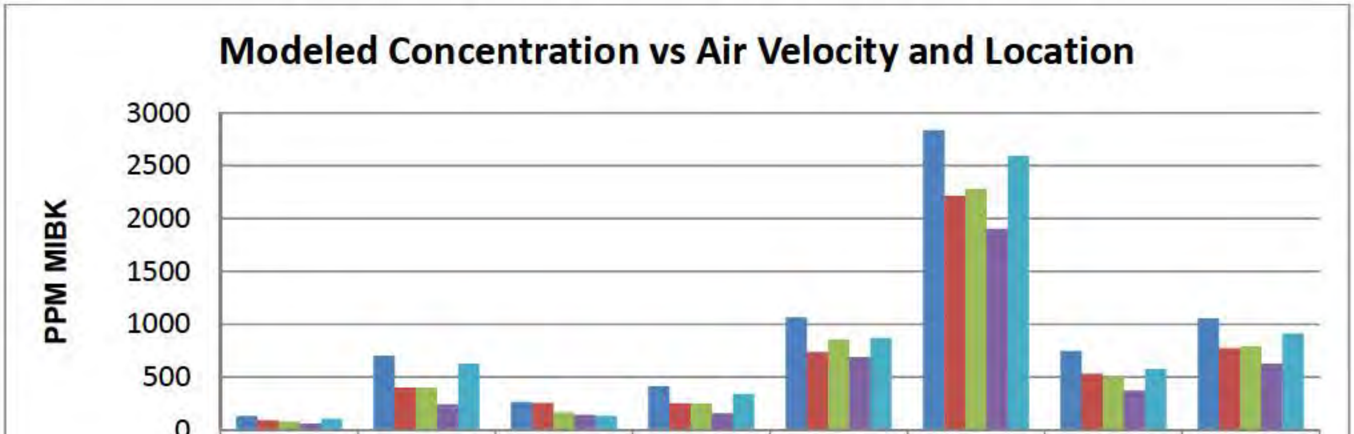
Figure 17 also shows the similarity of 65.0 fpm and 86.6 fpm, especially at critical worker locations. In the difficult to ventilate area under the landing gear hatch, the 65.0 and 86.6 fpm concentrations are 402 and 401 ppm. While the location geometric mean for 65.0 fpm of 532 ppm is somewhat higher than the 505 ppm at 86.6 fpm, the concentration at 65.0 fpm was lower than at 86.6 fpm at the two sprayer locations (which represent the highest exposures): 738 ppm and 2212 ppm vs. 857 ppm and 2279 ppm. The lowest concentrations occurred for the balanced 108 fpm rate, for all locations other than the portside hoseman location, which had the lowest concentration at the 108/65.0 fpm supply/exhaust condition.

Additional CFD simulations (Figure 18) using what is generally considered a more accurate turbulence model (RNG k-ε) 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 18 includes the arithmetic mean, because the geometric mean seemed overly influenced by the concentrations that were very close to zero. The arithmetic mean indicates here that the lower velocity is generally more protective, while the geometric means indicates that the higher velocity is generally slightly more protective. The RNG k-ε model results show concentrations generally lower than the previous simulations that used the standard k-ε turbulence model and a higher convergence error tolerance. A reasonable interpretation is that the RNG k-ε model and the lower convergence error tolerance resolved the steep, near-source concentration gradients more precisely, with less numerical diffusion. Therefore, the second set of simulations were worth doing and at least as accurate as the first set, if not more so.

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 across the filter face 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.

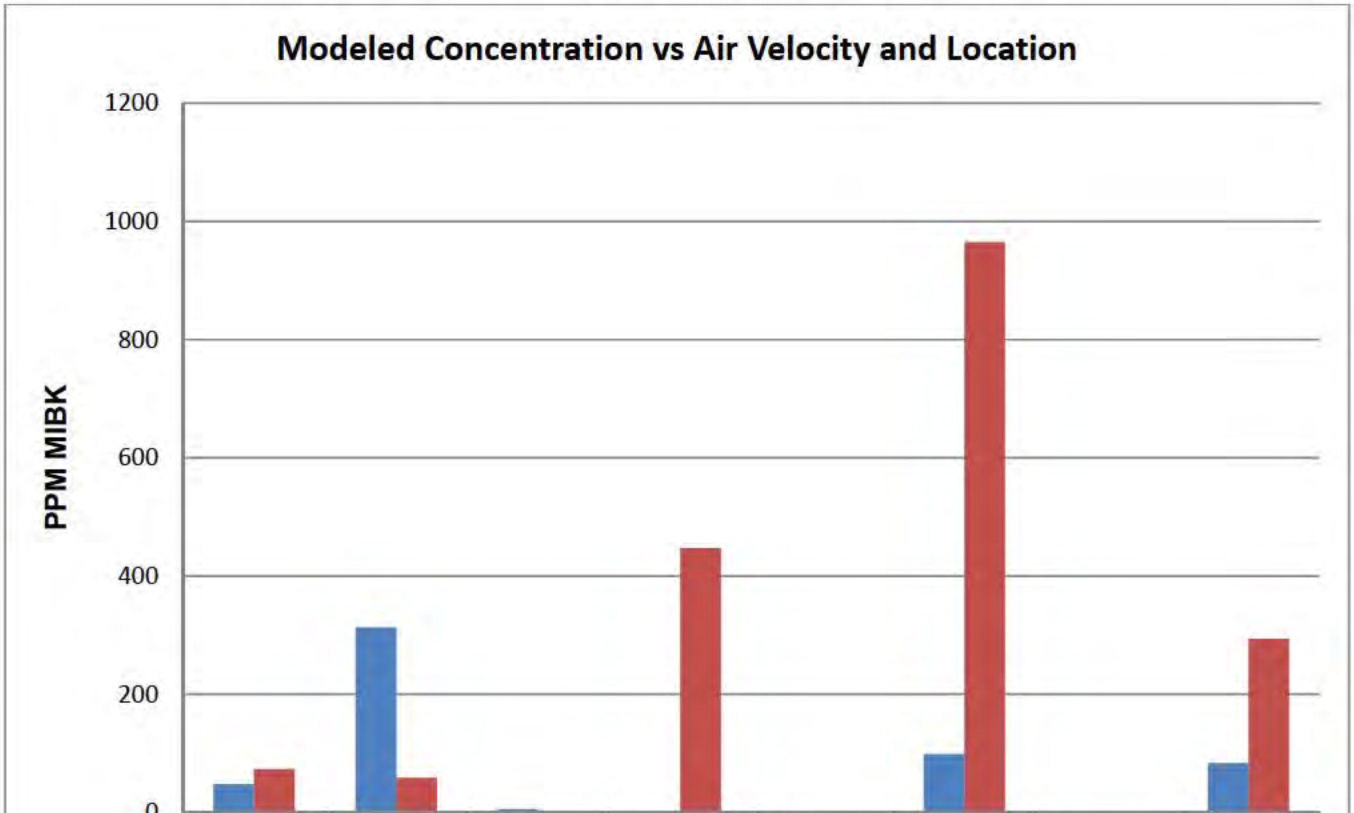
The inability of the exhaust to keep pace with the supply is due to the pressure drop across the exhaust wall filter bank. As the filters get loaded with overspray, the flow resistance increases, resulting in a decrease in overall flow and a channeling of exhaust flow through the cleaner areas of the filter wall, further reducing the ventilation effectiveness where concentrations are highest. The pressure observed during this flow measurement was 1.67 in. water gauge. The filter material is not replaced until the pressure drop reaches 2.5 in. water gauge. 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 simulated dispersion of 10µm MIBK droplets shown by Figure 19, 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.



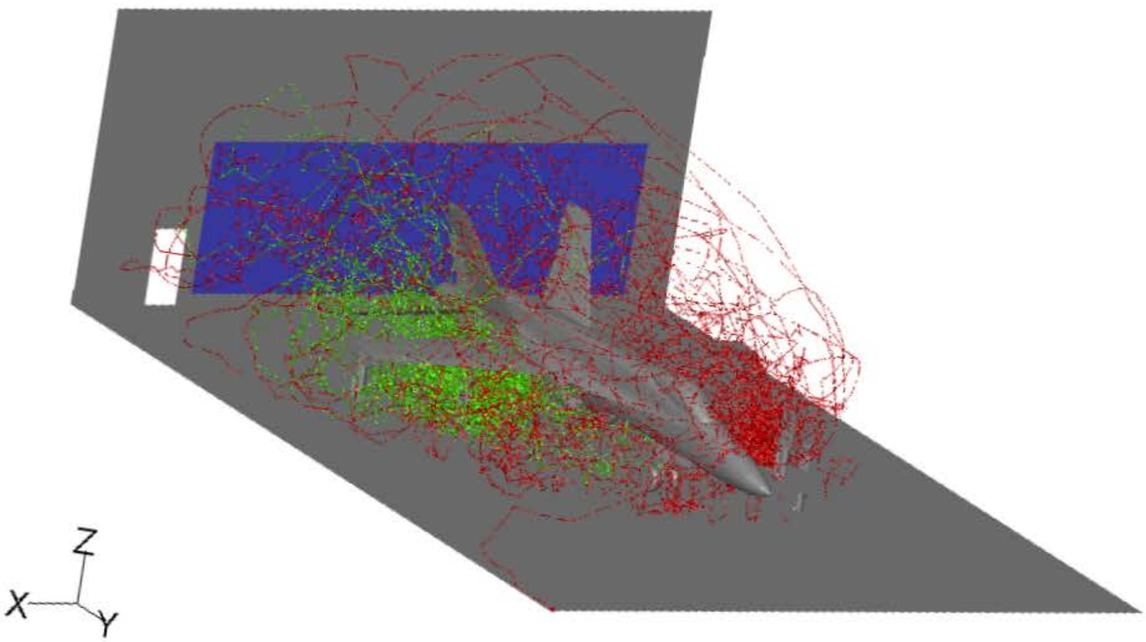
	BZ Height	Under Plane	Hoseman Port	Hoseman Starboard	Sprayer Port (scaffold)	Sprayer Starboard (wing)	Geometric Mean	Arithmetic Mean
43.3 FPM	133.7	702	264	413	1066	2833	746	1056
65 FPM	92.7	402	257	253	738	2212	532	772
86.6 FPM	79.3	401	168	251	857	2279	506	791
108 FPM	61	243	143	157	691	1902	372	627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

Figure 17: Concentrations of a gas with the properties of MIBK calculated using CFD, for various air velocities and observed worker locations.



	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 18: CFD results at 75 fpm and 100 fpm using the RNG k-ε turbulence model and a convergence criterion of 10-4 for the normalized residuals.



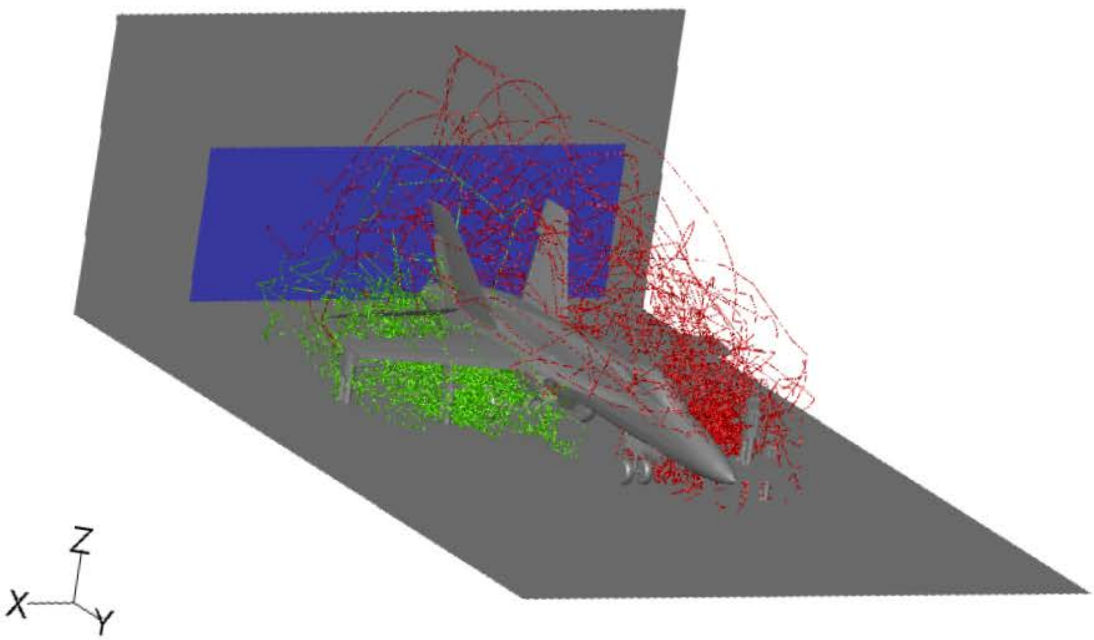
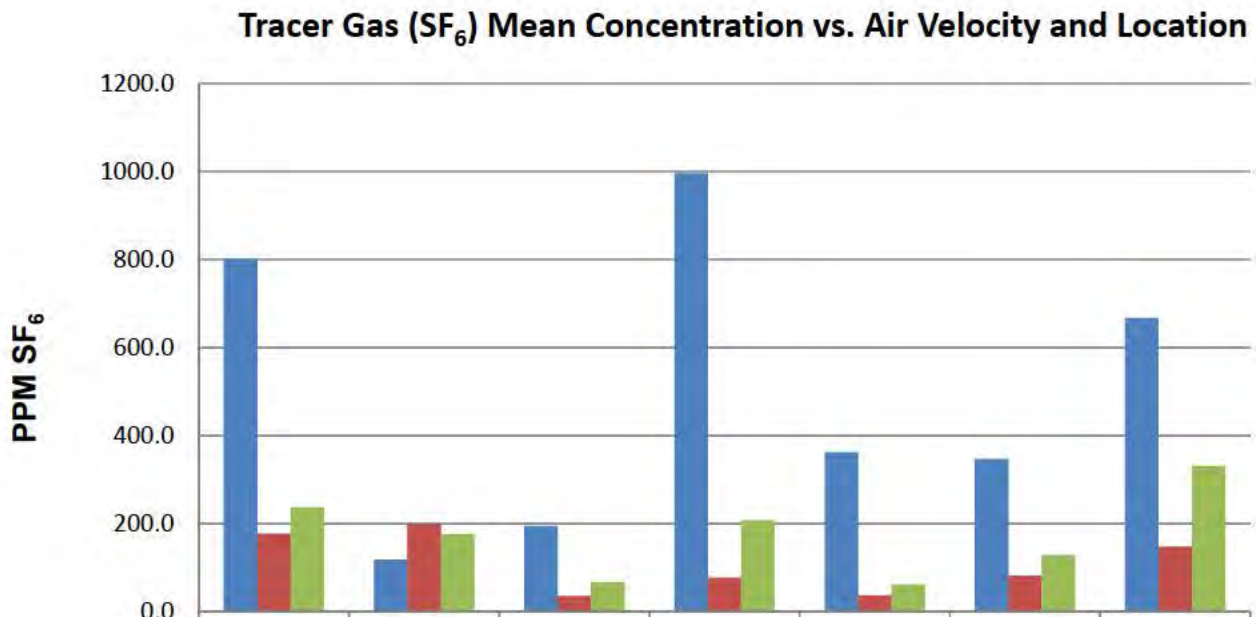


Figure 19: Particle tracks for the unbalanced 108 fpm supply – 65.0 fpm exhaust case (top image) and the balanced 65.0 fpm case (bottom image).

The 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 20 and Table 6.



	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 20: Time-averaged concentrations of SF6 by measurement location and ventilation system status. Values at the five locations are geometric means for trials of three source configurations.

Table 5: Tukey's Studentized Range (HSD) Test for Tracer Gas Log Mean Concentration.

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	

*** **Comparisons statistically significant at the p = 0.05 level**

Figure 21 shows the mean MIBK concentrations modeled using CFD alongside the tracer gas experiment concentrations, as means across the monitoring locations. To more clearly compare the predicted effects of adjusting the ventilation velocity, the data were normalized by dividing the CFD concentrations by the tracer gas concentration at full-flow. As only the first set of CFD simulations were based on the unbalanced conditions measured in the hangar, only these simulations were used in the comparison with the tracer experiments. CFD simulations and tracer experiments show a similar decrease in concentration when the flow was lowered from full- to 3/4-flow. In Figure 21, the tracer experiments indicated a large increase in normalized concentration (from 0.5 to 2.2 times larger than the full-flow concentration) when the flow rate was decreased further, from 3/4- to half-flow. In the CFD simulations, however, there appears to be no discernable difference between the spatial average concentrations at 3/4- and half-flows. Possible reasons for the discrepancy between methods will be given in the Discussion section.

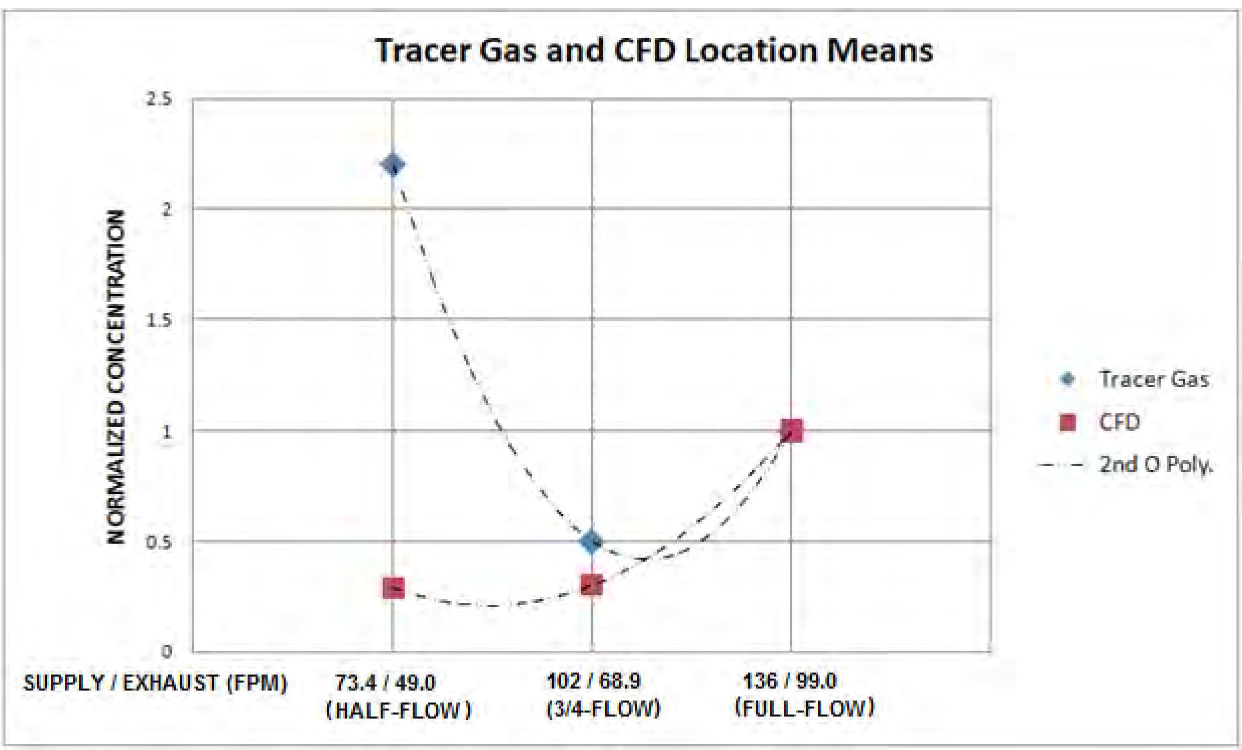


Figure 21: Five-Location-Mean Concentrations for CFD Simulations and Tracer Gas Experiment means as a Function of Flow Rate.

Another way to evaluate the effect of flow reduction is through pair-wise comparisons. In Figure 22, the tracer location means are shown in blue, along with their 95% error bars for the multiple comparison test (Tukey's studentized range HSD test). The plot shows that both CFD and tracer experiments seem to indicate higher concentrations for half- than for full-flows. Half-flow concentrations were statistically significantly higher than 3/4-flow concentrations. For the 3/4 vs. full comparison, CFD and tracer diverge in their prediction, with CFD showing 3/4-flow concentrations higher than full-flow concentrations and the tracer experiments showing 3/4-flow concentrations as lower than full-flow concentrations. The CFD prediction is within the 95% confidence limits for the measurements at all flow conditions shown.

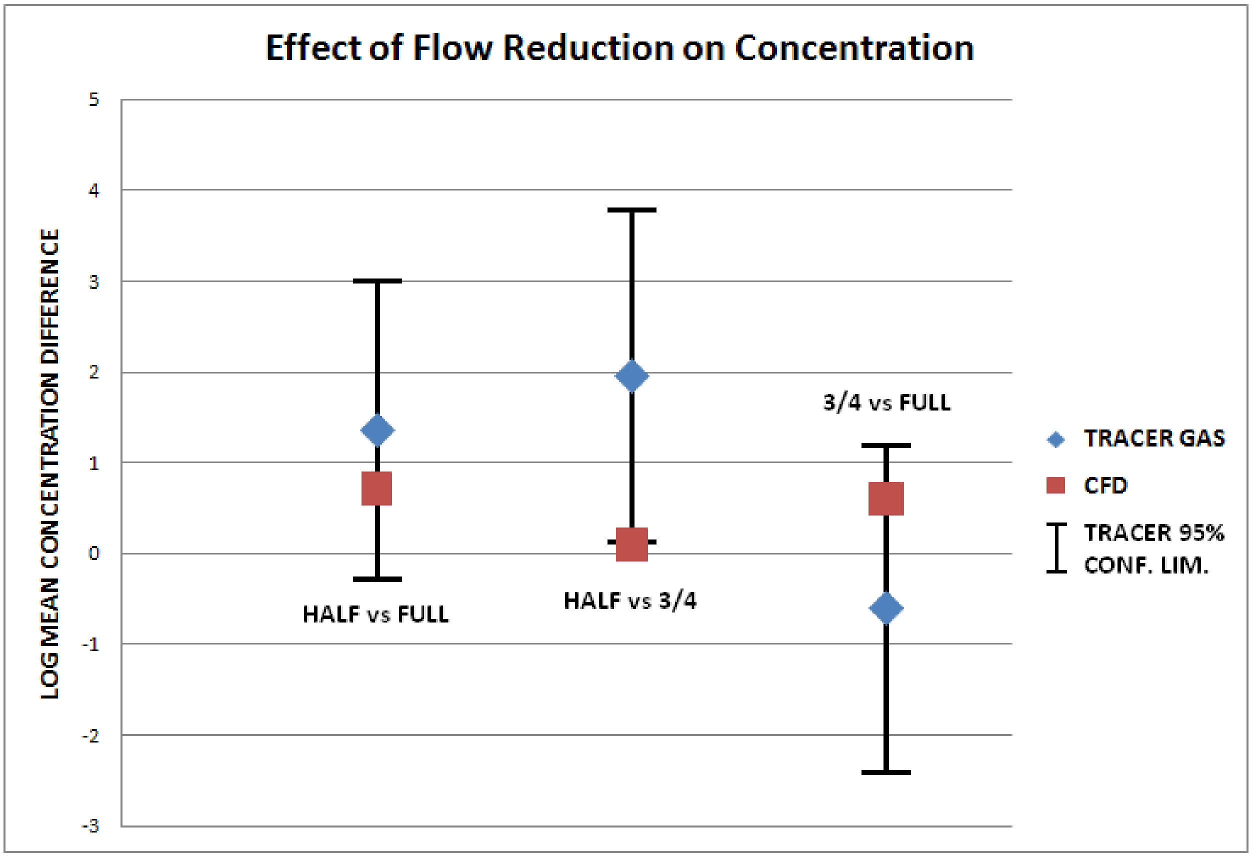


Figure 22: Flow rate comparison by CFD and tracer gas methods.

5.5.2 Marine Corps Air Station Cherry Point

Figures 23 and 24 display simulated contaminant plumes modeled using CFD, comparing the 75 fpm and 100 fpm flow rates. Figure 23 illustrates the far-field, low-concentration zone using colored iso-surfaces which indicate a contaminant mole fraction of 0.01. Yellow is for the contribution of sprayer #1, purple for sprayer #2, and green for sprayer #3. The size of the low-concentration plume decreases at the higher flow-rate. Figure 24 presents a similar comparison for the near-field, high-concentration zone using iso-surfaces of 0.03 mole fraction. There is no significant difference in the size of these high-concentration plumes between the two flow rates.

Figure 25 summarizes the iterative history of the breathing zone concentration scalar variable for each of the three sprayers at each of the three simulated flow rates of 50, 75, and 100 fpm. Each airflow condition was run for over approximately 35,000 iterations. The graphics in Figures 23 and 24 were generated at 5,000 iterations, where the three flow rates were indistinguishable. After that point in the solution process, the lower speed cases have the higher mole concentrations, before the solutions have become stationary-- when the values of the scalar variables are no longer trending. Figure 25 also shows that for locations #1 and #2, 75 and 100 fpm are indistinguishable after 22,000 iterations, while 50 fpm remains higher until 30,000. Finally, for a given simulated airflow, sprayer #3 experiences the highest concentration, while sprayer #2 experiences the lowest, and the additional air movement generated by 100 fpm helps in reducing the exposure of Sprayer #3.

Figure 26 illustrates the importance of taking the solution deep into iterative convergence, well after the residuals have been reduced to generally accepted convergence values, as the concentration field is obviously still changing. Concentration is a scalar quantity and can be thought of metaphorically as the tail wagged by the dog, in the sense that the flow field can be converged before its effect is fully expressed in the concentration field.

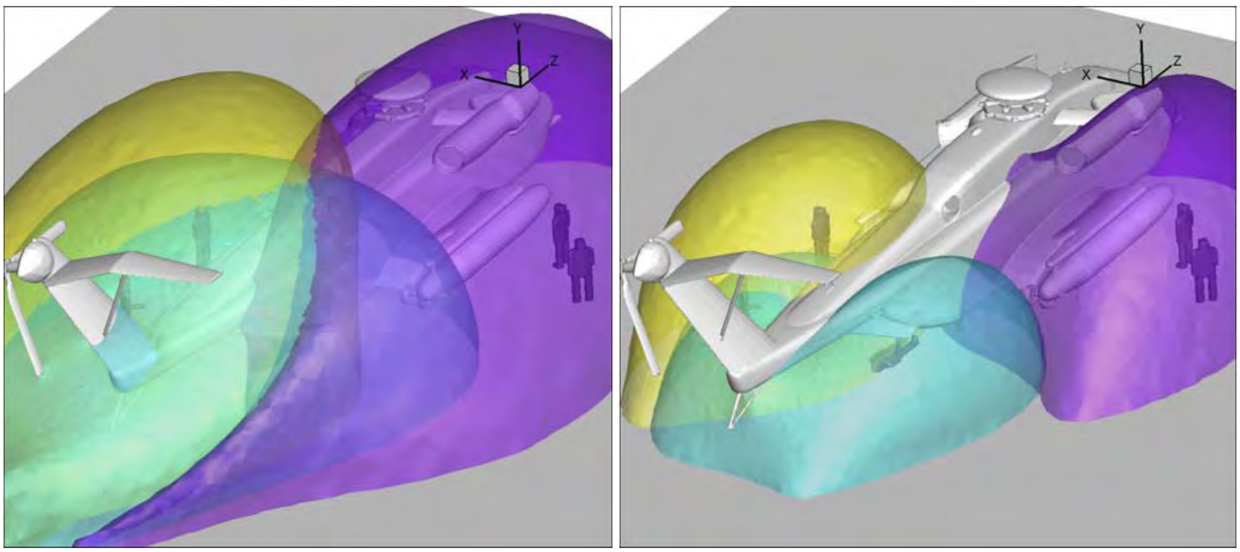


Figure 23: CFD iso-surface plots of the far-field, low-concentration zone at 75 fpm (left) and 100 fpm (right). The colored surfaces indicate a contaminant mole fraction of 0.01. A different color is used to represent the influence of each of the three spray teams. The 100 fpm flow rate appears slightly more effective at dispersing contaminants.

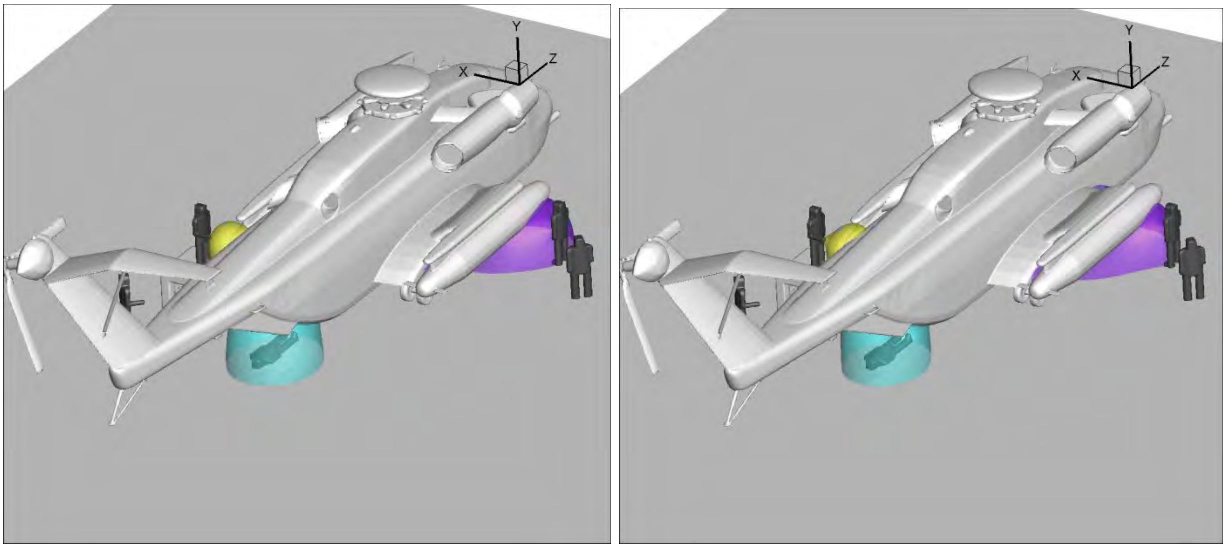


Figure 24: CFD iso-surface plots of the near-field, high-concentration zone at 75 fpm (left) and 100 fpm (right). The colored surfaces indicate a contaminant mole fraction of 0.03. Minimal difference is observed between the two flow rates.

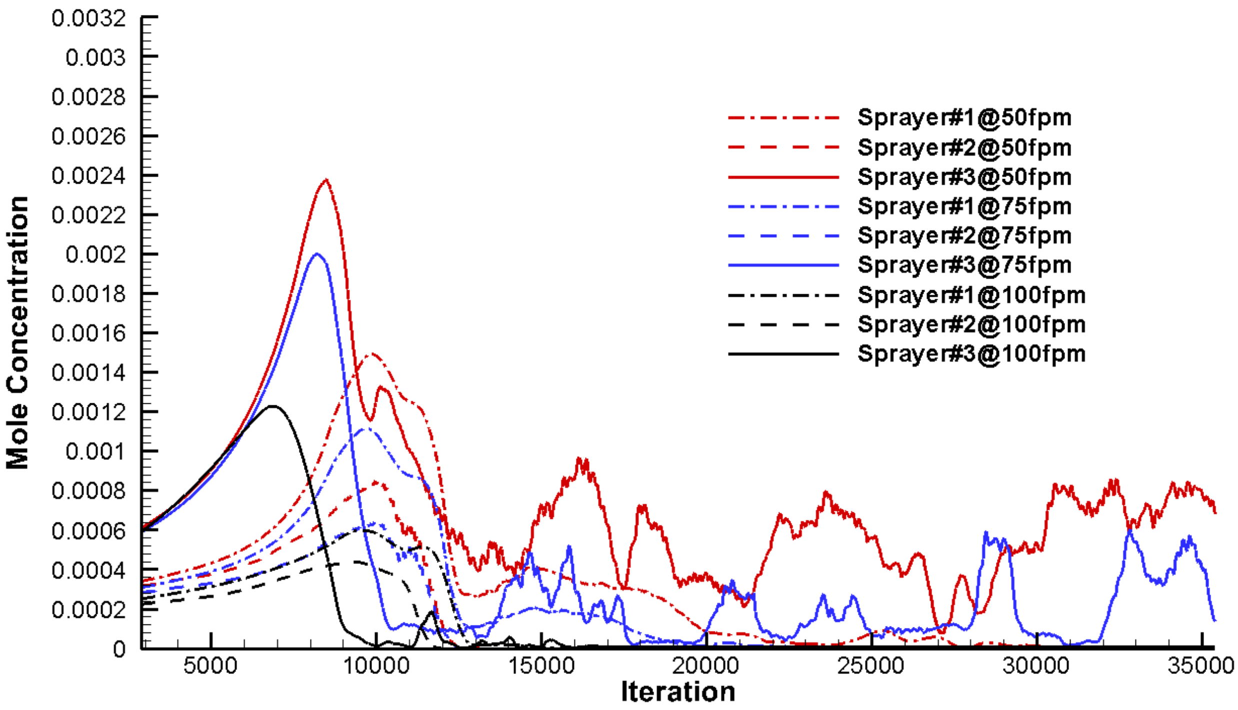


Figure 25: A graph of contaminant concentration vs. iteration of the CFD model for each of the three sprayers at each of the three simulated flow rates.

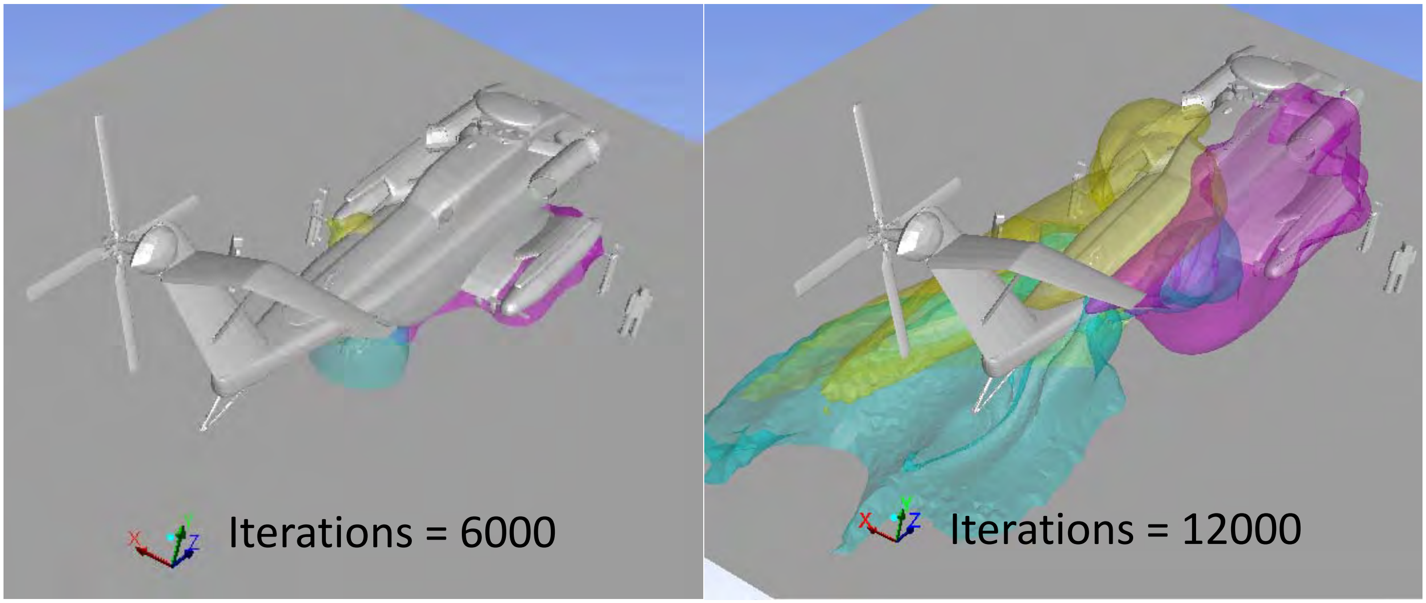


Figure 26: The importance of deep iterative convergence shown by the change in the shape of the 0.03 mole fraction iso-surfaces generated by each sprayer.

5.5.3 Sioux City Air National Guard Base

Only one site visit was made to the Sioux City Iowa Air National Guard Paint Facility, where F-15 and F-16 aircraft are painted. Along with basic hangar characterization observations, some preliminary airflow measurements were collected. In the Bay 3 paint hangar, average velocities across the faces of the supply and exhaust filters were observed to be 161 and 191 fpm, respectively. Velocities elsewhere inside the bay ranged from 77 to 97 fpm. In the Bay 5 hangar, airflow was not as strong, with average velocities of 112 fpm across the supply filters and 78 fpm across the exhaust filters. At various locations within the working space of the bay, velocities ranged from 55 to 83 fpm. Although no further investigation of the site has been conducted at this time, it was considered a good candidate for inclusion in the study, as an example of strike fighter aircraft painting ventilation.

5.5.4 Joint Base Lewis-McChord

5.5.4.1 McChord AFB C-17 Painting Hangar

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

Figures 27 through 30 summarize the results of the air flow measurements as contour plots of air velocity magnitude. Note that in these figures, the shape of the nose end of the hangar and the velocity into the exhaust hoods are not shown accurately, and contour lines extending through the airframe should be taken as an artifact of the plotting software. Likewise, velocities far away from the aircraft are also not portrayed accurately because no data was gathered at points more than 20 feet away from the aircraft. These distant velocity values are merely extrapolations of the field of data points closer to the plane.

Figure 27 represents the velocity magnitudes measured on day 1 at the breathing zone height when working on the leading and trailing edges of the wings, which is about 17 feet above the floor. The technical sergeants who manage the hangar indicated that these areas were among those most often painted. Figure 28 shows the air velocity magnitude on day 1 measured at typical working heights for the upper surfaces of the C-17, i.e. the tops of the wings, fuselage, and tail section. Like the artisans would when painting, the researchers used man-lifts to access these sections. Both Figures 27 and 28 indicate, on average, air flow significantly lower than the 100 fpm benchmark. There also appears to be more air movement on the starboard side of the aircraft, as expected given that the inoperative air handlers 4 and 5 deliver air focused on the port side of the aircraft.

Figure 29 is similar to the plot in Figure 27 except that it is constructed from data gathered on day 2 of the site visit, when all air handlers were functioning properly. This is reflected in the higher and more uniform velocities observed, with greater symmetry of velocity contours on either side of the plane. Unfortunately, due to travel constraints, the time-consuming measurements of the upper surface air flows using man-lifts were not repeated on day 2. Therefore, Figure 30, rather than showing actual day 2 data for the upper surfaces, shows the day 1 upper surface contour data (Figure 28) after applying a correction factor derived from the difference between the day 1 and day 2 lower-level wing section measurements (Figures 27 and 29). As a result, Figure 30 does not reflect true velocities, but still gives insight into what velocities might be expected above the aircraft on average. Note that the day 2 measurements seem to indicate that the 100 fpm benchmark is successfully reached or exceeded, on average, at most locations around the aircraft.

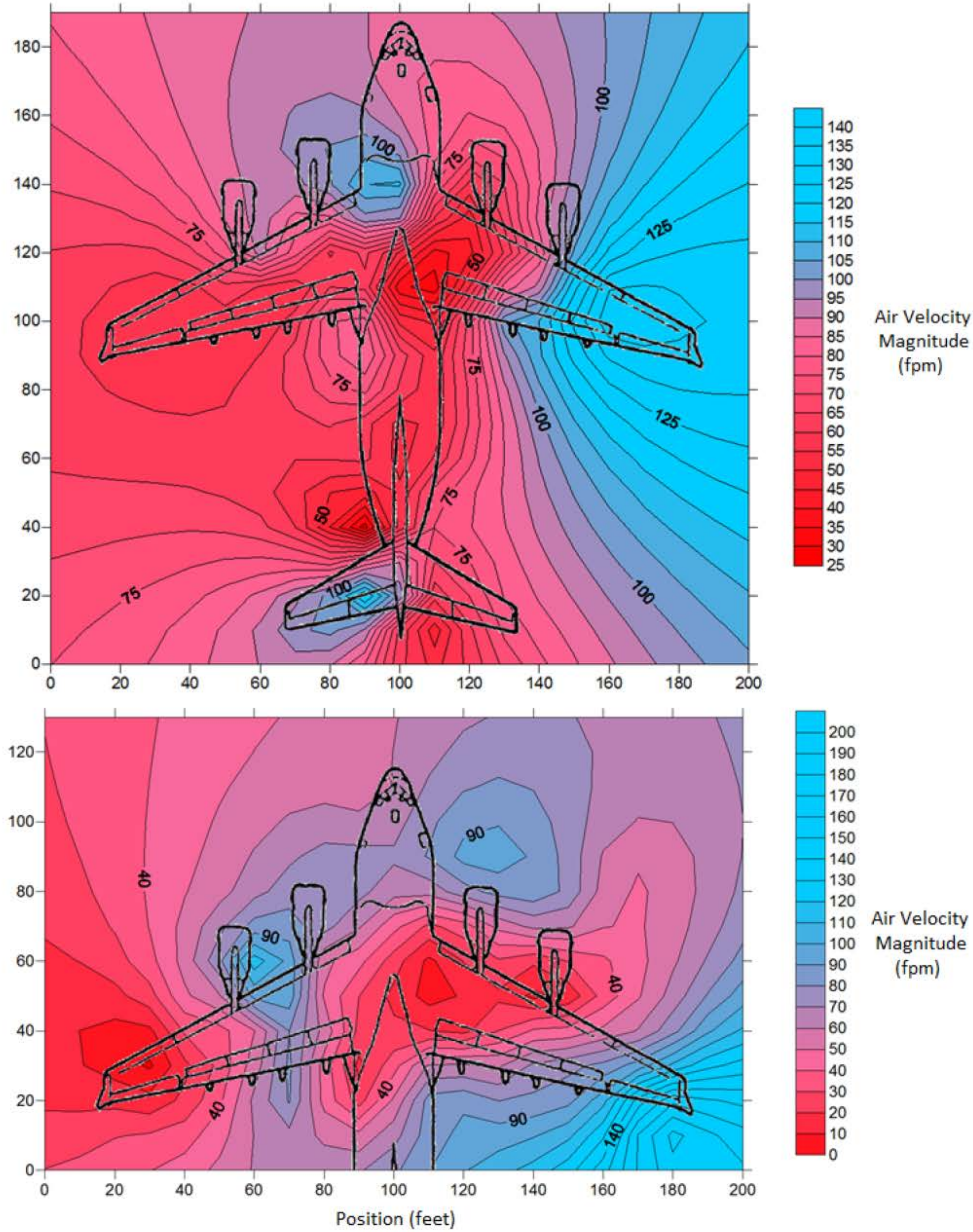


Figure 27: Day 1 contours of velocity magnitude at working height along the upper side of the aircraft, with air handler units 4 and 5 off.

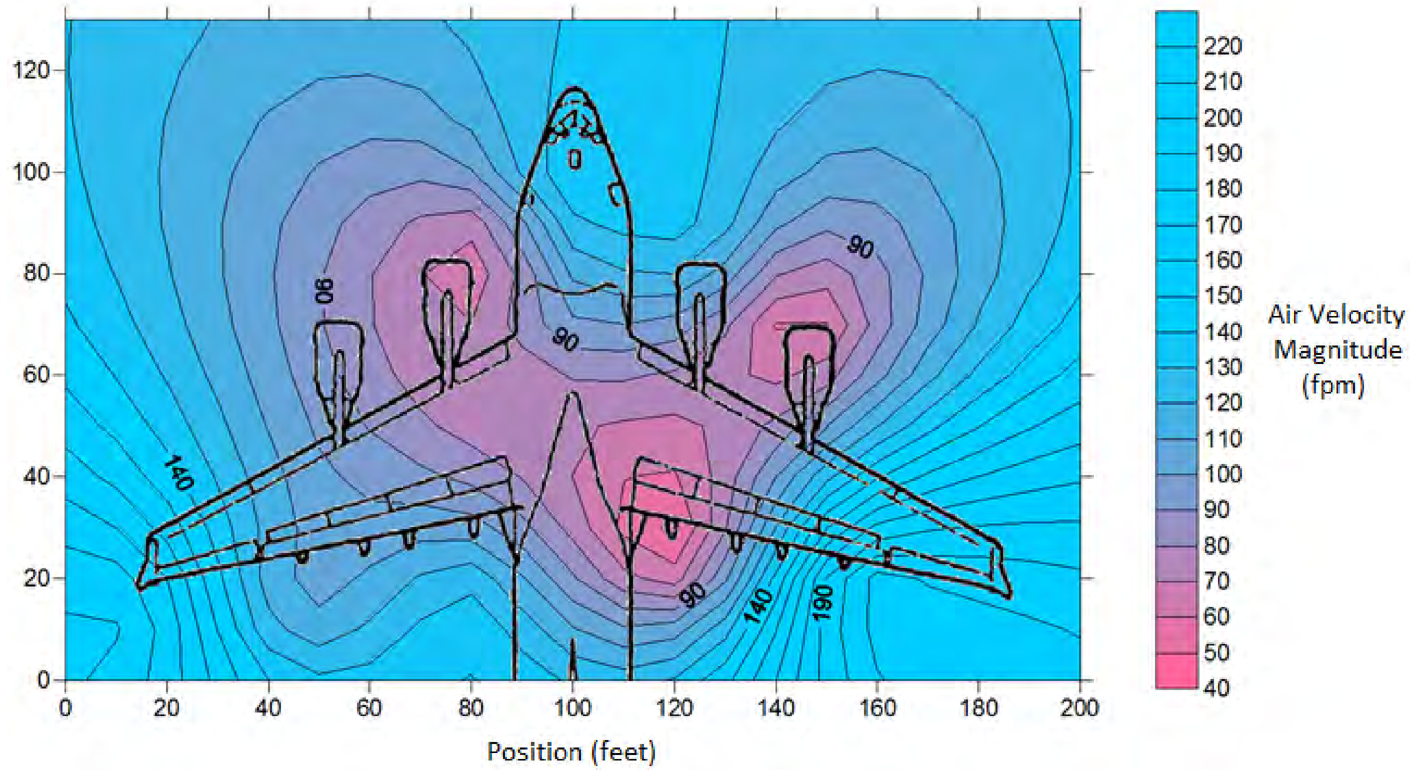


Figure 28: Day 2 contours of velocity magnitude along wing edges at working height, with all air handlers operating normally.

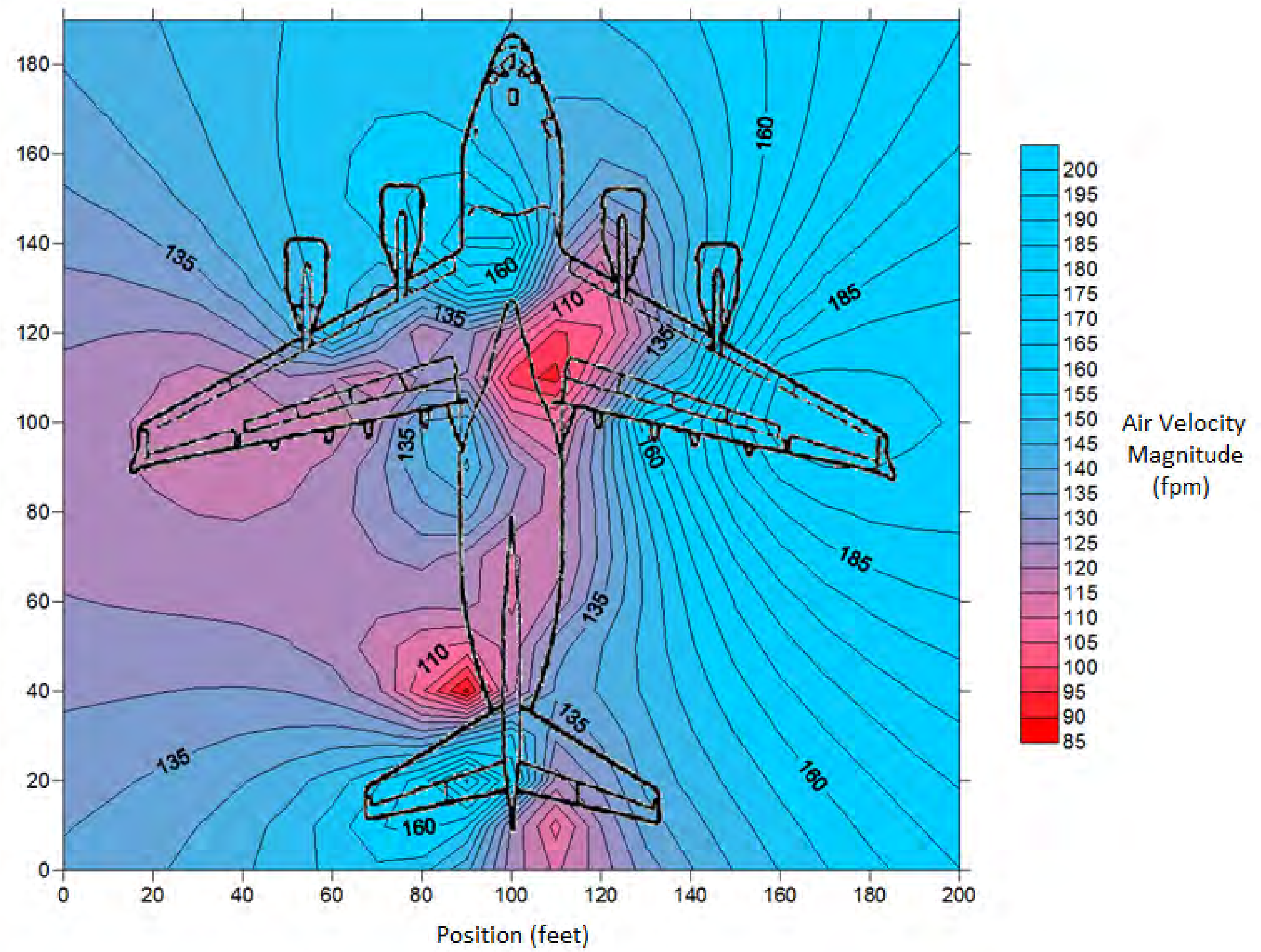


Figure 29: Contours of velocity magnitude at working height along the upper side of the aircraft, with values at full ventilation estimated from the measurements that were made with units 4 and 5 down.

5.5.4.2 Fort Lewis Helicopter Painting Facility

Some preliminary airflow measurements were obtained during the site visit to this location. Average velocity at the faces of the two supply filter columns was 201, with a range of 0 to 399 fpm. The higher values were measured at the lower half of the floor-to-ceiling columns, nearer to where the supply ducts connect to the column plenums. At the exhaust filter faces, average velocity was 182 and ranged from 23 to 295 fpm. Additional measurements were taken at various heights in the mid-plane of the hangar, halfway between the supply and exhaust filters. Average air velocity along this mid-plane was 93 fpm, and the range was 34 – 259 fpm, with higher velocities observed at ground level (160 fpm average) and breathing zone height (126 fpm average at 5 foot height), while lower velocities were seen near the ceiling (56 fpm average, at 18 foot height). Despite these velocity gradients, the smoke test performed by Army Industrial Hygienist Robert Anderson showed good directional flow through the work area from supply to exhaust.

All total particulate and hexavalent chromium samples for primer coating were collected on pre-weighed PVC cassettes and analyzed by NIOSH Methods 0500 and 7605, respectively [NIOSH 1994b,1994c] or OSHA Method 215. The initial F-18 painting samples were analyzed using treated glass fiber filters with NIOSH method 5525, while the post-modification painting samples were analyzed using this method and also treated glass fiber filters with OSHA methods 18 and 42, the ASSET tube with ISO 17734-1:2013, and impingers with NIOSH method 5525

Table 6 provides a comparison of real exposure data for paint finishing operations on three aircraft and two airflow velocities, although the matrix is not complete. Only for the F-18 are two velocities tested for the same aircraft design. The shading in the table illustrates four outcomes of the comparison.

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

The interpretation of these outcomes is not strictly statistical, because only one replicate for the F-18 lower velocity sampling was available, due to the termination of the project. Exposure was interpreted as higher (orange) or lower (blue) if the single value was higher or lower, respectively, than the range of the baseline data, i.e. outside the range. If the single value was within the baseline range, the finding was not conclusive but the comparison outcome was still noted as higher (yellow) or lower (green). Looking at the table, a reasonable interpretation of the data, overall, is that airflow of 80.0 fpm is not less protective than airflow of 104 fpm. There are specific contaminants and worker positions where one velocity is more protective than the other, according to this data. The bigger picture seems to be that velocity in this range does not make much of a difference. A rigorous statistical test for differences based on airflow velocity is unlikely to detect differences that are statistically significant, because of the very small sample size. To rely on such a test, then, might bias the interpretation toward the “velocity makes no difference” position. Instead, reporting the outcomes as was done here is a best effort at drawing objective conclusions with limited data

Table 6: Comparison of Air Sampling Results.

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
Mid-Hangar	Mean Velocity (fpm)	104	20	81.1	8	81.1*	8	80.0	8
	Paint Quantity (gal)	13	1	16	1	18	1	7/13	1
	Paint Formula HDI-NCO/olig (%)	0.143/9.97	1	0.022/4.53	1	0.016/5.16	1	0.043/9.27	1
Sprayer mean/geo-mean [range]	ASSET (µg/m3) HDI Monomer			11.4/11.0 [7.32, 14.2]	3	5.44/5.43 [5.15, 5.74]	2	10.6	1
	Monomer-NCO			5.65/5.41 [3.54, 7.12]	3	2.71/2.70 [2.55, 2.87]	2	5.40	1
	Oligomer-NCO			712/638 [329, 1062]	3	423/419 [362, 484]	2	1115	1
	NIOSH (µg/m3) HDI Monomer	33.1/32.2 [25.0, 49.6]	6	11.3/10.5 [6.06, 14.2]	3	7.31/7.25 [6.37, 8.26]	2	30.9	1
	Monomer-NCO	16.5/16.1 [12.5, 24.8]	6	5.61/5.24 [3.03, 7.06]	3	3.65/3.62 [3.18, 4.13]	2	15.4	1
	Oligomer-NCO	279/259 [178, 484]	6	191/169 [78.6, 265]	3	242/242 [240, 245]	2	725	1
	OSHA (µg/m3) HDI Monomer					<2.8/<2.8 [<2.7, <2.9]	2	<3.9	1

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
	Oligomer-NCO					245/245 [240, 250]	2	97.4	1
	Total particulate (mg/m3) NIOSH	20/18 [7.0, 26]	6					14.1	1
	Hexavalent chromium (µg/m3) NIOSH	530/500 [220, 650]	6					364	1
	Hexavalent chromium OSHA							30.7	1
Hoseman mean/geo-mean [range]	ASSET (µg/m3) HDI Monomer			5.18/4.86 [3.39, 6.97]	2			7.09	1
	Monomer-NCO			2.51/2.36 [1.67, 3.36]	2			3.50	1
	Oligomer-NCO			307/284 [191, 422]	2			593	1
	NIOSH (µg/m3) HDI Monomer	6.19/3.99 [<0.7, 11.3]	6	3.88/3.62 [2.49, 5.27]	2			19.6	1
	Monomer-NCO	3.10/2.06 [<0.4, 5.62]	6	1.93/1.81 [1.24, 2.63]	2			9.79	1
	Oligomer-NCO	81.7/42.7 [<3, 153]	6	61.5/54.9 [33.8, 89.2]	2			673	1

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
	OSHA (µg/m3) HDI Monomer							<3.4	1
	Oligomer-NCO							<42.2	1
	Total Particulate (mg/m3) NIOSH	5.2/4.3 [1.4, 10]	6					5.9	1
	Hexavalent chromium (µg/m3) NIOSH	150/120 [37, 300]	6					172	1
	Hexavalent chromium OSHA							9.48	1
Downstream mean/geo-mean [range]	NIOSH (µg/m3) HDI Monomer	6.09/4.98 [2.59, 14.2]	6	8.72/5.49 [<1.3, 15.5]	3			11.6†	1
	Monomer-NCO	3.05/2.49 [1.29, 7.11]	6	4.36/2.75 [<0.65, 7.75]	3			5.80†	1
	Oligomer-NCO	89.0/79.3 [36.5, 147]	6	95.9/34.2 [4.68, 249]	3			4.43†	1
	NIOSH impinger (µg/m3) HDI Monomer	11.1/11.1 [11.0, 11.2]	2	6.27/2.95 [1.00, 16.2]	3				

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
	Monomer-NCO	5.54/5.53 [5.49, 5.58]	2	3.16/1.48 [0.501, 8.18]	3				
	Oligomer-NCO	140.5/140.5 [139, 142]	2	26.5/23.6 [14.8, 44.7]	3				
	OSHA (µg/m3) HDI Monomer			<1.9 [<1.9, <1.9]	3			<3.3	1
	Oligomer-NCO			30.4/27.4** [<23.8, 50.0]	3			133***	1
	ASSET (µg/m3) HDI Monomer			8.49/3.63 [0.961, 22.3]	3			12.4	1
	Monomer-NCO			4.16/1.79 [0.475, 10.9]	3			6.03	1
	Oligomer-NCO			546/195 [42.2, 1475]	3			1778	1
	Total particulate (mg/m3) NIOSH	4.0/2.8 [,0.7, 11]	6					10.1***	1
	Hexavalent chromium (µg/m3) NIOSH	125/83.9 [13.0, 340]	6					252***	1

Sample Location	Aircraft	F-18 Painting Bay 6 (Initial Survey)	N	E-2 Painting Bays 7-8 (Post-mod)	N	C-2 Painting Bays 7-8 (Post-mod)	N	F-18 Painting Bay 2 (Post-mod)	N
	Hexavalent chromium OSHA							73.5	1

*Assumed to be the same as the velocity during E-2 painting, as the C-2 was painted in the same bay, although one month later.
**Values below the LOQ were divided by √2 for calculation of means.
***The area sampler was placed between the tail section and exhaust—the worst case location—whereas previous area samples included two locations downstream of the wing ends, where less painting occurs.

6.0 PERFORMANCE ASSESSMENT

Because this ESTCP project ended prematurely, the performance objectives could not be assessed. The results and findings from the site visits are listed per site below.

6.1 Naval Base Coronado

The tracer gas experiments and CFD results agreed well for 3/4-flow, but diverged at half-flow (See Figure 21). Because CFD simulations that involve the Reynolds-averaged-Navier-Stokes (RANS) equations in the treatment of turbulence tend to be less accurate at lower Reynolds numbers, the CFD results for half-flow should be given less weight than the tracer results. Thus, the CFD result of half-flow being as effective as 3/4-flow should be treated with some circumspection.

Considering both the CFD and tracer experiments, it can be said that the full-flow condition was not more protective than the 3/4-flow condition, as shown in Figures 20 and 21. The 3/4-flow condition can be summarized as producing velocities in the hangar volume that are bracketed by the normalized velocities at the filters, thus a range of 68.9 to 102 fpm, and similarly for full-flow: 99.0 to 136 fpm. The mid-bay velocity averages, for 3/4-flow and full-flow, were 73.6 and 104 fpm, respectively.

The results of the simulation generally show the limitations of controlling exposure through ventilation alone. If we look at a horizontal slice through the hangar at typical breathing zone height, the relationship of concentration and ventilation rate follows the intuitive idea that more air is better. Figure 19 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.

Perhaps the more important locations to consider are those where the aircraft painters were commonly observed working or where conditions seemed to represent a worst case. 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 2,212 ppm at 65.0 fpm, but 2,279 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. Balanced 65.0 fpm was the second most effective velocity at the highest exposure locations, the sprayers.

The CFD results in Figure 19 (RNG k-ε turbulence model and convergence criterion of 10^{-4}) are quite different than those in Figure 15 (standard k-ε turbulence model and convergence criterion of 10^{-3}). The concentrations in Figure 16 are generally lower than those in Figure 18. A reasonable interpretation is that the model with the lower error tolerance (Figure 19) resolved the steep, near-source concentration gradients more precisely, with less numerical diffusion. In Figure 18, 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 18 or Figure 19) best represents real contaminant transport during the refinishing process is difficult to say, definitively. While the results in Figure 19 are more accurate from a numerical point of view, the concentration variability as a function of location and velocity is larger than what intuition would suggest. There are mixing processes (which reduce concentration variability) in a real work environment, such as a worker's motion while spraying, that were not captured here. It is possible that the increased numerical diffusion from the k-ε model (shown in Figure 18) may better represent real mixing processes to some degree.

6.1.1 Follow-Up Survey

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

Air samples gathered during the follow-up survey showed an 85.8% decrease in HDI monomer concentration and a 32.5% increase in oligomer concentration compared to the measurements gathered during the initial survey. It is difficult to determine whether this is a meaningful result because significantly different conditions were present between the two surveys. The surveys were conducted in different bays (Bay 6 versus combined Bays 7 and 8), during the painting of different aircraft (F-18 versus E-2), and used different quantities of paint. The samples were also analyzed using different methods. Therefore, the change in contaminant concentrations cannot be conclusively attributed solely to the modified ventilation systems, but rather may also be a result of differences in other painting conditions or sampling methods. The air sampling results, therefore, are inconclusive and give no definitive answer as to whether or not the ventilation modifications significantly affected contaminant concentration.

6.2 Marine Corps Air Station Cherry Point

A comparison of the modeled concentrations at the breathing zones of individual sprayers reveal that the sprayer located underneath the aircraft, at position #3, received the highest exposures in all cases (see Figures 23-25 and Table 6). The airframe obstructs the flow, resulting in lower velocities in the space between the fuselage and floor. Whereas intuition might predict an acceleration of the flow through this gap, what seems to happen instead is the aircraft is "seen" as a large obstruction and “avoided” by the streamlines. The situation might be improved by focusing additional ventilation under the aircraft, perhaps using local exhaust through flexible ducts or a fan driving flow under the airframe toward the main exhaust. Like the H-53 rotary wing aircraft here, for the F-18 strike fighter aircraft painted at Naval Base Coronado the concentrations were also highest under the fuselage.

CFD results suggest that a velocity of 100 fpm is not more effective than 75 fpm at controlling contaminant and preventing cross-contamination of workers at positions #1 and #2, in the hangar (Figure 23). Also, increasing the flow rate from 75 to 100 fpm makes no significant difference in the size of the near-field high-concentration contaminant zone near the sprayers, where protection is most important (Figure 24). This suggests that a reduction in delivered air flow might be possible without compromising worker health and safety. Additional on-site tracer gas and exposure monitoring tests are recommended to investigate this possibility further and confirm these findings.

6.3 Sioux City Air National Guard Base

Significantly higher air flow velocities were observed in the Bay 3 painting hangar compared to the Bay 5 painting hangar. Bay 3 average velocities at the filter face were 161 fpm for the supply and 191 fpm for the exhaust, compared to only 112 fpm supply and 78 fpm exhaust in Bay 5. Measurements at each bay midpoint reflected this difference: Bay 3 ranged from 77 to 97 fpm, whereas Bay 5 ranged from 55 to 83 fpm. Some particularly low velocities at the exhaust filter in Bay 5 corresponded to paint-coated areas directly downstream from more active work areas. Bay 3 is already within the acceptable range, and with some minor adjustments and filter maintenance, it is likely that airflow in Bay 5 could be increased to operate near the 100 fpm benchmark. The results of these preliminary measurements, combined with the configuration of the two hangars that is fairly representative of the normal design of the majority of DoD ACCPFF, suggest that the two Sioux City Air National Guard painting hangars are good candidates for continuing future investigations.

6.4 Joint Base Lewis-Mc-Chord

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

7.0 CONCLUSIONS, RECOMMENDATIONS, FUTURE STUDIES

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

7.1 Conclusions

- Reduction in delivered airflow from 100 fpm to 75 fpm may not increase contaminant exposure.
- By reducing airflow:
  - Electricity consumption is reduced
  - Greenhouse gas emissions are reduced
- Ventilation rate within 75 to 100 fpm does not significantly influence contaminant exposure in crossflow ACCPFF.
- Ventilation configuration and facility design are significant exposure variables, based on observed flow patterns.
- Ventilation system maintenance was an issue in all facilities visited.
  - Some individual fans were down when the system controls were set to full on at most facilities.
  - Exhaust filter overloading and supply filter disrepair were common.
  - Pressure imbalances greater than 0.05 in. w.g. were measured during many of the site visits.

7.2 Recommendations

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

- The results of this project indicate that a modest decrease in linear air velocity from approximately 100 fpm to the range 75 to 80 fpm is a viable method of maintaining occupational health and safety, while reducing energy costs and carbon emissions associated with ACCPFF. The observations below support this position.
  - Computational fluid dynamics studies of an F-18 and H-53 in separate hangars and tracer studies of the F-18 facility have shown that exposures resulting from 75 fpm and from 100 fpm are generally indistinguishable, while each are clearly lower than from 50 fpm.

        - For spaces that are largely obstructed, such as underneath the fuselage, a main flow velocity of 100 fpm may provide more air movement through these spaces (although this movement will be less than 100 fpm).
        - Because these spaces are not well ventilated by the bulk airflow through the hangar and have the highest exposures, it may be more effective to provide local exhaust via a flexible duct (elephant trunk) or to impel the air toward the exhaust using a stand-alone fan.
    - Depending on factors such as ventilation configuration and hangar geometry, higher air velocity may generate turbulent flow patterns that can disperse contaminants into the breathing zone rather than move them directly to the exhaust.
    - Personal exposure monitoring of paint finishing artisans at 104 and 80 fpm has not shown a general increase in exposure for the lower velocity.
        - Exposures for the higher exposed group, sprayers, were lower for the lower velocity.
        - Exposures for the lower exposed group, helpers or hose men, were higher for the lower velocity.
        - Protecting the higher exposure group can be reasonably considered the priority.
        - Significant variability in the results across various sampling methods has shown the importance of using identical media and analytical techniques, when investigating the effect of velocity on concentration.
- Maintaining a balance between supply and exhaust flow rate is important for effective transport of contaminants away from work areas and toward the exhaust.
    - Imbalanced supply and exhaust amounts to excess energy usage, because the degree to which one side of the system outpaces the other adds no contaminant removal benefit. Furthermore, an imbalance reduces ventilation effectiveness by causing (with too much supply) large circulations and additional turbulence in the flow or (with too much exhaust) infiltration of flows near the exhaust that short-circuit the normal flow through the work area.
    - If supply rate exceeds the exhaust rate significantly, exposure control and air pollution permit compliance will be improved by balancing the supply and exhaust. A slight excess of exhaust is preferred to maintain negative hangar pressure, perhaps -0.05 in. water gauge, to prevent fugitive emissions to the environment.
    - If there is an exhaust deficit, a practical way to balance the system may include replacing exhaust pre-layers more frequently and keeping all exhaust filters at the lower end of the maintenance life, i.e. filter pressure drop. The exhaust velocity and the overall airflow patterns that were intended by design cannot be achieved when exhaust filters are blocked by the accumulation of paint droplets. Flow blockage also results in increased energy costs as the exhaust fan RPM must increase to deliver the required flow across a larger pressure drop.
        - In speaking with the managers at the study sites, a common frustration was the electric bill, and the filter maintenance costs are handled by separate administrative entities. As a result, filters are often not replaced when needed, which can create inefficient system operation.

    - In future designs, careful matching of supply blower and exhaust fan sizing or linked control, perhaps through variable frequency drives, are system balancing techniques that are worth considering.
- While it is recognized that not all configurations are practical for all facilities and aircraft, the following is a ranking of configurations, from most to least effective for exposure control:
    - Directional flow from nose to tail, created by floor-to-ceiling and wall-to-wall plenums, especially important for the supply.
        - Design deviations are acceptable if flow reversals do not occur in the active work area.
    - Directional flow across the airframe, from one side to the other.
        - While the aircraft profile presents a large flow obstruction, the most important feature of effective ventilation is bulk air moving toward the exhaust in an organized manner, without reversals and with a minimum of turbulence.
    - Hybrid of ceiling supply and exhaust near nose and leading edge of wings seemed to work reasonable well for very large aircraft. Switching supply and exhaust in this configuration seems reasonable as well.
    - Directional flow from ceiling to floor or floor to ceiling
        - This configuration is difficult to implement, without resorting to a number of individual air terminal devices—diffusers and intakes—that are generally unable to create uniform directional flow.
        - If the air terminal devices are located near or arrayed in the pattern of the airframe—a design perhaps conceived with the mistaken concept that air in a free volume will move in a straight line— the situation may be improved by introducing curtains and partitions that channel the flow through the work area.
    - The situation that must be avoided is mixing ventilation, which is characterized by circulations, airflow reversals, wide velocity variability, and long contaminant residence times.
        - A common scenario that creates mixing occurs when a large space is served by only a small number of air terminal devices. When supply jets are too far apart, their plumes do not merge into a single bulk of air, and flow reversals are set up between the plumes.
    - Individual exhaust terminals (as compared to a large plenum filter) are very limited in their range of capture, because they draw air in from all open directions. The ventilation system should be designed and maintained to encourage flow through the hangar as if it were a very large rectangular duct.
- Any changes in ventilation operation should include provisions to prevent possible safety hazards (e.g. doors blowing open or closed) created by changes in hangar pressure.
- An airborne exposure assessment should be performed again after any process changes to further verify worker protection.
- A letter of interpretation from OSHA, regarding operating at a modestly reduced flow in the range discussed in this study, should be obtained before ACCPFF ventilation policy is modified.

7.3 Potential Future Studies

- In addition to modeling existing paint finishing hangar ventilation systems, there remains room for continued exploration of innovative design using CFD. Reducing the hangar cross-sectional area to more closely fit each aircraft size and maintain a desired velocity at a lower volumetric flow rate, directing supplying air to the work zones more precisely, and bringing exhaust terminals closer to contaminant sources are examples of possible paths to consider that may reduce worker exposures, while also reducing associated energy costs.
- Real process exposure monitoring at different ventilation velocities was performed during paint refinishing of an F-18 strike fighter aircraft. Similar monitoring of a rotary wing and a larger fixed wing airframe would be logical next steps in the validation of reduced flow. Such direct evidence, if favorable, should reasonably mitigate the implementation risk of any remaining skepticism among industrial hygienists, in light of the analyses presented in this report.
- The original protocol included obtaining a letter of interpretation from OSHA, based on the complete study dataset. As this did not occur prior to cancellation, the regulatory situation still requires clarification.

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