In-Depth Survey Report

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

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

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Abstract

Since 2008, researchers from the Centers for Disease Control and Prevention/National Institute for Occupational Safety and Health (CDC/NIOSH) have been collaborating with Naval Facilities Engineering Service Center (NAVFAC ESC) engineers and Navy Medical Center San Diego (NMCSD) industrial hygienists to evaluate ventilation in a Navy aircraft painting hangar. The Navy seeks to keep worker exposures to air contaminants, including hexavalent chromium (CrVI), hexamethylene diisocyanate (HDI), methyl isobutyl ketone (MIBK), and others, at levels that meet regulatory health and safety standards, while limiting the environmental footprint, i.e. energy use, and operational costs of painting hangar ventilation. All project work, including the present study, refers to Naval Base Coronado, Building 465, Bay 6, in San Diego, California.

In early 2008, computational fluid dynamic (CFD) simulations were performed to model the relationship between air velocity and worker exposure levels in a Navy aircraft painting hangar. A walk-through survey was conducted June 16-19, 2009, encompassing range-finding personal and area air sampling (for CrVI, HDI, and any other contaminants found on the material safety data sheets) and the gathering of hangar dimensions, geometric details, and ventilation boundary conditions that would be used to set-up the CFD simulations. Next, the 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 in order to monitor three painting processes, which are typically spaced days or weeks apart. Accurate statistical characterization of exposures required sampling of three processes. 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.

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

1. 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.
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 address worker exposure and required supplementing with 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.

The additional work called for in item 6 is the subject of the current report.

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 were as follows:

Setting 1: 1/4 supply and 2/4 exhaust	Setting 2: 2/4 supply and 3/4 exhaust
Setting 3: 2/4 supply and 4/4 exhaust	Setting 4: 3/4 supply and 4/4 exhaust

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 stationary 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 consult 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 would begin at 0600 hrs. While the source and measurement locations and settings were duplicated as closely as possible on the second night, some variability was expected. Thus, the data from each night was analyzed separately. Still, sufficient data was collected to make comparisons between the velocity at Setting 4 (3/4 supply and 4/4 exhaust) and the velocities at Settings 1, 2, and 3.

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

<u>Conclusions</u>

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 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 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 exposures (from 1742 to 249.7 ppb). Increasing the average velocity from 66.1 to 75.3 fpm lowered exposures (from 1526 to 353.7 ppb), while increasing the average velocity from 75.3 to 85.3 fpm increased exposures (from 353.7 to 1193 ppb).

<u>Recommendations</u>

1. Achieving balanced flow (perhaps -0.05 in. water gauge, if prevention of fugitive emissions to the environment is desired) 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.

Introduction

Background for Control Technology Studies

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

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

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

Background for this Study

Researchers from CDC/NIOSH collaborated with Naval Facilities Engineering Service Center (NAVFAC ESC) and the Navy Medical Center San Diego, industrial hygienists and engineers to evaluate the ventilation system in a Navy aircraft painting hangar. The Navy seeks to keep worker exposures to air contaminants, including hexavalent chromium (CrVI), hexamethylene diisocyanate (HDI), methyl isobutyl ketone (MIBK), and others, at concentrations that meet regulatory health and safety standards, while limiting the environmental footprint, i.e. energy use, and operational costs of paint hangar ventilation.

In early 2008, preliminary computational fluid dynamic (CFD) simulations were performed to model the relationship between air velocity and worker exposures in a Navy aircraft paint finishing hangar. The results of this brief study were promising enough to pursue more realistic CFD modeling, exposure monitoring, and tracer experiments. NIOSH then initiated the current project, with funding support from NAVFAC.

Thus, a walk-through survey was conducted June 16-19, 2009, encompassing range-finding air-sampling (for CrVI, HDI, and other contaminants found on the material safety data sheets) and the gathering of hangar dimensions, geometric details, and ventilation boundary conditions that would be used to set-up the CFD simulations. Next, the ventilation system performance in terms of contaminant control was evaluated through comprehensive personal and area air sampling of solvent, primer, and topcoat constituents, on July 22 and August 3, 2009 and April 13, 2010. 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. The results from the 2009 and 2010 air sampling, tracer gas and CFD simulation studies are available in a NIOSH report [NIOSH 2011].

Results from that report indicated that the ventilation system of the evaluated Navy aircraft painting hangar was under positive pressure at all observed filter load conditions (approximately 1.0 to 2.5 “w.g.) and that additional tracer gas and CFD simulations were needed, so that the effect of air velocity could be observed under balanced conditions.

The painting process air sampling and the tracer gas experiments conducted in 2009 and 2010 and described in NIOSH 2011 took place under ventilation conditions that existed or were achievable at the time of the NIOSH surveys. The CFD simulations (also described in NIOSH 2011) were performed for conditions of interest from a design perspective. These two sets of conditions were similar, but not identical. In discussions between Navy and NIOSH engineers and industrial hygienists, the lack of CFD simulations for the exact ventilation conditions observed in the painting bay during the 2009 and 2010 NIOSH surveys emerged as an information gap.

Thus, additional CFD simulations were performed in 2011 to model the painting bay ventilation conditions present at the time of the 2009 and 2010 NIOSH survey. The additional CFD simulations along with tracer gas data from the 2009 and 2010 studies are provided in this current report under “CFD Simulations and Tracer Experiments I,” beginning on page 9. Another information gap from the 2009 and 2010 NIOSH surveys was a lack of tracer gas measurements under balanced conditions, where the supply rate was approximately equal to the exhaust rate, with the exhaust rate slightly higher, for containment. In March 2011, NIOSH researchers conducted the additional tracer gas evaluations. The supplemental CFD and tracer studies are the subject of this report.

Facility Description

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

The refinishing of whole aircraft is performed in Buildings 464 and 465, which each containing 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 1), which paints approximately twenty aircraft 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. For wheeling in large aircraft (such as the C-130), the supply walls of both bays are opened like a gate, the accordion door is opened and the two bays become one big hangar, served by two identical ventilation systems.

Description of Controls and Equipment

Engineering Controls

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

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

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

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

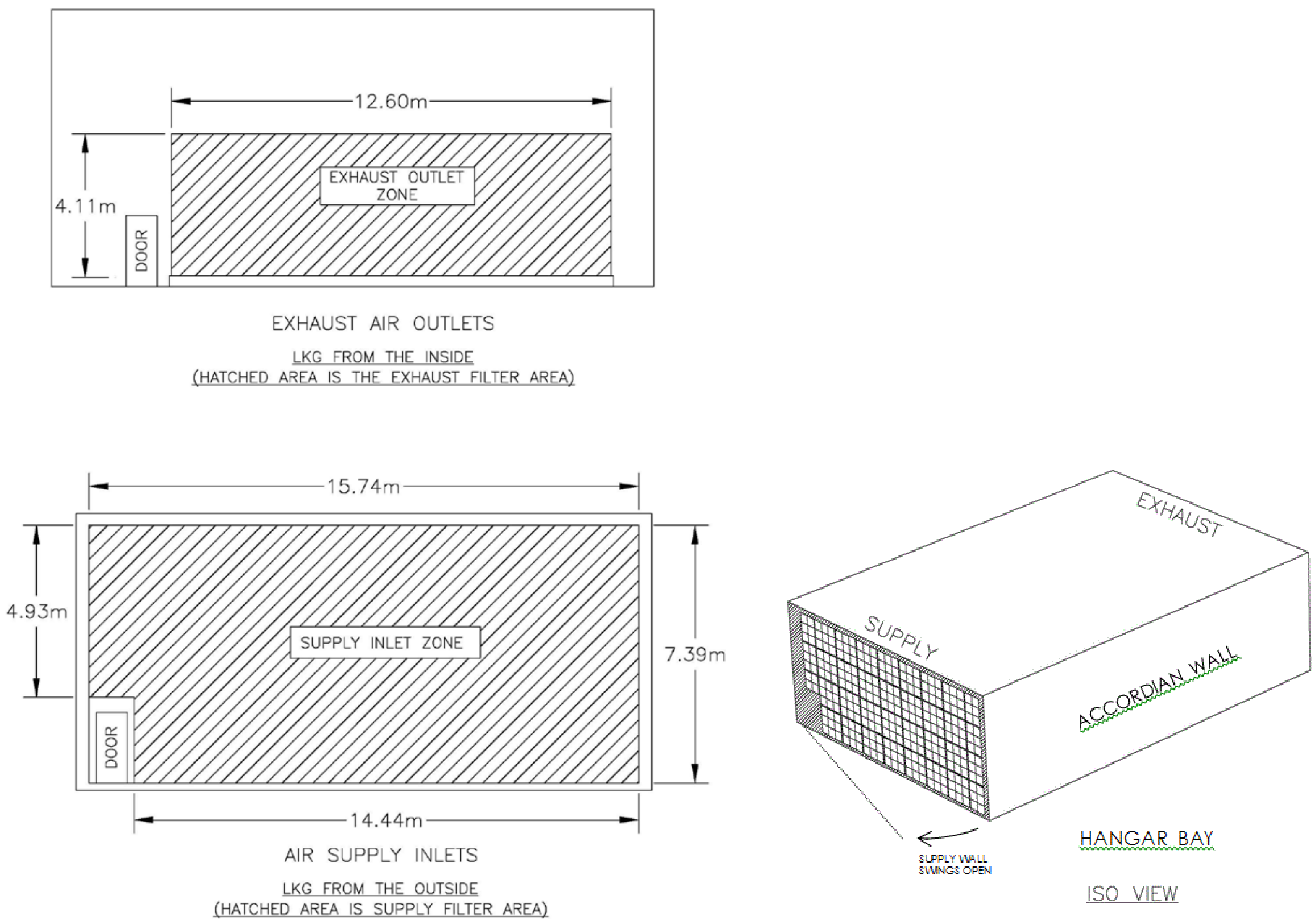

Figure 1. Drawing showing filter area of Bay 6, Building 465, Fleet Readiness Center Southwest, San Diego, CA.

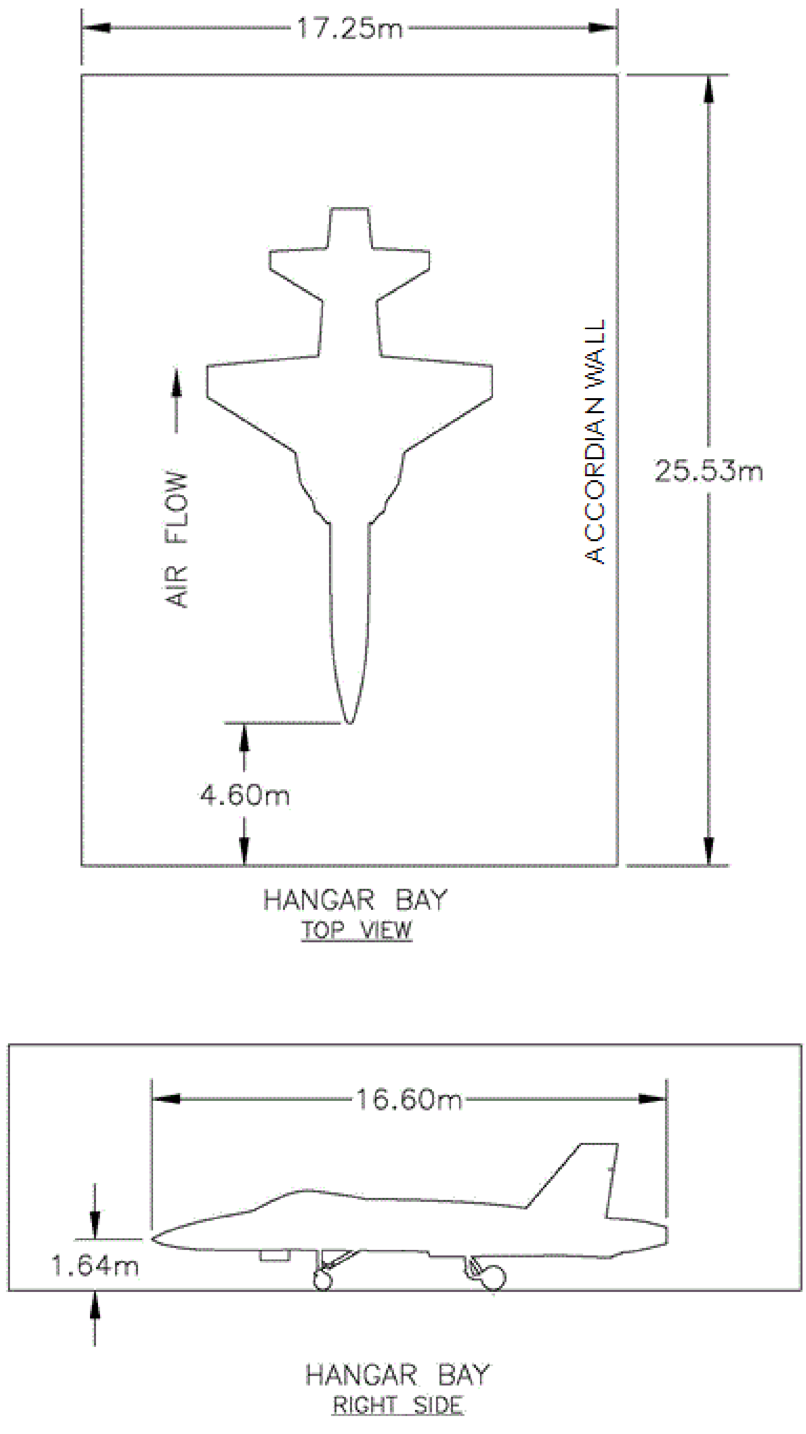

Figure 2. Drawing showing interior of bay and F/A-18C/D Hornet. Bay 6, Building 465, Fleet Readiness Center Southwest, San Diego, CA.

Methodology

NIOSH researchers conducted tracer gas evaluations and CFD simulations of ventilation in a Navy aircraft painting hangar. Two tracer gas studies were conducted. The first tracer gas study was conducted in 2010 at the same time as air sampling and CFD simulations, and are summarized in a separate report [NIOSH 2011]. The 2010 tracer gas study, referred to in this report as “Tracer Experiments I,” is presented again in this report to compare with new CFD simulations. Another tracer gas study was conducted in 2011 to evaluate four additional ventilation settings in the Navy aircraft painting hangar. The 2011 tracer gas study is presented in this report under “Tracer Experiments II.”

Both tracer gas experiments used similar methods to quantitatively compare the effectiveness of different ventilation settings of the Navy aircraft painting hangar. The tracer gas used was 99.5% minimum purity sulfur hexafluoride (SF_6). A dual stage series 200 brass regulator with a CGA 590 inlet was connected to the tracer gas cylinders. The gas was supplied through ¼ in. diameter Teflon® tubing and controlled using a mass flow controller. The mass flow controller was manufactured by Aalborg (model GFC17, Aalborg Instruments and Controls, Inc., Aalborg, Denmark) and had a flow range of 0-1000 ml/min when calibrated to SF_6.

CFD Simulations and Tracer Experiments I

For Tracer Experiments I, SF_6 was released during three different tracer gas release scenarios each having a different configuration of the source at the release location near the front of the F/A-18C/D Hornet. During the first release scenario, the source configuration was a single source of SF_6 located near the front of the jet released at 500 ml/min as shown in Figure 3. During the second and third release scenarios, the source configurations were split into two locations each releasing 250 ml/min of SF_6 as shown in Figure 3, which was necessary to disperse the SF_6 widely enough to be detected by the instruments at the various locations of interest.

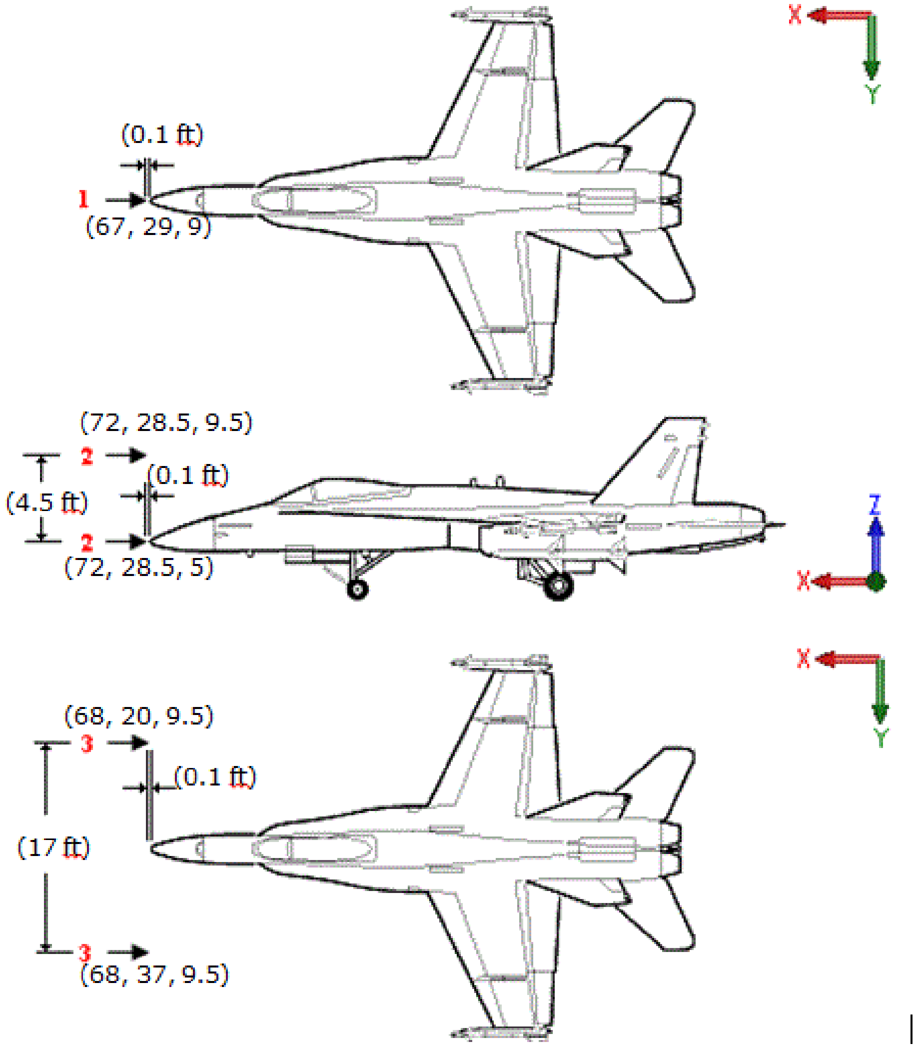

Figure 3: Source locations (x,y,z) in feet, relative to the origin shown, for the release of SF_6 near the front of the F/A-18C/D Hornet. Source: http://www.boeing.com/defense-space/military/fa18/fa18cd3v.htm

When evaluating the ventilation system, the concentration of the SF_6 was measured using five MIRAN® Sapphire Specific Vapor Analyzers (Thermo Environmental Instruments, 8 West Forge Parkway, Franklin, MA 02038). Each MIRAN® measured SF_6 continuously for 30 minutes at each ventilation setting. The ventilation system was adjusted to achieve room velocities corresponding to approximately 118 fpm, 85.4 fpm, 61.2 fpm, or 30.0 fpm. Tracer gas concentrations of SF_6 were logged to each MIRAN® Sapphire at two-second intervals and later downloaded on a laptop computer. Approximate locations of each MIRAN® Sapphire around the F/A-18C/D Hornet during the first release scenario are shown in Figure 4. Source locations and sample locations for the first source release scenario are provided in Table 1. The origin of the coordinate system is the point where the starboard wall, exhaust wall, and floor intersect, shown schematically in Figure 4.

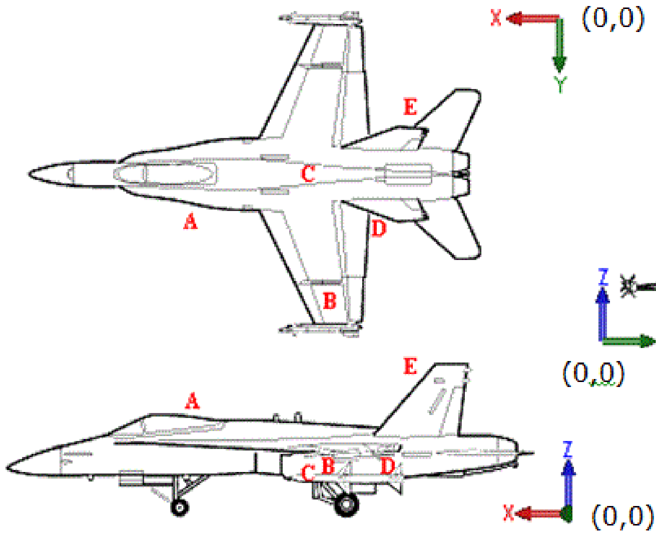

Figure 4: Approximate locations of the five MIRAN® Sapphires around the F/A-18C/D Hornet during the first release scenario. Source: http://www.boeing.com/defense-space/military/fa18/fa18cd3v.htm

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

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

Sample location D was placed on the port side of the aircraft during the first tracer gas source release scenario. This was done because preliminary testing indicated that the ventilation system caused the tracer gas to migrate to the port side of the aircraft when a single source was placed near the nose. Sample location D was placed on the starboard side of the aircraft for the second and third tracer gas release scenarios. Approximate locations of each MIRAN® Sapphire around the F/A-18C/D Hornet during the second and third release scenarios are shown in Figure 5. Source locations and sample locations for the second and third source release scenarios are provided in Table 2.

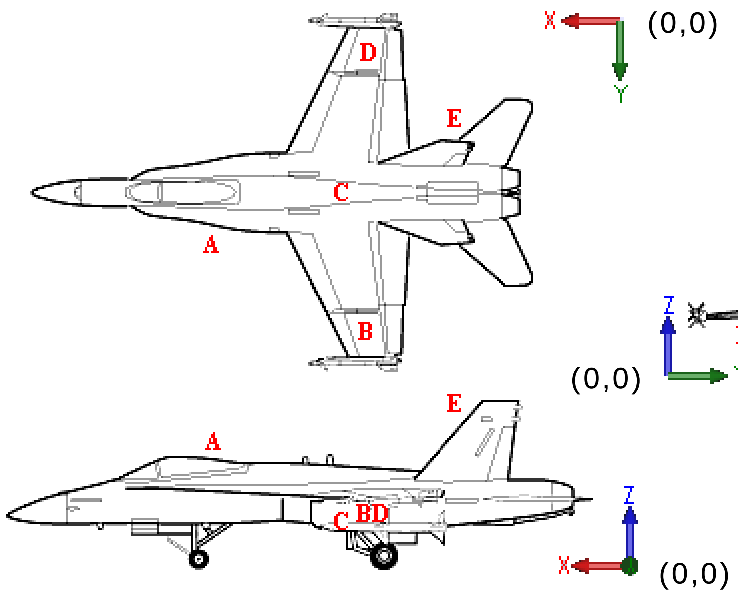

Figure 5: Approximate locations of the five MIRAN® Sapphires around the F/A-18C/D Hornet during the second and third release scenarios. Source: http://www.boeing.com/defense-space/military/fa18/fa18cd3v.htm

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

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

Each configuration was monitored for thirty minutes. The changeover to a new ventilation rate, including checking the status of the five MIRAN real-time tracer gas monitors and fifteen minutes to let the new flow situation reach equilibrium, also required about thirty minutes to complete.

During the tracer gas test, basic operation of the ventilation system, i.e. which fans are on or off, was observed by noting the sequence number that the system was set to and by climbing up to the hangar building roof and noting sound and vibration. Secondarily, a computer was sometimes available with software that tracked the performance of the exhaust fans. The four supply air fans and four exhaust air fans located on the roof supplied and exhausted air to plenums on opposite walls of the hangar. For Tracer Experiments I, the supply and exhaust fans were operated in pairs at three different ventilation settings. The three ventilation settings were:

- Full-flow: 4 supply fans operating with 4 exhaust fans
- 3/4 -flow: 3 supply fans operating with 3 exhaust fans
- Half-flow: 2 supply fans operating with 2 exhaust fans

Air velocity measurements were taken at the supply and exhaust walls of the hangar in equal areas as shown in Figure 6. Velocity measurements were also taken in a matrix of 16 locations at the bay midpoint between supply and exhaust walls. The equipment consisted of a Shortridge AirData Multimeter, AMD-860 with current calibration certification, a Shortridge VelGrid, two sections of 20-foot tygon tubing, and an extension pole capable of 25 feet in length. The pressure drop across the exhaust filter bank was read from the gauge in the control room before the start of each painting cycle. Average air velocity and pressure measurements at each ventilation setting are provided in Table 3.

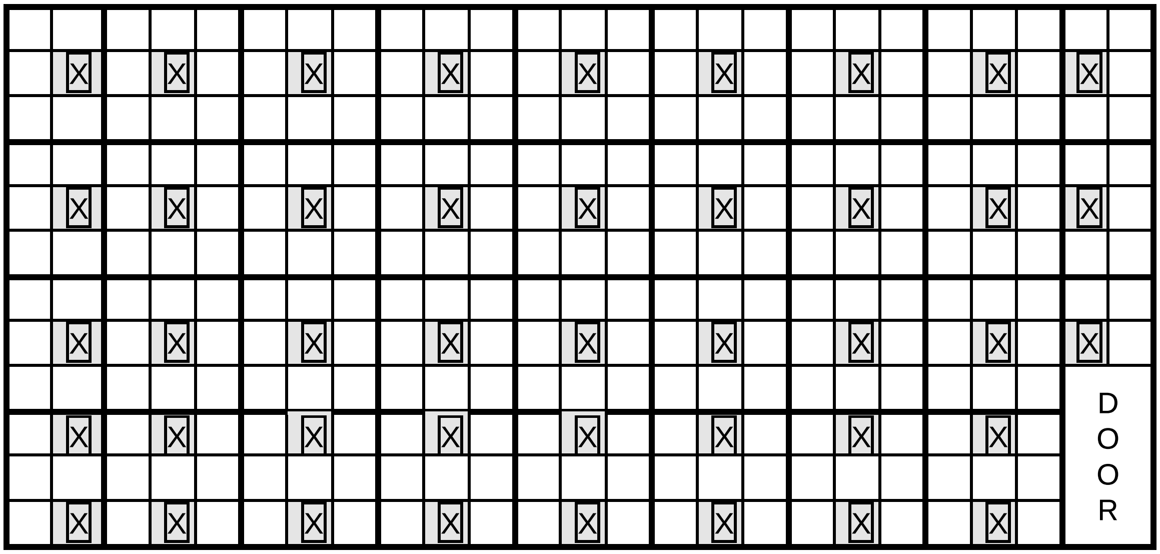

Figure 6. Supply measurement matrix of 43 locations on the filter, viewed from inside the bay

Table 3: Measured (Average) Air Velocities

Fraction of Current Flow Rate	Supply Velocity [range] (fpm)	Mid-hangar Velocity [range] (fpm)	Exhaust Velocity [range] (fpm)	Pressure Relative to Ambient (in. water)
Half-flow	73.4 [54.6, 107]	71.8 [50.0, 103]	49.0 [34.5, 124]	0.0725
3/4-flow	102 [82.3, 126]	73.6 [43.0, 99.0]	68.9 [24.0, 96.3]	0.0933*
Full-flow	136 [106, 167]	104 [31.1, 134]	99.0 [45, 152]	0.102

* The pressure was not recorded for this flow condition. It was estimated as $P_{3/4} = P_{full} (V_{3/4}/V_{full})^{0.8}$, simply because the exhaust velocity and the pressure fit this relationship, when comparing the half and full-flow measured pressures.

CFD simulations provided in this report were performed for the three ventilation settings and velocities from Table 3 above. In the model, contaminant with the physical properties of MIBK was emitted, in both vapor and liquid droplet forms, from the hand areas of two simulated workers at commonly observed spraying locations, at a flow rate specified by the spray gun manufacturer. 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 x 10^{-6} kg/m-s, which is less than half as viscous as air. The MIBK droplets were given their documented density of 800 kg/m^3 (specific gravity 0.8) and a diameter of 10 µm. The overall fluid properties were allowed to vary according to the fraction of contaminant in the contaminant-air mixture that composed "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). NIOSH provided solid models representing workers in Tyvek® suits, using Solidworks (Dassault Systemes SolidWorks Corp., Concord MA). The geometry shown in Figure 7 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. The iterative convergence criteria were normalized residuals decreasing below 10^{-4} to nearly 10^{-5} in most cases. 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.

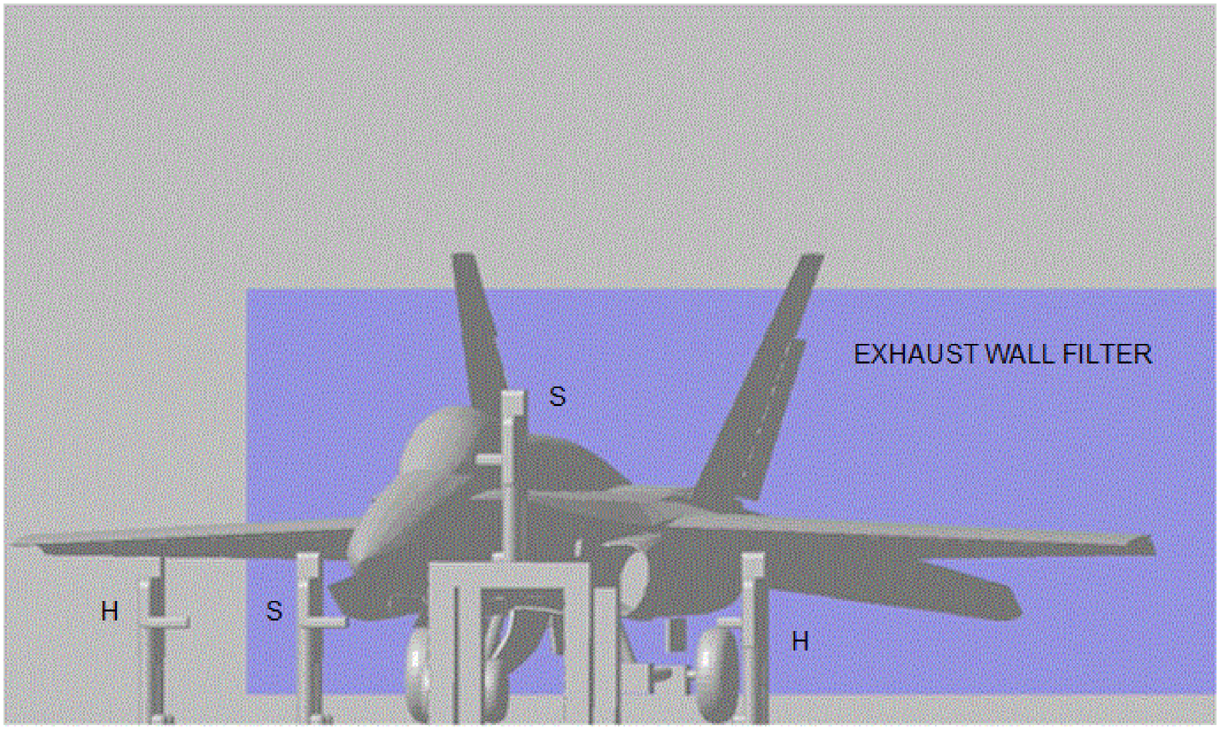

Figure 7. Geometry of workers, exhaust wall filter, and F/A-18C/D Aircraft. Hosemen (H) are further from the aircraft and further downwind than sprayers. The contaminant source is located at the end of the sprayers' (S) right arms. One sprayer is on a scaffold.

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 achieve stationarity, with periodic 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.

Tracer Experiments II

The second round of tracer experiments were performed for additional combinations of supply and exhaust fan operation that were possible by modifying the controller programming. Each ventilation setting involved running fewer supply units than exhaust units to avoid the positive pressure issue found during Tracer Experiments I. In that study, supply and exhaust units could only be turned on or off in tandem, which unfortunately maintained the positive imbalance.

In the second experiments, for example, a setting of 3/4 supply and 4/4 exhaust indicates that three of the four supply blowers were operating to pressurize the filter bank plenum at the front end of the hangar, while all four exhaust fans were operating to create a vacuum in the filter plenum at the back end of the hangar. Various on/off combinations of the four supply and four exhaust fans were tested at the site, in an attempt to balance the flow. The four ventilation settings for Tracer Experiments II are listed below.

Setting 1: 1/4 supply and 2/4 exhaust
Setting 2: 2/4 supply and 3/4 exhaust
Setting 3: 2/4 supply and 4/4 exhaust
Setting 4: 3/4 supply and 4/4 exhaust

All four configurations put the painting hangar under substantial negative gauge pressure, ranging from -0.35 to -0.22 in. water, even though the VFD exhaust controllers should have theoretically reduced the exhaust fan speed enough to match the supply rate and rebalance the system. Too much negative pressure may waste energy, affect the flow pattern, and create possible safety hazards, from doors blowing open or closed. The additional tracer gas experiments were carried out despite this obstacle to gain further data on concentration and flow conditions.

Air velocity measurements for the second set of tracer experiments were taken at the supply and exhaust walls and at the hangar cross-section near the nose of the aircraft using the same methods and equipment as the first experiment, described earlier in this report. Average air velocity measurements taken at each of the ventilation settings for Tracer Experiments II are shown in Table 4.

Table 4: Measured (Average) Air Velocities

Fraction of Current Flow Rate	Fan Operation (HV = supply unit) (EF = exhaust unit)	Supply Velocity [range] (fpm)	Velocity at Aircraft Nose Cross-section [range] (fpm)	Exhaust Velocity [range] (fpm)	Pressure w.r.t Ambient (in. water)
1/4 supply 2/4 exhaust	HV- 23 EF- 22, 23	41.0 [35.0, 86.0]	51.2 [-43.0, 140]	37.6 [49.0, 166]	-0.225
2/4 supply 3/4 exhaust	HV- 23, 25 EF- 22, 23, 24	63.2 [72.0, 125]*	79.0 [49.0, 207]	56.2 [78.0, 258]	-0.265
2/4 supply 4/4 exhaust	HV- 23, 25 EF- 21, 22, 23, 24	63.2 [72.0, 125]*	88.1**	74.5 [102, 339]*	<-0.335***
3/4 supply 4/4 exhaust	HV- 22, 23, 25 EF- 21, 22, 23, 24	84.2 [111, 157]	97.3 [83, 114]	74.5 [102, 339]*	-0.335

*The filter traverse measurements were performed only once for each unique configuration and number of operating fans.

**Estimated from average ratio of nose velocity to supply and exhaust velocities for the other ventilation scenarios.

***The pressure was not recorded for the half supply and full exhaust condition. The value was probably slightly more negative than -0.335 in. water, the value for the 3/4 supply and full exhaust condition, because the half supply was less able to make-up for the air drawn by the full exhaust.

The second round of tracer experiments used similar equipment and methods as the first experiment with some differences in sample and release locations. In the Tracer Experiments II, SF_6 was released at two locations (S_1 and S_2) and measured at five locations, chosen to represent observed worker locations and to reliably detect tracer gas concentrations within the instrument range of the MIRAN Sapphires. Note that, while there were six measuring instruments (A – F), there were only five distinct measurement locations because the intakes for instruments D and E were at the same point. This redundancy tested instrument reliability in a difficult to measure location (under the landing gear well). The trials occurred on March 14th and 15th, 2011.

Approximate locations of each MIRAN® Sapphire around the F/A-18C/D Hornet are shown in Figure 8. Source and sample locations are provided in Table 5. The origin of the coordinate system is the point where the starboard wall, exhaust wall, and floor intersect, shown schematically in Figure 8.

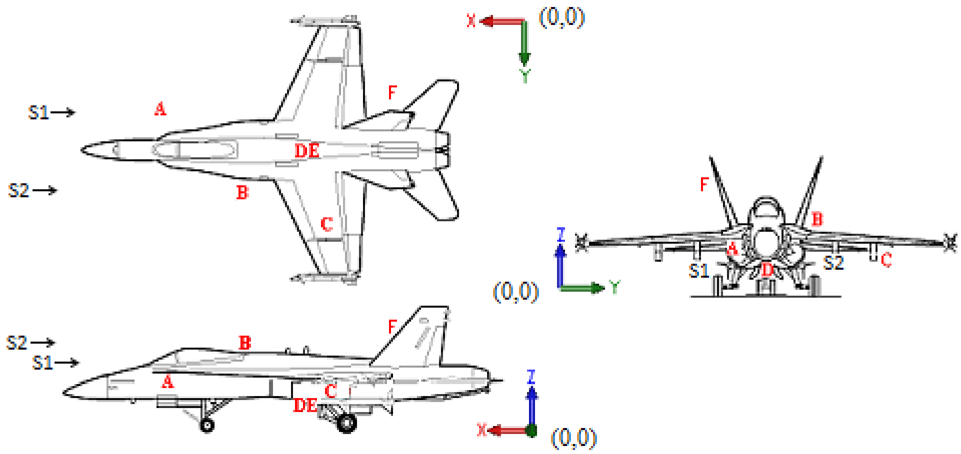

Figure 8. Source and sample locations for the release of SF6 near the front of the F/A-18C/D Hornet. Source: http://www.boeing.com/defense-space/military/fa18/fa18cd3v.htm

Table 5: Source and sample locations for the second round of tracer gas testing

Location	**X (ft)**	**Y (ft)**	**Z (ft)**
Starboard Source (S1)	23	67	6.5
Port Source (S2)	32	70	6.8
A	23	61	5.5
B	34.5	50	10.5
C	34	34.5	4.3
D	27	42	3
E	27	42	3
F	19	30	10

For this tracer experiment, the source configuration was split into two locations each releasing 400 ml/min of SF_6 as shown in Figure 8. Tracer gas concentrations of SF_6 were logged to each MIRAN® Sapphire at six-second intervals and later downloaded to a laptop computer. Each MIRAN® measured SF_6 continuously for each fifteen-minute trial. Note that analysis of the results in Tracer Gas I, which used thirty-minute trials, had shown that fifteen-minute trials (following a fifteen-minute stabilization period), was a sufficient duration to achieve a stationary time-average. Nineteen trials were conducted over two nights while randomizing ventilation settings.

Results

CFD Simulations and Tracer Experiments I

CFD simulations of MIBK concentrations were modeled and compared with tracer gas concentrations for three ventilation settings that were evaluated during Tracer Experiments I conducted in 2010. These ventilation settings were:

- Full-flow: 4 supply fans operating with 4 exhaust fans
- 3/4 -flow: 3 supply fans operating with 3 exhaust fans
- Half-flow: 2 supply fans operating with 2 exhaust fans

Face velocity measurements were taken in equal areas at the supply and exhaust filters of the hangar for each ventilation setting. Velocity measurements at the filters were normalized, using the ratio of the filter area to the mid-plane area, so that the reported velocity would be proportional to the volumetric flow rate. The average normalized face velocities measured at the supply filter were 73.4, 102, and 136 fpm for half-flow, ¾-flow, and full-flow, respectively. The average normalized face velocities measured at the exhaust filter were 49, 68.9, and 99 fpm for half-flow, ¾-flow, and full-flow, respectively.

Table 6 shows the CFD results of MIBK concentrations at each average normalized velocity for five locations in the computational domain of the paint hangar that correspond to observed worker locations. The highest calculated MIBK concentration occurred for the full-flow condition, underneath the rear landing gear well. The lowest calculated concentration was in the breathing zone of the sprayer helper, or hoseman, standing on the ground to the port side of the aircraft; for each flow condition, the calculated concentrations were essentially zero at this location. The geometric and arithmetic location means were quite different, and it is unclear which better describes the exposure situation. As a way to summarize ventilation effectiveness, then, each flow condition was given a rank, from lowest (1) to highest (3) mean concentration. The ranks were then summed, across the geometric and arithmetic means, to form a score, with lower being better.

Table 6: CFD results of MIBK concentrations at five worker locations in the painting hangar

Average Normalized Face Velocity (fpm) (supply/exhaust)	Under Plane (ppm)	Hoseman Port (ppm)	Hoseman Starboard (ppm)	Sprayer Port Scaffold (ppm)	Sprayer Starboard Wing (ppm)	Geometric* Mean (ppm)	Arithmetic* Mean (ppm)	Rank Score**
73.4/49	118	1.59E-15	81.3	1.68E-14	46.4	2.60E-05	49.2	4
102/68.9	244	1.97E-14	6.44	3.99E-14	3.99E-14	3.46E-08	50.1	3
136/99	854	2.48E-11	0.00135	6.18E-14	0.192	1.28E-05	171	5

*Both geometric and arithmetic means are presented because of the large range of observed values.
**Rank scores are the sums of the ranks (1-3) for the two types of means (larger rank is higher concentration).

Figure 9 shows the mean MIBK concentrations modeled using CFD alongside the tracer gas experiment means. 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. CFD simulations and tracer experiments show a similar decrease in concentration when the flow was lowered from full- to 3/4-flow. In Figure 9, 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.

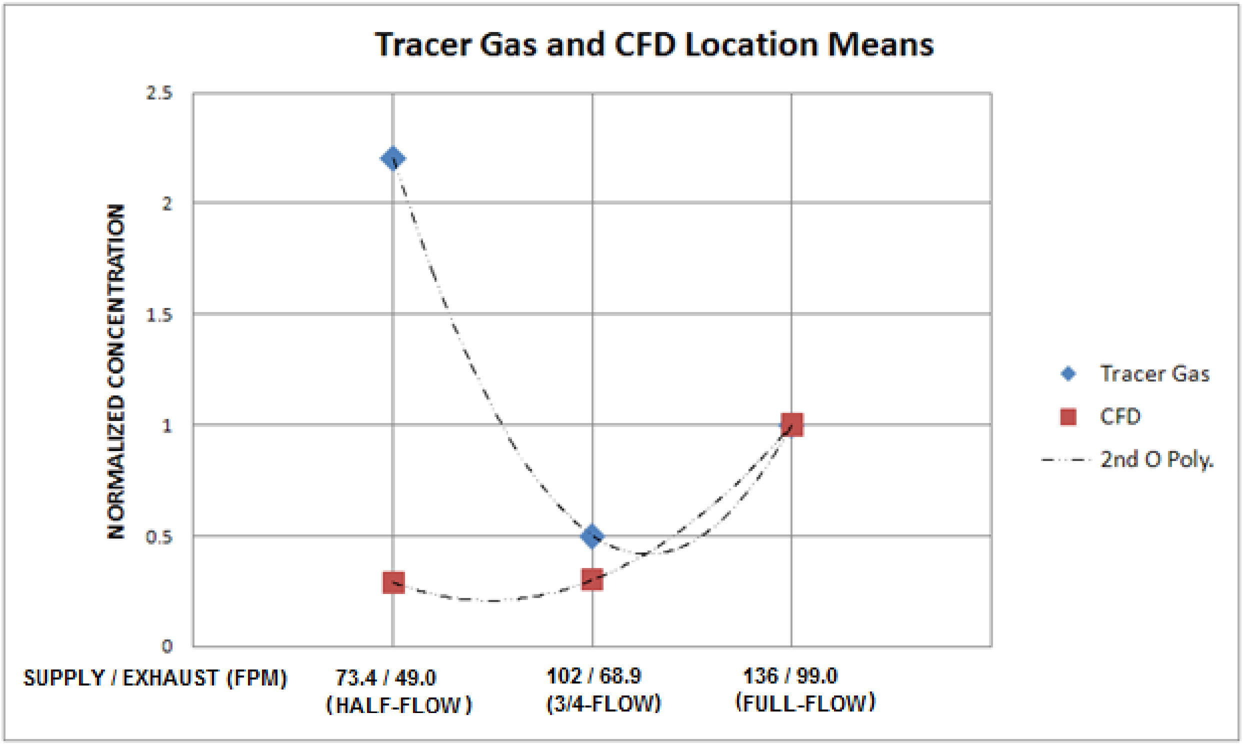

Figure 9: Five-location-mean concentrations for CFD simulations and tracer gas experiment means, as a function of flow rate.

Another way to look at the effect of flow reduction is through pair-wise comparisons. In Figure 10, the tracer location means are shown in blue, along with their 95% error bars for the multiple comparison 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, using the error computed from the tracer gas study, while the CFD prediction is at the low end of the error bar. 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. Here also, the CFD prediction is within the tracer experiment error bars.

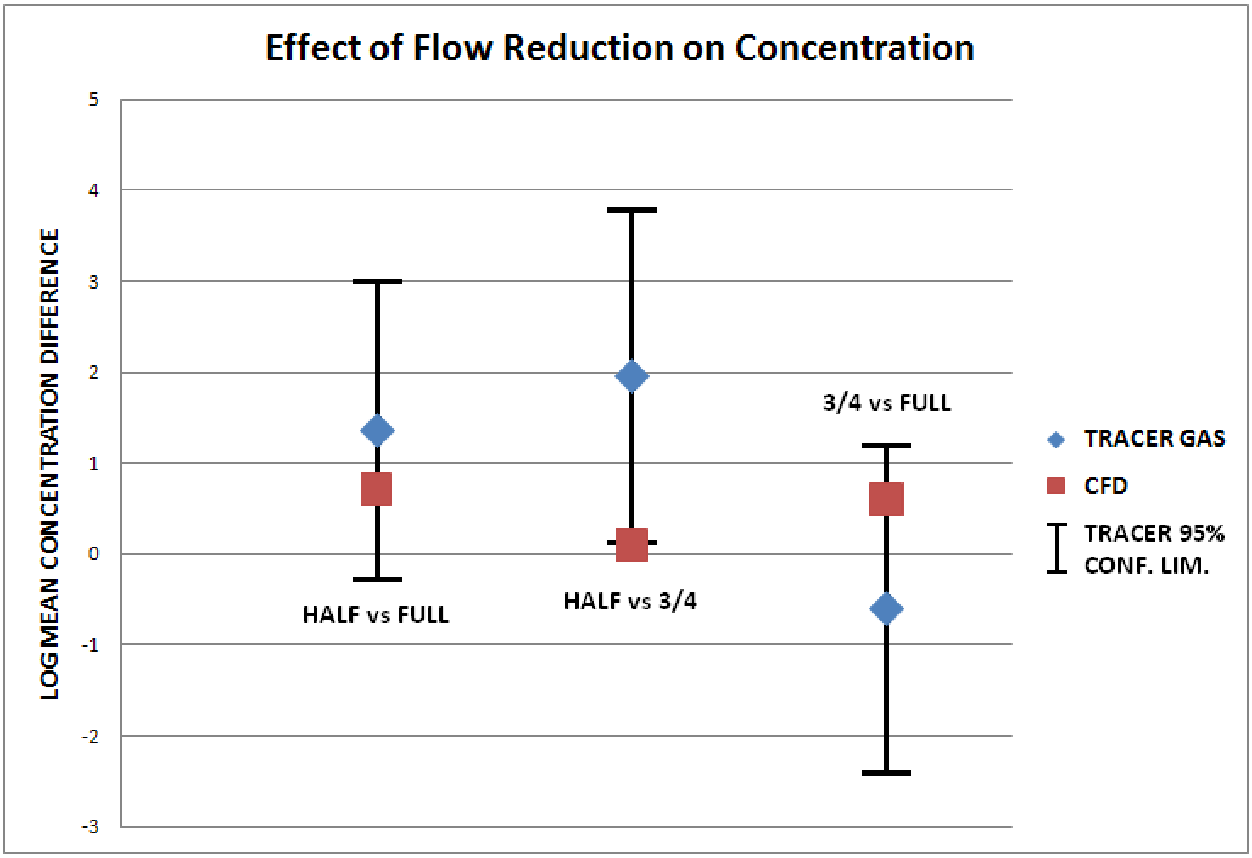

Figure 10: Flow rate comparison by CFD and tracer gas methods.

Tracer Experiments II

The second round of tracer experiments were performed for additional combinations of supply and exhaust fan usage. The four ventilation settings for the additional tracer gas experiments conducted in 2011 were:

Setting 1: 1/4 supply with 2/4 exhaust
Setting 2: 2/4 supply with 3/4 exhaust
Setting 3: 2/4 supply with 4/4 exhaust
Setting 4: 3/4 supply with 4/4 exhaust

Air velocity measurements for the second set of tracer experiments were taken in equal areas at the supply and exhaust walls and at the hangar cross-section near the nose of the aircraft. Velocity measurements at the filters were normalized, using the ratio of the filter area to the mid-plane area, so that the reported velocity would be proportional to the volumetric flow rate. The arithmetic means of the normalized velocities at each filter and the absolute mean velocity at the hangar cross-section are provided in Table 7. When the low end of the measured concentration range was zero, the limit of detection (LOD) divided by the square root of two is reported instead, after Hornung and Reed [1990]. For the MIRAN Saphires, the LOD was 1 ppb.

Sulfur hexafluoride concentrations at the five measurement locations for each ventilation setting are summarized by the arithmetic means listed in Table 7. Results for the two nights of tracer gas trials are reported separately in the table, because the tracer experiments were conducted on two different nights. Thus, the source and measurement locations and the source nozzle direction could not be held precisely constant. Also, the filter pressure drop had increased (by approximately 0.3 "w.g.), from night one to night two, because of the filter loading caused by painting on day two.

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, vs. setting 4, had statistically significantly higher mean tracer gas concentrations. 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, vs. settings 3 and 4. 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 stationary 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 consult 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 would begin at 0600 hrs. While the source and measurement locations and settings were duplicated as closely as possible on the second night, some variability was expected. Thus, the data from each night was analyzed separately. Still, sufficient data was collected to make comparisons between the velocity at Setting 4 (3/4 supply and 4/4 exhaust) and the velocities at Settings 1, 2, and 3.

Table 7: Tracer experiments II, SF_6 concentrations, and air velocity measurements

Fraction of Current Flow Rate	Normalized Supply Velocity**** [range] (fpm)	Arithmetic Mean Absolute Velocity at Aircraft Nose Cross-section [range] (fpm)	Normalized Exhaust Velocity**** [range] (fpm)	Arithmetic Mean of Candidate Velocities (fpm)	Arithmetic Mean Conc. Night One (ppb SF_6) [range]	Geometric Mean Conc. Night One (ppb SF_6) [95% C.L.]	Arithmetic Mean Conc. Night Two (ppb SF_6) [range]	Geometric Mean Conc. Night Two (ppb SF_6) [95% C.L.]
Setting 1: 1/4 supply 2/4 exhaust	41.0 [35.0, 86.0]	51.2 [-43.0,140]	37.6 [49.0,166]	43.3	1742 [446.3,4985]	840.0 [387,1822]		
Setting 2: 2/4 supply 3/4 exhaust	63.2 [72.0,125]***	79.0 [49.0,207]	56.2 [78.0,258]	66.1			1526 [113.4,8286]	504 [209, 1217]
Setting 3: 2/4 supply 4/4 exhaust	63.2 [72.0,125]***	88.1**	74.5 [102,339]***	75.3			353.7 [39.32,1096]	39.6 [10.9, 144]
Setting 4: 3/4 supply 4/4 exhaust	84.2 [111,157]	97.3 [83,114]	74.5 [102,339]***	85.3	249.7 [0.707*,1521]	34.1 [15.7,73.0]	1193 [0.707*,7877]	32.7 [13.6, 79.0]

* LOD/√2

** Estimated from average ratio of nose velocity to supply and exhaust velocities for the other ventilation scenarios.

*** The filter traverse measurements were performed only once for each unique configuration and number of operating fans.

****An explanation of the mean normalized supply velocity and mean normalized exhaust velocity is in the Discussion section of this report.

The lowest arithmetic mean concentration on night one occurred for Setting 4, the 3/4-supply|full-exhaust configuration (249.7 vs. 1742 ppb). The lowest arithmetic mean for night two occurred for Setting 3, the half-supply|full-exhaust configuration (353.7 vs. 1526 and 1193 ppb). Using the geometric means shown in Table 7, the statistically significant differences among flow configurations at the 95%-confidence level were: Setting 1 (1/4-supply|half-exhaust) had higher concentrations than did Setting 4 (3/4-supply|full-exhaust), 840 vs. 34.1 ppb. Setting 2 (half-supply|3/4-exhaust) was higher than both Setting 3 (half-supply|full-exhaust) and Setting 4 (3/4-supply|full-exhaust), i.e. 504 vs. 39.6 and 32.7 ppb, respectively. No significant concentration difference was found between Setting 3 (half-supply|full-exhaust) and Setting 4 (3/4-supply|full-exhaust), 39.6 vs. 32.7. Table 7 contains three velocities for each ventilation scenario and their average. This average is a convenient, simplified number that characterizes the configurations to some extent or at least distinguishes them from one another. In summary, considering the arithmetic mean velocity, arithmetic mean concentration, and geometric mean concentration, Setting 3 (75.3 fpm, 354 ppb, 39.6 ppb) is either similarly or more protective than Setting 4 (85.3 fpm, 1193 ppb, 32.7 ppb), and both of these configurations are more effective at controlling exposures than either Setting 2 (66.1 fpm, 1526 ppb, 504 ppb) or Setting 1 (43.3 fpm, 1742 ppb, 840 ppb).

Discussion

Air Velocity Characterization

The velocity varies over any cross-section in the bay, from the supply filter through the mid-bay area and on through the exhaust filter. The spatial variability within a cross-section was caused by differences in momentum coming from upstream and interactions with objects (aircraft, workers, and equipment) and boundaries (walls, floor, and ceiling). There is further variability in the average velocity from one cross-section to another, depending on the effective area of the flow and possible fugitive emissions or infiltrations that would alter the volumetric flow rate along the length of the bay.

The supply filter area, taken as the area within the filter installation perimeter, was 118 m^2, and this approach was used in the CFD modeling. The filter is overlaid with a metal grid that holds the filter in place but also reduces the effective area. This effective area, 915 ft^2 (85.1 m^2), was calculated as the sum of the areas of the individual filter squares in between the metalwork lattice. Similarly, the exhaust filter perimeter was used to calculate an area of 551 ft^2 (51.2 m^2), whereas the effective area from summing the individual squares was 408 ft^2 (37.9 m^2). The velocity at filter faces was measured by placing the quad-pitot-tube rack at the filter surface, which implies that the measured velocity represents the flow through each filter square reasonably well. It is possible, however, that there was flow around or near the filter installation beams (the edges of the squares), at a different angle or an accelerated velocity, that was not accounted for in the measurement. Velocity measurements at the filters were normalized, using the ratio of the filter area to the mid-plane area, so that the reported velocity would be proportional to the volumetric flow rate. However, the CFD simulations and the experimental measurements used slightly different mid-plane areas: 1471 ft^2 or 137 m^2 (taken from the hangar engineering drawings) for CFD and 1415 ft^2 or 131 m^2 (measured in the field) for the experiments.

CFD Simulations and Tracer Experiments I

Tracer Experiments I and CFD results agreed well for full- and 3/4-flows, but diverged at half-flow. 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 CFD and Tracer Experiments I, it can be said that the full-flow condition was not more protective than the 3/4-flow condition, as shown in Figures 9 and 10. In light of the velocity measurement results (Table 3), 3/4-flow can be summarized as being in the range, 68.9 to 102 fpm, and full-flow can be summarized by the range, 99.0 to 136 fpm. The mid-bay velocity averages, for 3/4-flow and full-flow, were 73.6 and 104 fpm, respectively.

Tracer Experiments II

In the second round of tracer experiments, some velocity measurements were made at the hangar midsection (middle cross-section, or "mid-plane") and at the nose of the aircraft. These flows may be a good representation of the intended effect of the ventilation system--moving air through the work zone. Whether the midsection measurement, the filter perimeter method, or the individual filter square method is the most accurate is unclear. For exposure control, the micro-flow near the worker is an important determinant [Bennett 2003], whereas for ventilation design, the average velocity through the bay (equivalent to the volumetric flow rate per unit area), the macro-flow, may be the target variable [ACGIH 2010]. The OSHA Ventilation Standard specifies that air velocity shall be "…measured upstream [of] …the object being sprayed" [CFR]. An HVAC engineer might specify equipment that would deliver a target velocity through an empty hangar, which is what seems to be suggested by the Uniform Facilities Criteria, in stating that the velocity be furnished "…across the entire cross-section area of the hangar bays" [DOD 2010]. While the micro- and macro-flows are related, optimizing one does not necessarily optimize the other. Interestingly, as the number of fans operating (supply plus exhaust) increased, variability in the hangar air velocity decreased, perhaps because variability of velocity across the filter banks decreased.

Given the uncertainty in the velocity characterization, the average of the three velocity measurements seems like a reasonable summary parameter. Accepting this velocity definition, the velocities tested in Tracer Experiments II were 85.3, 75.3, 66.1, and 43.3 fpm. It should be noted that 100 fpm was not tested with the velocities defined in this manner. However, the average of 85.3 fpm corresponded to 97.3 fpm measured at the aircraft nose, and the average of 75.3 fpm corresponded to 88.1 fpm estimated as the velocity at the nose. One effect of the exhaust filter having a smaller area and larger velocity than the supply filter may be to focus the flow in a kind of channel that surrounds the aircraft and work process.

Considering Tracer Experiments II, it can be said that Setting 3 (75.3 fpm) is either similarly or more protective than Setting 4 (85.3 fpm), and both of these configurations are more effective than either Setting 2 (66.1 fpm) or Setting 1 (43.3 fpm). The air velocities given here are thought to be the single values that best represent the velocities throughout the hangar bay. The spatial variation in these velocities is shown in Table 7.

Conclusions and Recommendations

Based on the additional tracer gas tests and CFD simulations, the following conclusions and recommendations can be 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 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 (i.e. supply rate and exhaust rate nearly equal, with 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 exposures (from 1742 to 249.7 ppb). Increasing the average velocity from 66.1 to 75.3 fpm lowered exposures (from 1526 to 353.7 ppb), while increasing the average velocity from 75.3 to 85.3 fpm increased exposures (from 353.7 to 1193 ppb).

Recommendations

1. Achieving balanced flow (perhaps -0.05 in. water gauge, if prevention of fugitive emissions to the environment is desired) 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 clearly 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.

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