



AFRL-SA-WP-TR-2019-0007

Exploratory Studies of Chemical Contaminants in Pilot Breathing Air and on the Flight Line at Luke Air Force Base



Christin Duran, PhD; Daniel Reilly, MS; Danielle McKenzie-Smith, MS; Megan Steele; Darrin Ott, PhD



March 2019

**Final Report
for June 2017 to December 2017**

**DISTRIBUTION STATEMENT A. Approved
for public release. Distribution is unlimited.**

**Air Force Research Laboratory
711th Human Performance Wing
U.S. Air Force School of Aerospace Medicine
Aeromedical Research Department
2510 Fifth St., Bldg. 840
Wright-Patterson AFB, OH 45433-7913**

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

Qualified requestors may obtain copies of this report from the Defense Technical Information Center (DTIC) (<http://www.dtic.mil>).

AFRL-SA-WP-TR-2019-0007 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//SIGNATURE//

DR. DARRIN K. OTT
CRCL Force Health Protection

//SIGNATURE//

DR. RICHARD HERSACK
Chair, Aeromedical Research Department

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

REPORT DOCUMENTATION PAGE				<i>Form Approved</i> OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 28 Mar 2019		2. REPORT TYPE Final Technical Report		3. DATES COVERED (From – To) June 2017 – December 2017	
4. TITLE AND SUBTITLE Exploratory Studies of Chemical Contaminants in Pilot Breathing Air and on the Flight Line at Luke Air Force Base				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Christin Duran, PhD; Daniel Reilly, MS; Danielle McKenzie-Smith, MS; Megan Steele; Darrin Ott, PhD				5d. PROJECT NUMBER 16-045	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) USAF School of Aerospace Medicine Aeromedical Research Dept/FHOF 2510 Fifth St., Bldg. 840 Wright-Patterson AFB, OH 45433-7913				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-SA-WP-TR-2019-0007	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSORING/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.					
13. SUPPLEMENTARY NOTES Cleared, SAF/PA, Case # 2019-0310, 16 Apr 2019.					
14. ABSTRACT Exploratory exposure studies were completed at Luke Air Force Base (AFB) to investigate various factors with potential to play a role in unexplained physiological events (UPEs) experienced by pilots. Potential factors investigated included: 1) chemical contamination in pilot breathing air, 2) aircraft exhaust re-entrainment from one jet to the intake of another and 3) chemical contamination on the flight line. To address the first concern of chemical contamination in pilot breathing air, a test system was designed to interface a suite of air sampling methods with pilot breathing air during engine ground runs. Results from engine run tests indicated a momentary spike in carbon dioxide, nitrogen monoxide and total volatile organic compounds (VOCs) just after engine start. A subset of VOCs was identified over the duration of the engine run at parts per billion levels, which were below occupational exposure limits. To assess the potential for exhaust re-entrainment, a sample scenario was designed using computational fluid dynamics aimed to model the behavior of a jet exhaust plume in typical weather conditions at Luke AFB. Results indicated that exhaust exposure to aircraft intakes and flight line maintainers was contingent on parking position and wind direction, where a subset of scenarios illustrated an increased risk of exposure. A limited set of experimental data were generated to confirm the findings. To investigate the third concern related to environmental factors, air sampling instruments were stationed at several locations around the flight line for a three-day period. Respirable particles dominated total particles present on the flight line. VOCs and combustion gases remained well below occupational exposure limits. Based on the findings of these exploratory studies, follow-on studies have been designed to address remaining research gaps and expand on preliminary findings. These include: 1) refinement of the test system for engine ground runs to include an updated gas sensor module with improved sensor response time and range, 2) additional testing of the ground engine run test system to evaluate the potential relationship between VOCs in pilot breathing air and UPEs, and 3) further refinement of jet exhaust plume dispersion and flight line air quality assessment approaches to better understand the impact of operational activity and infrastructure on chemical contaminants on the flight line and in pilot breathing air.					
15. SUBJECT TERMS Unexplained physiological events, chemical contamination, on-board oxygen generation system, exhaust re-entrainment, air pollution, computational fluid dynamics modeling, air dispersion modeling					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 61	19a. NAME OF RESPONSIBLE PERSON Christin Duran, PhD
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code)

This page intentionally left blank.

TABLE OF CONTENTS

	Page
LIST OF FIGURES	iii
LIST OF TABLES	iv
1.0 EXECUTIVE SUMMARY	1
2.0 MOTIVATION AND CONTRIBUTIONS	3
2.1 Motivation.....	3
2.2 Contributions.....	3
3.0 STUDY #1: CHARACTERIZATION OF PILOT BREATHING AIR	3
3.1 Introduction.....	3
3.2 Methodology	4
3.2.1 Engine Runs	4
3.2.2 BOS Cart Sampling.....	6
3.3 Results and Discussion.....	7
3.3.1 Engine Runs	7
3.3.2 BOS Cart Sampling.....	12
3.4 Conclusion and Future Work	13
4.0 STUDY #2: FLIGHT LINE EXHAUST PLUME MODELING	14
4.1 Introduction	14
4.2 Methods.....	14
4.2.1 Flight Line Exhaust Measurements	14
4.2.2 Computational Fluid Dynamics Model.....	14
4.3 Results	15
4.3.1 Flight Line Exhaust Measurements	15
4.3.2 Permutation Simulation Solutions	18
4.4 Conclusions	20
5.0 STUDY#3: FLIGHT LINE AIR QUALITY	21
5.1 Introduction.....	21
5.2 Methods.....	21
5.3 Results.....	23
5.4 Conclusion and Future Work	29
6.0 CONCLUSIONS AND FUTURE DIRECTIONS.....	29
7.0 REFERENCES	31

TABLE OF CONTENTS (concluded)

	Page
APPENDIX A: Tubing Outgassing	32
APPENDIX B: VOCs Sampled and Associated LODs	33
APPENDIX C: Domain and Mesh Sensitivity	36
APPENDIX D: Time Resolved Gas Levels on the Flight Line.....	39
APPENDIX E: Time Resolved Respirable and Total Aerosols on the Flight Line.....	51
LIST OF ABBREVIATIONS AND ACRONYMS	52

LIST OF FIGURES

	Page
Figure 1. Internal configuration of the BASS	4
Figure 2. Gas sensor data from pilot breathing air during engine run 1 (19 Jul 17)	8
Figure 3. Particle sensor data from pilot breathing air during engine run 1 (19 Jul 17)	9
Figure 4. VOCs identified during engine run 1 for each of the four different engine run phases in the two different air sources	10
Figure 5. Gas sensor data from pilot breathing air during engine run 2 (20 Jul 17)	11
Figure 6. Particle sensor data from pilot breathing air during engine run 2 (20 Jul 17)	12
Figure 7. Real-time air sample from BOS cart.....	12
Figure 8. Analytical characterization of BOS cart air	13
Figure 9. Simulation geometry for standard parking arrangement	15
Figure 10. Gas sensor data from locations around the jet during ground engine run 1 (19 Jul 18)	16
Figure 11. Gas sensor data from locations around the jet during ground engine run 2 (20 Jul 17)	17
Figure 12. Exhaust behavior for westward wind, nozzle velocity of 100 ft/s, and wind speeds of 5, 10, and 15 mph (left to right)	18
Figure 13. Exhaust wake behavior for westward wind, nozzle velocity of 300 ft/s, and wind speeds of 5, 10, and 15 mph (left to right)	18
Figure 14. Exhaust wake behavior in southerly wind, nozzle velocity of 100 ft/s, and wind speeds of 5, 10, and 15 mph (left to right)	18
Figure 15. Exhaust wake behavior for southerly wind, nozzle velocity of 300 ft/s, and wind speeds of 5, 10, and 15 mph (left to right)	19
Figure 16. Exhaust behavior for northly wind, nozzle velocity of 100 ft/s, and wind speeds of 5 and 10 mph (left to right).....	19
Figure 17. Exhaust dispersion model of eastward wind, nozzle velocity of 100 ft/s, and wind speeds of 5, 10, and 15 mph (left to right)	19
Figure 18. Exhaust dispersion model of eastward wind, nozzle velocity of 300 ft/s, and wind speeds of 5, 10, and 15 mph (left to right)	20
Figure 19. Map of sampling sites for flight line air quality assessment.....	22
Figure 20. Launch and recovery operations for two squadrons near sampling locations 1, 2, 4 and 5.....	23
Figure 21. Maximum and median concentrations of combustion gases and VOCs across three days of sampling at five locations sampled using MultiRAEs	24
Figure 22. NO data interpolated using inverse distance weighted average.....	25

LIST OF FIGURES (concluded)

	Page
Figure 23. O ₃ concentration at site 1	26
Figure 24. Particle data from mini-WRAS and Partector overlayed to show similarity in trends.....	27
Figure 25. Median and maximum concentrations for particulate matter at site 1.....	28
Figure 26. VOC concentration measured using TO-17 method at site 1	28

LIST OF TABLES

	Page
Table 1. Instruments in the BASS.....	5
Table 2. Gas Sensor Specifications.....	5
Table 3. Results from SO ₂ and NO/NO ₂ Methods	9
Table 4. Summary of Simulation Output.....	20
Table 5. Sampling Instruments used for Flight Line Air Quality	21
Table 6. Sampling Instruments at Each Sampling Site.....	23

1.0 EXECUTIVE SUMMARY

After an upsurge in unexplained physiological events (UPEs) experienced by pilots at Luke Air Force Base (AFB), the Joint Program Office (JPO) reached out the 711th Human Performance Wing (HPW) for support in determining what factors may play a role in these events. Studies were initiated to address three primary concerns: 1) chemical contamination in pilot breathing air, 2) jet exhaust re-entrainment by nearby aircraft, and 3) baseline chemical contaminants on the flight line. Communication with representatives at Luke AFB and the JPO was completed to ensure that all the conditions were met to complete field work and that studies were designed appropriately to address concerns.

To address the first concern of chemical contamination in the breathing system, a breathing air sampling system (BASS) was designed to interface a suite of air sampling methods directly with pilot breathing air during ground engine runs. The BASS was used to sample from both the cockpit and On-Board Oxygen Generation System (OBOGS) regulator simultaneously and incorporated commercial off-the-shelf (COTS) sampling equipment. COTS samplers included gas monitors equipped with sensors for oxygen (O₂), carbon dioxide (CO₂), carbon monoxide (CO), nitrogen monoxide and dioxide (NO and NO₂), hydrogen cyanide (HCN), sulfur dioxide (SO₂) and total volatile organic compounds (VOCs), particle monitors for lung deposited surface area concentration (LDSA) and ultrafine particle number concentration, and sampling pumps connected to sampling media for collecting air samples for offline analysis of VOCs, aldehydes, NO/NO₂ and SO₂.

The BASS system was initially fielded in July of 2017. Sampling events included one complete and one incomplete engine ground run, which was stopped short due to weather. The goal during the engine runs was to sample for chemical contaminants during four engine run phases, including Integrated Power Pack (IPP) start, idle, 30% engine thrust and maximum engine thrust. There was a momentary spike in carbon dioxide, nitrogen monoxide and total volatile organic compounds (VOCs) just after engine start. A subset of VOCs was detected at trace parts per billion by volume (ppbv) levels throughout the engine run. The VOC profile was slightly different in cockpit compared to OBOGS air, but similar compounds were detected. The levels of aldehydes, NO/NO₂ and SO₂ collected on sampling media were below the respective limits of detection (LOD).

During the same July 2017 field event as the engine run tests, the backup oxygen system (BOS) cart was sampled to follow-up regarding contaminants tentatively identified previously by Luke AFB bioenvironmental engineers. None of the chemical contaminants sampled were identified using real-time sensors. Trace levels of VOCs were identified when collected using Summa canisters. The same trace VOCs were identified in the background sample taken on the flight line near the BOS cart.

Preliminary data for CO₂ and CO around the aircraft were collected during the ground engine runs in July 2017. These results indicated that wind conditions strongly affect CO₂ levels around the aircraft. However, the data were limited to a small set of sample locations around a single aircraft. In order to provide a more comprehensive understanding of the exposure environment on the flight line and address the second concern regarding the potential for exhaust re-entrainment into the engine intake of nearby aircraft, a sample scenario was designed using computational fluid dynamics (CFD) in COMSOL Multiphysics software.

The sample scenario modeled using CFD software included two parking rows: one with six aircraft facing southwest and the other with three aircraft facing southeast. Both exhaust nozzle velocity and wind speed were varied based on expected ranges based on a limited set of exhaust data provided through interactions with subject matter experts and weather data typical for Luke AFB. Results indicated that re-entrainment and exposure to flight line maintainers in neighboring parking canopies were contingent on aircraft parking position and wind direction, where north-south winds caused the greatest area of jet exhaust exposure. The coverage area of the jet exhaust plume increased with increasing exhaust nozzle velocity and decreasing wind speed. Results were communicated with bioenvironmental engineers at Luke AFB in November 2017 in the form of a slide deck.

To assess the third concern regarding flight line air quality, a second field sampling event was completed in September 2017. During this event, air sampling instruments were stationed at several locations around the flight line for a three-day period. Combustion gases and VOCs sampled were found to be orders of magnitude lower than occupational exposure limits (OELs). Particles in the respirable sized fraction dominated total particles present on the flight line, indicating the dominance of exhaust components. However, due to a limited amount of baseline data and lack of exposure limits for ultrafine particles, it is not known based on this preliminary assessment whether the level of ultrafine particles identified are cause for concern. Additional contaminants measured included NO, ozone (O₃) and VOCs. Additional research is required to compare flight line air quality at Luke AFB to other bases to determine whether there is an association between environmental factors and UPE occurrence.

Based on the findings of these exploratory studies, follow-on studies have been designed to address remaining research gaps and expand on preliminary findings. These include refinement of the BASS for engine ground runs, additional testing with the BASS to establish a baseline for chemical contaminants in pilot breathing air and further evaluation of the potential relationship between VOCs and other chemical contaminants in pilot breathing air and UPEs. Refinements required for the BASS include the need for a more robust test system requiring less input from the operator and eliminating the potential for foreign object debris. Further, there is a need for an improved O₂ sensor capable of sampling at concentrations approaching 100% to exceed the current upper limit of 30% for the COTS sensor, as well as gas sensors with faster response times to improve upon the COTS sensor response time of five seconds. There is also a need to enhance the breadth of chemical sampling approaches used in the BASS.

In addition to refinement of the BASS, there is also a need to further improve jet exhaust plume dispersion models and flight line air quality assessments to better understand the impact of operational activity and infrastructure on chemical contaminants on the flight line. The coupling of jet exhaust re-entrainment scenarios and ground engine run tests using the BASS are also required to evaluate the extent to which exhaust re-entrainment presents an exposure risk to the pilot. Beyond exposure assessments, research is needed to evaluate VOCs identified in pilot breathing air for their toxicity as a mixture under the conditions of flight. The path forward for each of the research topics discussed will be intentionally designed with flexibility, as the concerns surrounding UPEs, aircraft maintainer and pilot exposure health, and the advanced aircraft training mission continue to evolve.

2.0 MOTIVATION AND CONTRIBUTIONS

2.1 Motivation

The exploratory projects at Luke AFB were a combined effort amongst aircraft squadrons and BEEs at Luke AFB (POC: Maj Kenneth Kirk), the JPO (POC: Andrew Klein), and engineers and industrial hygienists from the 711th HPW Exposure Assessment Team of the USAFSAM Force Health Branch (FHOE). The JPO communicated the need for a better understanding the potential for chemical contaminants in pilot breathing air and the need to address the concern that exhaust re-entrainment could lead to chemical contaminants in pilot breathing air. The JPO also communicated the concern that environmental conditions could play a role in UPEs.

2.2 Contributions

AF personnel at Luke AFB coordinated with researchers from the 711th HPW to provide indoor space to calibrate, charge and prepare testing equipment, escort on the flight line, and access to aircraft during ground engine runs. The 711th HPW Exposure Assessment Team supplied the sampling equipment, consumable media, air quality expertise, CFD modeling capability, and data analysis to complete this effort. Sampling media for VOCs used during engine ground run tests and flight line air quality sampling were analyzed by collaborators in the Human Signatures Branch of the AFRL Airman Systems Directorate (RHXB; POC: Jennifer Martin, PhD). Sampling media for NO/NO₂, SO₂ and aldehydes used during engine ground run tests and Summa canisters to characterize the BOS were outsourced to ALS Environmental, Ltd (Cincinnati, OH).

3.0 STUDY #1: CHARACTERIZATION OF PILOT BREATHING AIR

3.1 Introduction

Due to the fact that the partial pressure of oxygen decreases with increasing altitude, some form of pressurization or oxygen supply is required in order to sustain pilots during flight [1]. In the advanced aircraft under investigation for the present study, O₂ is supplied to the pilot *via* an on-board oxygen generation system (OBOGS). The OBOGS is designed to concentrate O₂ in a molecular sieve that contains crystalline zeolite material designed to capture nitrogen molecules. A pressure swing technique is used to periodically purge nitrogen, allowing new nitrogen capture sites to become available. The product gas of the OBOGS contains about 95% O₂ and remaining argon [2].

The OBOGS is fed by the environmental control system that is pressured by bleed air from the engine compressor [1]. Since the OBOGS was not designed to filter gases and VOCs from engine bleed air, chemical contaminants may pass through into the pilot breathing air. Further, it has been noted that under certain conditions when the OBOGS is malfunctioning or perceived to malfunction, pilots may drop their masks and breath cockpit air directly [3]. Therefore, it is important to characterize both cockpit and breathing air from the OBOGS independently to understand potential contaminants that are inhaled by pilots.

Ideally, characterization for chemical contaminants would be completed during flight. However, the capability to complete characterization during ground engine runs bridges the gap in time required to certify sensors and instrumentation to be installed on aircraft to be used during flight. This is especially important at a time when the chemicals that may be present in the system are unknown, resulting in evolving characterization methodology. Therefore, members of the 711th HPW engineered a portable air quality sampling system to characterize pilot breathing air during engine ground runs. The first version of the test system was named the Breathing Air Sampling System (BASS).

3.2 Methodology

3.2.1 Engine Runs. The BASS was comprised of two independent manifolds secured inside a ruggedized case (Fig. 1). The inlet of one flow path within the system was designed to connect directly to the OBOGS regulator *via* a three-pin bayonet and pilot interface connector, while the inlet of the other was designed to be left open to sample ambient cockpit air. The two pathways in the system were labeled 'Mask' and 'Vent' respectively. In the first version of the BASS, COTS instruments were used exclusively, and the case was required to be left open for the duration of the ground engine run test.

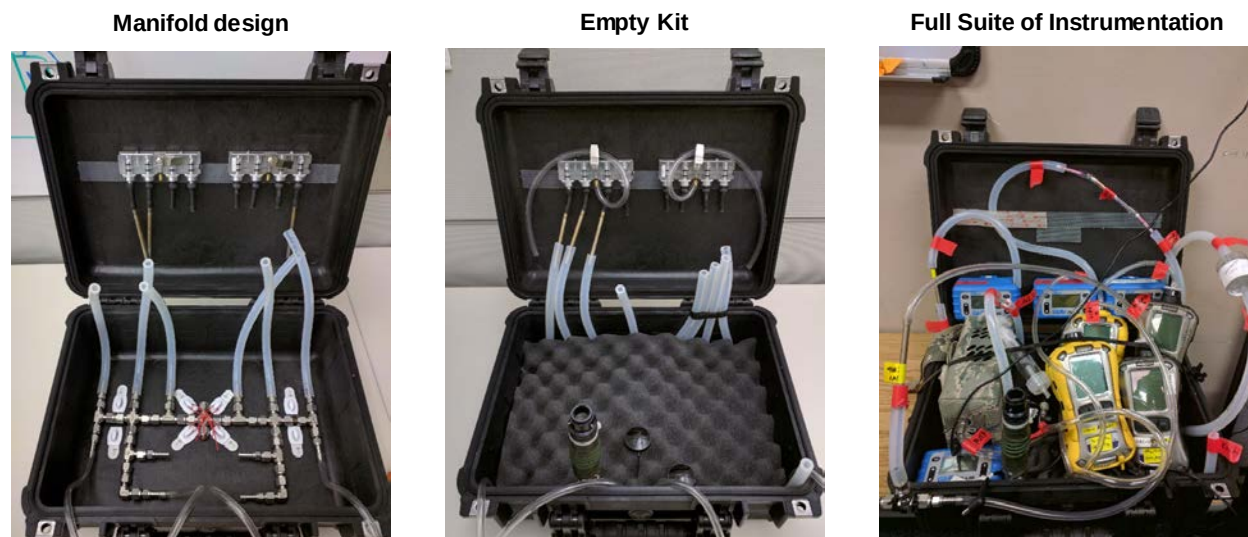


Figure 1. Internal configuration of the BASS

The majority of the flow paths were constructed with stainless steel tubing and fittings. When flexible tubing was required, medical grade silicone was chosen based on an in-house outgassing comparison study, which is described in Appendix A. For particle sampling, black conductive silicone tubing was used to mitigate particle loss. Tubing connected downstream of sampling media was given less consideration and was commonly composed of Tygon.

The instruments in the BASS included direct reading instruments and sampling pumps (Table 1). Direct reading MutliRAEs were used to monitor gases in real-time. Gas sensors included volatile organic compounds (VOCs), oxygen (O₂), carbon dioxide (CO₂), carbon monoxide (CO), nitrogen oxide (NO), nitrogen dioxide (NO₂), hydrogen cyanide (HCN), sulfur

dioxide (SO₂) and hydrogen disulfide (H₂S). Ultrafine particle counters included an electrometer and a water-based particle counter. All direct reading instruments collected data at a frequency of 1 Hz. Sampling pumps were connected to different types of media to collect samples for offline analysis.

Table 1. Instruments in the BASS

Technology	Manufacturer	Model	Output
direct reading gas monitor with sensors for VOCs, CO, HCN, SO ₂ , NO ₂ *	RAE Systems, Inc	MultiRAE Pro	real-time gas concentrations
direct reading gas monitor with sensors for CO ₂ , O ₂ , CO, H ₂ S, NO, NO ₂ *	RAE Systems, Inc	MultiRAE Lite	real-time gas concentrations
particle electrometer	Naneos Particle Solutions, GmbH	Partector	real-time lung deposited surface area concentration
water-based condensation particle counter	Enmont LLC	Personal Ultrafine Particle Counter, C100	real-time particle number concentration
air sampling pumps	Sensidyne, Inc	GilAir Plus	total air volume sampled

*Sensor specifications in Table 2.

When available, instruments were present in duplicate to sample from each air source. Due to the limited availability of instruments for ultrafine particles at the time of the initial engine ground run sampling events described here, ultrafine particles were only sampled at the OBOGS regulator. The specifications for gas sensors used in the MultiRAEs are shown below (Table 2). Note that the O₂ sensor range was limited to an upper range of 30% using COTS instruments.

Table 2. Gas Sensor Specifications

Gas	Instrument	Sensor type	Range	Resolution	Response time (t ₉₀)
O ₂	Lite	Electrochemical	0–30% volume	0.1% volume	15 s
VOCs	Pro	Photoionization detector (PID)	10–2,000 ppb	10 ppb	49 s ± 13 s
CO ₂	Lite	Non-dispersive infrared (NDIR)	0–50,000 ppm	100 ppm	not reported
CO	Pro	Electrochemical	0–500 ppm	1 ppm	not reported
CO / H ₂ S	Lite	Electrochemical	0–500 ppm (CO); 0–200 ppm (H ₂ S)	1ppm (CO); 0.5ppm (H ₂ S)	not reported
HCN	Pro	Electrochemical	0–50 ppm	1 ppm	200 s
NO	Lite	Electrochemical	0–250 ppm	0.5 ppm	not reported
NO ₂	Pro & Lite	Electrochemical	0–20 ppm	0.1 ppm	not reported
SO ₂	Pro	Electrochemical	0–20 ppm	0.1 ppm	not reported

The sampling pumps were used to collect a volume of 550 mL air on soil vapor intrusion (SVI) thermal desorption (TD) tubes analyzed using the Environmental Protection Agency (EPA) TO-17 method for VOCs by collaborators in the Human Signatures Branch of the Airman Systems Directorate (RHXB; POC: Jennifer Martin, PhD) using a gas chromatographer - mass spectrometer (Thermo Fisher Scientific, Inc). The full list of VOCs measured with corresponding LODs are shown in Table B1 (Appendix B).

Additional sampling pumps were used to collect samples to be analyzed off-line for SO₂, aldehydes and NO/NO₂ by ALS Environmental. SO₂ was collected onto a cellulose / sodium carbonate treated filter preceded by 0.8 µm cellulose ester membrane and analyzed using an ion chromatographer (Dionex ICS-2000 with Dionex AS40 automated sampler) according to the National Institute for Occupational Safety and Health (NIOSH) 6004 method. NO/NO₂ were collected onto sorbent tubes containing (oxidizer + 2 triethanolamine-treated molecular sieve) and analyzed using a visible absorption spectrophotometer according to the NIOSH 6014 method. Aldehydes were collected onto sorbent tubes containing 10% 2-(hydroxymethyl) piperidine on Amberlite® XAD®-2, which is a hydrophobic copolymer of styrene-divinyl benzene resin (120 mg/60 mg) and analyzed using a gas chromatographer – mass spectrometer according to the NIOSH 2539 method. The sampling pump flow rates were calibrated before and after each sampling event using a primary flow calibrator (Defender, Mesa Laboratories, Inc). Gas meters were also calibrated before and after each sampling event using calibration gases of known concentration.

A successful ground test consisted of four engine run phases, including IPP start, engine start, 30% engine thrust, and max engine thrust. The OBOGS regulator was switched to the normal operation position upon engine start. Certified aircraft personnel (pilot, crew chief or maintainer) operated the aircraft and BASS while being coached by a 711th HPW field technician member standing next to the aircraft. Real-time instruments collected data from the time the operator was sitting in the cockpit and handed the BASS, to the time the BASS was handed back to a 711th HPW field technician after test completion. Sampling pumps connected to consumable media were either running for the full duration of the engine run or in shorter time blocks to capture specific phases of the engine run. The former approach was used for aldehydes and NO/NO₂, while the latter was used for SO₂ and VOCs. To sample SO₂ and VOCs, the operator manually inserted new media and started the corresponding pump at the beginning of each engine run phase and removed the used media and stopped the pump at the end of each engine run phase.

The total flow rate the BASS pulled from the OBOGS regulator was 3.64 L/min at the peak when VOC and SO₂ collection were running and 2.0 L/min constant. The breakdown is as follows: 0.50 L/min (MultiRAE × 2), 0.45 L/min (Partector), 0.30 L/min (C100), 0.11 L/min (EPA TO-17*), 1.50 L/min (NIOSH 6004*), 0.025 L/min (NIOSH 6014) and 0.25 L/min (NIOSH 2539). The asterisked methods were run for distinct 4-6 min periods within engine run phases.

3.2.2 BOS Cart Sampling. The BOS cart was sampled using a MultiRAE Lite, TD tubes and Summa canisters. The MultiRAE sampled continuously before the BOS cart valve was opened, while it was open and after it was closed. One TD tube and Summa canister were collected before the BOS cart valve was opened (background) and a second TD tube and Summa canister were collected while the valve was open (BOS cart). To sample the BOS cart output, the sampling instruments were held in the outlet stream. The sensors used in the MultiRAE included

O₂, CO₂ and CO (see instrument specifications in Table 1 and sensor specifications in Table 2). The Summa canisters were analyzed using EPA Method 25C for CO₂ and CO, EPA Method 3C for O₂ and N₂. EPA TO-3 method for light VOCs (methane, ethene, ethane and propane), and EPA TO-15 method for VOCs by ALS Environmental. The full list of VOCs with the respective LODs is shown in Table B2 (Appendix B).

3.3 Results and Discussion

3.3.1 Engine Runs. The first complete engine run sampled using the BASS was completed on 19 July, 2017. The data output from direct-reading gas monitors is shown in Figure 2. Mask O₂ peaked at 30% after the engine start, which is the maximum concentration of the COTS sensor that was used (Fig. 2A). Vent O₂ remained relatively stable throughout the run. The small variations were attributed to the proximity of the sensor outlet port from the mask source to the intake of the vent source. This was corrected for future engine runs. Mask CO₂ was stable at 200 ppm until the OBOGS regulator was activated at engine start, at which point the concentration peaked momentarily to 1100 ppm, and then dropped to 0 ppm once the OBOGS regulator was activated (Fig. 2B). The CO₂ in the cockpit peaked several times throughout the run, with the highest peak reaching 600 ppm.

VOCs were present in both mask and vent sources at low levels of ≤ 100 ppb (Fig. 2C). There was a momentary peak in mask VOCs reaching 300 ppb when the OBOGS regulator was activated, which corresponded to the peak in CO₂ observed. NO₂ was present on the flight line, but not in the mask or vent air (Fig. 2D). NO readings rose to 0.5 ppm in both mask and vent air before IPP start, which is about the time the BASS was lifted onto the lap of the pilot sitting in the cockpit. NO dropped back down to 0 ppm once the engine run ended (Fig. 2E). HCN read 0.5 ppm from the beginning of the measurement, but then dropped to zero during the run (Fig. 2F).

The data output from the particle monitors is shown in Figure 3. Mask ultrafine particles as measured using the water-based particle counter are apparent in the early readings when the system was running on the flight line (Fig. 3A). However, this is not shown in the readings from the electrometer (Fig. 3B). Particles were zero according to both instruments during the period from engine start (OBOGS activation) until the end of the engine run.

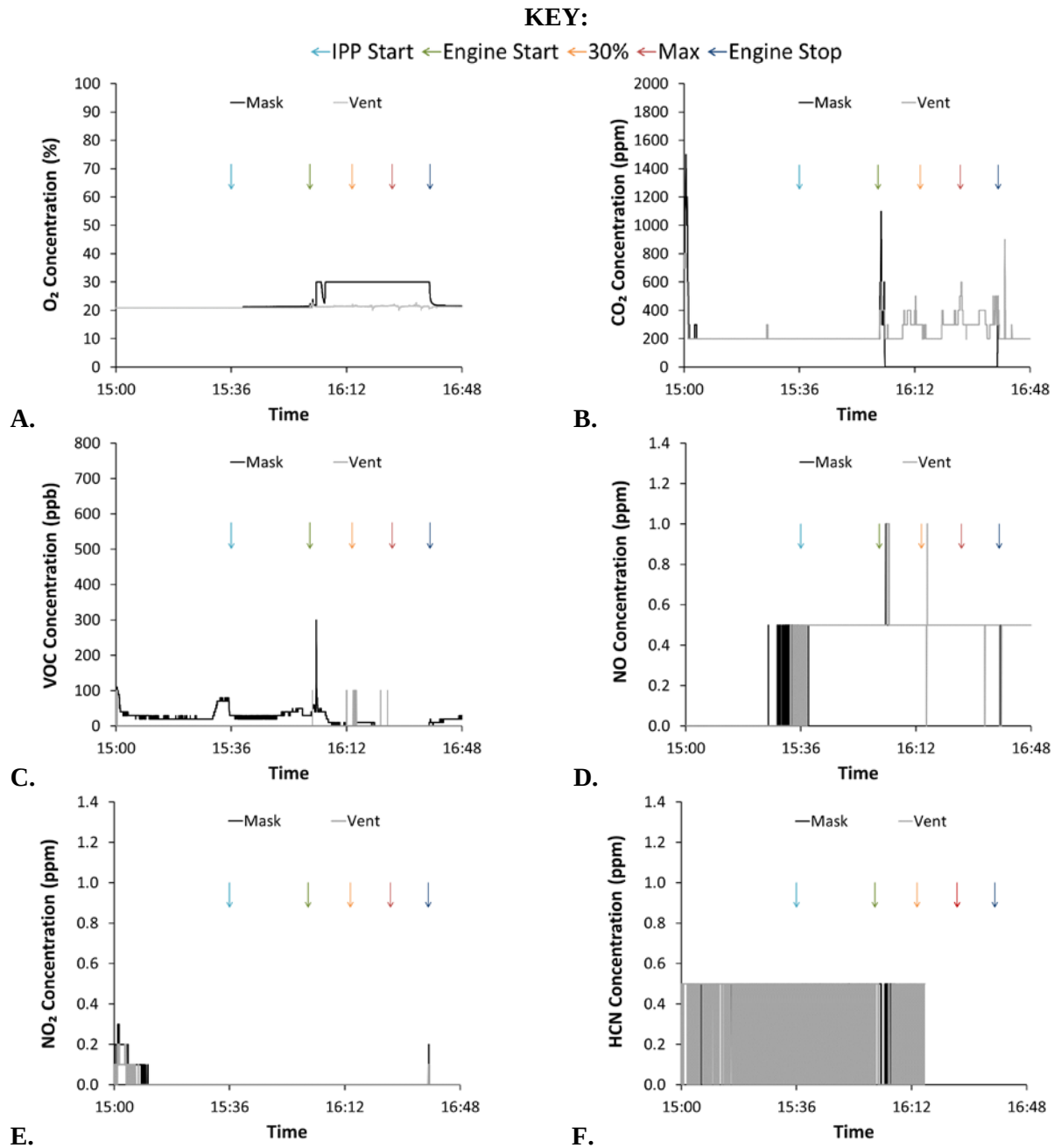


Figure 2. Gas sensor data from pilot breathing air during engine run 1 (19 Jul 17). Breathing air sources included Mask (OBOGS regulator) and Vent (cockpit). A. O₂; B. CO₂; C. VOCs; D. NO₂; E. NO; F. HCN. Notes: CO and SO₂ sensor data not shown. The CO sensor read zero in both air sources for the duration of the run. The SO₂ sensor was only used to sample the OBOGS regulator and read 0.1 ppm for the duration of the run.

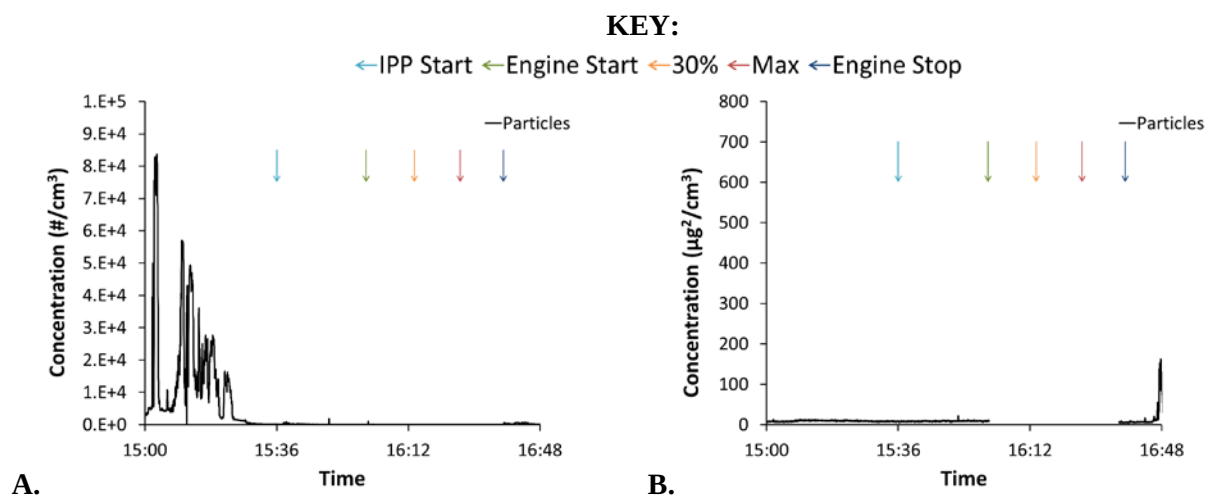


Figure 3. Particle sensor data from pilot breathing air during engine run 1 (19 Jul 17). A. Water-based condensation particle counter (C100, Enmont, LLC); B. Electrometer (Partector, CH Technologies, Inc).

Mask air was collected and analyzed using NIOSH method 6004 for SO₂ and NIOSH method 6014 for NO and NO₂. The results were below the LOD (Table 3).

Table 3. Results from SO₂ and NO/NO₂ Methods

Engine Run Phase	Particulate Sulfate (ppm)	SO ₂ (ppm)	NO (ppm)	NO ₂ (ppm)
IPP	<0.10	<0.16	<0.52	<0.34
Idle	<0.12	<0.19		
30%	<0.13	<0.20		
Max	<0.16	<0.25		

Aldehydes were also sampled continuously for the duration of the run from OBOGS air using NIOSH method 2539. The results were below the LOD (<0.075, <0.29, <0.055, <0.17 ppm for acetaldehyde, acrolein, formaldehyde and furfural, respectively).

VOCs were sampled from both OBOGS and cockpit air for each phase of the engine run (Fig. 4). The full list of VOCs measured with corresponding LODs are shown in Table B1 (Appendix B). The VOCs identified included 2-hexanone, methylene chloride, methyl ethyl ketone, propene, ethanol, 2-propenal, acetone, isopropyl alcohol, methyl isobutyl ketone and toluene. The latter three compounds were identified in OBOGS and background air, but not vent air. Chemicals identified in vent air, but not OBOGS air included 2-hexanone, methylene chloride and methyl ethyl ketone. There were no chemicals identified in only background air, but not OBOGS or vent air.

Ethanol, acetone and toluene was identified during all four phases of the engine run in OBOGS air with the highest concentration occurring during IPP start. Acetone was also identified in vent air and showed a similar trend. Ethanol was identified in vent air, but at lower initial concentrations and was below the LOD by the last engine run phase. Interestingly, methyl ethyl ketone did not show up until the last two phases of the engine run, which is the opposite

trend from the other chemicals identified in mask and vent air. All of the chemicals were below their respective OELs (see Table B3, Appendix B for list of OELs for each compound).

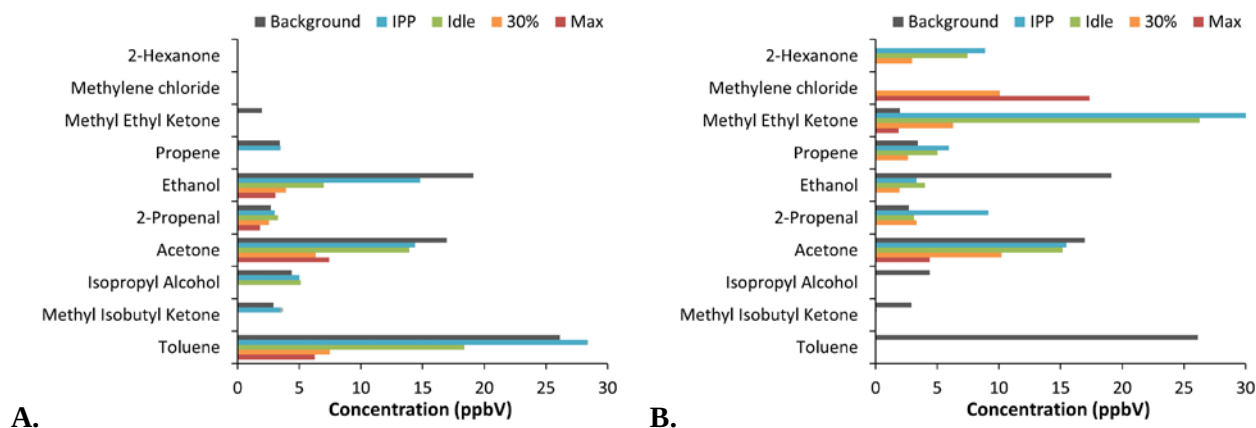


Figure 4. VOCs identified during engine run 1 for each of the four different engine run phases in the two different air sources. A. OBOGS (Mask) and B. Cockpit (Vent).

There were two tentatively identified compounds in all four samples from the vent side: 2,2,7,7-tetramethyloctane (retention time 14.57) and 2,2,4,4-tetramethyloctane (retention time 15.31). In each of the four cases, the former compound saturated the detector, and a concentration was not estimated for the latter compound. Limonene (retention time 14.59) was identified in three of the four samples from the Mask side at estimated concentrations ranging from 4.6 to 13.7 ppb. SO₂ was tentatively identified in the mask side at an estimated concentration of 24.7 ppb during maximum engine power thrust. However, since SO₂ was also identified in field blanks, this is thought to be an artifact. SO₂ was tentatively identified in both field blanks at estimated concentrations of 42 and 49 ppb. There were no other compounds identified in the field blanks. Field blanks were opened briefly and then closed to characterize the potential for passive exposure of chemicals to TD tube sorbent when switching samples.

A partial ground engine run was completed on 20 July 2017 (Engine Run 2). The test was cut short due to inclement weather. Therefore, sampling was only completed for the engine idle stage at OBOGS normal. The real-time data are shown in Figure 5. Mask O₂ peaked to 30% at engine start, but this was not sustained (Fig. 5A). Mask CO₂ peaked at 4000 ppm at engine start (Fig. 5B). The peak was wider and almost four times taller than in the first run. One large VOC spike to 700 ppb was observed in mask air just after 30% engine thrust was initiated (Fig. 5C). Mask and vent VOCs remained ≤100 ppb otherwise. NO₂ was not detected in either air source during the engine run (Fig. 5D). NO hovered around 0.5 ppm in mask air and 0 ppm in vent air (Fig. 5E). HCN remained near 0.5 ppm in both air sources throughout the run with two occurrences of spikes to 1.0 ppm in mask air that correspond with CO₂ spikes that were also observed in mask air (Fig. 5B, F).

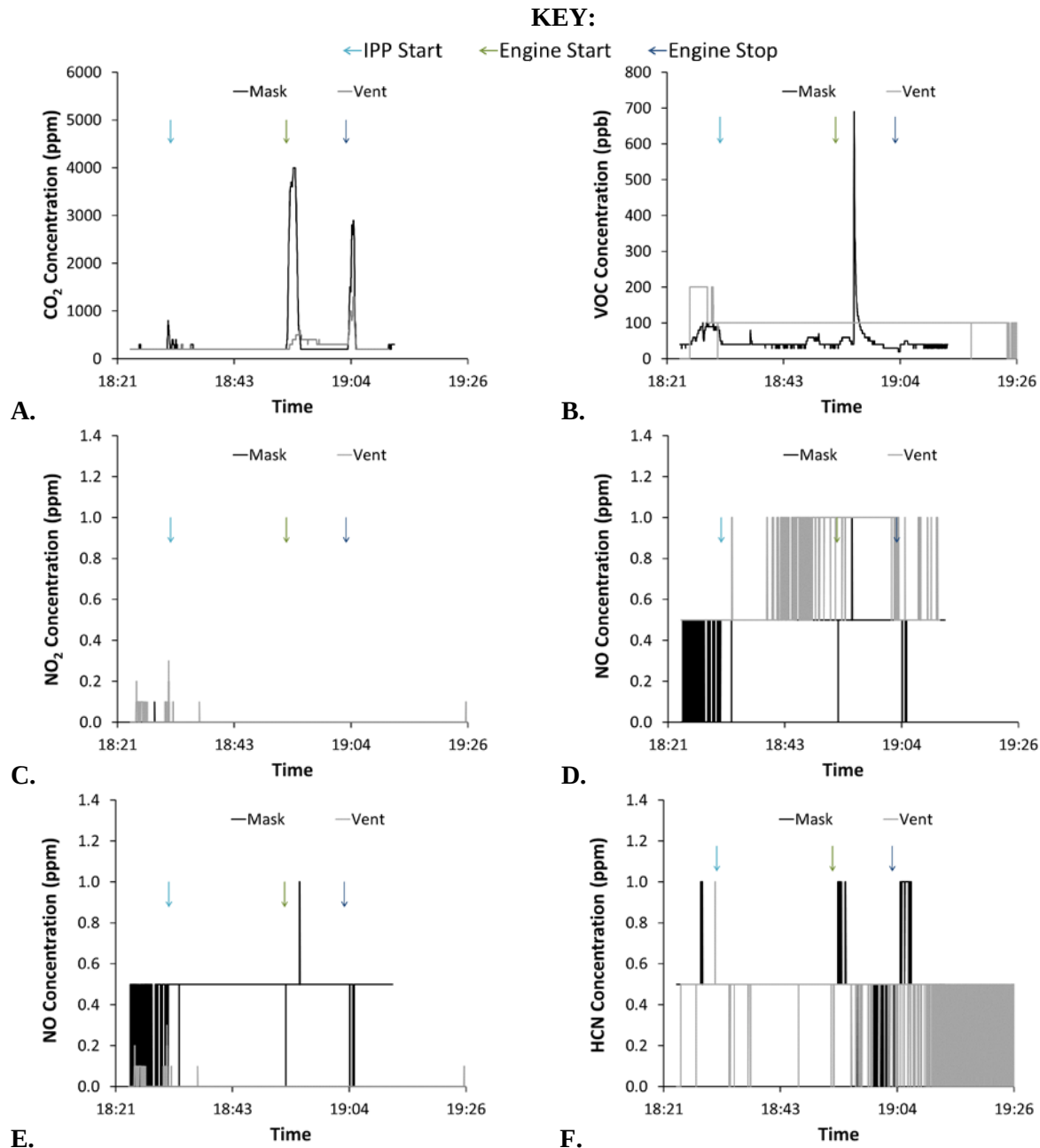


Figure 5. Gas sensor data from pilot breathing air during engine run 2 (20 Jul 17). Breathing air sources included Mask (OBOGS regulator) and Vent (cockpit). A. O_2 ; B. CO_2 ; C. VOCs; D. NO_2 ; E. NO; F. HCN. Notes: CO and SO_2 sensor data not shown. The CO sensor read zero in both air sources for the duration of the run. The SO_2 sensor was only used to sample the OBOGS regulator and read 0.1 ppm for the duration of the run.

OBOGS ultrafine particles are apparent in the early readings when the system was running on the flight line for both instruments (Fig. 6). Particles were zero during the period from engine start (OBOGS activation) until the end of the engine run, with the exception of a small peak observed by both instruments just after 30% thrust was achieved. Particles picked up again when the BASS was disconnected from pilot breathing air, and the aircraft was shut down.

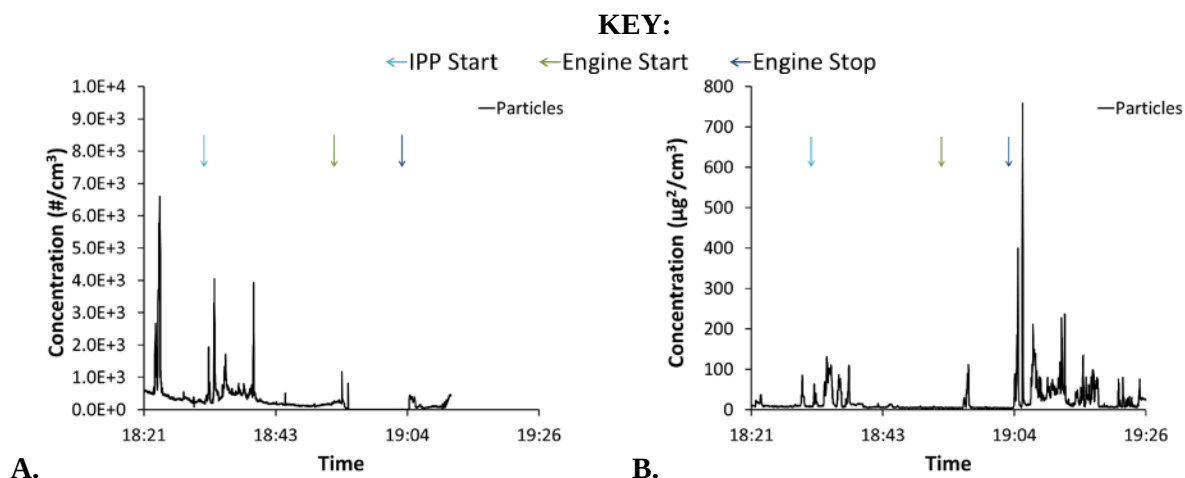


Figure 6. Particle sensor data from pilot breathing air during engine run 2 (20 Jul 17). A. Water-based condensation particle counter (C100, Enmont, LLC); B. Electrometer (Partector, CH Technologies, Inc).

Since the run was cut short, the media for VOCs, SO₂, NO/NO₂ and aldehydes were not analyzed.

Overall, all of the chemicals measured during ground engine runs were below limit set in the military standard for OBOGS output [4]. For a list of relevant standards from MIL-STD-3050, see Table B4 (Appendix B).

3.3.2 BOS Cart Sampling. The Backup Oxygen Supply (BOS) was sampled using a MultiRAE that contained a sensor for O₂, CO₂ and CO. CO was found to be zero. The plots for O₂ and CO₂ are shown below (Fig. 7). The arrows indicate the times at which the BOS valve was opened and closed.

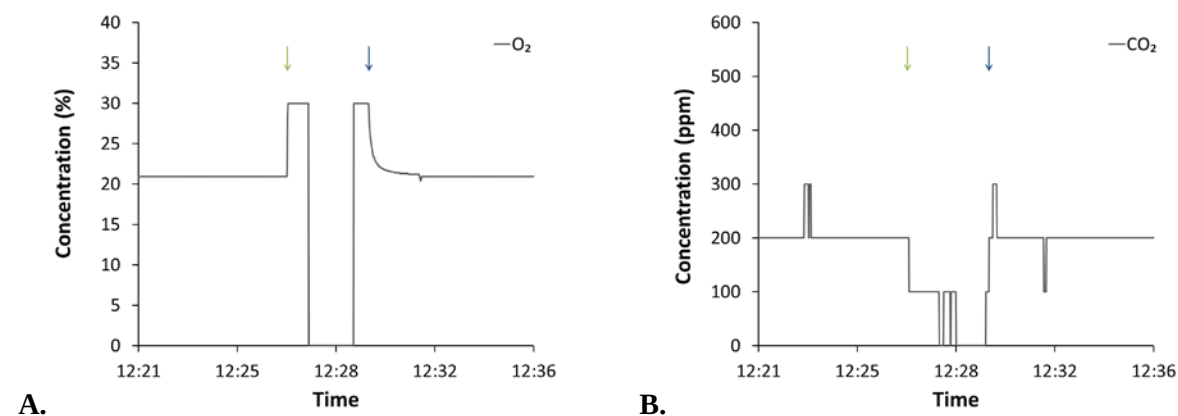


Figure 7. Real-time air sample from BOS cart. The time when the BOS valve was opened and closed are indicated by green and dark blue arrows, respectively. A. O₂; B. CO₂.

The BOS was also sampled using TD tubes and Summa canisters to test for contamination. There were no VOCs identified on TD tubes that were above the LOD. The Summa canister analysis revealed that the O₂ concentration was 97.7% with a balance of ~2.3% N₂ (Fig. 8). There were also trace amounts of CO₂ and methane (Fig. 8B), as well as toluene,

IPA, acetone, ethanol, dichlorofluoromethane and propene (Fig 8C). These VOCs were nearly identical in background air.

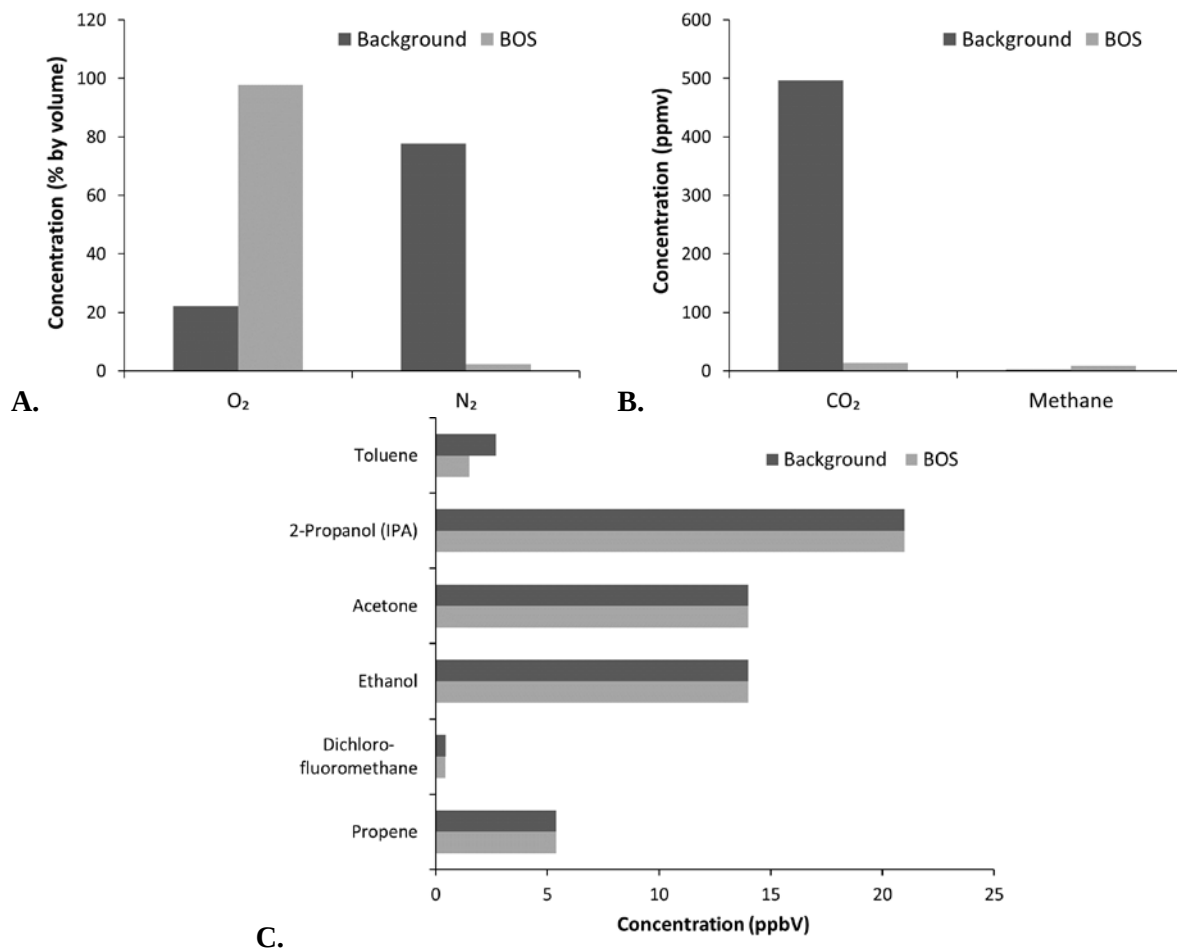


Figure 8. Analytical characterization of BOS cart air. A. O₂ and N₂; B. CO₂ and methane; C. VOCs. All data are from Summa Canisters. Data from TO-17 method was all below the LOD.

3.4 Conclusion and Future Work

Preliminary results from engine run tests indicated a momentary peak in CO₂, VOCs and NO just after engine start. Future work should be completed to confirm that this is routinely observed, determine what part of the start-up procedure this corresponds with, identify which VOCs cause the momentary peak observed, and finally, assess whether this exposure is toxicologically relevant to the pilot. For the remaining duration of the run, the pilot breathing air remained relatively clean of chemicals sampled. VOCs were identified at low ppbv levels, none of which approached OELs, but this should be further studied in reference to the relevance under the stressors of flight and association to aircraft susceptibility to be involved in a UPE.

Based on these preliminary studies, it is clear that more baseline data are needed to better understand the chemicals that are normally present in pilot breathing air. This is also the case for the BOS cart, which reported ppbv levels of VOCs that were similar to what was measured in

background flight line air. However, these data suffer from a single replicate. Additional replicates are required to better understand the findings.

Before additional replicates are acquired, shortcomings of the BASS must be addressed. Based on the lessons learned during this initial sampling event, requirements were developed for a second-generation test system, which includes implementation of OBOGS output flow rate measurement, improves response time on all gas sensors, O₂ sensor with a range up to 96% and a more robust design to remove the potential for foreign object debris and reduce manual operation of the test system. The details of this test systems will be further described in a follow-on report.

4.0 STUDY #2: FLIGHT LINE EXHAUST PLUME MODELING

4.1 Introduction

Exhaust re-entrainment occurs when exhaust generated by one aircraft is pulled into a subsequent aircraft intake, which results in the potential for chemical and ultrafine particulate contaminants to be introduced *via* engine bleed air into the environmental control system and ultimately delivered to the OBOGS. Since the OBOGS is designed to enrich oxygen, but not filter out contaminants, exhaust re-entrainment could potentially lead to introduction of chemical contaminants into pilot breathing air. A limited set of experimental data were generated during ground engine runs to track plume movement around the aircraft based on wind direction. In order to capture a large range of scenarios, CFD was used to predict the effect of weather conditions and aircraft spacing on plume dispersion and potential for exhaust re-entrainment. The model would be used as a basis for making critical decisions regarding potential base-wide wind monitoring designed to predict re-entrainment potential and operational maneuvers on the flight line.

4.2 Methods

4.2.1 Flight Line Exhaust Measurements. During the ground engine runs described in section 3.0, MultiRAE gas meters were placed at several points around the aircraft to sample the jet exhaust plume. Sensors were employed to monitor CO₂, CO and NO, which are known exhaust components. See Table 1 for gas meter specifications and Table 2 for sensor specifications. The wind speed and direction were also recorded using a Kestrel Weather Meter (Nielson Kellerman).

4.2.2 Computational Fluid Dynamics Model. COMSOL Multiphysics, a general-purpose differential equation platform software for modeling engineering applications, was implemented to generate the CFD models. Differential equation modules to track aircraft plume movement due to weather conditions and flight line operations included particle tracking, computational fluids, and heat transfer. These modules were used in parallel to predict three-dimensional thermodynamic exhaust plumes in a simulation domain aimed to mimic flight line spacing.

The basic model used for flight line geometry depicted a simplified aircraft geometry repeated six times in the first row and three times in the second row based on a typical parking arrangement at Luke AFB (Fig. 9). The aircraft in the lower left-hand corner (row 1, aircraft 1) was selected to simulate normal startup and taxi operations within the model, serving as the source of exhaust. The simulation domain was a 280 ft × 450 ft × 80 ft rectangular prism with a

computational mesh count of 985 thousand tetrahedral elements. The ideal height of the domain was determined using a domain sensitivity study, and the ideal mesh count was determined using a mesh sensitivity study (see Appendix C). The mesh was refined in the nearfield aircraft plume as well as near the surface of all simulated aircraft. Eight prism layers were implemented on all physical surfaces in order to ensure the wall distance was appropriate for boundary layer interaction, meaning the interaction between the fluid and surfaces were numerically sound.

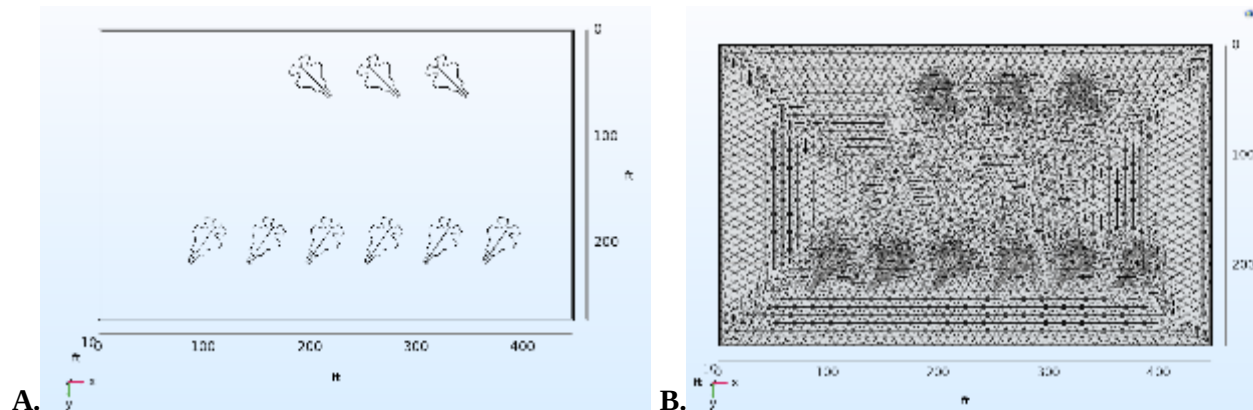


Figure 9. Simulation geometry for standard parking arrangement. A. Geometry; B. Computational mesh of tetrahedral elements.

A set of permutations were completed in order to help characterize the movement of the pollutant plume under four wind directions, two engine thrust powers and three wind speeds, making for 24 possible scenarios. The four wind directions were westward, southerly, northerly and eastward, and were implemented as velocity inlet boundary conditions on the four sides of the rectangular prism domain. The two wind speeds chosen to mimic wind speeds typical of Luke AFB were 5 and 10 mph. The ambient temperature was implemented to mimic Luke AFB conditions at 115°F

The engine thrust power was implemented as velocity and thermal boundary conditions normal to the nozzle face. The two velocities chosen to mimic possible low and high taxi thrust were 100 ft/s and 300 ft/s with a thermal aspect of 380°F and were implemented on the first aircraft in the first row. The velocities were chosen based on information provided by the Bioenvironmental Engineer shop at Luke AFB. A parametric study was completed for each parameter combination.

Each simulation was iterated until convergence criterion were satisfied. In all cases, convergence criterion was set to residuals dropping four orders of magnitude, which is accepted as a viable solution [5]. In the solutions, the plume was tracked using thermodynamic values associated with a thermal parameter of any value greater than 130°F and was depicted on an isosurface in order to visualize the distribution of plume contaminants.

4.3 Results

4.3.1 Flight Line Exhaust Measurements. The sampling locations and sensor readings during engine run 1 are shown in Figure 10. Gases were only detected at the two locations at the back of the aircraft. NO and CO₂ levels were highest at the back-left location, which is the direction downwind from the exhaust. The CO sensor did not report at that location, which was

unexpected. The span of the CO sensor is 500 ppm, so it is possible this sensor does not respond reliably at concentrations under 5 ppm.

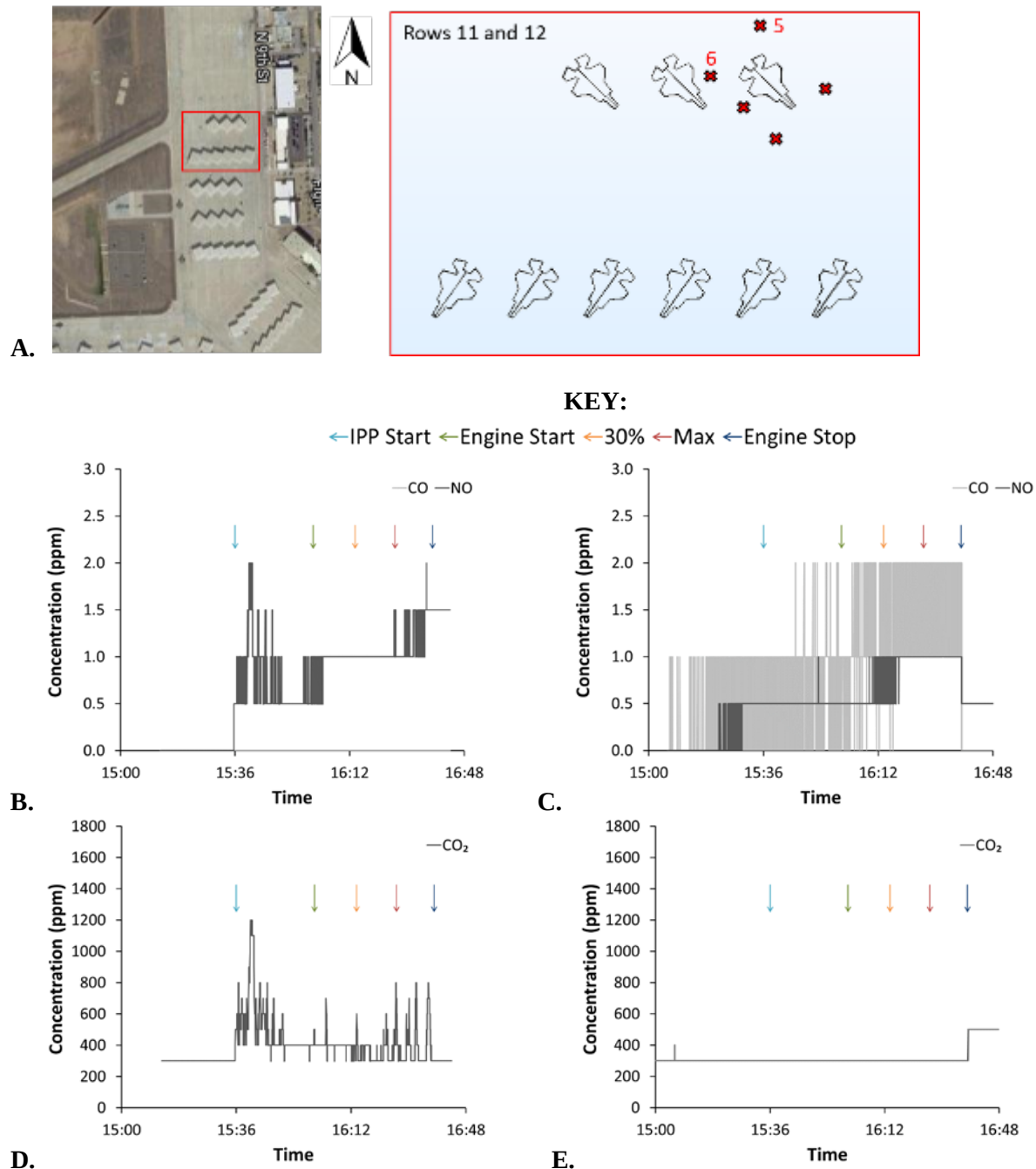


Figure 10. Gas sensor data from locations around the jet during ground engine run 1 (19 Jul 18). A. Schematic showing sensor placement; B. CO and NO data from the back left (location 6); C. CO and NO data from the back right (location 5); D. CO₂ data from the back left (location 6); E. CO₂ data from the back right (location 5). Wind measurements indicated a westward wind at 6 mph. The ambient temperature was 91°F.

The sampling locations and sensor readings during engine run 2 are shown in Figure 11. Gases were only detected at locations 1 and 3, which indicates the exhaust plume was redirected with the wind.

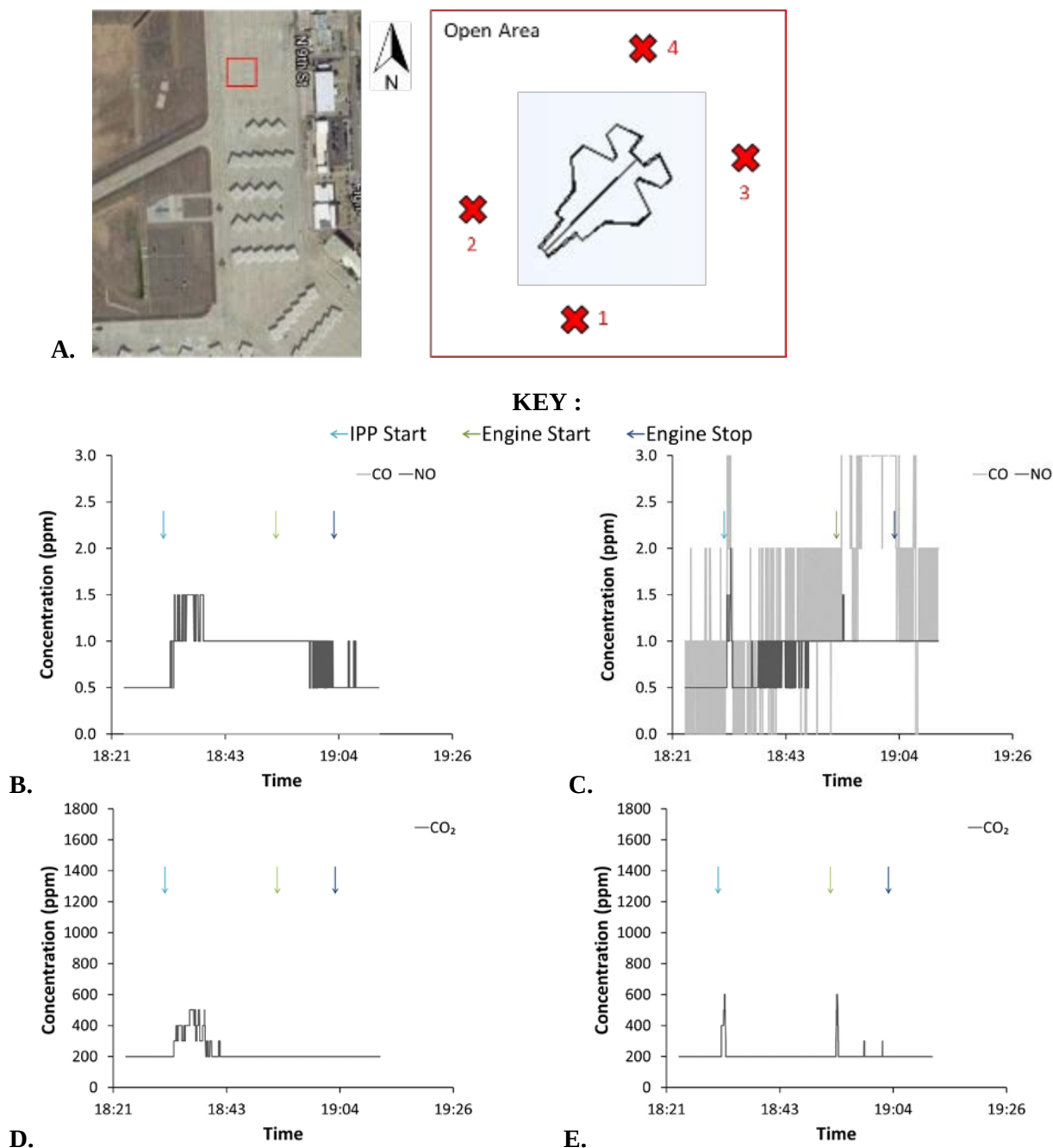


Figure 11. Gas sensor data from locations around the jet during ground engine run 2 (20 Jul 17). A. Schematic showing sensor placement; B. CO and NO data from the front left (location 1); C. CO and NO data from the back left (location 3); D. CO₂ data from the front left (location 1); E. CO₂ data from the back left (location 3). Note: CO was zero and CO₂ remained at baseline at the remaining locations for the duration of the ground run. NO was not measured at locations 2 and 4. Wind measurements indicated a southerly wind at 7 mph. The ambient temperature was 94°F.

4.3.2 Permutation Simulation Solutions. Plume interactions with the surrounding jets in westward wind conditions for nozzle velocity of 100 and 300 ft/s are shown in Figures 12 and 13, respectively. The likelihood of re-entrainment in these scenarios were low, as the exhaust plume was highly controlled by wind momentum, centralizing the plume to the taxi-way between the two rows of parked aircraft. The scenario displayed in Figure 13 was an exception to this overall observation. In this situation, the nozzle velocity's interaction with wind momentum actually increased the possibility of re-entrainment by aircrafts parked in the second row.

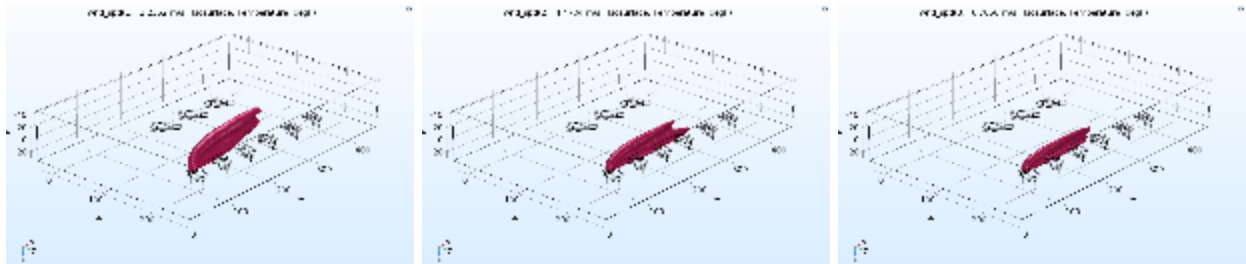


Figure 12. Exhaust behavior for westward wind, nozzle velocity of 100 ft/s, and wind speeds of 5, 10, and 15 mph (left to right).

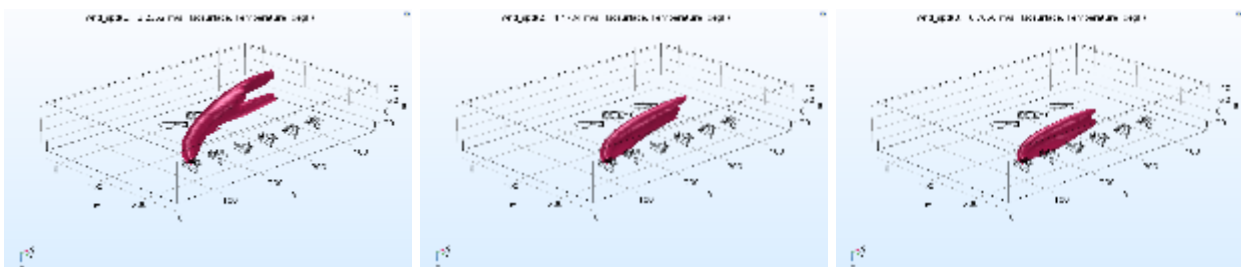


Figure 13. Exhaust wake behavior for westward wind, nozzle velocity of 300 ft/s, and wind speeds of 5, 10, and 15 mph (left to right).

Figures 14 and 15 depict a set of plume interactions simulated for southerly wind scenarios. Again, all exhaust wakes were wind-controlled and centralized away from neighboring aircrafts; however, this overall low-risk of re-entrainment observation is nuanced. Had the setup of the simulation used another aircraft from the first row, the risk of re-entrainment would be different and most likely higher.

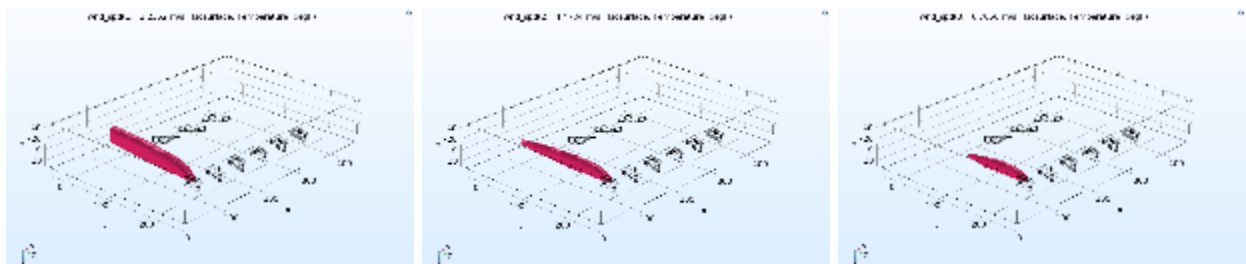


Figure 14. Exhaust wake behavior in southerly wind, nozzle velocity of 100 ft/s, and wind speeds of 5, 10, and 15 mph (left to right).

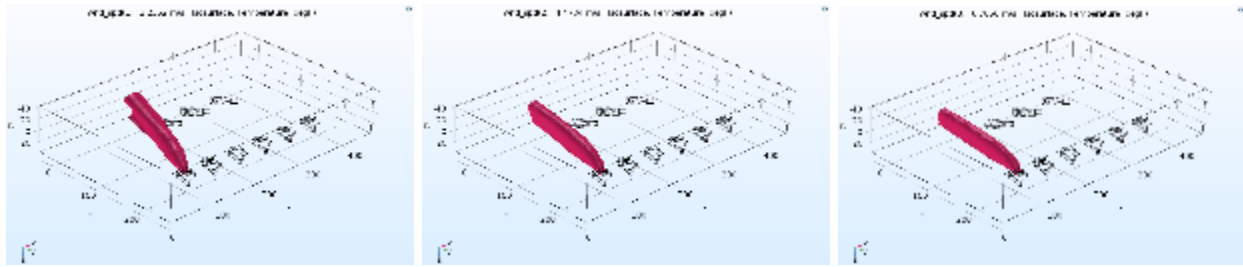


Figure 15. Exhaust wake behavior for southerly wind, nozzle velocity of 300 ft/s, and wind speeds of 5, 10, and 15 mph (left to right).

Simulations for northly wind exhibit obvious interaction between the modeled exhaust plume and aircraft in the first row. These cases highlight situations of highest concern and interestingly the jet producing exhaust emissions is the most at risk. However, re-entrainment possibilities for nozzle velocity of 100 ft/s and wind speeds of 5 and 10 mph were able to be accurately modeled (Fig.16). Convergence was difficult for the north to south vector wind cases for the highest conditions (nozzle velocity of 300 ft/s and wind speed of 15 mph). This was due to the difficult physics involved to calculate plume direction when there was high impingement between wind momentum and exhaust plume momentum.

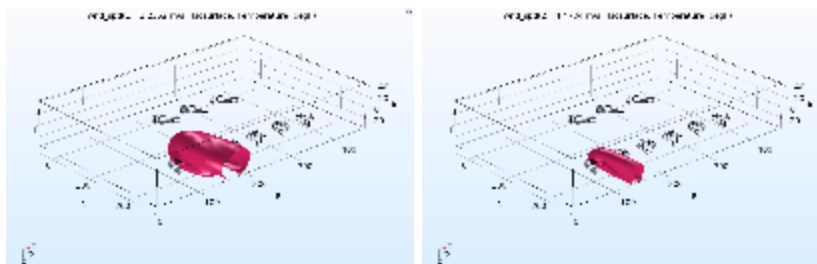


Figure 16. Exhaust behavior for northly wind, nozzle velocity of 100 ft/s, and wind speeds of 5 and 10 mph (left to right).

Figures 17 and 18 model re-entrainment potentials in eastern wind conditions. All such cases did not demonstrate interaction between the plume and subsequent aircraft. On average, it was observed the plume was directed immediately to the outlet of the simulations. Risk of re-entrainment would be dependent on aircraft movement on the flight line.

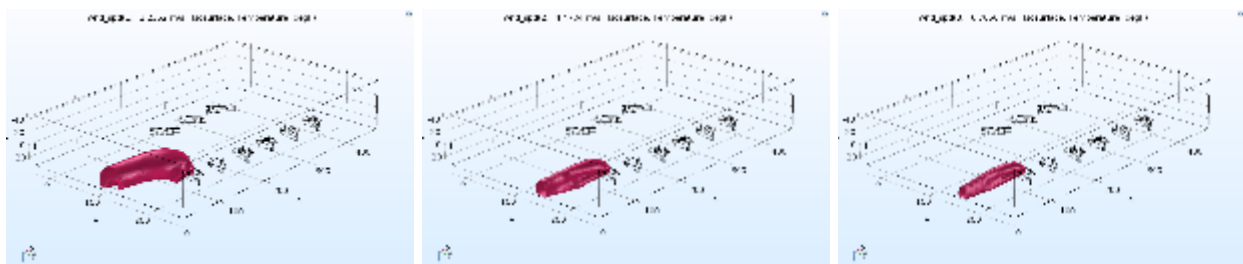


Figure 17. Exhaust dispersion model of eastward wind, nozzle velocity of 100 ft/s, and wind speeds of 5, 10, and 15 mph (left to right).

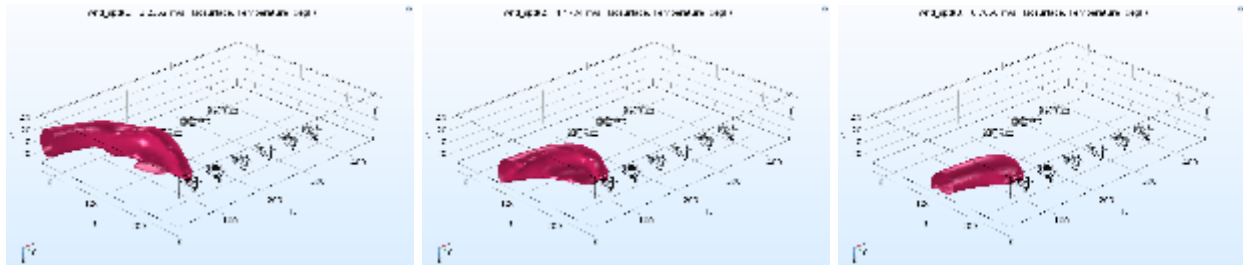


Figure 18. Exhaust dispersion model of eastward wind, nozzle velocity of 300 ft/s, and wind speeds of 5, 10, and 15 mph (left to right).

A summary of the CFD model output is shown in Table 4. Results and solutions presented in Figures 9-15 suggest there was low risk of re-entrainment in the modeled parking set up. This metric was based on plume interaction with subsequent aircraft which was characterized by an iso-surface of any temperature above 140°F. For this specific case, re-entrainment was most likely to occur when the wind direction was northerly causing the aircraft sourcing the exhaust to become engulfed. The simulations with the highest potential for exhaust re-entrainment by a nearby jet included southerly wind at all wind speeds, in addition to easterly wind at the lowest wind speed, where the plume remained fairly disperse. The simulations where the wind was directly opposing the exhaust plume exit did not converge in the model.

Table 4. Summary of Simulation Output

		Wind Speed and Direction											
		5				10				15			
Nozzle Velocity (ft/s)		N	S	E	W	N	S	E	W	N	S	E	W
	100	Green	Red	Green	Green	Green	Red	Green	Green	Green	Red	Green	Green
	300	Green	Purple	Red	Green	Green	Purple	Green	Green	Green	Purple	Green	Green

N = Northerly wind
S = Southerly wind
W = Westward wind
E = Eastward wind

Red: Plume interaction with subsequent aircraft
Green: NO Plume interaction with subsequent aircraft
Purple: Failed convergence

4.4 Conclusions

It is clear that there are a range of scenarios that affect jet exhaust plume dispersion with wind direction and speed playing a dominant role. Further work is to translate this information to be used for evaluating risk for UPE or diagnosing the role for exhaust re-entrainment in UPEs is required. One approach may be to implement the CFD output into an application where wind parameters can be entered as needed to understand risk. Ultimately, it may be more relevant to

take a step back and test the hypothesis that exhaust re-entrainment can cause chemical contaminants to enter pilot breathing air and play a role in UPEs.

5.0 STUDY#3: FLIGHT LINE AIR QUALITY

5.1 Introduction

There is a known correlation between environmental exposure to particulate matter and O₃ and respiratory health [6, 7]. This response has been shown to vary considerably within a study population and to be compounded for co-exposure to multiple pollutants. Based on this concept, there was concern at the JPO regarding flight line air quality at Luke AFB and whether it could play a role in UPEs. It is possible that air pollutants could induce an oxidative and inflammatory stress response in pilots that makes them more likely to experience health effects upon exposure to the stressors of flight. The goal of this exploratory study was to characterize air quality at Luke AFB during normal operations, providing a baseline of knowledge to derive future studies.

5.2 Methods

Air quality instrumentation monitored the following compounds: CO₂, CO, NO, SO₂, VOCs, O₃ and aerosols. The complete list of instruments is shown in Table 5. Not listed is the flow calibrator (Defender, Mesa Laboratories, Inc) used to calibrate flow rates of the air sampling pumps and the Logistically-Enabled Sampling System-Portable (LESS-P) before and after each sampling event. The LESS-P is a sampling pump with programmable valves to sequence sample collection onto TD tubes.

Table 5. Sampling Instruments used for Flight Line Air Quality

Technology	Manufacturer	Model	Output
direct reading gas monitor with sensors for VOCs	RAE Systems, Inc	ppbRAE Pro	real-time gas concentrations
direct reading gas monitor with sensors for VOCs*	RAE Systems, Inc	MultiRAE Pro	real-time gas concentrations
direct reading gas monitor with sensors for CO ₂ , CO, NO, NO ₂ *	RAE Systems, Inc	MultiRAE Lite	real-time gas concentrations
O ₃ meter	Aeroqual Limited	Series 500 Portable Air Quality Monitor	real-time ozone concentration
weather meter	Nielsen-Kellerman Company	Kestrel 5500	wind speed, direction
water-based condensation particle counter	Enmont LLC	Personal Ultrafine Particle Counter, C100	real-time particle number concentration
electrometer and optical particle counter	GRIMM Technologies, Inc	Mini Wide Range Aerosol Spectrometer (mini-WRAS)	real-time particle concentration and size distribution
sequencing pump system for TD tubes	Signature Sciences, LLC	LESS-P	total air volume sampled in pre-programmed time series
air sampling pumps	Sensidyne, Inc	GilAir Plus	total air volume sampled

One central station (site 1; red star) and four ancillary stations (sites 2-5; blue stars) were secured at various locations on the flight line (Fig. 19). Instruments allocated at each station collected data during normal base operations for twelve hours a day over the course of three days in September of 2017. Instruments were secured to tripods with industrial zip-ties, and tripods were secured to permanent structures on the flight line. All items with potential to become foreign object debris were carefully secured and inventoried during station set up, throughout the day and during station tear down.



Figure 19. Map of sampling sites for flight line air quality assessment.

The sampling instruments used at each location are listed in Table 6.

Table 6. Sampling Instruments at Each Sampling Site

Site	Equipment
1 (Central)	2× MultiRAEs (CO, CO ₂ , NO, SO ₂ , VOCs), 1× mini-WRAS, 1× LESS-P, 1× Aeroqual (O ₃), Gilair + SO ₂ cartridge, 1× Partector
2	2× MultiRAEs (CO, CO ₂ , NO, SO ₂ , VOCs)
3	1× MultiRAE (CO, CO ₂ , NO, SO ₂), 1× ppbRAE (VOCs)
4	1× MultiRAE (CO, CO ₂ , NO, SO ₂), 1× ppbRAE (VOCs)
5	2× MultiRAEs (CO, CO ₂ , NO, SO ₂ , VOCs)

Real-time data were downloaded at the end of each day and plotted and analyzed using Excel (Microsoft Corporation). Exposure maps were generated using geographical information system (GIS) software (ArcGIS, Environmental Systems Research Institute). The coordinates for instruments locations were overlaid with a map pulled from an ArcGIS online repository. Corresponding hourly averages were inserted at the instrument locations in ArcGIS, and an inverse distance weighting algorithm was used to interpolate pollutant values at unsampled locations within the area encompassed by the data points.

The operational activity each day included launch and recovery periods for two squadrons where aircraft were running on the flight line near sampling locations 1, 2, 4 and 5 (Fig. 20). Sampling location 3 was located away from launch and recover options.

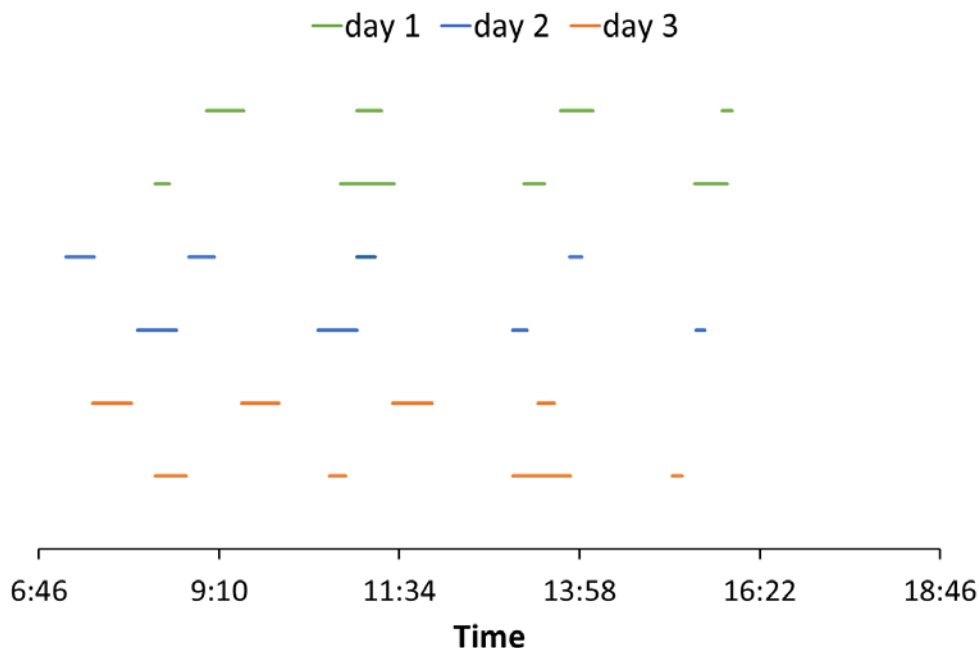


Figure 20. Launch and recovery operations for two squadrons near sampling locations 1, 2, 4 and 5.

5.3 Results

The concentration of combustion gases varied across the various sites. Graphs showing the evolution of gas concentration values at each site recorded throughout the day can be found

in Appendix D. Median and maximum values for CO₂, CO, NO and VOCs at each of the five sites are summarized in Figure 21.

The maximum concentrations reached for gases and VOCs varied by day and location (Fig. 21). The absolute maximum was 2500 ppm for CO₂ and 16 ppm for CO, which are much lower than NIOSH recommended exposure limit (REL) (30,000 ppm 15-min time-weighted average (TWA) short-term exposure limit for CO₂ and 200 ppm ceiling exposure limit for CO). The maximum concentration for VOCs was 14 ppm (Fig. 21C). There are no exposure limits to reference for total VOCs. Further speciation of VOCs is required using offline techniques. The peak concentration of NO was 1.4 ppm (Fig. 21D). The exposure limit for NO is limited to an 8 h TWA (no short-term or ceiling limit available).

The median values remained at around 300 ppm for CO₂ and zero for both CO and VOCs (Fig. 21A-C). The median concentration of NO was either 0 or 0.5 ppm (Fig. 21D). The NIOSH 8 h TWA REL is 5000 ppm and 35 ppm for CO₂ and CO, respectively. The NIOSH 8 h TWA REL for NO is 25 ppm. Therefore, exposure to the measured combustion gases is not likely a health risk.

KEY:

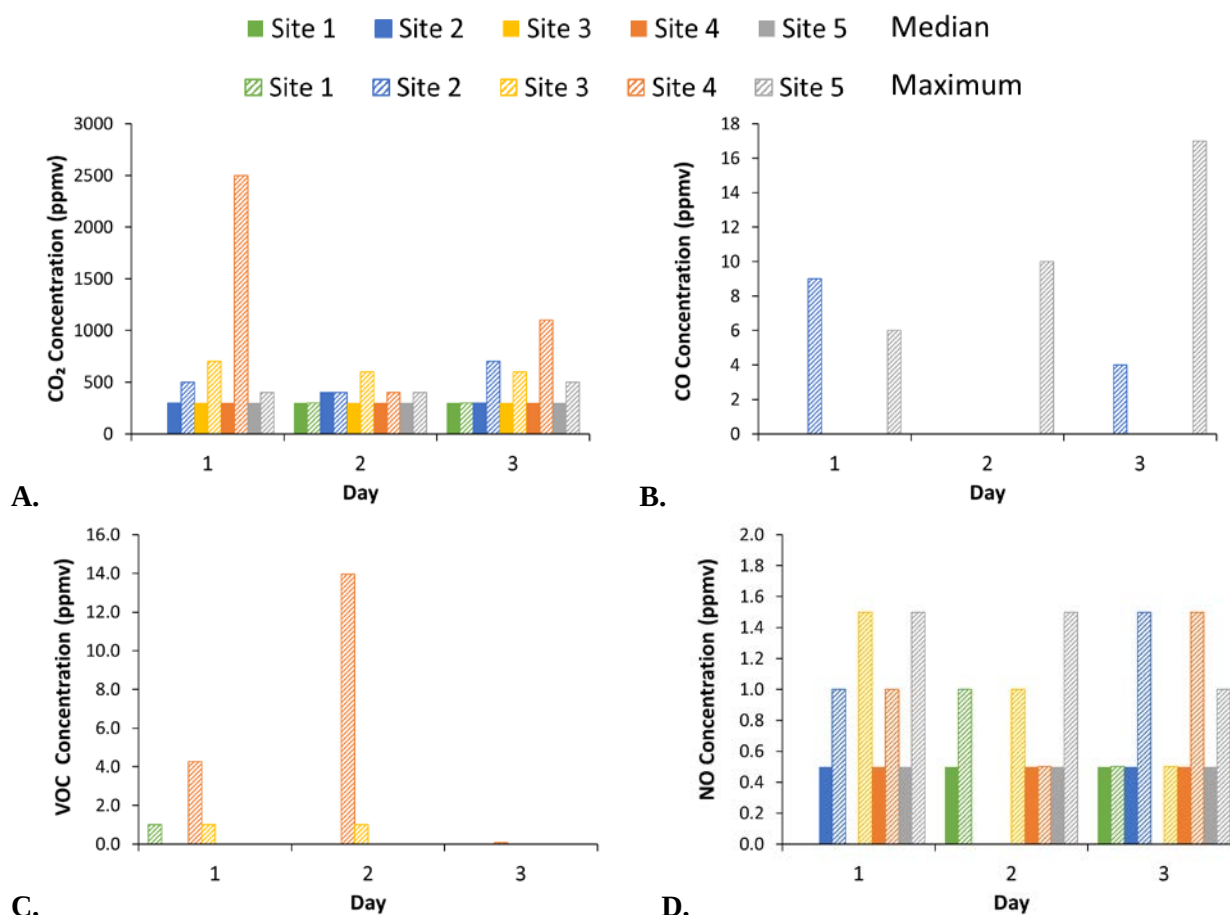


Figure 21. Maximum and median concentrations of combustion gases and VOCs across three days of sampling at five locations sampled using MultiRAEs. A. CO₂; B. CO; C. VOCs; D. NO. Notes: The MultiRAE at site 1 failed on day 1, so no data are shown. SO₂ did not peak above 0.2 ppm on any occasion.

Since NO was present consistently at each site throughout the day, concentrations were visualized across the five sites using an inverse distance weighted algorithm in GIS software (Fig. 22). The data are expressed as averages over one-hour periods, so the maximum values are not the same as in Fig. 21D. The concentration tended to reach a maximum in the middle of the day. The trends do not necessarily coordinate with the operational activity plot (Fig. 20), which showed launch and recovery options occurring throughout the day starting as early as 0700 and continuing until 1600. In future studies, mapping the operational activity spatially would improve the ability to make a correlation.

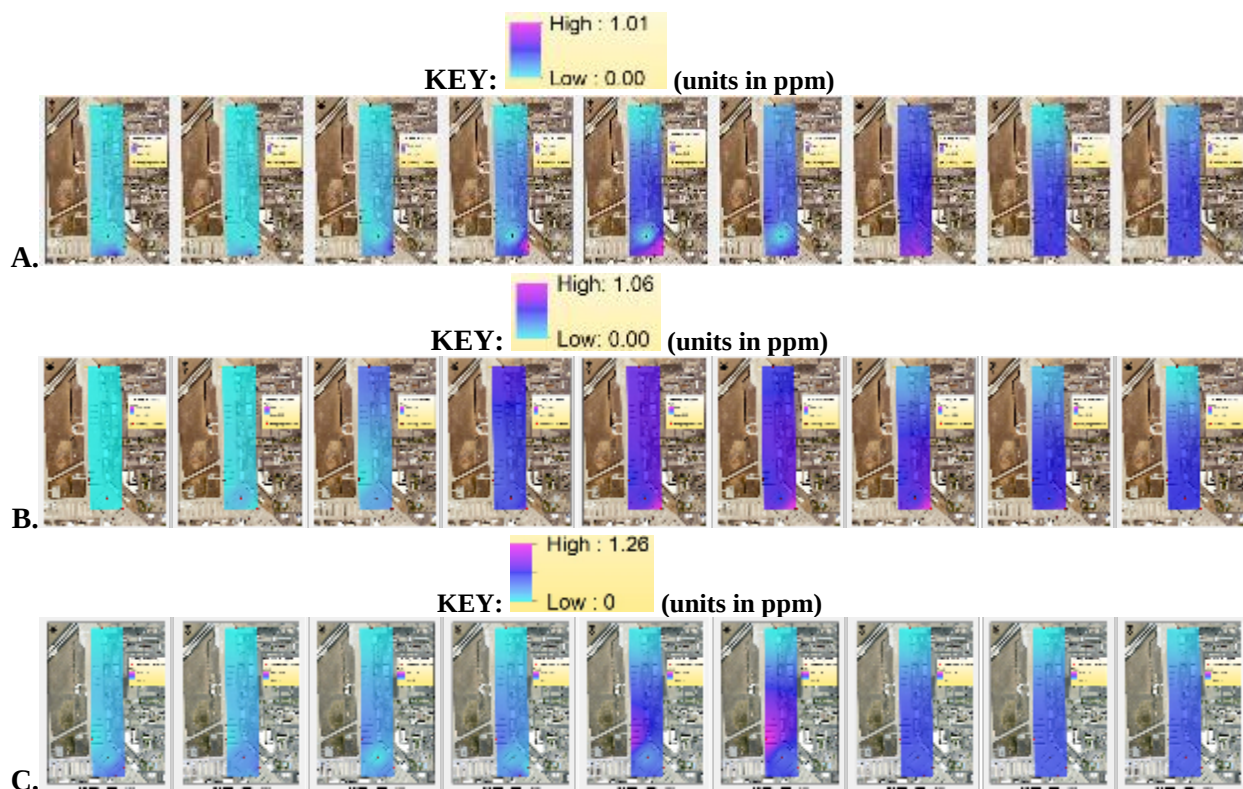


Figure 22. NO data interpolated using inverse distance weighted average. The plots represent 1 h time blocks progressing in time from left to right starting with 0800-0900 (furthest left) and ending with 1600-1700 (furthest right) for each day. A. day 1 (19 Sept 17); B. day 2 (20 Sept 17); C. day 3 (21 Sept 17). Exposure maps were generated using GIS software were prepared by Austin Wardall.

The time-resolved concentration plot for O₃ concentration indicate a steady rise throughout the day for days 1 and 2 (Fig. 23A-B). The O₃ monitor did not function properly on day 3. The median and maximum concentration values for O₃ concentration were 0.04-0.05 ppm and 0.07-0.08 ppm, respectively (Fig. 23C). The ACGIH 8h TWA threshold limit value (TLV) for O₃ is 0.05 ppm under conditions of heavy work, 0.08 ppm under conditions of moderate work and 0.1 ppm under conditions of light work [8].

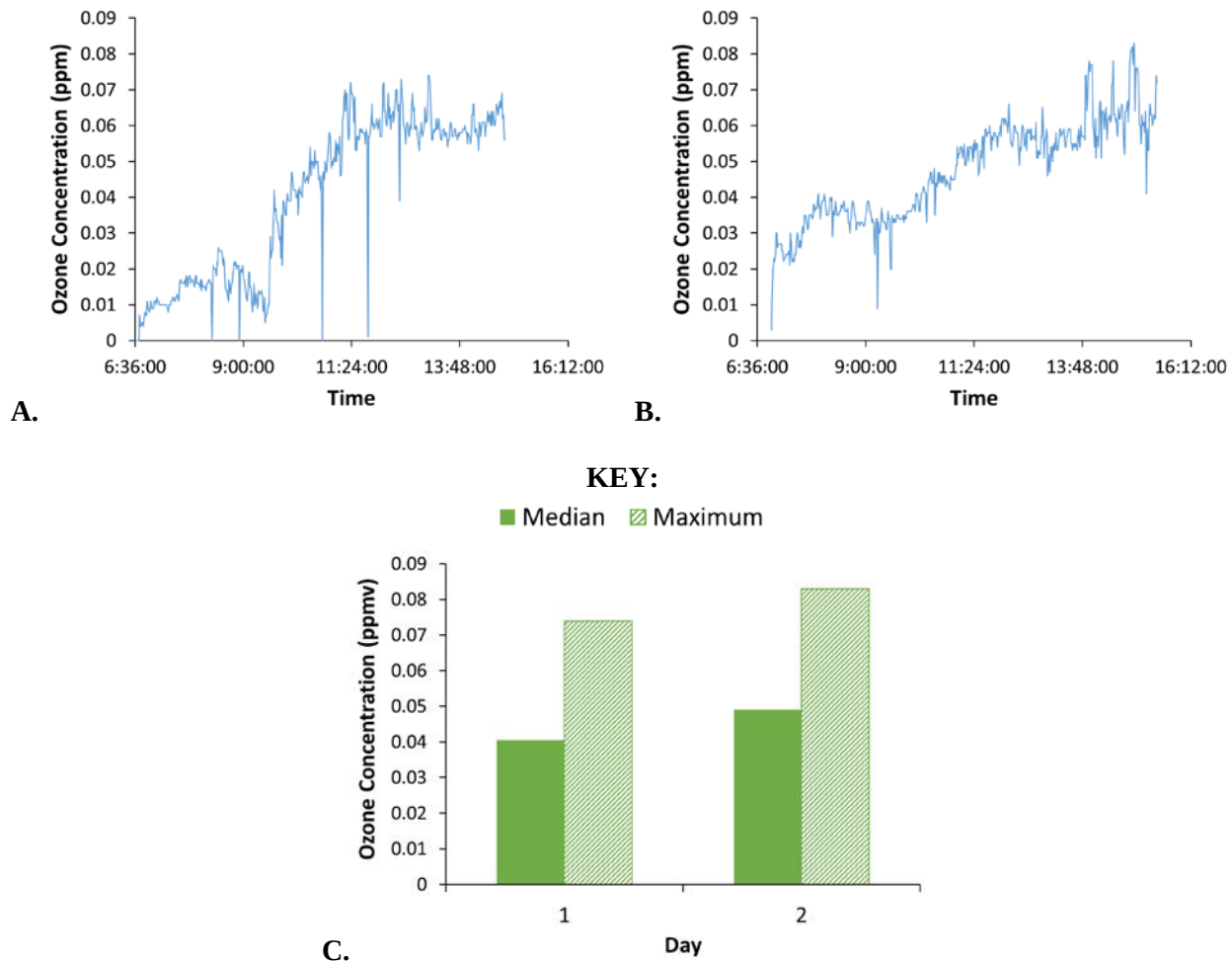


Figure 233. O₃ concentration at site 1. A. Time resolved concentration on day 1 (19 Sept 17); B. Time resolved concentration on day 2 (20 Sept 17); C. Median and maximum levels.

Comparison of respirable size fraction counts ($< 4 \mu\text{m}$) and total particulate counts ($0.01 - 35 \mu\text{m}$) recorded by the mini-WRAS demonstrated respirable sized particles dominate the composition of total airborne particles (Fig. E1, Appendix E). An additional method used to sample ultrafine particles was an electrometer, which measures lung deposited surface area (LDSA). The LDSA is the approximate surface area of particles that deposit in the lung based on charging probability, which is highest for particles in the diameter range of 20-300 nm, which have the highest probability to deposit efficiently in the lower airways in the lung. Therefore, the LDSA indicated by the Partector is accurate to within 30% for particles between 20 and 400 nm. It is overestimated for particles $< 20 \text{ nm}$ and underestimated for particles $> 400 \text{ nm}$ [9, 10].

When comparing the number of particles ($0.01 - 4 \mu\text{m}$) recorded by the mini-WRAS and LDSA peaks recorded by the Partector, there was good agreement in the timing of the peaks (Fig. 24). Since ultrafine particles are a known component in jet exhaust, these data suggest that the peaks may be associated with aircraft parked at idle or taxiing near the sampling station.

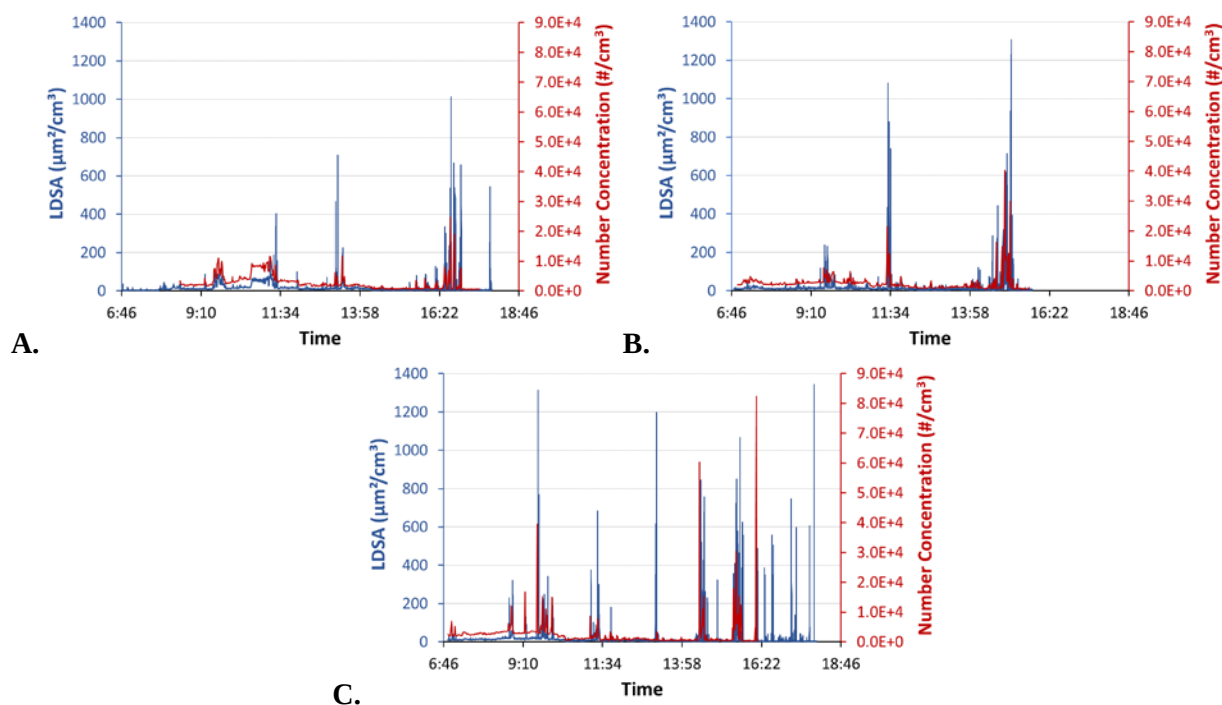


Figure 24. Particle data from mini-WRAS and Partector overlayed to show similarity in trends. A. day 1 (19 Sept 17); B. day 2 (20 Sept 17); C. day 3 (21 Sept 17).

The total particle number concentration (10 nm to 35 μm) and l (LDSA) concentration (sub 1 μm) for site 1 are summarized in Figure 25. The maximum number concentration of total particles was higher by a factor of four on day 3 compared to day 1. The trend was similar, but to a lesser extent for LDSA. The median concentration was 1800 ± 440 particles/ cm^3 and 10 ± 2 $\mu\text{g}/\text{cm}^3$ across the three days (Fig. 24A). The maximum particle number concentrations were 2.5×10^4 , 4.0×10^4 and 8.2×10^4 particles/ cm^3 for days 1, 2 and 3, respectively (Fig. 25B). The maximum LDSA concentrations were 1.0×10^3 , 1.3×10^3 and 1.3×10^3 $\mu\text{g}/\text{cm}^3$ for days 1, 2 and 3, respectively (Fig. 25B).

There are no published exposure limits for ultrafine particles. There was a study published comparing output from a Partector and a P-Trak® ultrafine particle counter (TSI Model 8525, TSI Incorporated, Shoreview, USA) for particles size range of 20 to 300 nm based on the condensation particle counting technique using isopropyl alcohol [11]. The maximum concentration observed in the near the breathing zone of workers in a welding booth was found to be 3.0×10^5 particles/ cm^3 and 0.8×10^3 $\mu\text{g}/\text{cm}^3$. The maximum concentration observed near the breathing zone of workers in a canteen kitchen was 5.0×10^5 particles/ cm^3 and 4.0×10^3 $\mu\text{g}/\text{cm}^3$ with deep-frying causing the highest exposure. The maximum values in the present study were more similar to the welding booth with a slightly lower for particle number concentration, but slightly higher LDSA, which could be attributed to the difference in equipment used for particle counting. The mini-WRAS uses an electrometer for particles that are smaller than the optical range of the instrument (< 0.3 μm).

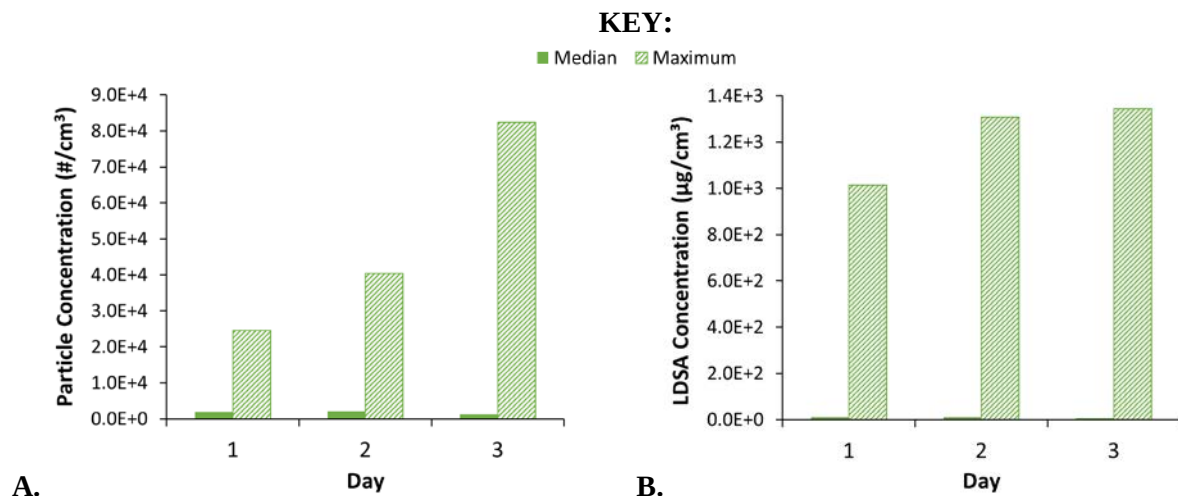


Figure 25. Median and maximum concentrations for particulate matter at site 1. A. Total particle number concentration (10 nm to 10 µm); B. lung deposited surface area (LDSA) concentration.

VOCs as measured using the TO-17 method were all present at concentrations below 150 ppbv (Fig. 26). Seven analytes were detected at various quantities on all three days, including: propene, ethanol, acrolein, acetone, isopropyl alcohol, n-hexane and benzene. Toluene was detected on the second and third days of sampling only. No OELs established by OSHA or recommended by NIOSH or ACGIH were exceeded [8].

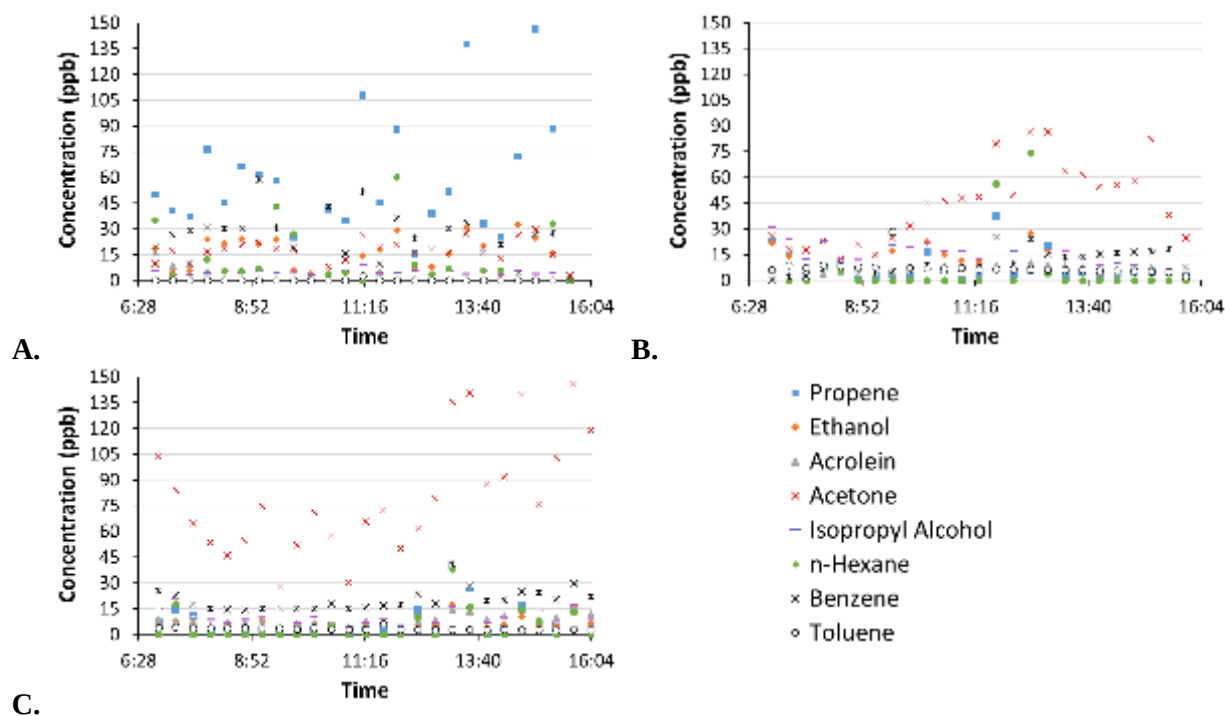


Figure 26. VOC concentration measured using TO-17 method at site 1. A. day 1 (19 Sept 17); B. day 2 (20 Sept 17); C. day 3 (21 Sept 17).

Offline analysis of SO₂ cartridges collected on September 20th and 21st were determined by ALS Environmental to be below the LOD.

5.4 Conclusion and Future Work

Flight line air quality data suggests that the primary exposures of concern included O₃ and ultrafine particles. O₃ levels increased throughout the day, so levels during early sorties are less of a concern than later sorties where levels met the 8h-TWA REL for moderate activity. Since pilots are likely considered to be completing light work during their time spent on the flight line, their exposure to O₃ is below exposure limits. However, this exposure is occurring simultaneously to the ultrafine exposure, which was found to occur at levels similar to what is experienced in a welding booth.

Future work could be completed to collect data for O₃ and ultrafine particles at several locations to map exposure across the flight line. It may also be useful to monitor these exposures on multiple days and under multiple operational activity levels to evaluate whether there is a correlation between particularly high levels and increased potential for UPEs. One option could include a wearable ultrafine particle monitor on the pilots, since spatial variability is expected to be much more considerable for this endpoint.

6.0 CONCLUSIONS AND FUTURE DIRECTIONS

Three exploratory studies were completed to address concerns related to the role of chemical contaminants in the occurrence UPEs. In the first study, chemical contamination in pilot breathing air was investigated using a sampling system that incorporated a suite of assessment tools that could be interfaced directly with the OBOGS regulator during ground engine runs. In the second study, the potential for jet exhaust re-entrainment on the flight line was assessed under the assumption that it could play a role in the introduction of chemical contaminants into pilot breathing air. Both computational and experimental approaches were used to characterize the effect of wind on jet plume dispersion. In the third and final study, flight line air quality was assessed at five locations to investigate baseline pilot and aircraft chemical exposures during normal ground operations. Each of these studies produced baseline data from which to draw preliminary conclusions and also highlighted the need to further refine the approaches used to address the ultimate objective to understand the role of chemical exposures in the occurrence of UPEs and conditions under which these exposures occur.

Preliminary data from the first study characterizing pilot breathing air during ground engine runs demonstrated a purge of chemical contaminants into pilot breathing air occurs during start-up procedures, but chemical contaminants remained relatively low for the duration of the tests. VOCs were identified at ppbv levels well below occupational and military LODs. Preliminary data from the second study characterizing jet exhaust re-entrainment indicated that wind direction and speed played a dominant role in jet exhaust plume dispersion and that there are a multitude of scenarios where re-entrainment likely occurs. Preliminary data from the third study characterizing baseline air quality suggest that the primary exposures of concern include O₃ and ultrafine particles and that levels of combustion gases and VOCs are well below occupational exposure limits.

In addition to a set of baseline data, the present exploratory studies produced knowledge to understand how exposure assessment tools need to be improved for a more extensive baseline data collection. Refinements required for the BASS used to characterize pilot breathing air during ground engine runs include the need for a more robust, automated test system that requires less input from the operator and eliminates the potential for foreign object debris. Further, there is a need for an improved O₂ sensor capable of sampling at concentrations approaching 100%, as well as gas sensors with faster response times to ensure that momentary spikes in contaminants are accurately measured. There is also a need to enhance the breadth of chemical sampling approaches used in the BASS.

In addition to refinement of the BASS, there is also a need to further improve jet exhaust plume dispersion models and flight line air quality assessments to better understand the impact of operational activity and infrastructure on chemical contaminant dispersion. The coupling of jet exhaust re-entrainment scenarios and ground engine run tests using the BASS are also required to evaluate the extent to which exhaust re-entrainment presents an exposure risk to the pilot. Instruments used for collecting data across the flight line could be refined and expanded to sample the contaminants of concern at several locations. Making these refinements will allow for the possibility to collect more extensive baseline data and be prepared to respond to future UPEs.

More extensive baseline data collection is essential for understanding the inherent chemical make-up of pilot breathing air and the role in UPEs. Additionally, baseline data are needed to understand the role of jet exhaust re-entrainment in contamination of pilot breathing air, as well as the operational, infrastructure and weather conditions under which this is a concern. Further, baseline data for flight line air quality are required to characterize various environmental and chemical exposures to pilots during ground operations and evaluate whether this plays a role in the potential to experience a UPE.

There are additional exposures that occur beyond chemical, including noise and heat. It is important to consider these variables in future studies. Further, additional research is needed outside the field of exposure assessment to better understand the health effects of the chemical and physical stressors identified and evaluate their role on pilot health and susceptibility to experience a UPE. This could be approached using a multitude of tools, including pharmacokinetic modeling, epidemiology, biomarker assessment in pilots and controlled human exposure studies. Since the 711th HPW is home to subject matter experts in each of these areas, future work will ideally be completed with a comprehensive approach including input from multiple disciplines to address the remaining research gaps and further develop an understanding of causal factors for UPEs that are related to chemical and physical exposures to the pilot during ground operations and in the air.

7.0 REFERENCES

1. Federal Aviation Administration Chapter 16. Cabin Environmental Control Systems. Aviation Maintenance Technician Handbook-Airframe, Vol 2; 2012. [Accessed 4 Mar 2019]. Available from: https://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/media/amt_airframe_hb_vol_2.pdf.
2. Gertler, J. 2017. Out of Breath: Military Aircraft Oxygen Issues. Congressional Research Service. [Accessed 4 Mar 2019]. Available from: <https://fas.org/sgp/crs/weapons/IN10723.pdf>.
3. USAF Scientific Advisory Board. Report on Aircraft Oxygen Generation. Defense Technical Information Center. SAB-TR-11-04; 2012. [Accessed 4 Mar 2019]. Available from: <http://www.dtic.mil/dtic/tr/fulltext/u2/a567568.pdf>.
4. Department of Defense. Design Criteria Standard. Aircraft crew breathing systems using on-board oxygen generation systems (OBOGS). MIL-STD-3050 215. [Accessed 4 Mar 2019]. Available from: http://everyspec.com/MIL-STD/MIL-STD-3000-9999/MIL-STD-3050_52145/.
5. Oberkampf, William L. Guide for the Verification and Validation of Computational Fluid Dynamics Simulations (AIAA G-077-1998(2002)); 1998. doi:10.2514/4.472855.001.
6. Folinsbee LJ. Human health effects of air pollution. Environ Health Perspect. 1992; 100:45-56.
7. Strak M, Janssen NA, Godri KJ, Gosens I, Mudway IS, et al. Respiratory health effects of airborne particulate matter: the role of particle size, composition, and oxidative potential—the RAPTES project. Environmental health perspectives. Environ Health Perspect. 2012; 120(8):1183-1189.
8. ACGIH. Guide to Occupational Exposure Values. Signature Publications, Cincinnati (OH); 2018.
9. Fiertz M, Meier D, Steigmeier P, Burscher H. Aerosol measurement by induced currents. Aerosol Sci Tech. 2014; 48(40):350-357.
10. Naneos Particle Solutions, GmbH. Partector Aerosol Dosimeter Operation Manual; 2015. [Accessed 4 Mar 2019]. Available from: http://www.naneos.ch/pdf/naneos_partector_operation_manual.pdf.
11. Geiss O, Bianchi I, Barrero-Moreno J. 2016. Lung-deposited surface area concentration measurements in selected occupational and non-occupational environments. J Aerosol Sci. 2016; 96:24-37.
12. Mussato B, Varisco S, Tsurikova L. Assessment of volatile organic compounds from tubing used for soil vapour sample collection. CARO Analytical Services, Richmond, BC; 2009. [Accessed 4 Mar 2019]. Available from: <https://www.caro.ca/Documents/CARO%20-%20VOCs%20in%20Tubing%20Materials%20Assessment,%20Final%20April%201,%202009.pdf>.
13. Slagle T, Lee A, Montalvo L. 2010. Operating Procedure: Soil Gas Sampling. Region 4 U.S. Environmental Protection Agency Science and Ecosystem Support Division Athens, Georgia; 2010. [Accessed 4 Mar 2019]. Available from: https://www.epa.gov/sites/production/files/2014-03/documents/appendix_p_soil_gas_sub_slab.pdf.

APPENDIX A: Tubing Outgassing

Five types of sampling tubing were chosen: stainless steel (reference), conductive black silicone (principally for aerosols), Tygon, Teflon, and medical grade silicone. A stream of 65% O₂ at a flow rate of 6.81 L/min was passed through a manifold at room temperature. From this manifold, a foot of each tubing type was attached to three separate TD tubes. The TD tubes were analyzed using TO-17 method. The only chemicals identified in all three replicates for any individual material included ethanol and 2-propenal (Table A1). According to these data, Tygon outgassed the most, followed by the remaining materials, which were all equivalent.

Table A1. Chemicals Identified in Five Tubing Types, shown in ppm

Material	Ethanol	2-propenal
Stainless steel	< 2.0	1.0 ± 0.6
Black conductive silicone	< 2.0	0.9 ± 0.2
Tygon	5.4 ± 4.1	1.4 ± 0.2
Polytetrafluoroethylene (Teflon)	< 2.0	1.2 ± 0.2
Medical Grade Silicone	< 2.0	0.8 ± 0.1

CARO analytical services compared off-gassing from Teflon, Nylon (Nylaflow), Nylon (Extra-Flex), silicone, polyvinyl chloride, Tygon and polyethylene for a larger set of volatiles. Nitrogen (99.999%) at 25°C was passed through tubing of equal lengths at 100 mL/min for 100 minutes. There were no detectable VOCs when nitrogen was passed through Teflon and Nylon (Nylaflow). Several VOCs were identified on the Nylon (Extra-Flex), silicone, polyvinyl chloride, Tygon and polyethylene [12].

The Environmental Protection Agency suggests that tubing for sampling organic chemicals should be composed of Teflon or stainless steel [13].

APPENDIX B: VOCs Sampled and Associated LODs

Table B2. VOCs Measured and LODs for Samples Collected using TD tubes *for Analysis by EPA Method TO-17*

Compound	LOD (ppbv)
Propene	<2.000
Dichlorodifluoromethane	<2.000
1,2-Dichlorotetrafluoroethane	<2.000
Chloromethane	<2.000
Vinyl Chloride	<2.000
1,3-Butadiene	<2.000
Chloroethane	<2.000
Trichloromonofluoromethane	<2.000
Ethanol	<2.000
Acrolein (2-Propenal)	<2.000
Acetone	<5.000
1,1,2-trichloro-1,2,2-trifluoroethane	<2.000
Ethene, 1,1-dichloro-	<2.000
Isopropyl Alcohol	<2.000
Carbon disulfide	<4.000
Methylene chloride	<2.000
trans 1,2-dichloroethylene	<2.000
n-Hexane	<2.000
1,1-Dichloroethane	<2.000
Methyl Ethyl Ketone	<2.000
Ethyl acetate	<2.000
cis 1,2-Dichloroethylene	<2.000
Tetrahydrofuran	<2.000
Chloroform	<2.000
1,1,1Trichloroethane	<2.000
Cyclohexane	<2.000
Carbon Tetrachloride	<2.000
Benzene	<2.000
1,2-Dichloroethane	<2.000
Heptane	<2.000
Trichloroethylene	<2.000
Methyl Methacrylate	<2.000
1,2-Dichloropropane	<2.000
1,4-Dioxane	<2.000
Bromodichloromethane	<2.000
Methyl Isobutyl Ketone	<2.000
Toluene	<2.000
1,1,2-Trichloroethane	<2.000
Butyl Methyl Ketone (2-Hexanone)	<2.000
Tetrachloroethylene	<2.000
1,2-dibromo ethane,	<2.000

Chlorobenzene	<2.000
m,p-xylene	<4.000
Ethylbenzene	<2.000
o-xylene	<2.000
Styrene	<2.000
Tribromo methane	<2.000
1,1,2,2-tetrachloro ethane	<2.000
1,2,4-Trimethyl benzene	<2.000
1,3,5-Trimethyl benzene	<2.000
4-Ethyltoluene	<2.000
1,3-Dichloro benzene	<2.000
1,4-dichloro benzene,	<2.000
1,2-Dichloro benzene,	<2.000
1,2,4-Trichloro benzene,	<2.000
Hexachloro-1,3-butadiene	<2.000
Naphthalene	<2.000

Table B2. VOCs Measured and LODs for Samples Collected using Summa Canisters for Analysis by EPA Methods 3C, TO-3 and TO-15

Compound	LOD (ppbV)
Ethene (ppmV)	<0.36
Ethane (ppmV)	<0.36
Propane (ppmV)	<0.36
Propene	<1.0
Dichlorodifluoromethane	<0.36
Chloromethane	<0.87
1,2-Dichloro-1,1,2,2-tetrafluoroethane	<0.26
Vinyl Chloride	<0.7
1,3-Butadiene	<0.81
Bromomethane	<0.46
Chloroethane	<0.68
Ethanol	<9.6
Acetonitrile	<1.1
Acrolein	<3.1
Acetone	<7.6
Trichlorofluoromethane	<0.32
2-Propanol (IPA)	<7.3
Acrylonitrile	<0.83
1,1-Dichloroethene	<0.45
Methylene Chloride	<0.52
3-Chloro-1-propene (Allyl Chloride)	<0.58
Trichlorotrifluoroethane	<0.23
Carbon Disulfide	<5.8
trans-1,2-Dichloroethane	<0.45
1,1-Dichloroethane	<0.44
Methyl tert-Butyl Ether	<0.5
Vinyl Acetate	<5.1
2-Butanone (MEK)	<6.1
cis-1,2-Dichloroethene	<0.45
Ethyl Acetate	<1.0
n-Hexane	<0.51
Chloroform	<0.37
Tetrahydrofuran	<0.61
1,2-Dichloroethane	<0.44
1,1,1-Trichloroethane	<0.33
Benzene	<0.56
Carbon Tetrachloride	<0.29
Cyclohexane	<1.0

1,2-Dichloropropane	<0.39
Bromodichloromethane	<0.27
Trichloroethene	<0.34
1,4-Dioxane	<0.50
Methyl Methacrylate	<0.88
n-Heptane	<0.44
cis-1,3-Dichloropropene	<0.40
4-Methyl-2-pentanone	<0.44
trans-1,3-Dichloropropene	<0.40
1,1,2-Trichloroethane	<0.33
Toluene	<0.48
2-Hexanone	<0.44
Dibromochloromethane	<0.21
1,2-Dibromochloromethane	<0.23
n-Butyl Acetate	<.38
n-Octane	<0.39
Tetrachloroethene	<0.27
Chlorobenzene	<0.39
Ethylbenzene	<0.41
m,p-Xylenes	<0.83
Bromoform	<0.17
Styrene	<0.42
o-Xylene	<0.41
n-Nonane	<0.34
1,1,2,2,-Tetrachloroethane	<0.26
Cumene	<.38
alpha-Pinene	<0.32
n-Propylbenzene	<0.37
4-Ethyltoluene	<0.37
1,3,5-Trimethylbenzene	<0.37
1,2,4-Trimethylbenzene	<0.37
Benzyl Chloride	<0.35
1,3-Dichlorobenzene	<0.30
1,4-Dichlorobenzene	<0.30
1,2-Dichlorobenzene	<0.30
d-Limonene	<0.32
1,2-Dibromo-3-chloropropane	<0.19
1,2,4-Trichlorobenzene	<0.24
Naphthalene	<0.34
Hexachlorobutadiene	<0.17

Table B3. Exposure Limits for Chemicals Identified during Ground Engine Runs

Compound	TLV, 8h-TWA (ppm)	TLV, STEL/C (ppm)	NIOSH REL / OSHA PEL (ppm)
Propene	500	-	-
Dichlorodifluoromethane	10	-	-
Ethanol	-	1000 STEL	1000 (NIOSH REL, 8h-TWA)
2-Propenal (Acrolein)	-	0.1 (C)	0.1 (NIOSH REL, 8h-TWA)
Acetone	250	500 (STEL)	-
2-Propanol (IPA)	200	400 (STEL)	-
Methylene Chloride	50	-	125 (OSHA STEL)
2-Butanone (MEK)	200	300 (STEL)	-
Toluene	20	-	150 (NIOSH REL, STEL)
2-Hexanone (Methyl n-Butyl Ketone)	5	10 (STEL)	-
Methyl Isobutyl Ketone	20	75 (STEL)	-

Abbreviations: ACGIH = American Conference of Governmental Industrial Hygienists; C = ceiling; NIOSH = National Institute for Occupational Safety and Health; OSHA = Occupational Safety and Health Administration; PEL = permissible exposure limit; REL = recommended exposure limit; STEL = short-term exposure limit; TLV = threshold limit value. Notes: The NIOSH REL and OSHA PEL were only listed if there was not a TLV available. NIOSH was prioritized above OSHA, since the RELs are based on more recent data than the PELs. The STEL is a 15 min – TWA exposure. The ceiling is an instantaneous exposure. The TLVs are recommended exposure limits published by the ACGIH [8].

Table B4. Maximum Allowable Concentrations in Pilot Breathing Air, from MIL-STD-3050

Compound	Maximum Allowable Concentration (ppmV)
Acrolein	0.05
Aldehydes	0.20
Aromatics	0.10
Carbon Dioxide	500
Carbon Monoxide	10
Ethanol	500
Fluorine (as HF)	0.05
Halogenated Solvents	0.20
Hydrogen Peroxide	0.50
Methyl Alcohol	100
Methyl Bromide	1.0
Nitrogen Oxides	0.1
Ozone	0.05
Total Remaining Hydrocarbons	25
Unsaturated Hydrocarbons (alkenes, alkynes)	0.2
Oil and Particulate Matter	0.2 mg/m ³

APPENDIX C: Domain and Mesh Sensitivity

External aerodynamics simulation solutions are highly dependent on the size of the simulated volume (domain) and number of locations the numerical solution is calculated throughout the volume (mesh). Analysis of both domain and mesh sensitivity were completed for the proposed flight line parking setup to ensure the mesh count and size of the volume surrounding the aircraft were not a factor in the final CFD solutions. The purpose of this step is to minimize computation complexity to maximize the number of simulations that can be completed. Simulation physics were set to constant parameters with a segregated solver. The parameters included 100 mph inlet velocity, 380°F inlet temperature on the nozzle, 5 mph wind and 115°F ambient temperature velocity inlet on the left domain boundary condition, and a Courant Friedrichs and Lewy condition of five, meaning the simulation used a stable numerical pseudo-time step. The simulations were steady state, meaning the results were not variable with time. Geometry setup along with locations of inspection can be seen in Figure C1. The dotted green lines visually depict the three parallel lines through the plume where data was exported from the simulation and plotted.

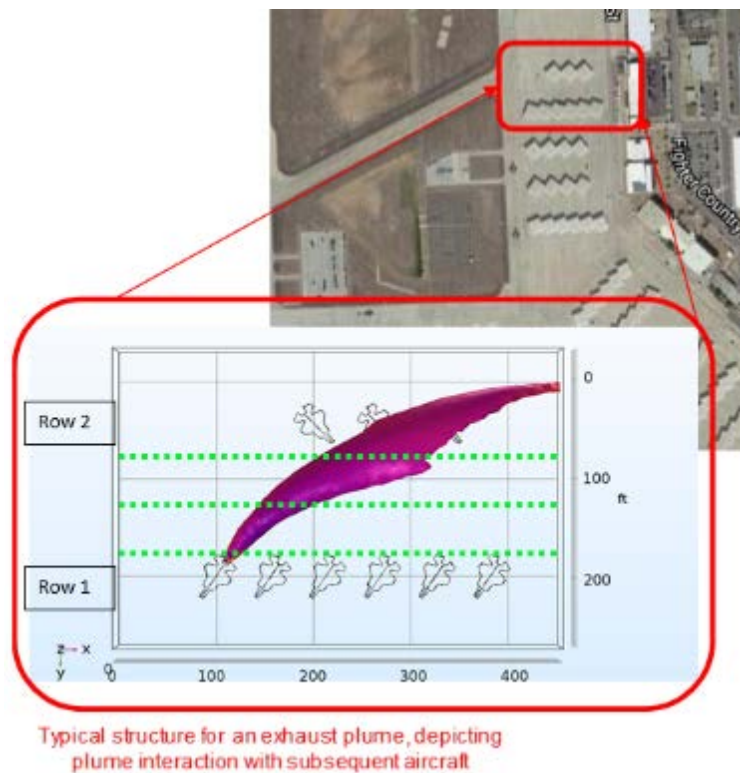


Figure C1. Infographic of the modeled simulation with a depiction of positions where predictions were extracted from the model.

A domain sensitivity analysis study compared the solution for domains of varying height. The domain X and Y bounds were implemented at a stationary 450 ft and 280 ft respectively as they acted as the inlet, outlet, and freestream boundary conditions. The top surface was modeled as a wall condition and height was then varied as follows: 60 ft, 80 ft, 100 ft, and 120 ft. Figure

C2 demonstrate velocity and temperature profiles at the three locations as the plume progresses and diffuses: directly behind the nozzle, 50 ft from the nozzle, and 100 ft from the nozzle. As the distance from the nozzle increased, the plume became increasing diffuse due to the wind momentum boundary condition, indicating the need for a larger vertical domain. The 80 ft domain produced peak results within 0.91% of the 120 ft domain while the 60 ft and 100 ft domains showed significantly more variation at 5.84% and 3.89% difference respectively. These results were unexpected as solutions generally trend sequentially toward the largest domain solution. Follow-on studies could investigate this behavior. Results suggested that an 80 ft height boundary was sufficient for domain sizing due to the solution percent differences from the largest domain. This led to a 280 ft×450 ft×80 ft domain for further permutation simulations.

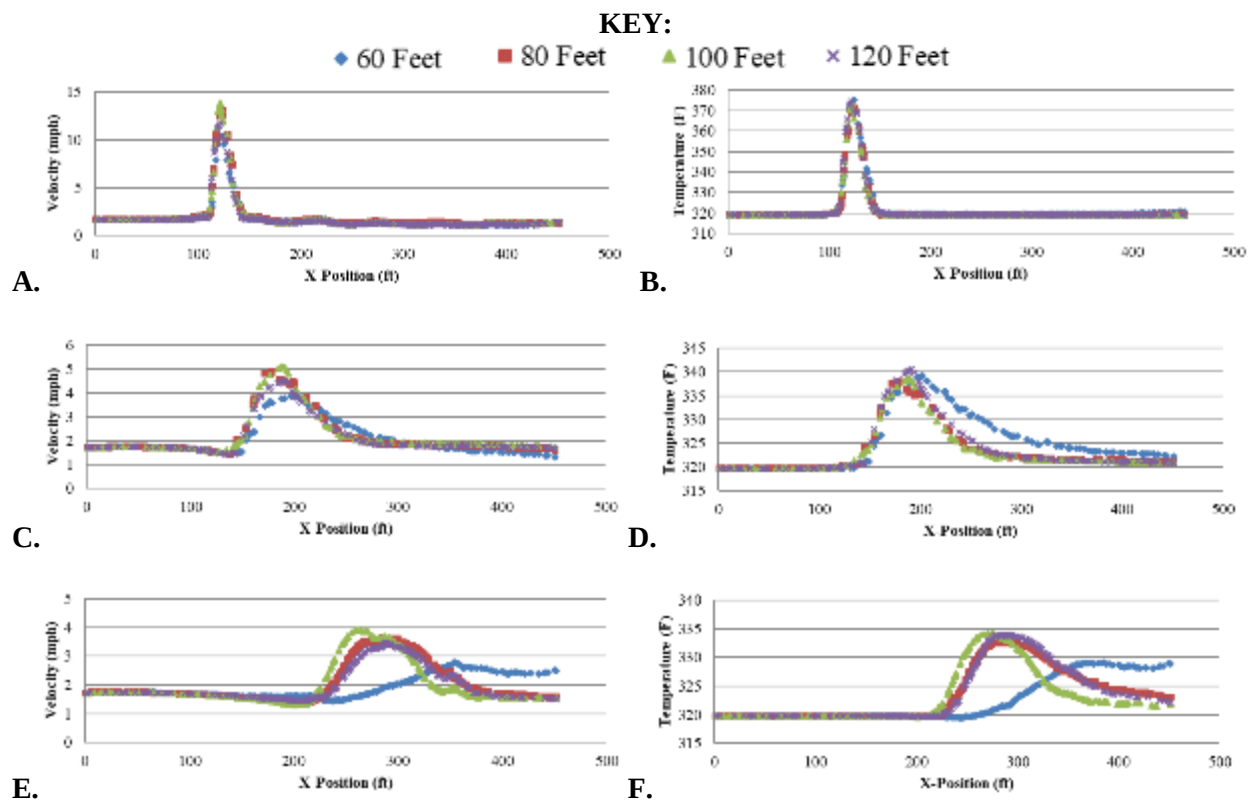


Figure C2. Domain sensitivity results of predictions for velocity and temperature at different distances behind the nozzle. A. velocity at 0 ft domain height; B. temperature at 0 ft domain height; C. velocity at 50 ft domain height; D. temperature at 50 ft domain height; E. velocity at 100 ft domain height; F. temperature at 100 ft domain height.

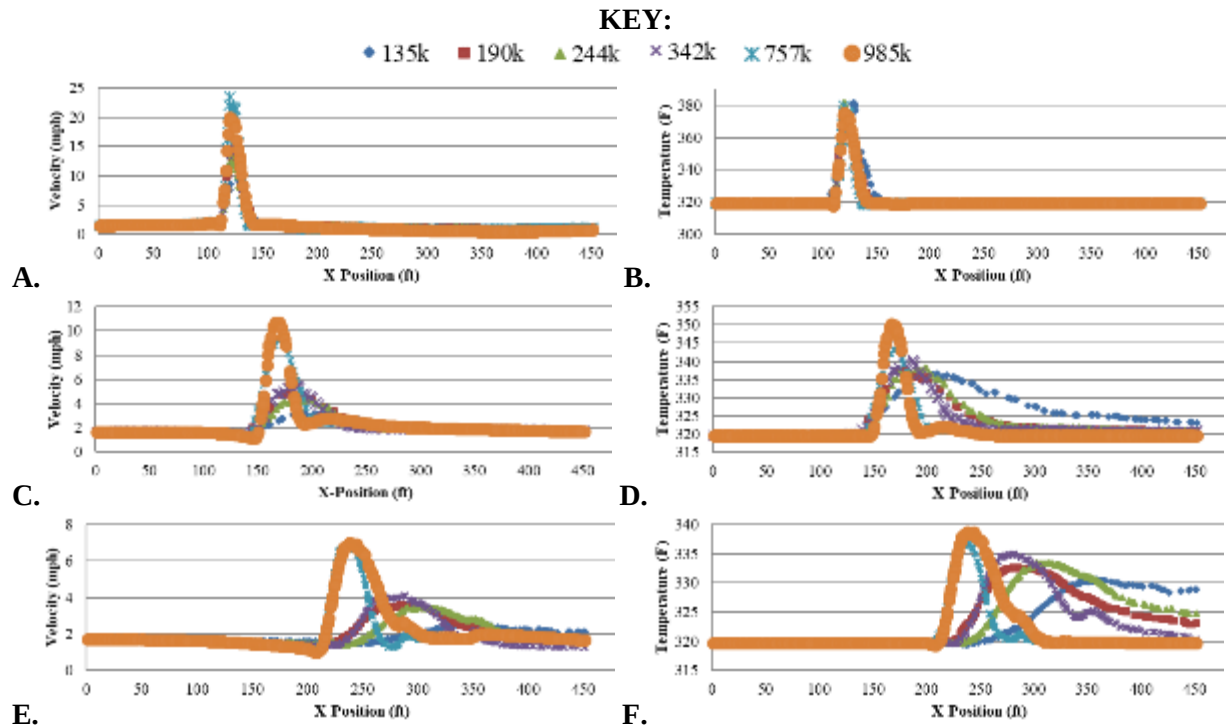


Figure C3. Mesh sensitivity results of predictions for velocity and temperature at different distances behind the nozzle. A. velocity at 0 ft; B. temperature at 0 ft; C. velocity at 50 ft; D. temperature at 50 ft; E. velocity at 100 ft; F. temperature at 100 ft.

APPENDIX D: Time Resolved Gas Levels on the Flight Line

The concentration of gases, including CO, CO₂, NO and SO₂ throughout three days of flight line air quality sampling at five sampling sites are described in the following figures. The locations of the sampling sites are shown in Figure 19.

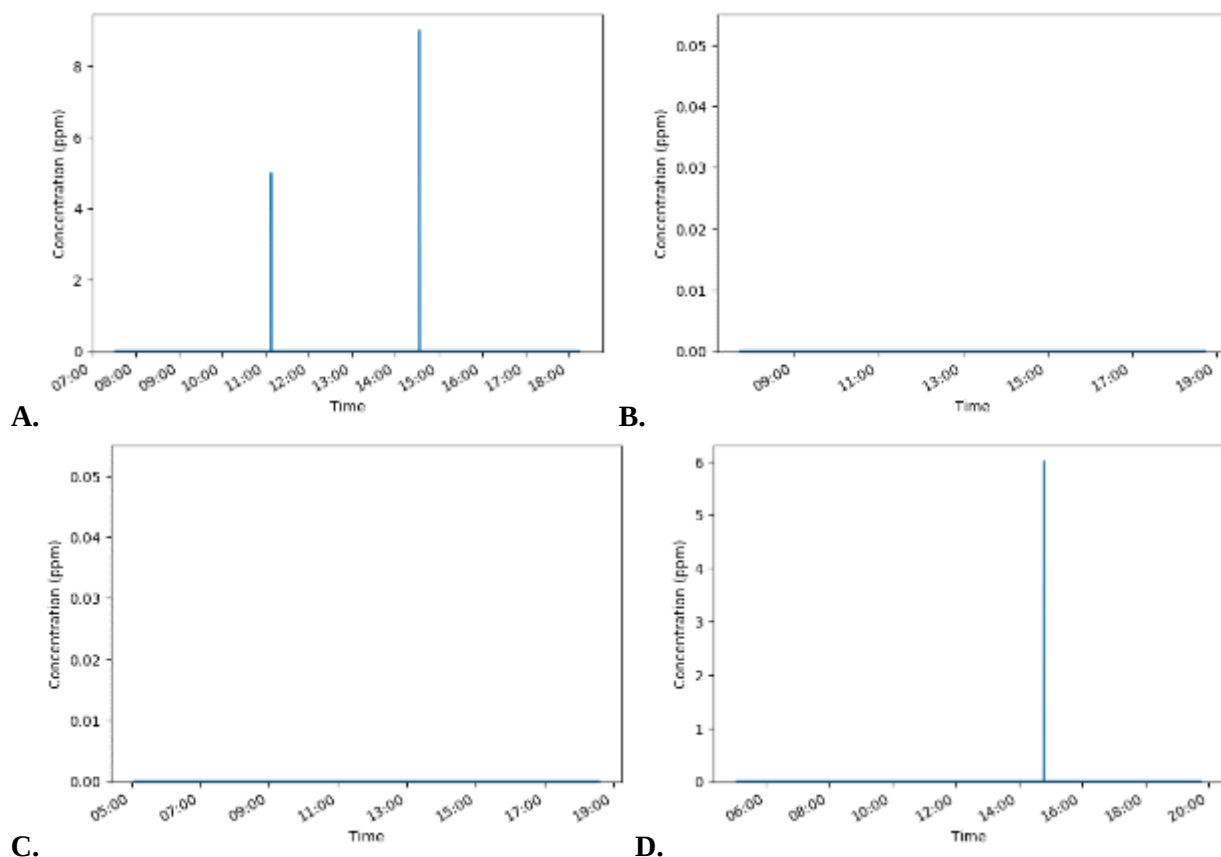


Figure D1.4 CO concentrations on day 1 (19 Sept 17) from four sites. A. Site 2; B. Site 3; C. Site 4; D. Site 5. Note: The gas monitor at site 1 malfunctioned and did not produce data on day 1.

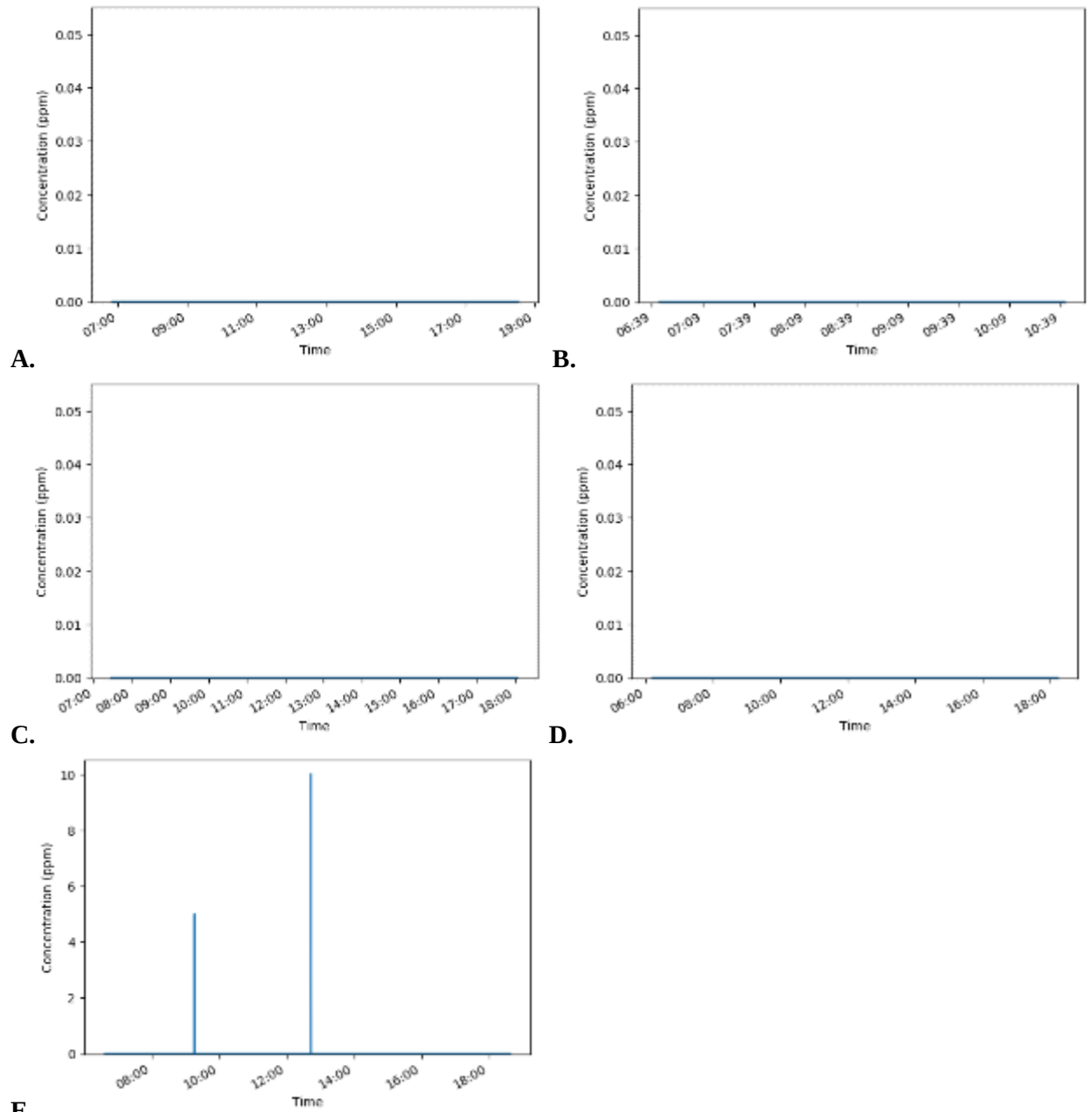


Figure D2. CO concentrations on day 2 (20 Sept 17) from five sites. A. Site 1; B. Site 2; C. Site 3; D. Site 4; E. Site 5.

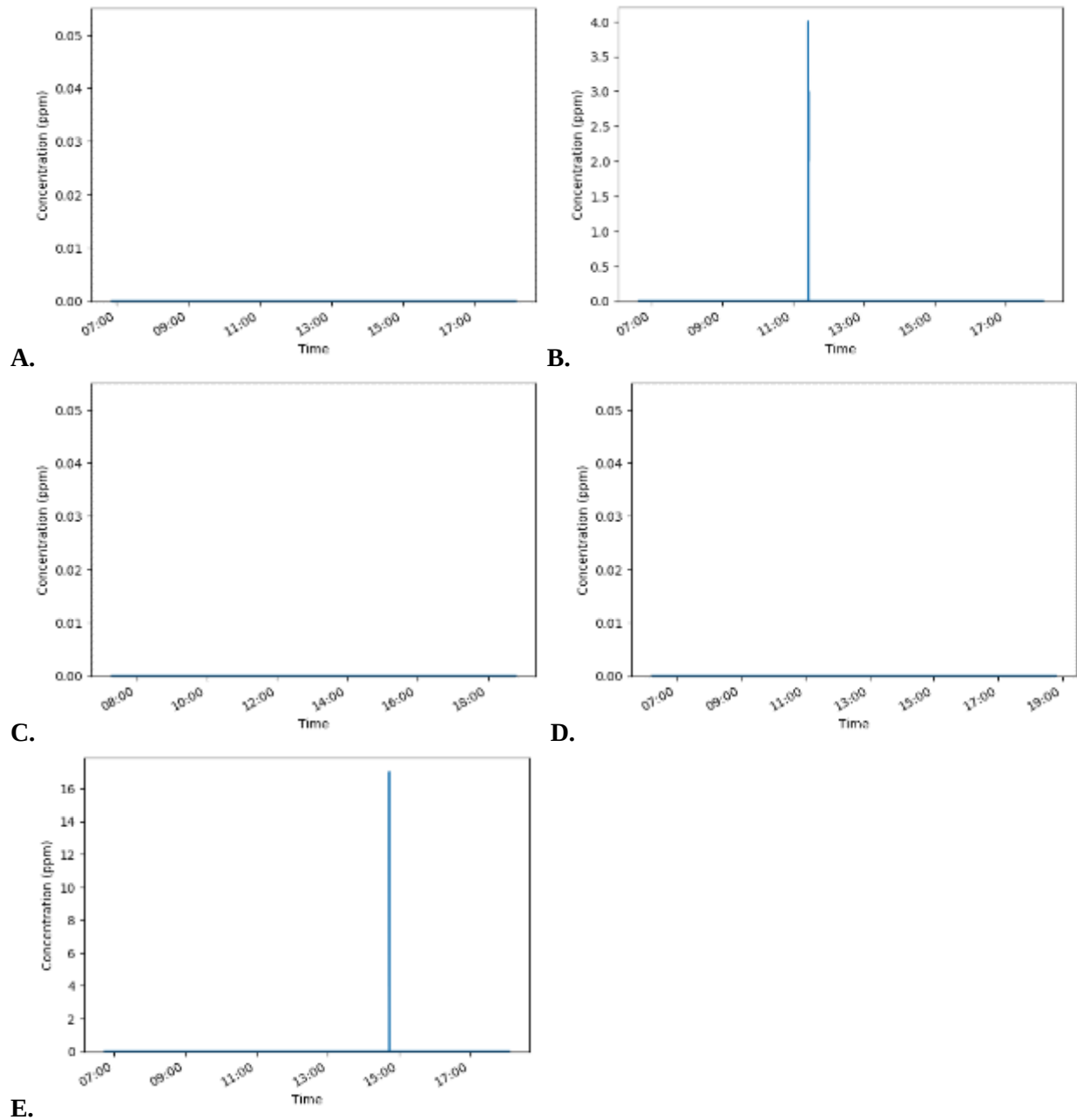


Figure D3.5 CO concentrations on day 3 (21 Sept 17) from five sites. A. Site 1; B. Site 2; C. Site 3; D. Site 4; E. Site 5.

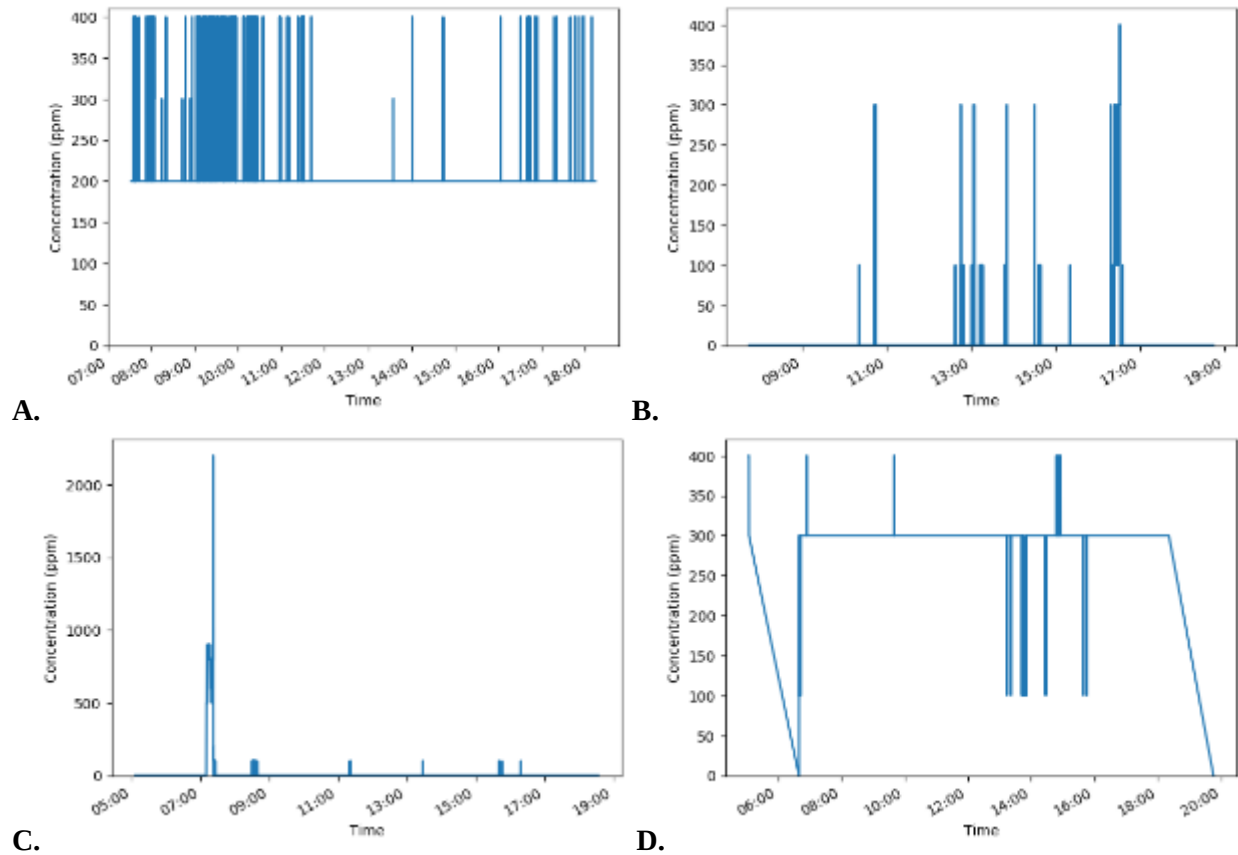


Figure D4.6 CO₂ concentrations on day 1 (19 Sept 17) from four sites. A. Site 2; B. Site 3; C. Site 4; D. Site 5. Note: The gas monitor at site 1 malfunctioned and did not produce data on day 1.

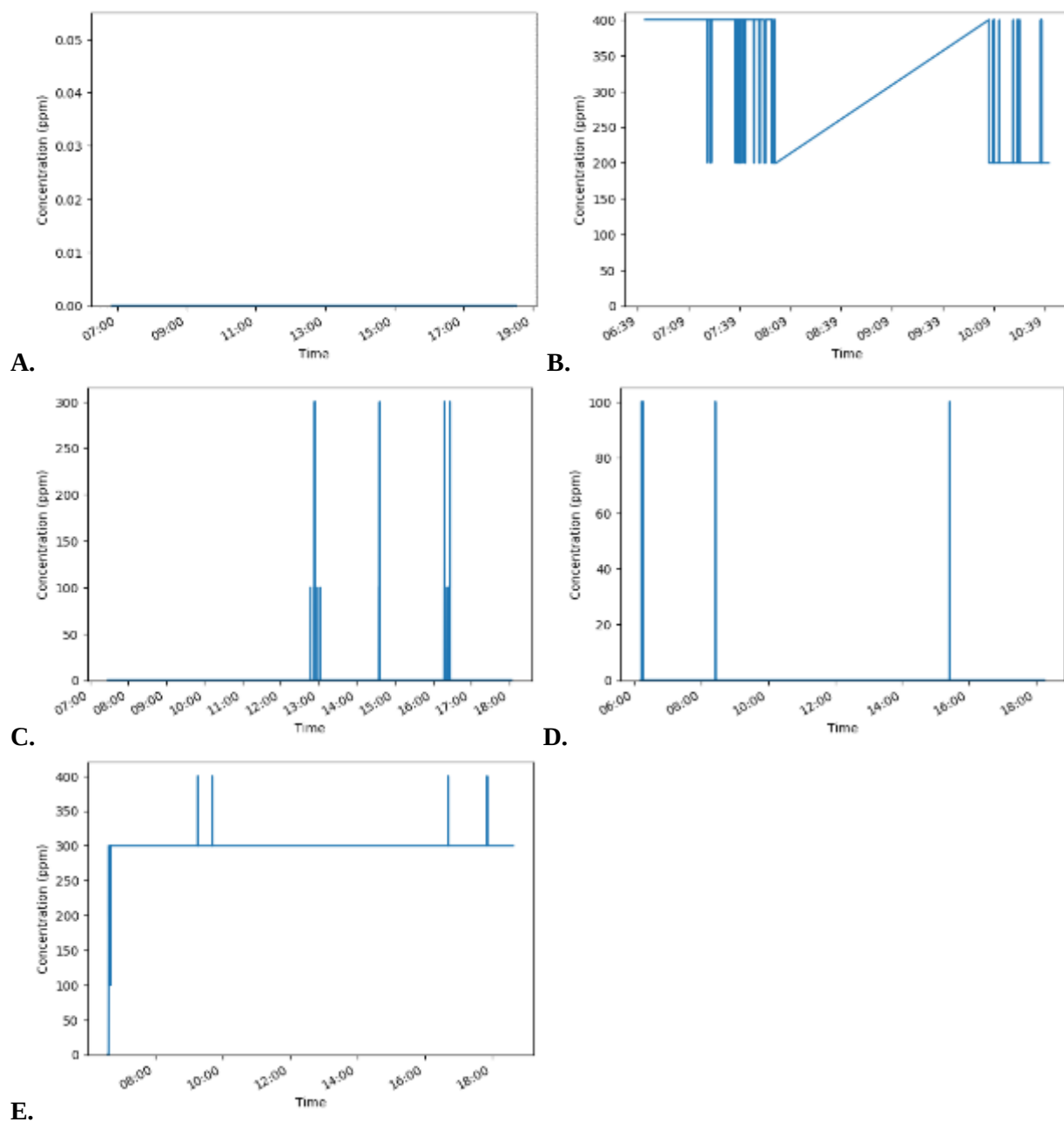


Figure D5.7 CO₂ concentrations on day 2 (20 Sept 17) from five sites. A. Site 1; B. Site 2; C. Site 3; D. Site 4; E. Site 5.

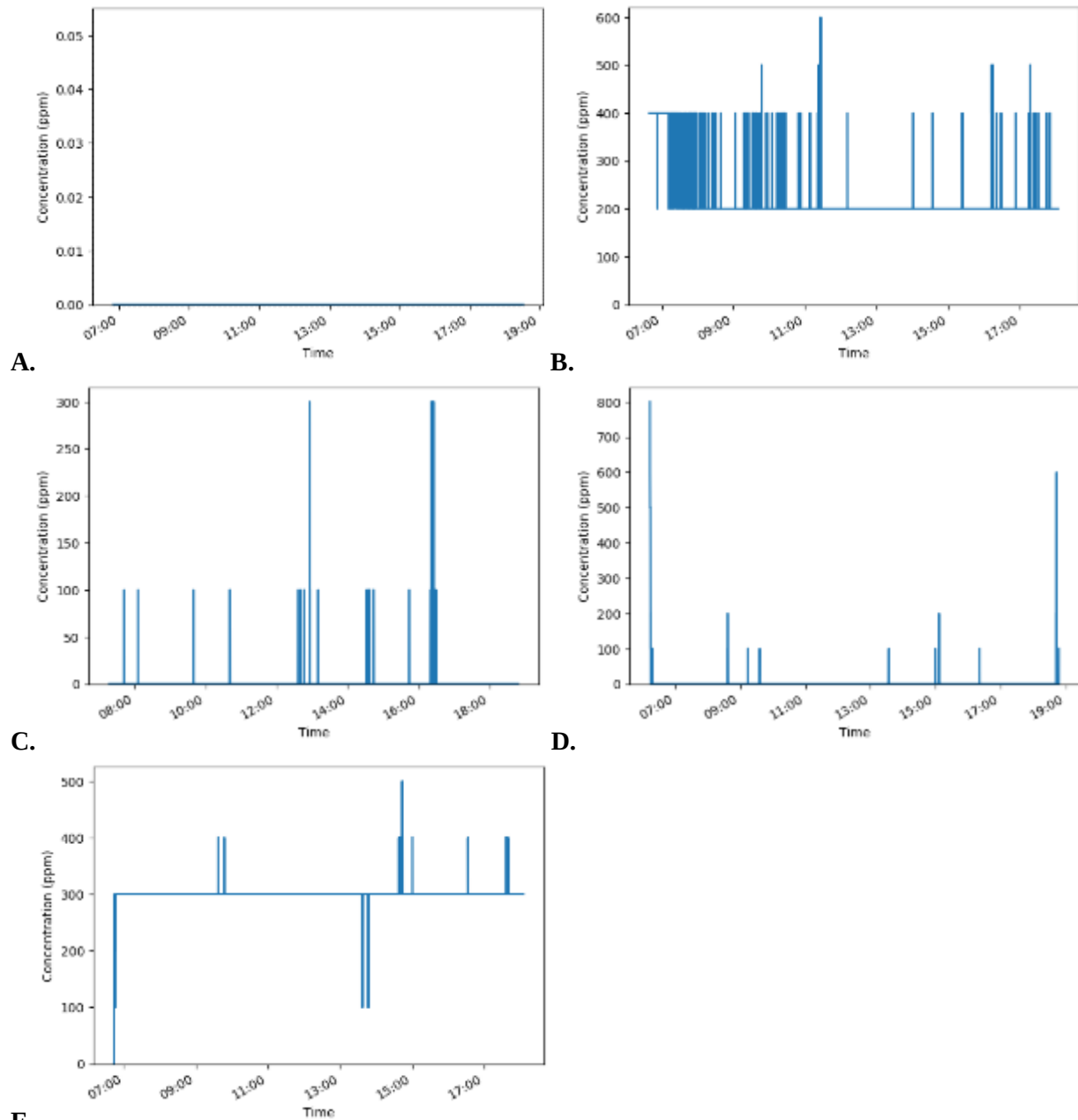


Figure D6.8 CO₂ concentrations on day 3 (21 Sept 17) from five sites. A. Site 1; B. Site 2; C. Site 3; D. Site 4; E. Site 5.

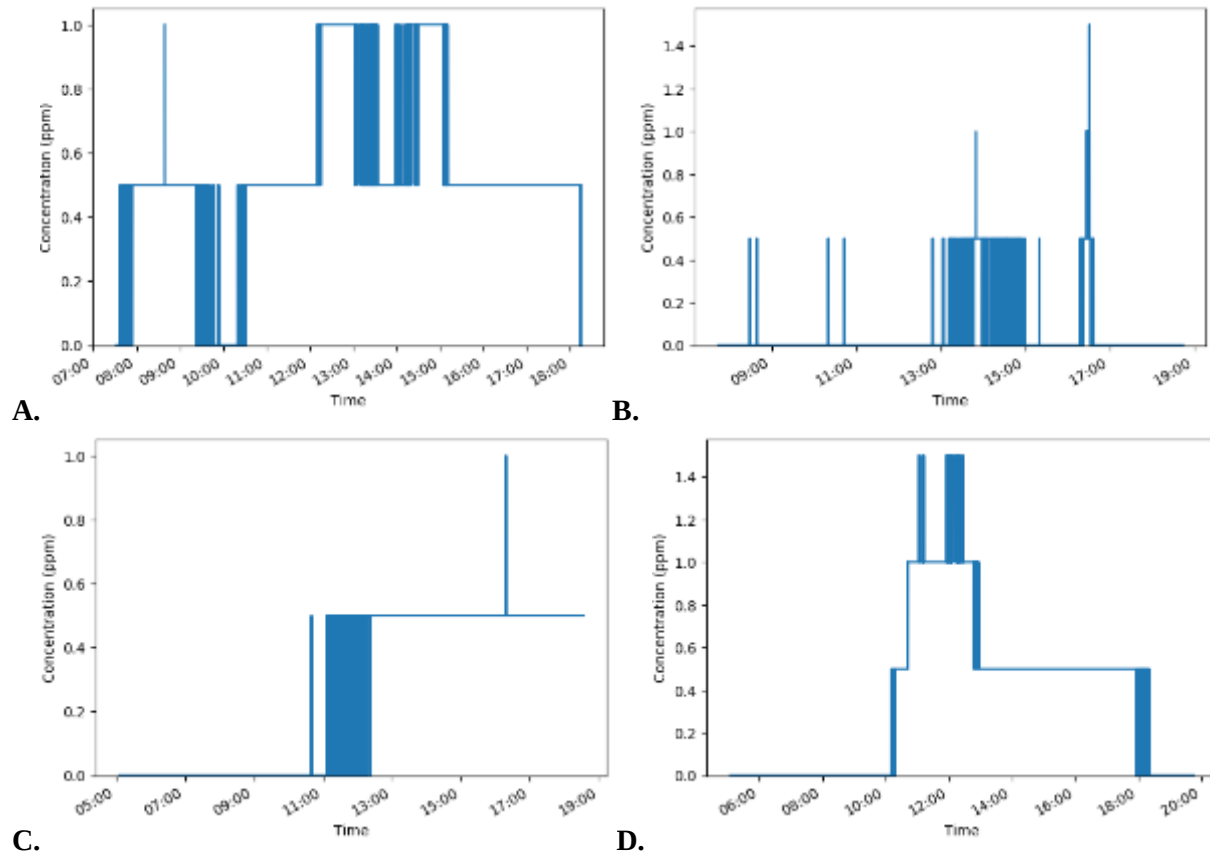


Figure D7.9 NO concentrations on day 1 (19 Sept 17) from four sites. A. Site 2; B. Site 3; C. Site 4; D. Site 5. Note: The gas monitor at site 1 malfunctioned and did not produce data on day 1.

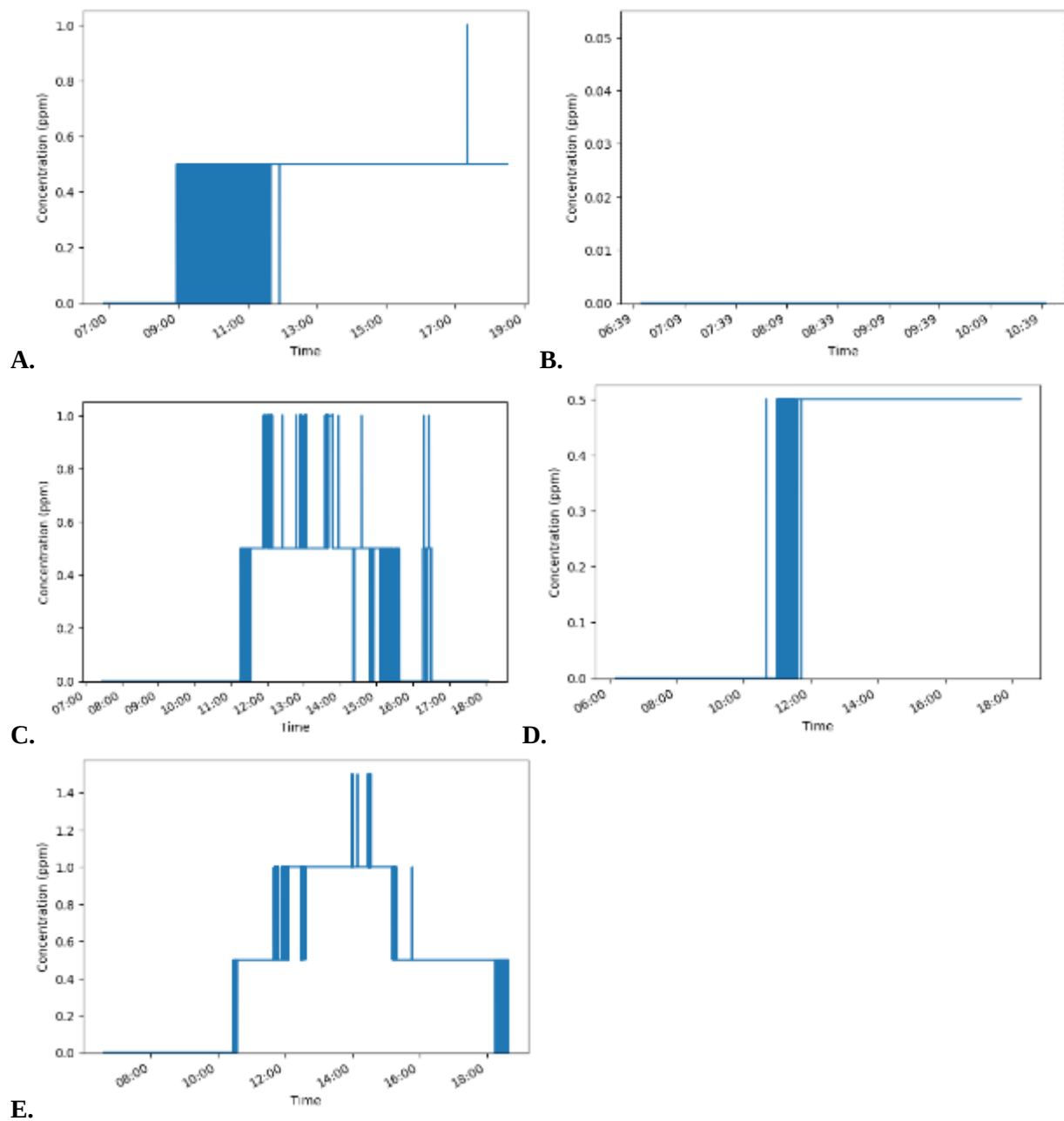


Figure D8. NO concentrations on day 2 (20 Sept 17) from five sites. A. Site 1; B. Site 2; C. Site 3; D. Site 4; E. Site 5.

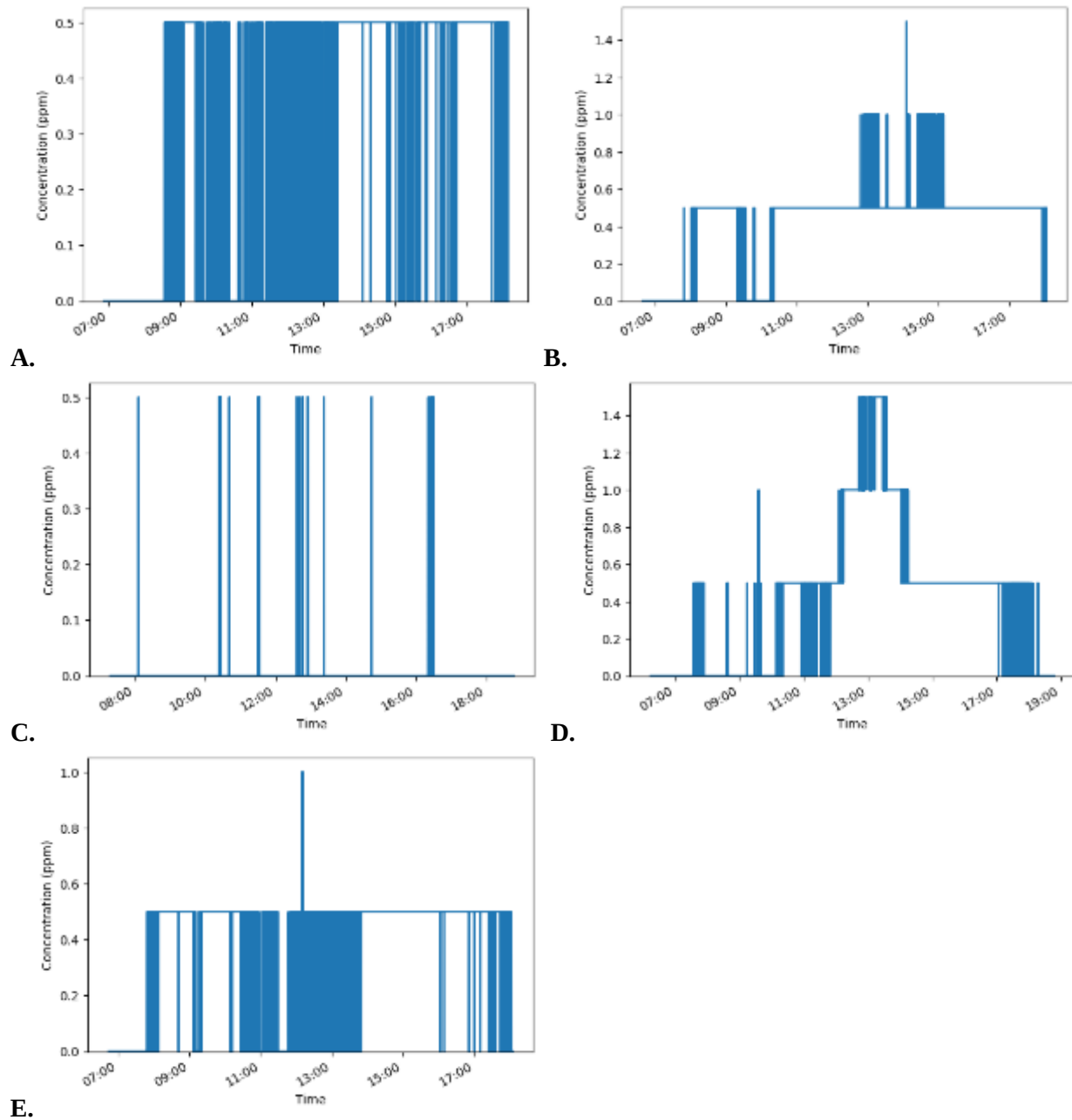


Figure D9. NO concentrations on day 3 (21 Sept 17) from five sites. A. Site 1; B. Site 2; C. Site 3; D. Site 4; E. Site 5.

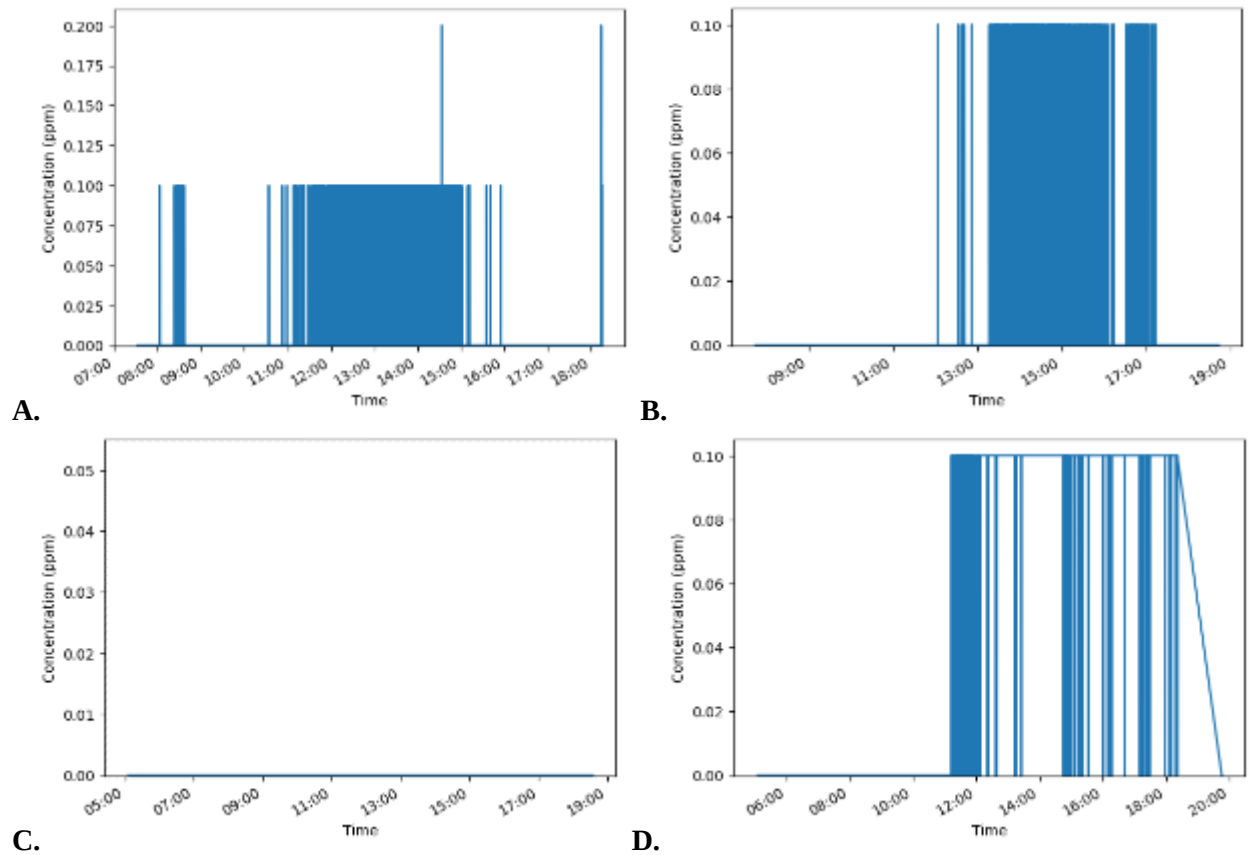


Figure D10.10 SO₂ concentrations on day 1 (19 Sept 17) from four sites. A. Site 2; B. Site 3; C. Site 4; D. Site 5. Note: The gas monitor at site 1 malfunctioned and did not produce data on day 1.

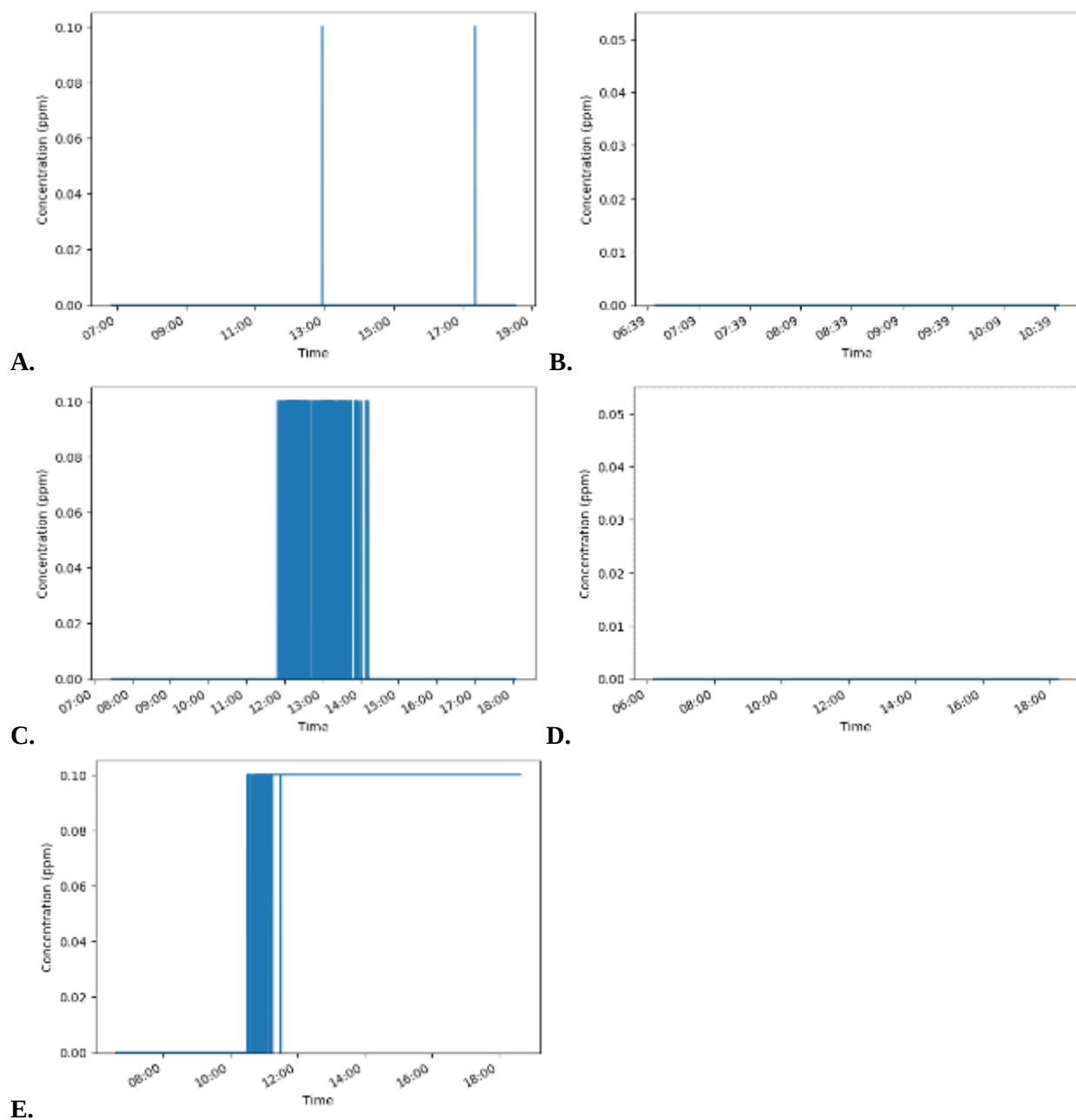


Figure D11. SO₂ concentrations on day 2 (20 Sept 17) from five sites. A. Site 1; B. Site 2; C. Site 3; D. Site 4; E. Site 5.

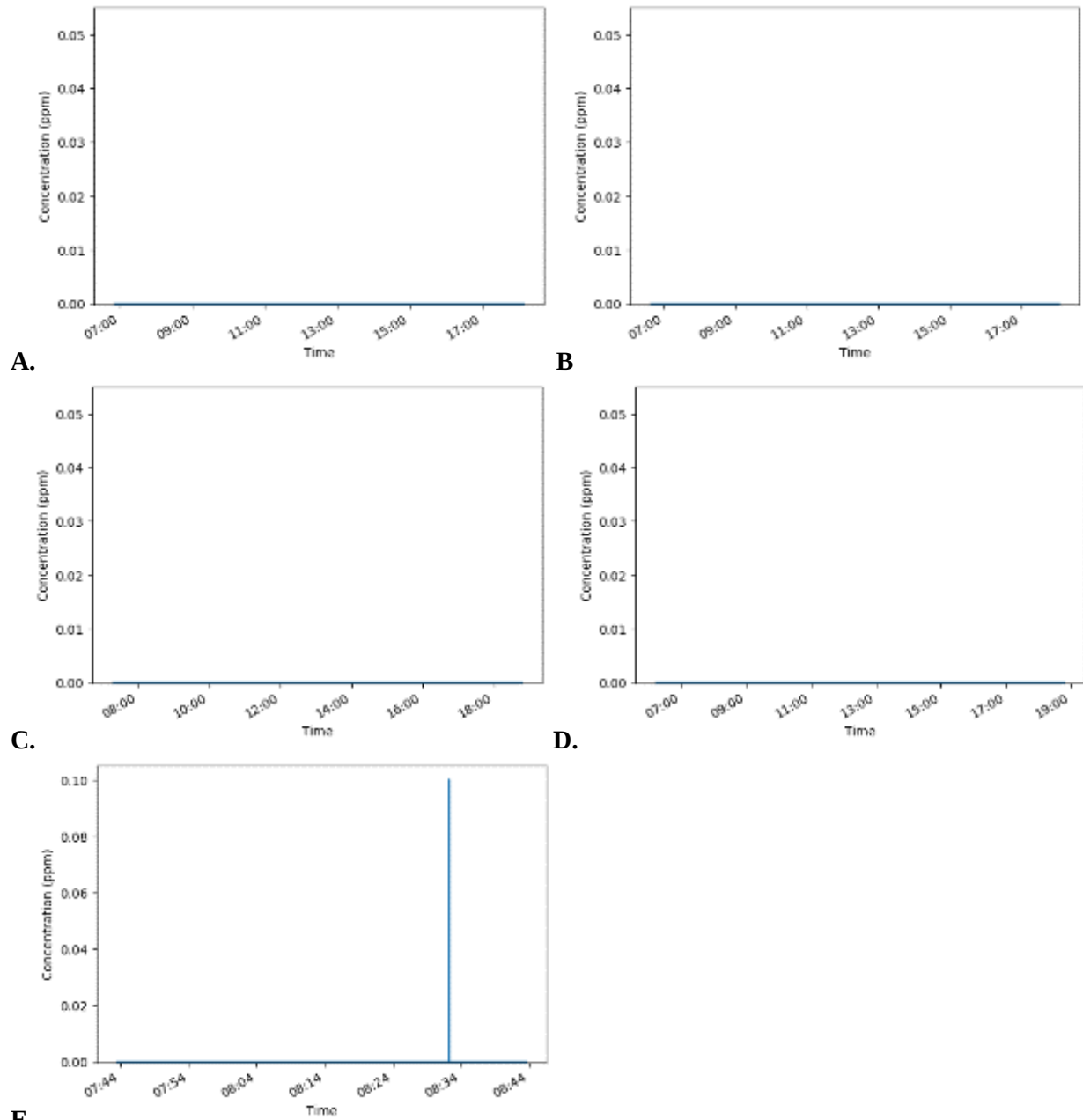


Figure D12. SO₂ concentrations on day 3 (21 Sept 17) from five sites. A. Site 1; B. Site 2; C. Site 3; D. Site 4; E. Site 5.

APPENDIX E: Time Resolved Respirable and Total Aerosols on the Flight Line

Comparison of respirable size fraction counts ($< 4 \mu\text{m}$) and total particulate counts ($0.01 - 35 \mu\text{m}$) recorded by the mini-WRAS demonstrated respirable sized particles dominated the composition of total airborne particles (Fig. E1).

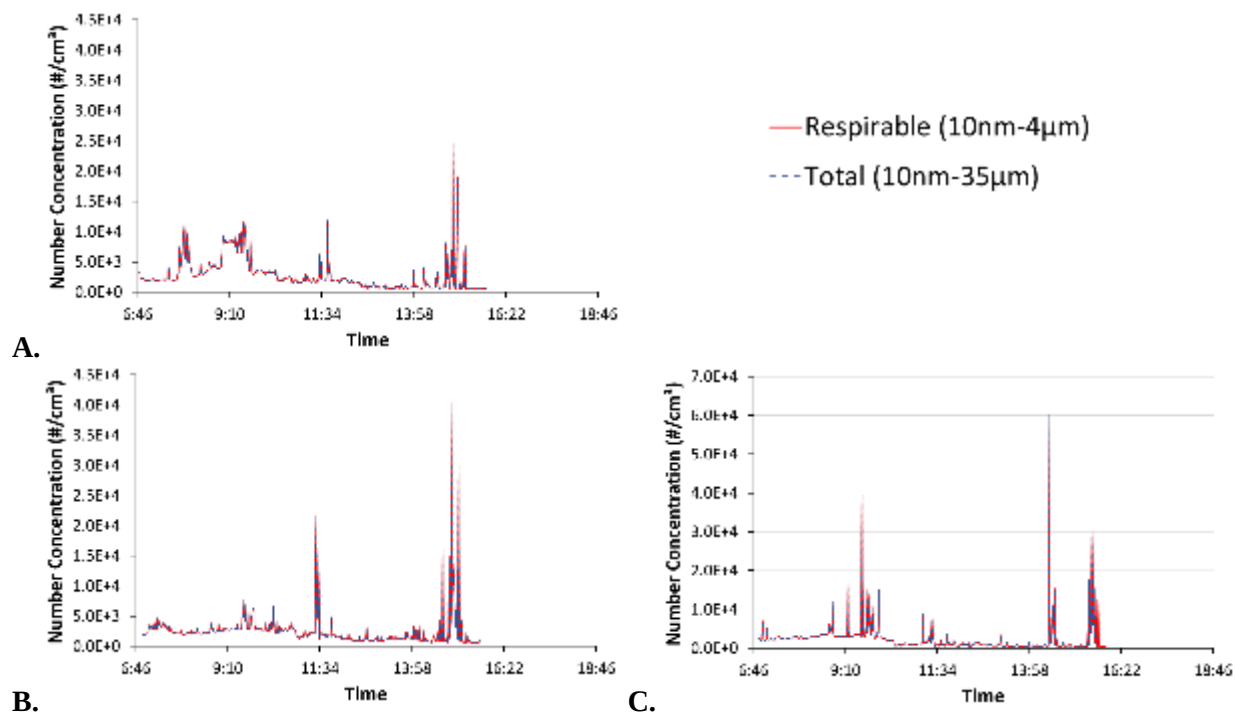


Figure E1. Comparison of total particulate count and respirable range particulate count data recorded by the mini-WRAS (21 Sept 17).

LIST OF ABBREVIATIONS AND ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
AFB	Air Force Base
BASS	breathing air sampling system
BOS	backup oxygen system
C	ceiling exposure limit
CFD	computational fluid dynamics
CO	carbon monoxide
CO₂	carbon dioxide
COTS	commercial off-the-shelf
EPA	Environmental Protection Agency
H₂S	hydrogen disulfide
HCN	hydrogen cyanide
HPW	Human Performance Wing
IPA	isopropyl alcohol
IPP	integrated power pack
JPO	Joint Program Office
LDSA	lung deposited surface area
LOD	limit of detection
NDIR	non-dispersive infrared
NIOSH	National Institute for Occupational Safety and Health
NO	nitrogen monoxide
NO₂	nitrogen dioxide

O₂	oxygen
O₃	ozone
OBOGS	on-board oxygen generation system
OSHA	Occupational Safety and Health Administration
PID	photoionization detector
POC	point of contact
ppbv	parts per billion by volume
ppbm	parts per million by volume
REL	recommended exposure limit
SO₂	sulfur dioxide
STEL	short-term exposure limit (15 min TWA)
SVI	soil-vapor intrusion
TD	thermal desorption
TLV	threshold limit value
TWA	time weighted average
UPE	unexplained physiological event
VOC	volatile organic compound