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Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Aircraft Air Quality and Bleed Air Contamination Detection; On-Wing Tests, Sensor Technologies, and Chemical Sampling (Phase 2, Volume 2)

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Final report

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16. Abstract

The purpose of this project was to provide a data driven process to identify sensor technologies with the potential for detecting and identifying low levels of contaminants that may occasionally be present in aircraft engine bleed air supplies. Bleed air from a ground-based aircraft propulsion engine and an auxiliary power unit (APU) were used to supply air through an ozone/volatile organic compound (VOC) converter to the environmental control system on a Boeing 747, while injecting controlled amounts of fluid contaminants (i.e., aircraft engine oil, hydraulic fluid, and deicing fluid). Measurements of contaminants were performed at the ozone/VOC converter inlet and exit, and at the air conditioning pack exit. Ultrafine particles (UFP) were found to be a sensitive marker for engine oil contamination with measurements at all three locations showing similar, highly elevated UFP concentrations with a mean diameter near 40nm and smaller when the sample stream was cooled to near room temperature. In situ measurements showed that UFPs are generated by condensation and high UFP concentrations were not detected in uncooled bleed air. Oil contamination VOC levels were very low upstream of the ozone/VOC converter at bleed air temperatures up to 220˚C and increased at bleed temperatures of around 315˚C; however, oil contamination VOC levels remained at sub-ppmv levels. Fine particle concentrations also increased with oil contamination at lower bleed air temperatures, but not with temperatures around 315 ˚C. Secondary contaminants including pentanoic acid, heptanoic acid, acetic acid, formaldehyde, and acetaldehyde formed in the ozone/VOC converter as the oil aerosol oxidized. Consideration must be given to contaminant deposition within the bleed air system and sample lines as this deposition may lead to delayed responses and contaminant release during temperature transients. Of the sensor technologies assessed, spectrometers provided the best opportunity to detect and identify contaminants. Carbon monoxide (CO) measurements confirmed that CO is not generated in sufficient quantities to be of value as a marker for engine oil or hydraulic fluid contamination of bleed air. CO may be useful as a marker for ingestion of engine exhaust in some cases. However, carbon dioxide (CO2) is a much better marker for engine exhaust ingestion.

17. Key Words Bleed air; Contaminant; Ultrafine particle; Ionization; Carbon Monoxide;	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

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Acronyms

Acronym	Definition
AAC	Atmospheric analysis consulting laboratory
ACM	Air cycle machine
AMS	Aerosol mass spectrometer
APS	Aerosol particle sizer
APU	Auxiliary power unit
ASHRAE	American Society of Heating Refrigerating and Air-conditioning Engineers
AT	Aerotracer
BASF	Badische Anilin- und Sodafabrik (German for 'Baden Aniline and Soda Factory)
CAMI	Civil Aerospace Medical Institute
CAS	Chemical Abstract Service
CRDS	Cavity ring down spectrometer
CO	Carbon monoxide
CO2	Carbon dioxide
DIN	Deutsches Institut für Normung e. V. (German for ‘Institute for Standardization e. v’)
DMA	Differential mobility analyzer
DNPH	Dinitrophenylhydrazine
EASA	European Union Aviation Safety Agency
EC	Elector-chemical cell
ECS	Environmental control system
EDD	Electronic data deliverable
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FP	Fine particles
HP	High pressure
HPLC	High performance liquid chromatography
HTTVOC	High temperature total volatile organic compounds
i.d.	Inside diameter
INOP	Inoperable
IMS	Ion mobility spectrometer

IPA	Isopropyl alcohol
ISO	International Organization for Standardization
ITEM	Institute for Toxicology and Experimental Medicine
KSU	Kansas State University
LP	Low pressure
MOS	Metal oxide sensor
MW	Molecular weight
NAWCAD	Naval Air Warfare Center Aircraft Division
NDIR	Non-dispersive infrared spectrometry
NIST	National Institute of Standards and Technology
o.d.	Outside diameter
OCP	Organochlorine phosphate
OP	Organophosphorous compounds
PAH	Polycyclic aromatic hydrocarbon
PID	Photoionization detector
PM	Particulate matter
PN	Particle number
PTFE	Polytetrafluoroethylene
RJLG	Robert J. Lee Group Analytical Laboratories
SAE	SAE International (formerly Society of Automotive Engineers)
SDS	Safety data sheet
SIFT-MS	Selective ion flow tube mass spectrometer
SIM	Selective ion mode
SMPS	Scanning mobility particle sizer
S/N	Serial number
SP	Special
SVOC	Semi-volatile organic compounds
TCP	Tricresylphosphate
TIC	Tentatively identified compounds
TVOC	Total volatile organic compounds
UFP	Ultra fine particles
VDI	Verband Deutscher Ingenieure (German for ‘/ Association of German Engineers’)
VIPR	Vehicle Integrated Propulsion Research (NASA Research Program)

VOC	Volatile organic compound
WJHTC	William J. Hughes Technical Center

Symbol	***Unit(s)***
^{o}C	Degrees Celsius
cc	Cubic Centimeter
cm	Centimeter
eV	Electron volt
˚F	Degrees Fahrenheit
hr	Hour
in	Inch
L	Liter
lbm	Pounds mass
m	Meter
µg	Micrograms
µm	Micrometers
min	Minute
mL	Milliliter
mm	Millimeter
nm	Nanometer
#	Number of particles
o.d.	Outside diameter
ppb	Parts per billion
ppbv	Parts per billion by volume (by Moles)
ppm	Parts per million
ppmm	Parts per million by mass
ppmv	Parts per million by volume (by Moles)
psia	Pounds per square inch absolute
psig	Pounds per square inch gauge
SLPM	Standard liters per minute

Executive summary

The FAA Reauthorization Act of 2018 (Congress, 2018), in Section 326, Aircraft Air Quality, subsection (C)(1) directed the Federal Aviation Administration (FAA) to commission a study with the following objectives:

1. Identify and measure the constituents and levels of constituents resulting from bleed air in the cabins of a representative set of commercial aircraft in operation of the United States.
2. Assess the potential health effects of such constituents on passengers and cabin and flight deck crew.
3. Identify technologies suitable to provide reliable and accurate warning of bleed air contamination, including technologies to effectively monitor the aircraft air supply system when the aircraft is in flight.
4. Identify potential techniques to prevent fume events.

The Phase 1 Kansas State University (KSU) research project addressed objective 1 of the Congressional mandate (Jones, 2022). The Phase 2 research project (Fox, Richard B; Jones, Byron W; Kansas State University, 2023) focused on objectives 3 and 4 of the Congressional mandate and assisted the FAA's Civil Aerospace Medical Institute (CAMI) to perform objective 2 of the Congressional mandate by collecting laboratory samples and sending them to outside laboratories for analysis. The analysis of laboratory chemical data to assess health effects is beyond the scope of the KSU contract, and the FAA/CAMI performed its health effects assessment independently. Phase 2 generated two reports. The first report focused on engine test bed testing conducted in May 2022 at KSU. Sensors and instruments were identified, and a test plan was developed. Testing was conducted over a period of approximately one week. Results from this test with respect to sensor ability to detect bleed air contaminants were then used for on-wing tests performed in 2023, which is the focus of this second phase 2 report.

This second phase 2 report provides information to the FAA which identifies currently available technologies that could be adapted to monitor aircraft air supply system contamination from an aircraft environmental control system. Instruments utilized during the testing were not designed for permanent installation on an aircraft for a variety of reasons, such as the need for an operator to be present to obtain samples and monitor the instrument, high power consumption, or the requirement to replenish fluids every few hours of operation. Some of these lesser practical instruments for installed applications provide high quality data that helped the research team better identify influence of system components on condensing contaminants and later releasing them when engine or air conditioning systems change. Prior to the engine tests at KSU in 2022, it was believed that contamination produced in the engine passed directly through the air conditioning system to the aircraft cabin. The tests on an engine and heat exchanger in 2022 and the ground-based, on-wing aircraft tests in 2023 have demonstrated that other locations in the air conditioning system can lead to contaminant condensation and entrainment when proper conditions cause their release. This study recommends that bleed air contaminants be measured in multiple locations in the bleed system, rather than within the aircraft cabin to assess the presence of bleed air contaminants. Measurement only in the cabin does not permit differentiation between engine derived contamination, ingested contamination, and re-entrained contamination that may occur as location, altitude, and power settings change. The ground-based, on-wing aircraft portion of the study provided further information on sensor detection capability. Ultrafine particle measurements and spectrometer measurements were the most successful methods for detecting the presence of contaminants. Other measurements such as carbon dioxide measurement aided in screening for engine exhaust ingestion. The ground-based, on-wing aircraft study with propulsion engine and APU bleed air temperatures that ranged from 180℃ to 330℃ indicated that carbon monoxide (CO) is not produced at levels above 1ppmv, as was observed in May 2022 for the KSU Allison 250 C28B test engine, that had bleed air temperatures that ranged from 200℃ to 260℃.

1 Introduction

The FAA Reauthorization Act of 2018 (Congress, 2018), in Section 326, Aircraft Air Quality, subsection (C)(1) directed the Federal Aviation Administration (FAA) to commission a study with the following objectives:

1. Identify and measure the constituents and levels of constituents resulting from bleed air in the cabins of a representative set of commercial aircraft in operation of the United States.
2. Assess the potential health effects of such constituents on passengers and cabin and flight deck crew.
3. Identify technologies suitable to provide reliable and accurate warning of bleed air contamination, including technologies to effectively monitor the aircraft air supply system when the aircraft is in flight; and
4. Identify potential techniques to prevent fume events.

The Phase 1 Kansas State University (KSU) research project performed objective 1 of the research (Jones, 2022), conducted a literature review, and conducted preliminary auxiliary power unit (APU) and engine tests.

The Phase 2 project consisted of two parts. First, engine stand test data and results were used to inform and further refine test plan development for the follow-on the second part, consisting of ground-based, on-wing aircraft tests.

1.1 Viable aircraft for ground-based on wing aircraft testing

The ground-based, on-wing aircraft testing was conducted on a single aircraft, utilizing a single propulsion engine, and the auxiliary power unit (APU) to provide bleed air with known types and quantities of injected fluid contaminants (i.e., engine oil and hydraulic fluid) through the aircraft environmental control system (ECS) to contaminant detection instrumentation.

1.1.1 Contact with aircraft owners

Letters were sent to select aircraft owners/operators and to the FAA to determine what aircraft might be available to perform ground-based, on-wing aircraft testing. The draft letter appears in Appendix A. The KSU team evaluated responses from the aircraft manufacturers and owner/operators and concluded that based on the responses, none of the respondents would be willing to provide access to aircraft and engines/APU for the desired temperatures and test durations.

1.1.2 Evaluation of FAA aircraft and facility

The FAA has multiple aircraft at the FAA William J. Hughes Technical Center (WJHTC) located in Atlantic City, New Jersey. Three test aircraft were identified as potential candidates and several members of the test team visited the FAA aircraft on October 21, 2022, to evaluate the suitability of the various aircraft to be used for the ground-based, on-wing aircraft study. Boeing 737-200, 747-200SP, and 757-200 aircraft were examined. A debrief following the examination was held to summarize the findings and determine the next steps toward aircraft selection.

1.1.2.1 Boeing 737-200 #544

The Boeing 737-200 (Figure 1) has older style pressurization and air conditioning kits (i.e., packs) and was highly simplified. The aircraft has no recirculation system, and the air cycle machine (ACM) has no reheater, no water extractor, no bleed air condenser, and no ozone converters. The conclusion of the examination was that this was not a representative aircraft, as required by the KSU contract.

Figure 1. Boeing 737-200 front view

1.1.2.2 Boeing 757-200

The Boeing 757-200 (Figure 2) appeared to be in clean condition, but it had mechanical issues that would have needed to be addressed to make the aircraft operable for the KSU testing. The left side ACM had failed. The #1 engine air starter had failed. The APU was non-functional. The reason for its inoperability was not determined. There were some recognized system/component failures reported (e.g., #1 engine starter inoperable (INOP), APU INOP, #1 ACM INOP, and others).

Figure 2. Boeing 757-200 right side view

1.1.2.3 Boeing 747SP

The Boeing 747SP (Figure 3 and Figure 4), known as Friendship One, which raised $500,000 for children's charities, was acquired from United Airlines shortly after setting a speed record for around-the-world flight in 36 hours on January 30, 1988. The speed record was broken shortly thereafter by a Gulfstream IV a month later, and then by the Concorde SST in 1992. Its specifications are presented in Table 1. The Boeing 747-200 SP has four Pratt & Whitney JT-9D engines, three air conditioning packs, and three ozone converters. The ECS system was functional. The aircraft has low pressure packs that utilize coalescer socks for water extraction.

The FAA tested some of the necessary components on the Boeing 747SP to evaluate whether the aircraft might still be operable enough for consideration as a test candidate. Propulsion engine #3 (inboard, port side) and the APU were operable. The ECS operated in nominal configuration with no problem indications. Furthermore, the 747SP is already located on a testing pad where there is electrical power and a trailer to place equipment. Thus, the infrastructure to support the testing was already in place. Weather statistics indicate there is typically a 35% chance of rain in May, when the testing was planned. The interior of the aircraft had sufficient space that test equipment and personnel were sheltered from inclement weather. Tarps were utilized as required to cover the work benches below the aircraft.

Figure 3. Boeing 747-SP left side view

Figure 4. Boeing 747-SP right side view

Table 1. Boeing 747 SP specifications

Model	**Boeing 747-21 100SP**
Date of Manufacture	July 12, 1978
Original Airline	N538PA (Pan Am World Airways)
Second Airline	N147UA (United Airlines)
Registration Date	February 11, 1986
Manufacture S/N	21548
Aircraft Nose Number	4547
Line Number	331
Engine and APU Data	
Engines Type (Pratt & Whitney)	JT9D-7A
Engine Thrust	46,250 lbm
Burn Rate Idle	2,000lbs/hr; ~294 gallon/hour
Burn Rate Max Power	17,000lbs/hr; ~2,500 gallon/hour
APU Type	Honeywell/Garrett GTCP660-4
APU Fuel Burn Rate	1,200lbs/hr; ~177 gallon/hour
Aircraft Time	
Plane Total Time	71,476 Hours
Plane Total Cycles	9,197 Cycles
Time Remaining until “D” Check	2,155 Hours
Performance Data	
Max. Take Off Gross Weight	702,000 lbm
Max. Zero Fuel Weight	410,000 lbm
Max. Landing Weight	450,000 lbm
Operating Empty Weight	326,050 lbm
Max. Structural Payload – Partial	103,950 lbm
Max. Structural Payload – Full	83,950 lbm
Fuel Capacity @ 6.8 lbm/gal	341,632 lbm
Cruise (Mach)	.85
Max Cruise Altitude	43,000 feet
Interior	
Seat Capacity	244 Passengers
Class Split	18 (Weber) First Class
	62 (Weber) Business
	164 (Weber) Coach

The aircraft maintenance manual for the Boeing 747SP directs the user that if a single engine is to be operated that the number one pack must be utilized. Failure to follow the direction could cause premature failure of the packs. This direction therefore required that the #1 ozone converter be utilized. The FAA removed the outer skin of the aircraft to access the #1 ozone converter. The name plate (Figure 5) indicated that the #1 ozone converter (Part Number D019333-2, manufactured by Engelhard Corporation in November 1989) had an Inconel shell and a ceramic core (Figure 6). The FAA Technical Center marked the locations on the ozone converter inlet and exit where they desired to have threaded couplings for sample ports welded onto the converter when the unit was sent to the authorized repair center to be converted into a VOC/ozone converter. The unit was then shipped to AeroParts Manufacturing and Repair to have the threaded couplings welded on, undergo AeroCLEAN®, and to add AeroCOAT VOC to the test unit, prior to its return to the FAA. Figure 7 shows the positions for the threaded couplings on the ozone converter inlet and exit.

Figure 5. Name plate on #1 ozone converter, converted to a VOC/ozone converter

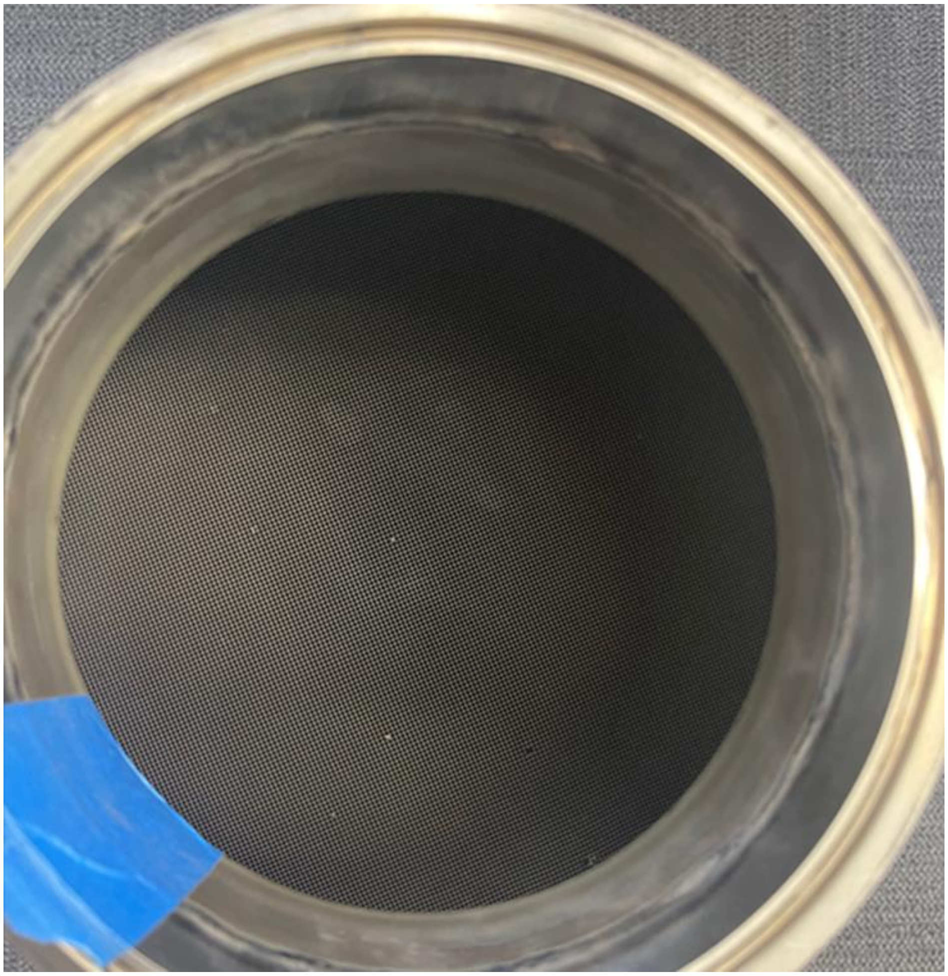

Figure 6. Ceramic core of #1 ozone converter

Figure 7. #1 ozone converter marked for bung attachments

The ozone converter was inspected by AeroParts and there was no visible damage to the ceramic core of the converter, and the fiberglass batting surrounding the core was in good condition (Figure 7). The ozone converter was cleaned using the AeroParts AeroCLEAN® process and the AeroParts VOC volatile organic compound catalytic coating was applied over the BASF ozone catalytic coating, making it a VOC/ozone converter. The VOC/ozone converter was tested to verify its ozone removal and VOC removal capabilities (Table 2).

Table 2. VOC/ozone converter test results

B747 Ozone Converter #1	**Incoming Test**	**Outgoing Test**
BASF P/N D-19333-2, S/N 62298	**BASF Ozone Catalyst**	**BASF AeroCOAT VOC**
Test Temperature	Not Reported	194℃ (392 ˚F)
Pressure Drop (psig)	1.059	Not Reported
Mass Flow Rate (lbm/min)	194	168
Inlet Pressure (psia)	34.6	34.7
Air density (lbm/ft3)	0.1	Not Reported
Ozone Conversion Efficiency	97.1	Not Applicable
Isobutylene Conversion Efficiency (%)	7.80	74.48
BASF - Badische Anilin- und Sodafabrik (German for 'Baden Aniline and Soda Factory)		

The VOC/ozone converter was returned to the FAA Technical Center where it was reinstalled in preparation for instrumentation installation (Figure 8).

Figure 8. VOC/ozone converter reinstalled for bleed air test

Electronics were secured prior to the first day of testing adjacent to the hot bleed duct, and also near the pack heat exchanger discharge. The instrumentation had to be relocated, and air venting from the pack heat exchanger exit directed away from work benches through a specially made enclosure to provide a cooler operational environment for electronics. The exceptions were the

Honeywell Bleed Air Contamination Sensor, and the Pegasor Heated UFP analyzer, which were designed to be secured to the hot bleed duct (red ovals-Figure 9).

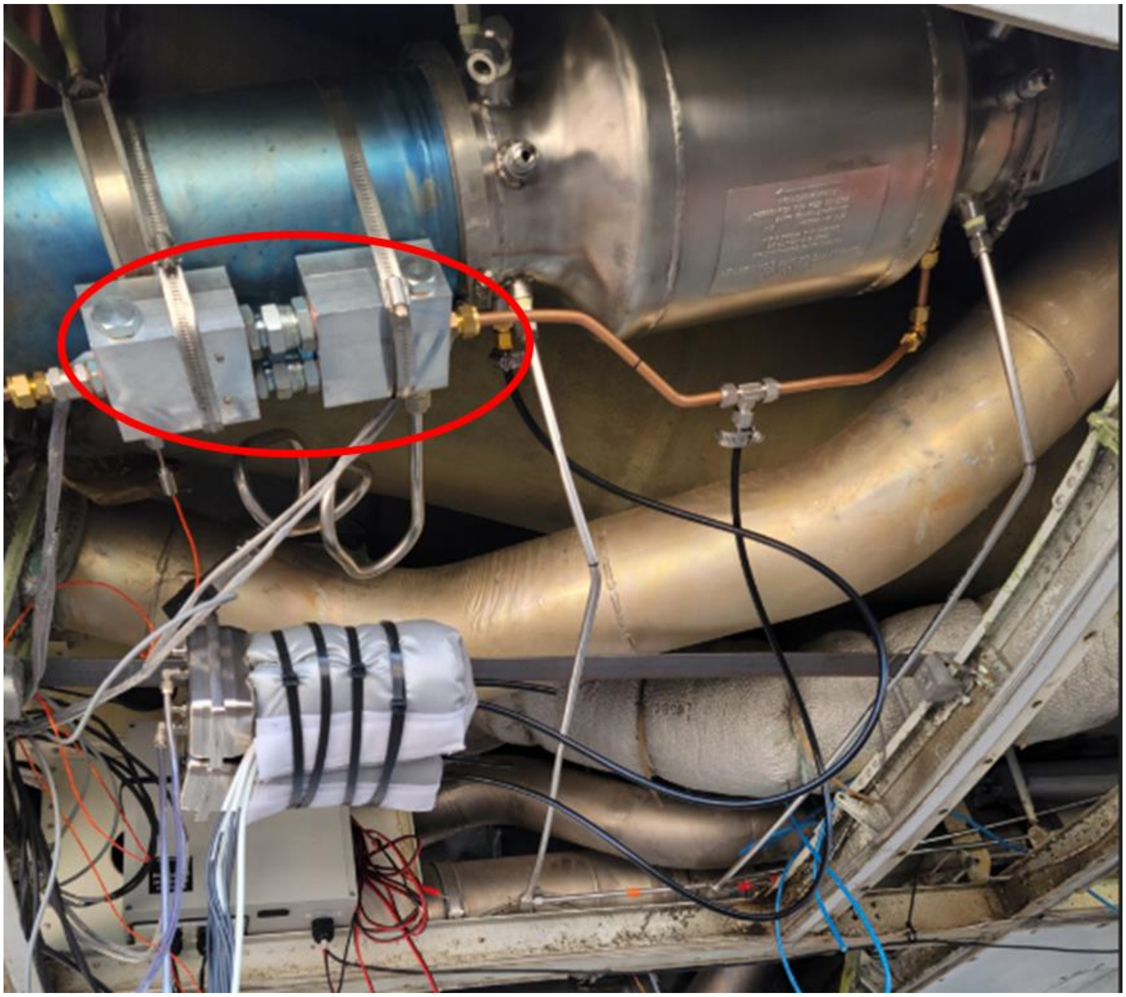

Figure 9. Hot bleed air contaminant sensors (bottom view)

1.1.2.4 FAA facilities

The topography of the test location is pictured in Appendix D Figure D- 1. The weather station was located on a light post pictured behind the Boeing 737 aircraft in Figure 1,approximately 15ft above ground level on a light pole (Appendix D Figure D- 2). The specific GPS coordinates of the weather station, near the conference room trailer with the station display in the conference trailer (Figure 10), are Latitude 39.459161 and Longitude -74.556971. The height of the weather station, depicted in Appendix D Figure D- 2 is approximately 20 feet (2/3 up a 30-foot light pole).

Weather data were recorded continuously throughout the times tests were conducted. The wind speed and direction data for the entire test period are shown in Figure 11. It is seen that the wind was from the southwest during testing times on May 15, 2023 and May 16, 2023, predominantly from the north during testing times on May 17, 2023, and predominantly from the east during testing times on May 18, 2023. The test aircraft was located with the nose pointed towards the southwest (see Appendix D Figure D- 1). Fortunately, this orientation allowed the wind to carry engine exhaust away from the air intakes for the majority of the time. No evidence of exhaust ingestion was seen in any of the CO_2 data for any of the test times, including those limited times when the wind was blowing directly from the direction of the aircraft tail. It is most likely that the high velocity, large volume, and engine exhausts carried the gasses well away from the aircraft.

Figure 10. Weather station display in conference trailer

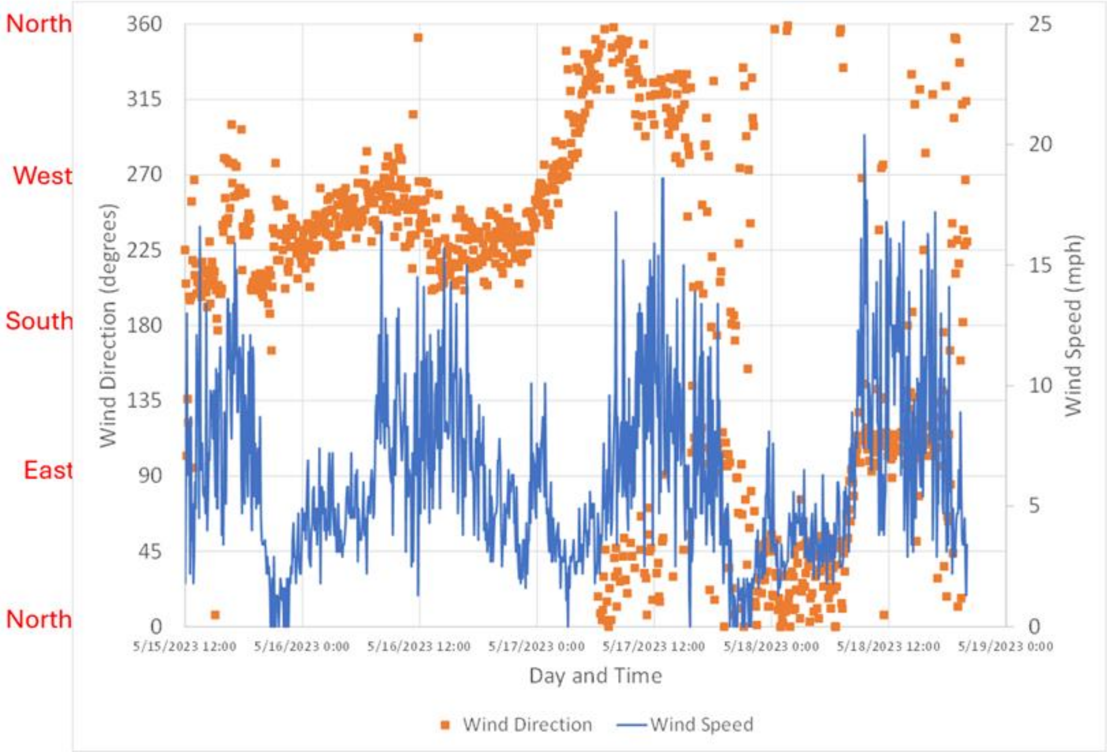

Figure 11. Continuously recorded weather data

The FAA recording instrumentation for aircraft test information (Figure 12) was in the FAA Instrumentation Trailer (See Appendix D Figure D- 1).

Ambient
68.70

Pre cooler
591.41

Pre converter
366.71

Post converter
366.58

Post pack
95.78

Pre converter Pressure
37.45

Post converter Pressure
34.06

Post pack Pressure
15.03

Figure 12. FAA data recording system display

The FAA ground air conditioning units provided fresh air to the flight deck and cabin during the testing to prevent test contaminants from entering the cabin. The unit is pictured in Figure 13. The ground air conditioning unit had two supply hoses. The first of these hoses was connected to the flight deck supply inlet to provide the flight deck with fresh conditioned air during the test (Figure 14). The second supply line was connected to the cabin supply ducting to provide fresh conditioned air to the cabin during the test (Figure 15).

Figure 13. Ground air conditioning unit

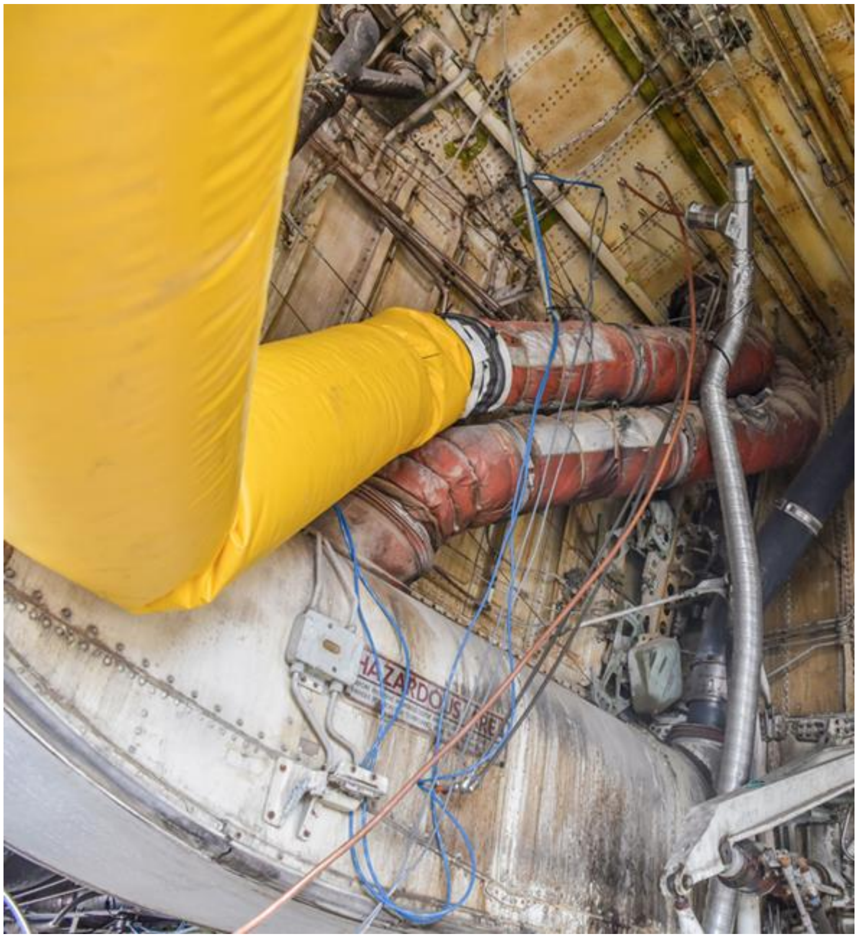

Figure 14. Flight deck fresh conditioned air supply

Figure 15. Cabin fresh conditioned air supply and ambient sample blower

1.1.3 Summary

The Boeing 747SP was the most test-ready of the three available WJHTC aircraft. KSU concurred with the FAA that the B-747SP aircraft was the best option that provided the least amount of budget and schedule risk to performing ground-based, on-wing aircraft tests during the week of May 15, 2023.

1.2 Test plan

The approved test plan (Appendix B Table B- 1, Table B- 2, Table B- 3, and Table B- 4) was based on the format used for the engine stand tests at Kansas State University the week of May 16, 2022. Four days of testing were planned, with the fifth day being reserved as a contingency day.

2 Boeing 747SP ground-based, on-wing aircraft testing

2.1 Test setup/layout

2.1.1 Auxiliary power unit (APU) contaminant injection into the bleed air system

The Garrett AiResearch Model GTCP 660-4 APU is installed in the tail of the Boeing 747 aircraft and utilizes an upward facing inlet duct. An access port (Figure 16) located in the bottom of the APU inlet housing permitted access to route the injection tubing to the lower inlet screen (red oval Figure 17). Contaminants were injected directly into the bottom of the APU inlet using a New Era Instruments Dual-1010-US Syringe Pump (Figure 18).

Figure 16. APU inlet housing access port

Figure 17. APU inlet screen

Figure 18. Dual syringe pump injection system

The Garrett AiResearch 660-4 APU is an integral bleed APU, meaning that the bleed air for the aircraft is extracted from the periphery of the combustion chamber. The inlet screen is highlighted with a small red circle toward the bottom of the cross section, and the bleed air exit to the aircraft bleed system is circled with the larger red circle (Figure 19).

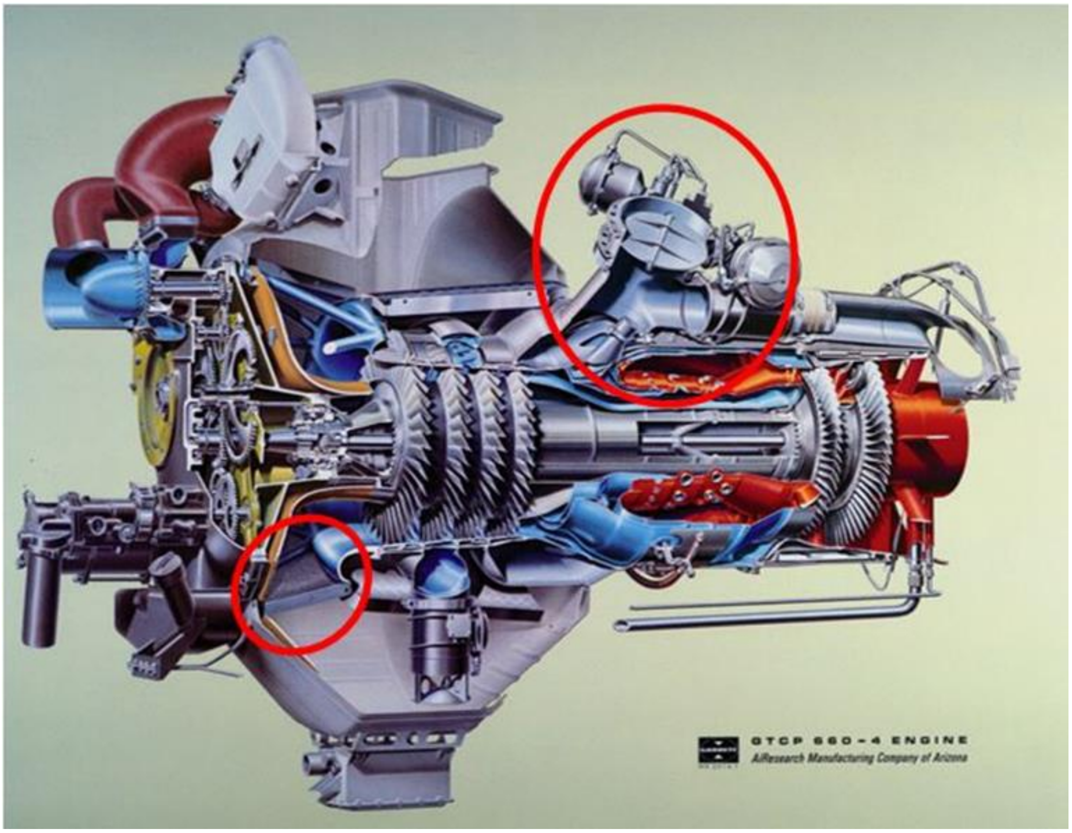

Figure 19. Garrett AiResearch 660-4 cross section

AiResearch, 1974; Retrieved from https://nara.getarchive.net/media/jet-engines-506472

Access rights through https://catalog.archives.gov/s

Engineering data on this model engine is difficult to locate. Honeywell provided limited information from an internal specification that permitted the estimation of total engine air flow (Figure 20). It was important to know the total air flow of the engine combustion path combined with the total bleed flow to calculate the approximate oil injection rate. Honeywell noted total inlet airflow varies between 20 and 30 lbm/second, depending on ambient temperature.” The graph below (Figure 21) is corrected airflow plotted against inlet total temperature. The Y-axis is the equivalent of -40 ˚F, and each grid square is 10 ˚F, ending up with 140˚F on the far right. The “400/0” nomenclature on the right end of the line refers to the total shaft horsepower, but in this case, airflow is constant regardless of the power draw” (B. Volkman (Honeywell), personal communication, April 27, 2023).

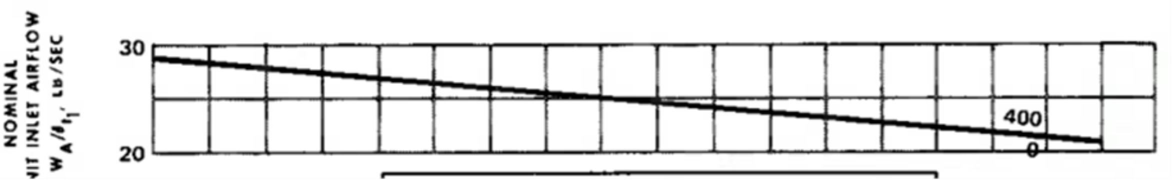

Figure 20. Garrett AiResearch 660-4 corrected airflow plotted against inlet total ºF temperature

Honeywell further cautioned in the email to the KSU team, “The specification for the 660-4 does has a limit for ‘oil consumption’ of 0.1lbm /hr. However, this number doesn’t really reflect bleed air leakage rate or what can be expected in day-to-day operation. It is primarily used to size the oil reservoir and define the maximum length mission for the APU. Oil consumed could exit as vapor through vents designed for that purpose or could get past seals at the hot end into the tailpipe exhaust, where it would not be noticeable, or the cold end, where it might be ingested into the bleed air compressor. The 0.1 lbm/hr consumption rate translates into just under 55 mL/hr, which is an unrealistically large volume to be leaking. Current engines set the allowable consumption at around 12 mL/hr, and numbers from recent endurance testing indicates the APU only consumes about half of that.”

KSU interpolated values from Figure 20 to create Figure 21. APU inlet temperature at the time of test is required to estimate total inlet air flow. The test location at the Atlantic City Airport (airport code: ACY) was near seal level, so ground elevation did not significantly affect air density.

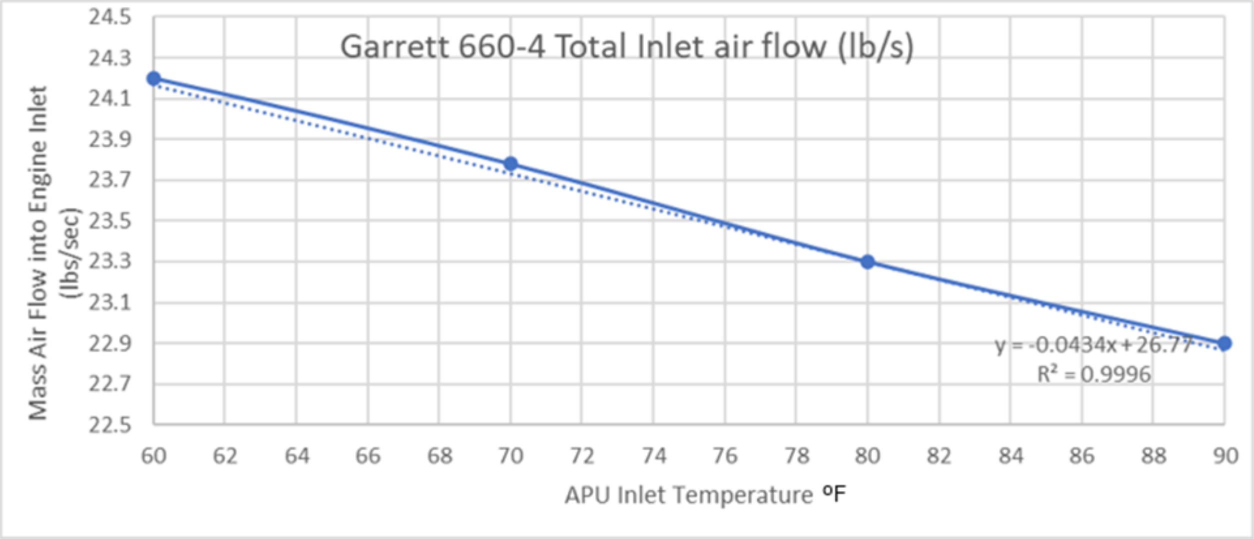

Figure 21. Interpolation of Figure 20 to refine APU mass air flow estimate

2.1.2 New era syringe pump test

The New Era syringe pump (used to inject contaminants into the APU inlet air) was tested on April 27, 2023, and results were as follows:

Test of New Era Dual-1010-US syringe pump

Master SN: 432123

Secondary SN: 432124

Mettler Toledo PR8002 mass balance

For these tests, water was used as the injection fluid and the check valves provided with the New Era P-DKIT dual plumbing kit were utilized. Syringes were NORM-JECT HSW 50(60) mL plastic syringes with Luer-Lock connections. Since the density of water is 1.00 grams/mL, one gram measured is equal to one mL dispensed. Tests were conducted with zero back pressure on the injection line. That is, the injected fluid was collected in a beaker open to the atmosphere. Following these tests, an evaporation test was conducted to determine if evaporation from the open beaker affected the results. The amount of evaporation was negligible compared to other uncertainties, 0.08 grams over 30 minutes.

Two tests were conducted, the first with a 20 mL stroke volume (Figure 22) and the second with a 40 mL stroke volume (Figure 23). “Stroke volume” is terminology used by the instrument manufacturer. It is different from displacement volume (as in an engine) in that displacement volume in an engine is determined by the geometry of the piston and cylinder. With an injection syringe and pump, the stroke volume is determined by the programming of the pump (within the limits of the syringe) and not by geometry of the syringe. For both tests, an injection rate of 200mL/hr was set. A substantial amount of dead band is evident when the pumps switch. This effect is most easily seen in Figure 23 with a 40 mL stroke volume. The amount dispensed tracks accurately with the set rate of 200mL/hr. There is then a drop-off in the rate when the pumps switch after 12 minutes. Once the switch is complete, the data are parallel to the 200 mL/hr line. The 180mL/hr line is also included for reference. It appears that the actual amount dispensed with this stroke volume would be closer to this value, on average over an extended time. With the smaller 20 mL stroke volume in Figure 22, it appears the actual average dispensing rate is closer to 175mL/hr.

Based on these tests, it was recommended that the rate be set to a value 10% higher than the desired injection rate when using a 40mL stroke volume, the 50 mL plastic syringes utilized in these tests, and the check valves provided with the New Era DKIT. Doing so should have provided an injection rate with at least 5% accuracy and likely better. It was not known if the source of the dead band is from elasticity of the syringes, elasticity of the plastic tubing, the check valves, or the pump mechanisms. Possibly, it was some combination of all of these factors. It was also noted during these tests that the injection flow did not appear to go to zero during the syringe switching. Thus, mechanical slack in the pump mechanism was unlikely to be the source of the dead band.

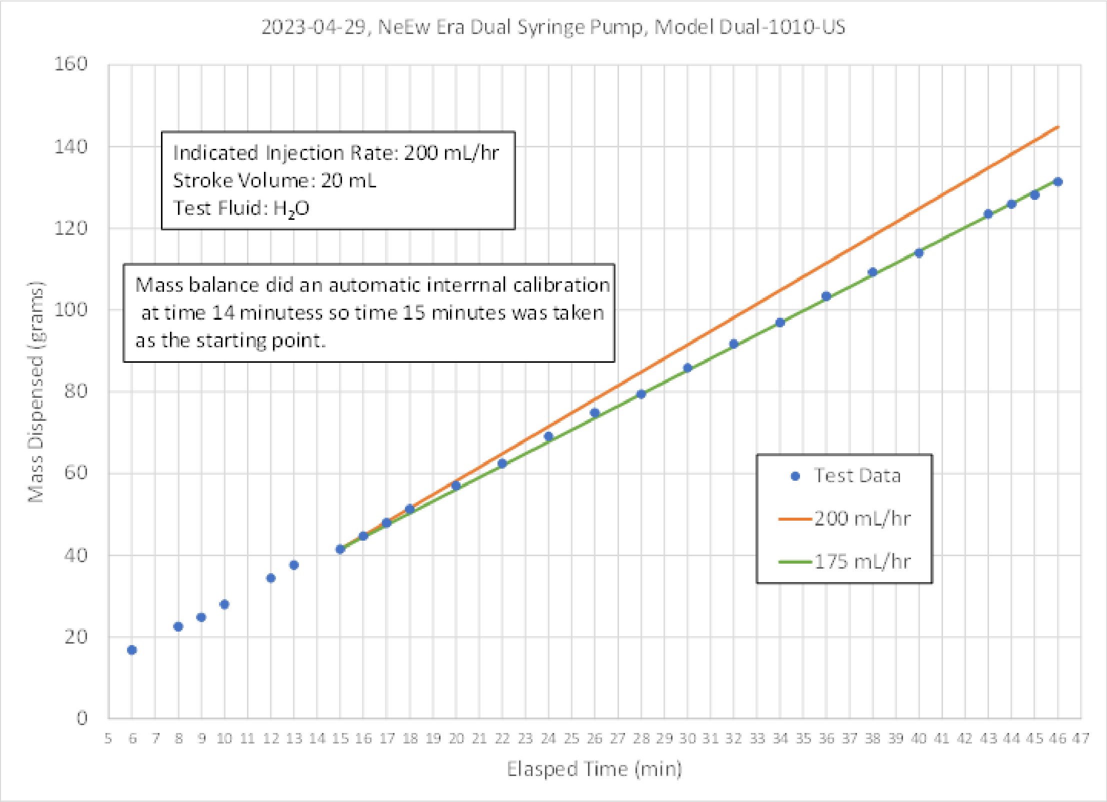

Figure 22. 20mL stroke volume test of new era digital pump

The check valves provided by New Era were not compatible with one of the injected fluid contaminants (Mobil Jet Oil II) and failed within a short time of initial use. One of the test participants had on hand 1/8 in(3mm) hose barbed, non-return, one-way check valves compatible with fuel, oil, air, or gas (Amazon Part Number aww-123101410). This enabled APU fluid injection to occur for both days of APU tests.

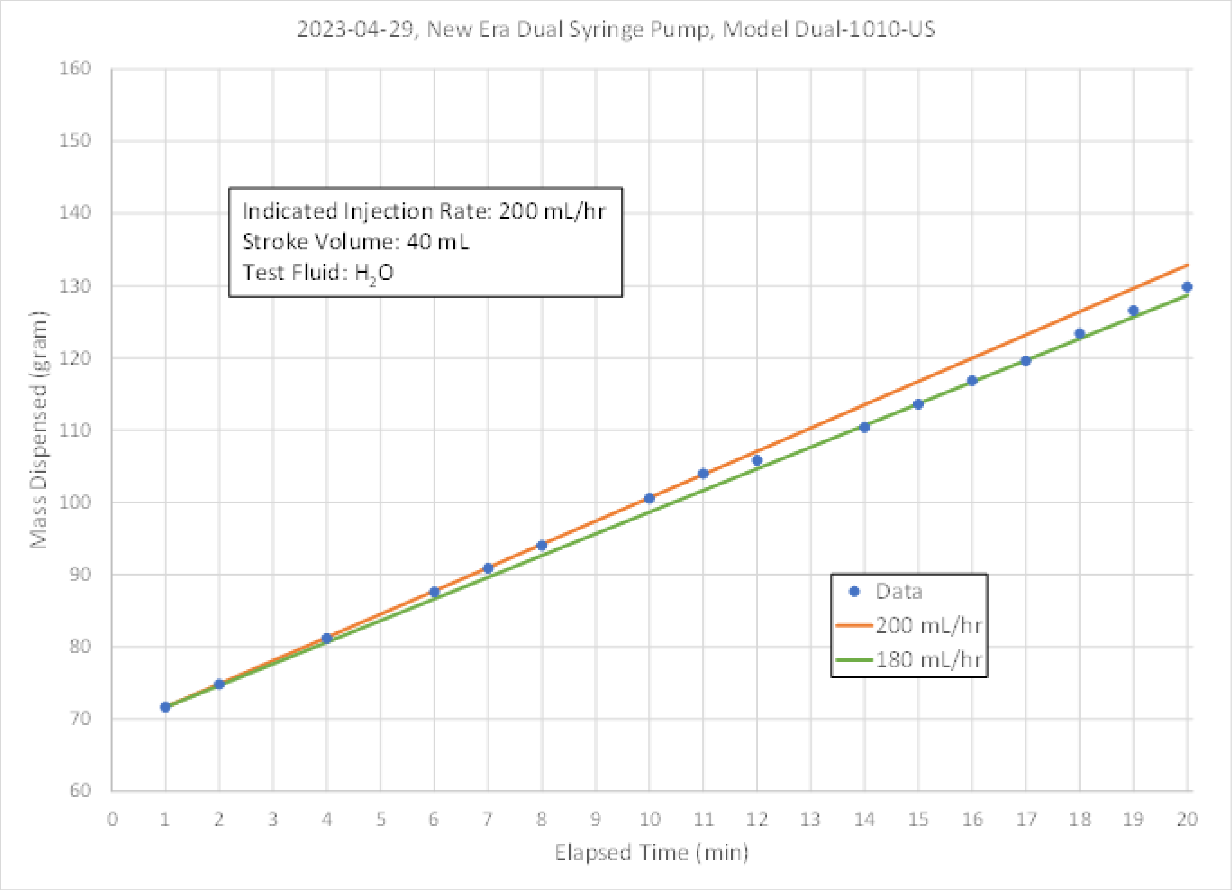

Figure 23. 40mL stroke volume test of new era digital pump

2.1.3 Number 3 propulsion engine contaminant injection

Pratt and Whitney Engine Company assisted KSU in developing the most suitable method for oil injection into the JT-9D propulsion engine. One of the main factors discussed was how to best represent oil injected at various locations to that of a real oil leak, in which oil might enter the bleed air.

Oil could not be injected at the engine inlet as there was no way to determine how much of the oil would enter the bleed air. Oil injected in the engine turbine section created potential risk of damage or destruction to the engine, and a safety risk to test participants. KSU conducted several studies of aerosolization of oil at high pressure and found that they could not achieve a small diameter aerosol that was representative of measurements in the May 2022 KSU engine stand tests (i.e., Phase 2, Volume 1 report).

A discussion was held with the aircraft owner, and the lowest safety risk approach was determined to be to install a port in the bleed adapter between the engine low pressure (LP) and high pressure (HP) bleed ports and the engine precooler. This location enabled selection of LP or HP air source and bleed temperature by operation of the engine #3 throttle. An image of the oil injection port behind the engine cowling is presented in Figure 24.

Figure 24. Oil injection port on engine bleed duct

The oil injection line was routed from a high pressure CHEMYX Model 6000X injection pump fitted with a 100mL stainless steel syringe and check valve (Figure 25).

Figure 25. CHEMYX high-pressure injection syringe

Oil was pumped through a 50ft long stainless-steel line to the #3 engine (Figure 26). It was secured with several hose clamps to the engine and routed to the port depicted in Figure 27**.**


Figure 26. Securing stainless injection line to number 3 engine

Figure 27. Contaminant injection port on number 3 engine bleed duct

The CHEMYX Model 6000X syringe pump was provided with a NIST traceable calibration, so no secondary calibration was necessary. The calibration certificate is presented in Figure 28.

CHEMYX www.chemyx.com

Certificate of Calibration

Certificate Details	
Certificate Number:	66848
Date of Issue:	4/20/2023
Instrument:	F6000X

Environmental Conditions	
Temperature:	27°C ± 1°C
Relative Humidity:	50% ± 10%
Mains Voltage:	220V/110V ± 10V
Mains Frequency:	50Hz / 60Hz

The instrument was calibrated against laboratory standards whose values are traceable to recognized NIST. The uncertainty limits quoted refer to the measured values only, with no account being taken of the instruments ability to maintain calibration after extended use or inadequate maintenance.

Systems are calibrated on a relative standard deviation factor coverage factor k=2, providing a level of confidence of approximately 95%.

Accuracy:	± < 0.35%	Pusher Force Verification:	Yes
Precision:	± < 0.05%	Adjustment Value:	N/A

Calibrated By:

Figure 28. CHEMYX syringe pump certificate of calibration

2.1.4 Air conditioning pack exit sampling and flow measurement

It was not necessary to know the total mass air flow passing through the engine since the oil injection occurred in the bleed air stream. The bleed air temperature and pressure were measured with the aircraft flight deck cockpit flight deck instruments. The bleed air temperatures were also captured at the VOC/ozone converter inlet and the VOC/ozone converter exit. Total air flow measurements were measured using a thermal anemometer (Figure 29), and by gathering differential measurements using a Kiel probe and static pressure measurement. The duct dimension at the Kiel probe (Figure 30) was 9.4375in diameter.

Figure 29. Total bleed air flow measurement and sample lines at pack exit

A Kiel probe is a device used to measure total pressure of air flow with high accuracy over a wide range of flow angles. The shroud over the probe (Figure 30) aided in improving the flow measurement in the area where it was installed, as the measurement section was immediately below a right-angle bend in the duct and had other probes near the location that could disturb the flow. The Kiel probe was tuned while the APU was operating by rotating the probe until the highest differential reading was observed between the Kiel probe pressure and static air pressure. Placement of the Kiel probe and the thermal probe was made with care to ensure that the air flow disturbance from the Kiel Probe did not adversely affect the measurement of the thermal probe. A comparative flow indication is presented in Figure 31. The flight deck ECS display in which the flight deck flow indication was derived is presented in Figure 32. The corrected indication was utilized to calculate oil injection rates at the #3 engine.

Figure 30. Kiel probe

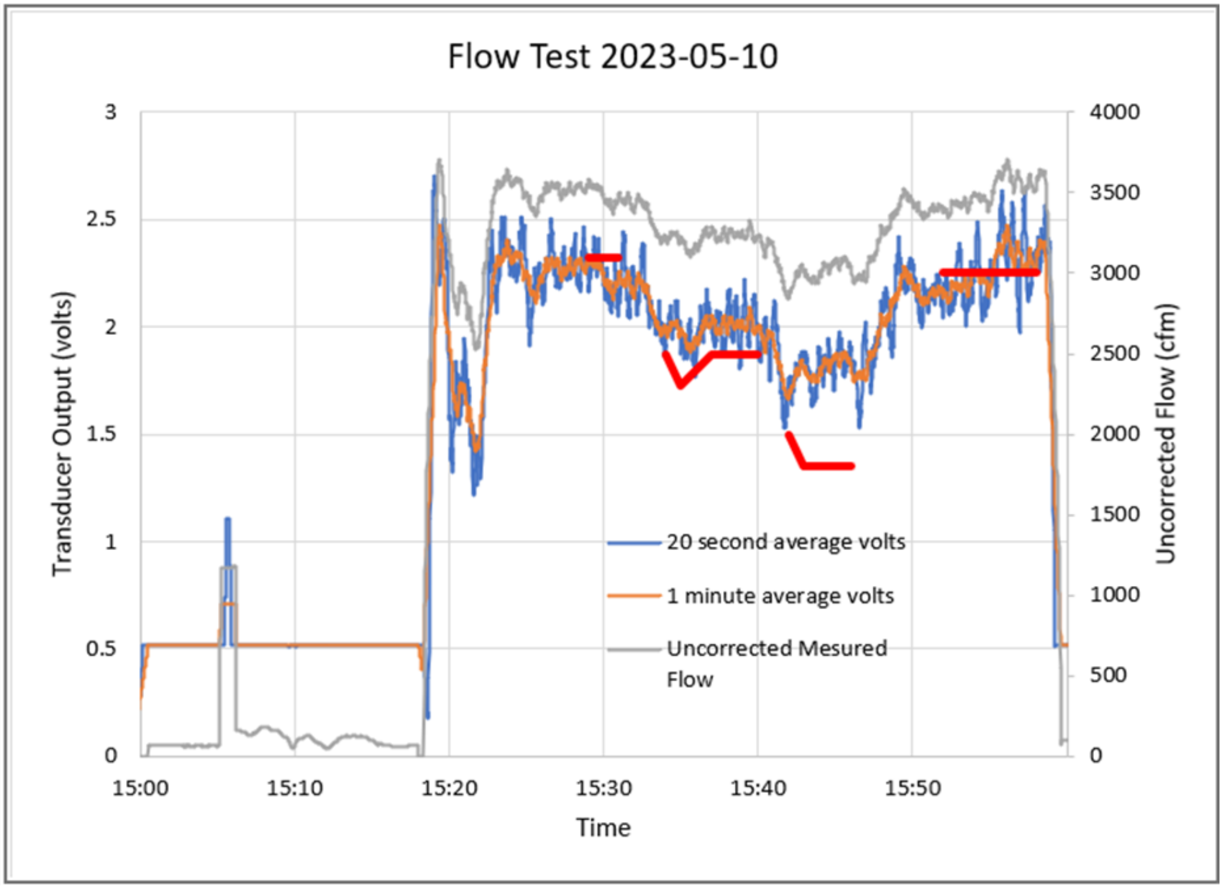

Figure 31. Comparison of flight deck flow measurement to laboratory flow devices

Figure 32. Flight deck ECS displays

2.2 Sample transfer to analytical benches

2.2.1 Ambient air sample system

An ambient air sample was provided to the cabin by placing a blower underneath the aircraft that drew air from the area under the aircraft behind the enclosure that was used to direct air from the pack heat exchanger outlet (Figure 15). This blower was adjacent to the adapter that was used to provide the fresh conditioned cabin air supply. The ambient air was ducted from the blower to the high volume semi-volatile sampling blower, and to the bulkhead fitting using a 3-inch aluminum flexible duct. Air sampling by the Syft Technologies van was conducted through a ¼-inch outside diameter (o.d.), 3/16-inch inside diameter (i.d.), virgin polytetrafluoroethylene (PTFE) line from a bulkhead fitting on the duct at the blower. The flex line at the bulkhead of the aircraft had a vent in the T-fitting for the 3-inch duct that ensured a continuous flow of ambient air up to the bulkhead (Figure 33).

2.2.2 Bleed air sample system

Figure 33. Sample adapters penetrating cabin bulkhead

2.2.3 Ozone/VOC converter inlet and outlet sampling

Sample lines were plumbed using ¼-inch o.d., 3/16-inch i.d. stainless steel tubing from the bungs on the VOC/ozone converter inlet, and outlet fittings to the bulkhead fittings pictured in Figure 33.

2.2.4 Air conditioning pack outlet sampling

The #3 engine bleed air passed through the #1 pack and water coalescer before passing through the flow measurement probes and exited past the knife valve which provided a slight amount of back pressure. The pack exit sample line was plumbed with 3/8-inch o.d., 5/16-inch i.d., copper tubing, which is visible exiting the right side of the duct in Figure 29. The sample line for the Syft van was plumbed with ¼-inch o.d., 5/16-inch i.d. virgin PTFE tubing from its own duct port. Details of the sampling line layout outside of the cabin are found in Appendix Figure D- 3. Details of the sampling line layout inside the cabin are found in Appendix Figure D- 4. Details of the in-cabin instrument layout are found in Appendix Figure D- 5. A block diagram of outside instrumentation is located in Appendix Figure D- 6. A detailed working list of sensors and sample locations is found in Appendix Figure D- 7. A marked-up aircraft ECS schematic from the aircraft maintenance manual indicates to the reader the locations in the bleed air flow path where contaminants were introduced to the bleed air flow path (Appendix Figure D- 8). Left and right isolation, and the APU isolation valve permitted selection of bleed air from either the APU or the #3 engine to be directed through the #1 ozone/VOC converter and the #1 pack.

Modifications to the aircraft ducting were required to enable sensor instrumentation connections. Appendix Figure D- 9 lists fittings, dimensions, and locations that the FAA utilized to modify the aircraft to enable instrumentation and sample lines.

Modification and repositioning of ductwork was necessary to provide access to the ductwork after ECS #1 pack and to prevent introduction of contaminated air into the occupied (by researchers and technicians) airplane cabin. Appendix Figure D- 10 and Figure D- 11 show removal of the ground air conditioning port and coalescer housing. Instrumentation lines were fabricated to enable reconnection of duct sensors. The duct exiting the #1 coalescer was rotated to face toward the ground, rather than facing upward toward the wheel-well (Figure D- 12). An upward view (Figure D- 13), side view (Figure D- 14), and rear view (Figure D- 15) looking forward from the wheel-well help the reader to visualize the complexity of this adaptation. Duct lengths were very short, so it was not possible to place flow metering equipment 5-to-10-line diameters below the last bend in the duct (Figure D- 16). There was some concern that gas sample probes and flow measurement probes might interfere with one another, so the ports for these probes were staggered around the diameter of the duct within the constraints of space available. A commercially available guillotine valve was identified (Figure D- 17) that could be adapted to the aircraft duct and was used to provide a typical pack exit duct pressure (Figure D-18).

2.3 Sensor and sensor technology plan

Table 3 lists instruments by type/detection method. It also provides a link within the manufacturer column to figures of the instrumentation within the body of this report.

Table 3. Sensor technology evaluated

Sensor Technology	**Sensor Name**	**Manufacturer**	**Make/Model**	**Analyte Detected**
Ultra-Fine Particles				
Electrostatic	Classifier	Thermo-Systems Company Incorporated (TSI)	3080	UFP

Sensor Technology	**Sensor Name**	**Manufacturer**	**Make/Model**	**Analyte Detected**
		Figure 34		
X-Ray	Particle Neutralizer	TSI Figure 34	3088	Particle Neutralizer
Condensation Particle Counter (CPC)	CPC	TSI Figure 34	3775	UFP
Corona Discharge	Partector II	Naneos Figure 39	Partector II	10-300 nm range, 0-10^6 PN/cc; 0-2,500 µg/m^3
Corona Discharge	G2 AIRIN	Pegasor Figure 35	Indoor UFP Analyzer	10-300 nm for particle mass, 10 nm to 1 µm for PN
Corona Discharge	PPS-G2	Pegasor Figure 37	Heated UFP Analyzer	10-300 nm for particle mass, 10 nm to 1 µm for PN
Radioactive Ionization Chamber	Modified Smoke Detector	BRK Industries	First Alert/3120B	UFP/PN
Radioactive Ionization Chamber	Modified Smoke Detector	Siemens Figure 40	DO-A3, 0-1200 Feet/minute air velocity	UFP/PN
Fine Particle (PM)				
Laser Time of Flight Spectrometer	Aerosol Particle Sizer (APS)	TSI Figure 34	3321	UFP
Laser Light Scattering	IPS 7100	Piera Systems Figure 41	IPS 7100	PM
Laser/Light Scattering	Canaree	Piera Systems Figure 42	I5	PM
Non-Dispersive Infra-Red Spectroscopy (NDIR)				
Gas Filter Correlation NDIR	Low Range CO	Teledyne Figure 43	300e	CO
NDIR	Low Range CO_2	PP Systems Figure 43	WMA-5	CO_2
Ion Mobility Spectrometer (IMS)				

Sensor Technology	Sensor Name	Manufacturer	Make/Model	Analyte Detected
IMS	Aerotracer	Airsense Figure 44	Aerotracer	VOC
Selected Ion Flow-Tube Mass Spectrometer (SIFT-MS)				
SIFT-MS	VOICE 200 Ultra	SYFT Figure 46	4 reagent ions	VOC
Metal Oxide Sensor (MOS)				
MOS	Hot Bleed Air Sensor	Honeywell Figure 48	Prototype	VOC
MOS	Canaree	Piera Systems Figure 42	I5	VOC
MOS	Aerotracer	Airsense Figure 44		VOC
Photoionization Detector (PID)				
PID	Aerotracer	Airsense Figure 44	Aerotracer	VOC
Electrochemical (EC)				
EC	Aerotracer	Airsense Figure 44	Aerotracer	CO

2.3.1 Ultrafine particle measurements

Ultrafine particle (UFP) sensors were identified during the KSU Phase 1 research project (i.e., literature review and current state of sensor technologies) as being one of the best markers for the presence of turbine oil. Three different UFP sensor technologies were evaluated during Phase 2 research (i.e., May 2022 KSU engine stand tests and May 2023 at the WJHTC ground-based, on-wing aircraft tests).

Condensation particle counting utilizes a fluid such as alcohol or water vapor to condense on the nanoparticles and grow their size sufficiently so that they can be detected by an optical particle counter. Corona discharge sensors ionize the particles in an aerosol using a corona discharge. The particles are then collected on an oppositely charged surface and the current generated is measured by an electrometer. An ionization sensor (e.g., an ionization smoke detector) ionizes the air between oppositely charged surfaces and the current between the surfaces is measured. Particles in the air interfere with the diffusion of the ions through the air and decrease the current and this decrease in current is measured.

The large number of nanoparticles may overwhelm some of the detectors. An electrostatic classifier may be used to study the number of particles across the size range of the instrument measuring capability. This may enable an instrument with lower dynamic detection capability to measure very high levels of particles. Some nanoparticle sensors tested had evidence of over-ranging with the quantity of particles produced during contaminant injection. Those sensors and scenarios will be discussed further in the results section.

The KSU Scanning Mobility Particle Sizer (SMPS) (Figure 34) consists of several subassemblies, including a long differential mobility analyzer (DMA) and an Aerosol Mass Spectrometer (AMS). The model 3081 DMA is set up to measure particles from 10 to 700 nm diameter.

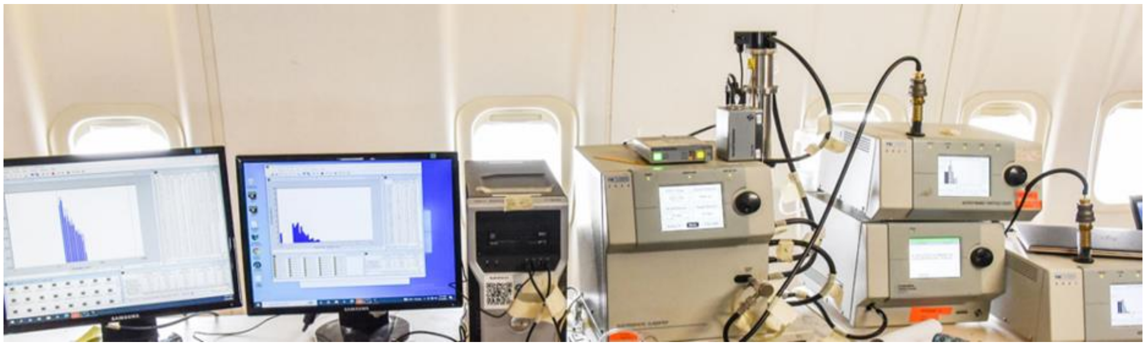

Figure 34. KSU SMPS and APS units

The Pegasor G-2 sensor is unique in that its design permits ultrafine particle sampling under high-temperature and high-pressure conditions. Two Pegasor G-2 heated sensors operated by Pegasor representatives provided KSU an opportunity to study UFP concentration entering and exiting the ozone/VOC Converter (Figure 35 and Figure 36). Two room temperature Pegasor G-2 sensors monitored (Figure 37) UFP at the ambient air sample box and at the pack exit sample box. The Pegasor sensor dynamic range spans from approximately 10 nm to 300 nm particle diameter and can count up to 5 x 10^7 particles/cm^3. The output from the four Pegasor G-2 analyzers was monitored on a single computer screen (Figure 38). Data from the four units was stored on the laptop computer and downloaded at the end of testing each day.

Figure 35. Pegasor heated UFP analyzers

Figure 36. Pegasor heated UFP analyzers

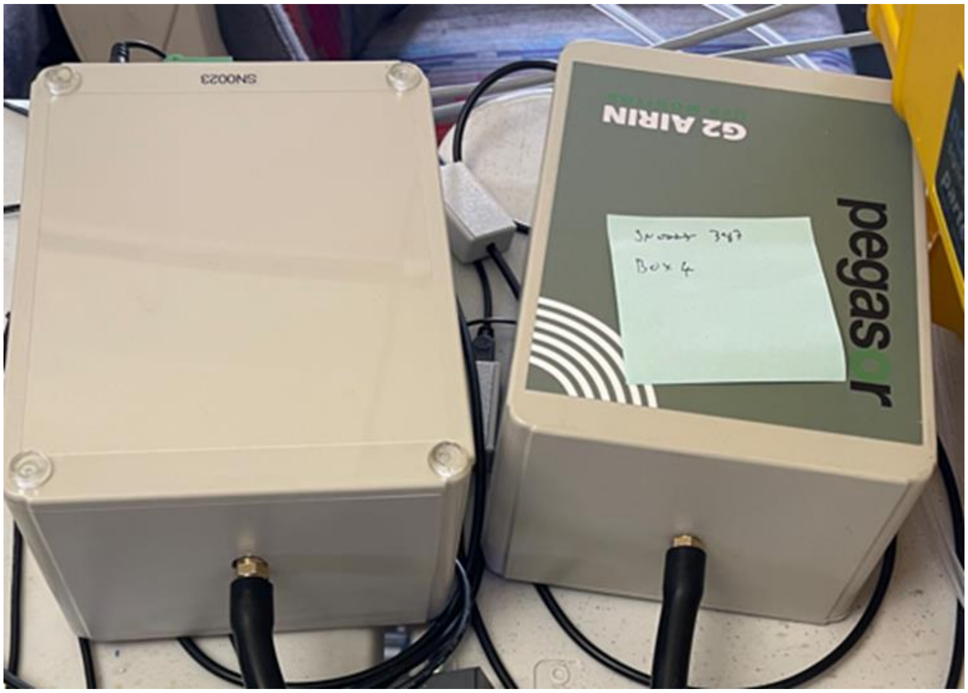

Figure 37. Pegasor room temperature UFP sensor

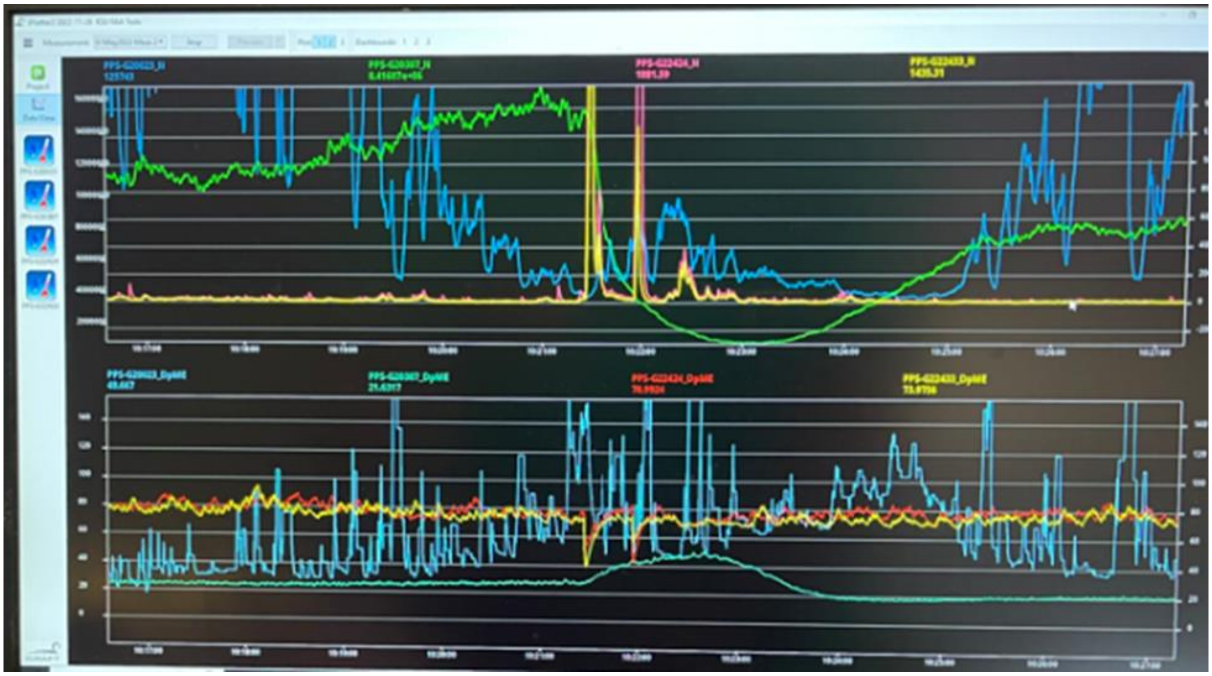

Figure 38. Pegasor multi-channel UFP display

Four Naneos particle analyzers were utilized to measure UFP concentrations at the four sample box locations inside the aircraft (Figure 39).

Figure 39. Naneos Partector II UFP detectors

Siemens ionizing smoke detectors were last produced approximately 30 years ago. Eight ionizing smoke detectors were provided by one of the test participants, enabling duplicate measurements to be made from each of the four sampling boxes. The display screen for the eight smoke detectors is displayed in Figure 40.

Two First Alert ionizing smoke detectors were provided by KSU. One was utilized for the ambient air box and one for the pack exit sample box. The 10 total smoke detectors were modified by connecting leads to a transistor output and signal ground to obtain an analog voltage output that responded to changes in particle concentrations. Ionizing smoke detectors cannot distinguish between UFP and PM and are affected by changes in humidity and temperature.

[1] CH1 - Box 1 - SN J2641: 7.44 V
[2] CH2 - Box 1 - SN J1812: 8.23 V
[3] CH3 - Box 2 - SN J4451: 13.45 V
[4] CH4 - Box 2 - SN J2632: 13.54 V
[5] CH5 - Box 3 - SN J2821: 11.03 V
[6] CH6 - Box 3 - SN 4000244: 8.77 V
[7] CH7 - Box 4 - SN J4452: 12.35 V
[8] CH8 - Box 4 - SN 4036345: 9.90 V

Figure 40. Siemens ionizing smoke detector response

2.3.2 Fine particle measurements

The KSU time-of-flight Aerosol Particle Sizer (APS) measures the aerodynamic velocity of particles ranging from 0.5 µm to 20 µm in aerodynamic diameter, over a range of 52 channels of size, and provides information on the range of particle size distribution and concentration. Two of these instruments were utilized, one for the pack exit and one for ambient air sample box.

The Piera Systems sensor utilizes a red laser to quantify fine particles in the size range of 0.1 µm to 10 µm. The instrument display for the Model 7100 is shown in Figure 41. The Canaree I5 display is shown in Figure 42. The particle counting optics in both Piera models have the same specifications. The Piera sensors detect particles in size down to the optical limit of 0.3 micron (300 nm) and extrapolate down to 0.1 µm (100 nm). Caution should be used in data analysis, as measurement units are presented as #/liter, rather than #/cm^3.

Figure 41. Piera Systems Model 7100 PM particle display

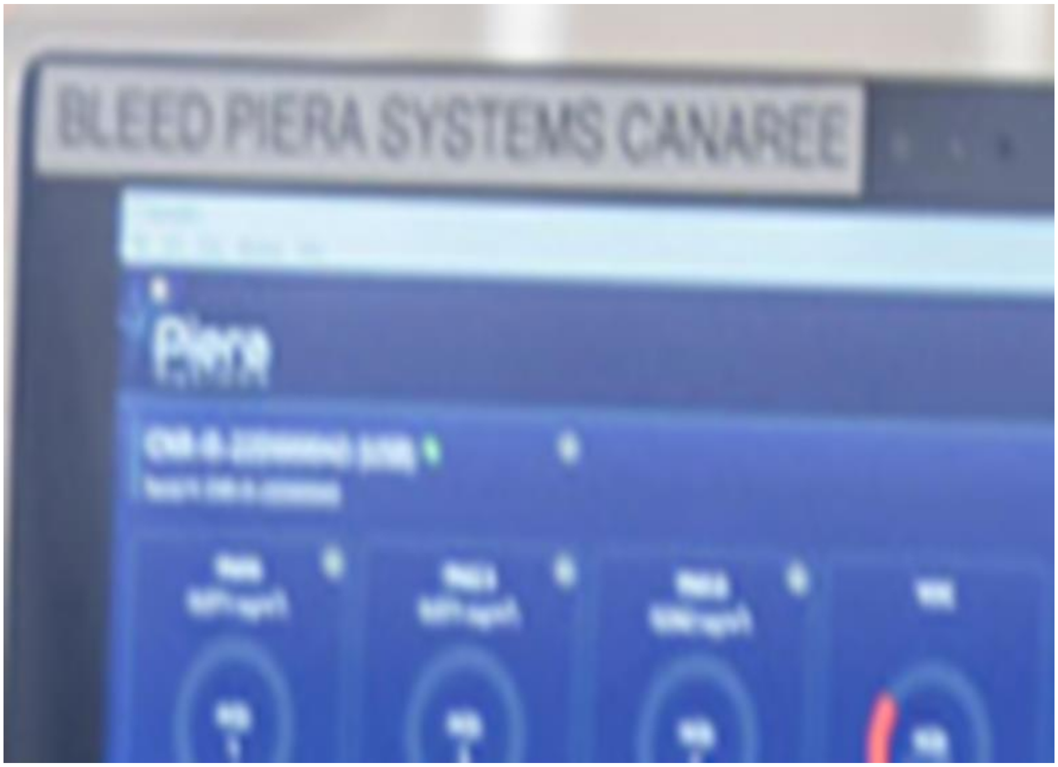

Figure 42. Piera Systems Canaree display of PM and VOC

2.3.3 Carbon dioxide and carbon monoxide measurements

2.3.3.1 Carbon dioxide

Molecules such as carbon dioxide and carbon monoxide are quantified utilizing non-dispersive infrared (NDIR) methodology with longer optical path-lengths for low range measurements (The PP Systems carbon dioxide analyzers are sitting on top of the Teledyne 300e carbon monoxide sensors in Figure 43). The carbon dioxide analyzers were connected to sample from the ambient air sample line and the pack-exit sample line that led to the laboratory sampling table.

Figure 43. NDIR analyzers for carbon dioxide and carbon monoxide

2.3.3.2 Carbon monoxide

The carbon monoxide analyzers were connected to VOC/ozone converter inlet and VOC/ozone converter exit sample lines that led to the laboratory sampling table. The NDIR instrumentation was fitted with in-line filters to remove particulate matter to prevent contamination of the instrumentation optics.

2.3.4 Spectrometry measurements

2.3.4.1 Ion mobility spectrometry (IMS)

Airsense is a global supplier of detection devices for dangerous substances. Airsense provided an Aerotracer (AT) ion mobility spectrometer (IMS) and operated it during the testing. The Airsense Aerotracer ion mobility spectrometer (Figure 44) utilizes a radioactive source to ionize the sample gas, and a high voltage within a chamber near atmospheric pressure to cause ions to move through a series of electric shutters to create pulses of ions that migrate toward a plate detector. The speed at which the ions reach the detector is based on the electrical mobility of the ionized particles. Analytes that do not form ions cannot be analyzed by IMS. Different types of ions with similar electrical characteristics may reduce the ability of the IMS to resolve the different VOC species.

Figure 44. Airsense aerotracer (AT)

2.3.4.2 Selected ion flow tube mass spectrometry (SIFT-MS)

Syft Analytics, (hereafter Syft) is a global supplier of fast real-time, direct injection mass spectroscopy. Syft provided a four-channel selected ion flow tube mass spectrometer (SIFT-MS) and an engineer to operate the mass spectrometer during the tests. SIFT-MS utilizes soft chemical ionization techniques to generate mass-selected reagent ions that aid in rapid quantification of VOC. The SIFT-MS process chooses one of four reagent ions and injects that ion into a flow tube so that it can react with the analyte. The analyte-reagent ion pair is then identified through a system library and quantified using a quadrupole mass spectrometer. This process enables real time analysis at trace analyte levels. Virgin PTFE tubing was utilized to obtain samples from the four sample locations underneath the aircraft (Figure 45). In hindsight, it would have been better to use very short, heated sample lines to prevent condensation of the sample, and to keep sample line lengths to a minimum. Due to the location of the instrumentation and the lack of availability of heated lines, the only option available was to utilize the virgin PTFE tubing. The SIFT-MS instrument installed in the Syft Van is pictured in Figure 46. A brass selector valve pictured on top of the instrument was utilized to switch between the four sample locations.

Figure 45. Syft analytics van with 4-reagent ion flow tube mass spectrometer

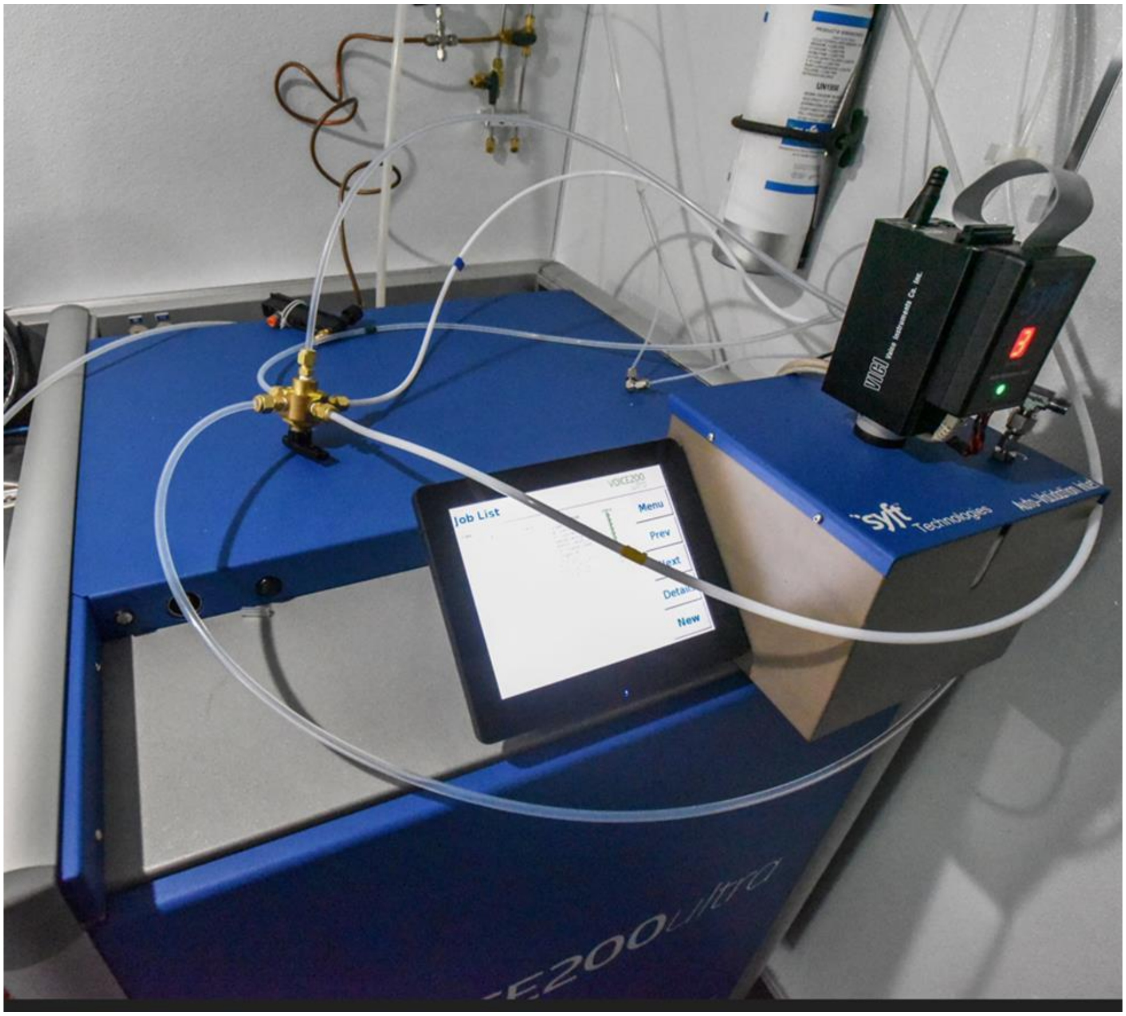

Figure 46. Syft 4-reagent ion flow tube mass spectrometer

A real time display screen (Figure 47) enabled the instrument operator to display specific analytes of interest in real-time during the sample run.

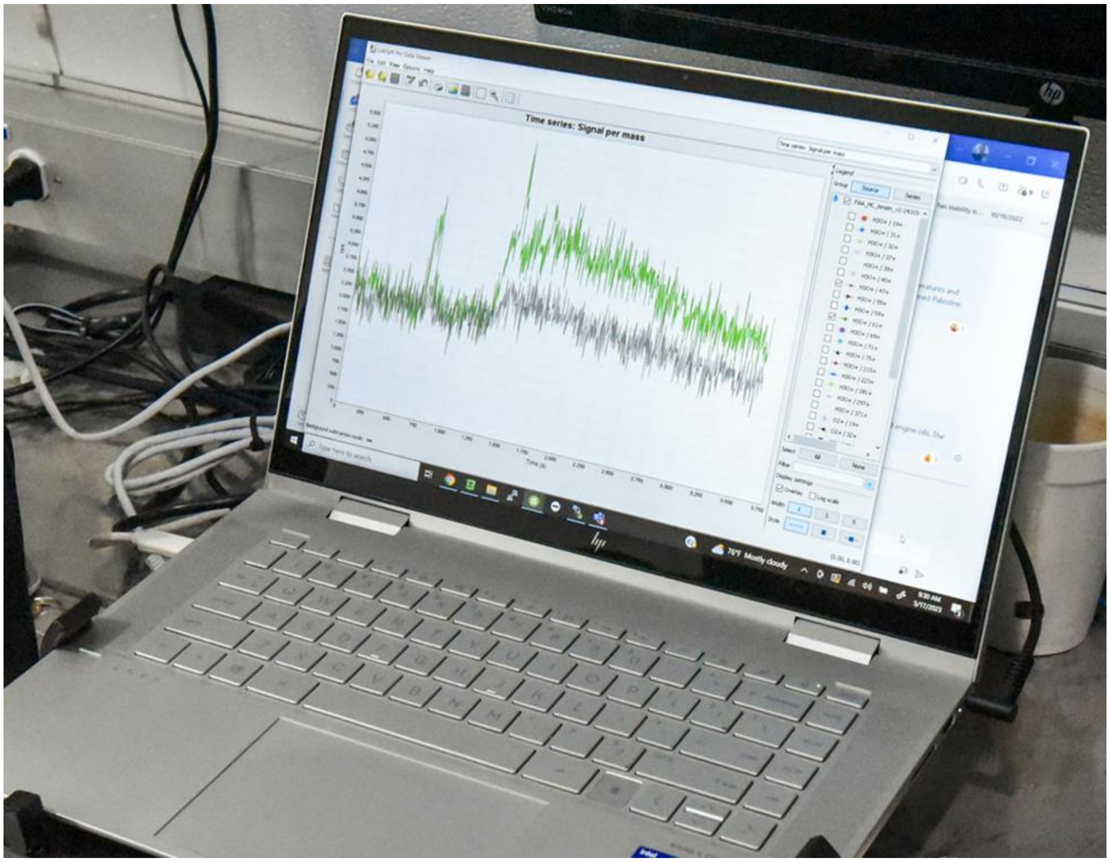

Figure 47. Syft mass spectrometer real time display

2.3.5 Honeywell hot bleed air sensor

Honeywell is a global supplier of aircraft products and provided a prototype hot bleed air sensor and an engineer to operate the Honeywell hot bleed air sensing system. Honeywell did require that the sensor be installed upstream of the VOC/ozone converter and to be secured on the heated bleed duct to ensure proper sensor operation (Figure 48). The electronics break-out box was initially installed adjacent to the sensor module, but the break-out box required placement in a cooler location during the first day of testing. Furthermore, the Pegasor heated sensor control modules were also not heat resistant and were repositioned adjacent to the Honeywell control module on the table below the aircraft. A shield to prevent the hot air from the pack heat exchanger from interfering with instrument operation was fabricated and positioned to force the hot air to flow toward the front of the aircraft. The plywood shield is visible adjacent to the Tisch-Environmental™ high-volume samplers in Figure 53.

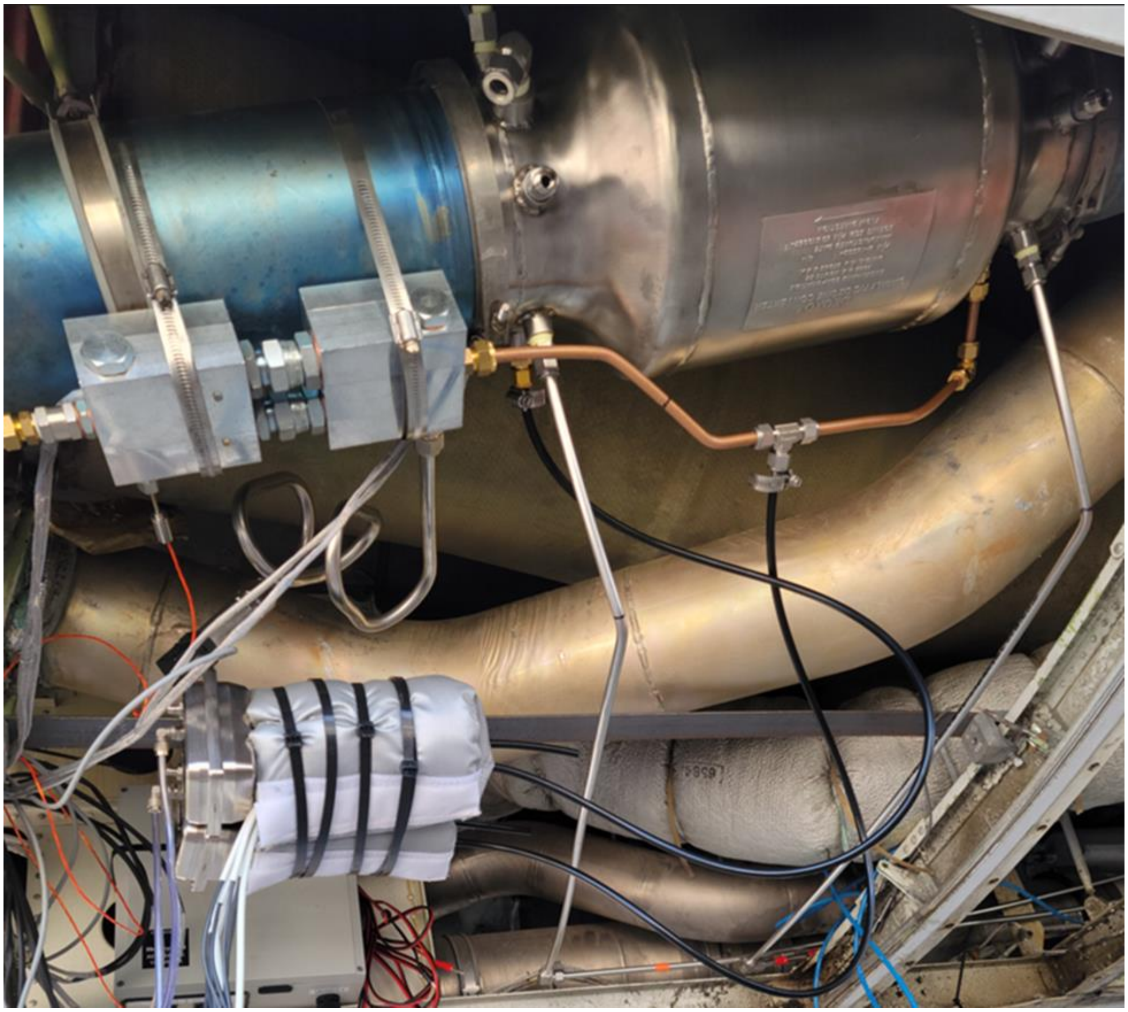

Figure 48. Honeywell hot bleed air sensor strapped to hot bleed duct

2.4 Laboratory chemical sampling plan

2.4.1 Contaminant selection

Full scale on-ground, on-aircraft testing had constraints based on number of days the aircraft was available, and the desire to run extended on-point tests to ensure valid steady-state results. Only one to two test conditions could be performed on a given test day. Based on the results of the May 2022 engine stand tests conducted at KSU (i.e., Phase 2, Vol. 1 results), there was a "down-selection" of fluid contaminants for the ground-based, on-aircraft experimental test runs.

- Two oils were selected for the ground-based tests (versus three oils used in the May2022 engine stand tests) due to there being little to no difference in the results among the three oils from the May 2022 engine stand tests.

- One hydraulic fluid was selected for the ground-based tests (versus two hydraulic fluids used in the May 2022 engine stand tests), again because there was little to no difference in the results between the two hydraulic fluids from the May 2022 engine stand tests.
- No deicing fluid was selected for the ground-based on-aircraft tests because the May 2022 engine stand test results were not significant (deicing fluid contains only glycol, water, and several trace components).

Therefore, two oils and one hydraulic fluid were selected as representative contaminants for the on-ground, on-wing test. Mobil Jet Oil II meets the qualifications for a standard type aircraft turbine oil and is most widely used in the industry, so was representative of the standard class of turbine oil lubricants. Eastman 2197 was selected as being a representative oil for high thermal stability turbine oils. Skydrol PE-5 was selected as being representative of hydraulic fluids. It is classified as a 5000-psi hydraulic fluid. The industry uses several classifications of hydraulic fluid but is migrating from 3000-psi hydraulic fluid to 5000-psi hydraulic fluid for performance reasons.

The laboratory chemical sampling plan included captured samples for analysis by United States Environmental Protection Agency (EPA) test methods at external laboratories. Sampling methods included dinitrophenyl hydrazine (DNPH) cartridges for EPA TO-11A carbonyls (i.e., aldehydes), quartz filters for EPA TO-13A semi-volatile organic compounds (SVOC) organophosphorus compounds (OP) and, thermal desorption tubes for EPA TO-17 longer chain volatile organic compounds (VOCs). A summary of the chemical sampling methods and sample quantities is provided in Table 4, and Appendix Table C- 1 summarizes the test conditions for each test run in the Engine and APU Test Log. There were six additional samples collected for OP TICS and SVOC that were not collected for polyaromatic hydrocarbons (PAH) analysis. Three EPA TO-13A samples for organophosphates and TICS were collected during a bake-out of the bleed duct, and three were collected during ingestion of 10 ppmm Mobil Jet II oil into the APU. Samples for organophosphates, VOC, and carboxylic acids were sampled on media provided by Fraunhofer Institute for Toxicology and Experimental Medicine (ITEM) and returned to them on blue ice for subsequent analysis. Separate laboratory chemical sampling for independent verification of sampling methods and analysis was performed by a chemical engineer from the U.S. Naval Air Warfare Center Aircraft Division (NAWCAD). NAWCAD's laboratory chemical sampling plan, sampling methods, and chemical analysis results for the ground-based, on-wing aircraft tests may be found in a separate report (Ortiz-Martinez, 2024).

Table 4. Summary of laboratory sample methods

Analyte	**Method**	**Sample Media**	**Flow Rate (SLPM)**	**Sample Duration (Minutes)**	**Sample Size (Liters)**	**# of Samples**
Carbonyls; AAC 230962 Rev2	EPA TO-11A	Waters Sep-Pack™ Part number WAT037500	1.5	20	30	18
OP TICS, SVOC TICS; RJLG W305169, Rev 1	EPA TO-13A	Sigma-Aldrich Cytiva/Whatman™ glass fiber filters (Tisch Part Number TE-2000P-13)	300	10	3000	39
PAH, RJLG W305170	EPA TO-13A	Sigma-Aldrich Cytiva/Whatman™ glass fiber filters (Tisch Part Number TE-2000P-13)	300	10	3000	33
Organophosphates (Schuchardt, 2017)	Measurement of flame retardants and plasticizers based on organophosphorus compounds - Phosphoric acid ester	Silica Gel (ISO, 2014)	2	30	60	11 of 12, one tube broken upon arrival at laboratory
VOC; RJLG W305171_Final	EPA TO-17	triple-bed glass Sigma Aldrich Markes™ tubes	0.2	20	4	34
VOC Fraunhofer (Schuchardt, 2017)	ISO 16000-6	Sigma-Aldrich stainless steel adsorbent tubes loaded with Carbotrap 202 40/60 (ISO, 2021)	0.2	15	3	12
Carboxylic Acids (CA) Fraunhofer (Schuchardt, 2017)	VDI 4301-Blatt7.	Sigma-Aldrich Orbo™-53 400/200	0.5	120	60	12

2.4.2 Dinitrophenyl hydrazine (DNPH) cartridge samples for EPA TO-11A carbonyls analysis

Atmospheric Analysis & Consulting (AAC) Laboratories Inc., Oxnard, CA provided WAT037500 Sep-Pak™ DNPH-silica cartridges for performing dinitrophenyl hydrazine (DNPH) carbonyl derivatization, enabling detection of the derivative compound by high performance liquid chromatography (HPLC). The bleed air passing through the AeroCOAT VOC converter also had virtually all ozone removed as it passed across the converter. Ozone levels were found to be negligible by using a 2B-Technologies model 106 ozone analyzer, so it was not necessary to utilize ozone scrubbers with the DNPH cartridges. Eighteen samples were collected and sent to AAC Laboratory for analysis by EPA TO-11A. Appendix C Table C-2 identifies the DNPH sample cartridges (Waters Sep-Pack™ Part number WAT037500) sent to AAC Laboratory for carbonyl (i.e., aldehydes) analysis by EPA TO-11A. The chain of custody forms for the samples are in the back of the AAC Laboratory final report.

A vacuum pump (Figure 49 and Figure 54) connected to APEX and ALICAT mass flow controllers[1] (Figure 51 and Figure 52) that were used to draw approximately 30L of air at a 1.5 standard liters per minute (SLPM) (±0.5%)[2] mass flow for 30 minutes through the DNPH sample concentration cartridges. Mass flowmeter flowrates were verified using a calibrated flow meter as a transfer standard (Figure 52). Flow meter information for the mass flow controllers is found in Table C- 9.

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[1] Established gas flow accuracy at 1 SLPM of ±0.5% of reading.

[2] Standard liter per minute (SLM or SLPM) is a unit of volumetric flow rate of a gas at standard conditions for temperature and pressure (STP). These conditions are 0 ˚Celsius and 1 atmosphere (atm) of pressure (100 kilopascals (kPa)).

Figure 49. Gast Model 0211-V45F-G8CX vacuum pump- top view

Figure 50. Gast Model 0211-V45F-G8CX vacuum pump-side view

Figure 51. Mass flow controllers with DNPH and Tenax thermal desorption tubes

Figure 52. TSI Model 4000 flowmeter transfer standard for mass flow controllers

2.4.3 Semi-volatile tentatively identified compounds (TIC), polycyclic aromatic hydrocarbon (PAH), and organophosphate (OP) compounds by EPA Method TO-13A

Thirty-nine samples were collected on 110 mm preconditioned Sigma-Aldrich Cytiva/Whatman™ glass fiber filters (Tisch Part Number TE-2000P-13) for analysis using EPA TO-13A to prepare the media to qualitatively assess tentatively identified compounds (TICs) of a SVOC nature. Few polyaromatic hydrocarbons are above method detection limits of the EPA TO-13A analysis.

EPA Method TO-13A was used to quantify specific organophosphate isomers on 33 samples. The high-volume filter sample summary is presented in Appendix Table C-3 for the EPA Method TO-13A target compounds and PAH compounds, and Table C-4 lists the speciated phosphate isomers.

Figure 53 depicts the four high volume samplers. A flow control valve and differential pressure gauge to measure flow across the filter is depicted in Figure 54.

Twelve samples were collected on silica gel cartridges for organophosphates by a Fraunhofer ITEM method based on the International Organization for Standardization ISO 16000-31:2014, but one of the 12 samples was broken upon arrival at the laboratory in Germany (ISO, 2014).

Figure 53. Tisch™ 102 mm quartz filter sample assembly

Figure 54. Tisch™ 102 mm quartz filter blower

Samples were stored in a refrigerator until being shipped in a cold ice chest to regional analytical laboratories in the United States (Figure 55).

Figure 55. Ice chest and blue ice used to transport sample media to regional laboratories

2.4.4 Volatile organic compounds (VOCs) by EPA TO-17

Thirty-four samples were collected on triple-bed glass Sigma Aldrich Markes™ tubes for VOC analysis by RJLG according to EPA TO-17. The log for the R.J. Lee VOC samples is located in Appendix Table C-6.

Twelve samples were collected on Sigma-Aldrich stainless steel adsorbent tubes loaded with Carbotrap 202 40/60 for VOC analysis according to ISO 16000-6:2021 (ISO, 2021). Sample log data for the Fraunhofer ITEM stainless steel cartridges is in Appendix Table C-7. The sample procedures did not require the samples to be kept near freezing, so they were transported by hand to Hanover, Germany in a container with small pouches of blue ice. In addition, twelve samples were collected on Sigma-Aldrich Orbo™-53 400/200 for analysis by Fraunhofer ITEM for carboxylic acids (CA).

2.4.5 Carboxylic acids (German Method)

Fraunhofer Institute for Toxicology and Experimental Medicine (ITEM) provided a sampling plan for sample media and analysis. The analytical results were provided by Fraunhofer, a not-for-profit Institute in Germany, and the Fraunhofer ITEM requests that any use of these results for reports, publications, and lectures state the origin of the information.

The carboxylic acids identification and quantitation method utilized by Fraunhofer ITEM is a company-derived (i.e., “in-house”) modification of the German Standard VDI_4301: Measurement of Indoor Air Pollution - Measurement of Carboxylic Acids (German Method Verband Deutscher Ingenieure [VDI] 4301-Blatt 7) (VDI, 2018). Fraunhofer’s modified method for aircraft bleed air sampling detects C1 to C8 carboxylic acids (propanoic acid, n-butanoic acid, 2-methylpropanoic acid, n-pentanoic acid, n-hexanoic acid, n-heptanoic acid, n-octanoic acid, nonanal, and decanal) in indoor air. Fraunhofer ITEM has found from their testing experience that C1 to C8 carboxylic acids are quite difficult to determine using conventional VOC analytical methods pursuant to Deutsches Institut für Normung (DIN) e. V. (German for Institute for Standardization) DIN ISO 16000-6 (ISO, 2021), as the conventional method produces poor recovery of carboxylic acids when using Tenax TA® as the sorbent. The sample medium provided by Fraunhofer ITEM for this analysis was Sigma-Aldrich Orbo™-53 400/200 mg, activated silica gel (catalog number 20265). Twelve samples were collected and sent to Fraunhofer ITEM (Germany) for carboxylic acid analysis. The carboxylic acid sample log for Fraunhofer ITEM is located in Appendix Table C-8. The log for organophosphate samples sent to Fraunhofer ITEM is presented in Appendix Table C-5.

2.5 Sensor instrumentation results

2.5.1 Assessment of ultrafine particulate measurements

2.5.1.1 Ultrafine particle response to oil contamination

Figures 56 through 63 summarize the ultrafine particle concentrations and size distribution as measured by the scanning mobility particle sizer (SMPS):

- Figure 56. Total ultrafine particle concentration, SMPS, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 57. Particle size distribution, SMPS, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 58. Total ultrafine particle concentration, SMPS, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 59. Particle size distribution, SMPS, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)

- Figure 60. Total ultrafine particle concentration, SMPS, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)
- Figure 61. Particle size distribution, SMPS, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)
- Figure 62. Total ultrafine particle concentration, SMPS, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal) and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)
- Figure 63. Particle size distribution, SMPS, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal), and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)

These measurements were all collected from a sample airstream connected to the pack exit. The SMPS was configured to measure particulate in the aerodynamic diameter size range of 15-670 nm.

The first, and perhaps key observation is that ultrafine particle concentrations increase considerably in response to oil contamination, at least at the 5 parts per million by mass (ppmm) contamination level and higher as seen in Figure 56, Figure 58, Figure 60, and Figure 62. The concentrations with oil contamination were all well above 106 particles/cc with contamination and sometimes even above 107 particles/cc. In comparison, baseline concentrations without oil injection were typically in the range of 103 to 104 particles/cc. These multiple orders of magnitude increase in ultrafine particle concentrations, in response to the oil contamination, show that ultrafine particles have a sensitive and readily discernable response, at least at the contaminant concentrations evaluated. Widely different engines were used for these tests: an auxiliary power unit, a propulsion engine at low power, and a propulsion engine at high power. Also, widely different contamination injection methods were used: injection into the APU inlet air with contaminants passing through the compressor and injection into the bleed air downstream of the engine compressor. While some differences in response are seen for the different test conditions and engines, the consistently large response in ultrafine particle concentrations in all cases indicates that this variable has good promise as an indicator of oil contamination.

Figure 57, Figure 59, Figure 61, and Figure 63 show that the bulk of the particles generated with oil contamination are smaller than 100nm with peak concentrations typically in the range of 25-60 nm. Comparing Figure 57 and Figure 63, increasing the oil contamination from 5 to 10 ppmm results in increasing particle size, yet only a modest increase in total concentration as seen in Figure 56 and Figure 62. Oil contaminant concentrations below 5 ppmm (nominal) were not evaluated in these experiments but, presumably, the trend would continue for lower oil contaminant concentrations and the particles generated would be even smaller which has implications for the size range required for any detection device.

Figures 64 through 67 present results from the ultrafine particle measurements with the Naneos Partector:

- Figure 64. Total ultrafine particle concentration, Naneos Partector, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 65. Total ultrafine particle concentration, Naneos Partector, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 66. Total ultrafine particle concentration, Naneos Partector, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)
- Figure 67. Total ultrafine particle concentration, Naneos Partector, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal) and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)

Separate Naneos Partector II sensors were supplied air from all four sample locations: ambient air, upstream of the ozone converter, downstream of the ozone converter, and the pack exit. The Naneos Partector II sensors measure total ultrafine particle concentrations and not the size distribution. Also, they are not intended for such high ultrafine particle concentration as experienced in the bleed air and sometimes experience a saturation effect where the ions available for detection are depleted. For example, in Figure 64, the measured concentrations at all three bleed air locations show a sharp increase at the start of oil injection and then drop slightly. Upon cessation of oil injection, the measured concentration increases before starting to decrease. Also, the Partector minimum detected particle size is less than the SMPS. Even with these limitations, the measured results with the Partector agree reasonably well with the SMPS results with oil contamination. The measured concentrations with the Partector are typically about 10^7 particles/cc with oil contamination. As noted in the discussion of the SMPS results, the lower detection limit was not addressed in these experiments. The concentration measured by the Partector decreased with the 10 ppmm injection rate in the APU (Figure 67) as compared to the 5 ppmm injection rate (Figure 64). This result is most likely due to the saturation effect as the SMPS shows the concentration to increase as expected.

The Partector measurements show very clearly that ultrafine particle measurements at any location along the bleed air path respond well to oil contamination, at least at the contaminant concentrations evaluated. Figure 64 through Figure 67 all show similar responses at all three locations (ozone converter inlet, ozone converter exit, and pack exit) in all cases of oil contamination. Very importantly, the Naneos Partector II analyzers were located remotely from the actual bleed air path and were supplied bleed air via sample lines with the bleed air cooled to approximately room temperature before being supplied to the sensors. This cooling is very important, as will be discussed in the next section.

2.5.1.2 Ultrafine particle generation mechanism

As has been previously discussed, ultrafine particles appear to be a sensitive marker for oil contamination of bleed air. It appears the ultrafine particles are the result of volatile substances being driven off the oil by the elevated temperature of the bleed air and subsequently condensing when the bleed air is cooled. Like the Naneos Partector, four Pegasor instruments were included with one for each of the four sample locations. Results for the Pegasor measurements are presented in Figure 68 and Figure 69. All four instruments used the same measurement technology, but the sensors upstream and downstream of the ozone converters were configured so they could measure the high ambient air temperature at those locations without sample cooling. The ultrafine particle concentration measurements with the Pegasor instrument at the pack exit are consistent with the SMPS and Partector. Figure 68 shows a three to four orders of magnitude increase in ultrafine particles at the pack exit with the APU and Mobil Jet Oil II contamination at 5 ppmm nominal as compared to the baseline with no injected oil contaminant. Very importantly, there is about one order of magnitude increase upstream and downstream of the ozone converter with the high temperature Pegasor measurements. There clearly is some ultrafine response at the ozone converter locations as can be seen by the momentary dips that occurred when the injection pump reversed. However, the overall response is over two orders of magnitude less than seen at the pack exit where the bleed air has been cooled.

With the propulsion engine and 5 ppmm nominal Mobil Jet Oil II contamination, there is perhaps a one order of magnitude increase in ultrafine particles over baseline with 225^{o}C bleed air and essentially no discernible increase with the 315^{o} C bleed air (Figure 69) for the Pegasor measurements. In either case, it would be difficult to differentiate between baseline conditions and contaminant injection conditions in the propulsion engine data. In comparison, there is a clear three to four orders of magnitude increase in ultrafine particle concentrations at the pack exit as compared to baseline.

The somewhat clearer response of ultrafine particles measured by the Pegasor analyzers upstream and downstream of the VOC/ozone converter for the APU data as compared to the propulsion engine data may be due to the different approaches to contaminant injection. With injection into the APU inlet, the oil passes through multiple stages of high-speed compressor blades which may generate some ultrafine particles. In the propulsion engine, with contaminant injection into the bleed air downstream of the compressor, there may have been less opportunity for ultrafine particle generation due to shearing action. The APU approach is probably closer to potential real-world contamination paths, but it does not make a lot of difference from a sensor detection perspective. The responses seen for the elevated temperature Pegasor measurement locations upstream and downstream of the VOC/ozone converter in either case are not conducive to reliable detection given the observed background variations.

This limitation on using ultrafine particles as an indicator of oil contamination does not imply that bleed air cannot be sampled at high temperature locations. The results from these ground-based, on-wing aircraft experiments show that the sampled air must be cooled to generate the highly elevated ultrafine particle concentrations. The Partector ultrafine particle sensors measured ultrafine particle concentrations in the bleed air sampled at all three bleed air locations: upstream and downstream of the VOC/ozone converter, and at the pack exit. However, the long sample lines from the sample location to the sensors mounted in the aircraft cabin ensured that the sample stream was cooled to near room temperature before entering the sensor. As seen in Figure 64 and Figure 65, highly elevated ultrafine particle concentrations are seen at all three locations with every case of oil contamination.

2.5.1.3 Oil contamination accumulation

Data indicated that oil contamination can accumulate in the bleed air system and then be released over time. A pattern emerged where ultrafine particle concentration remained elevated on injection cessation. Subsequently, data reflected a gradual decrease in UFP concentration over a time course of 30 minutes or longer. Of additional note, temperature transients may have caused eventual accumulated contamination release. For example, Figure 58 shows a substantial, temporary increase in ultrafine particle concentration at 1420 hours at an increase in bleed air temperature, even though the oil contaminant injection had been turned off for 20 minutes. In fact, the ultrafine particle concentration was significantly higher than during contaminant injection. Similar responses can be seen at time 1015 hours in Figure 58, at times 0930 hours and 1740 hours in Figure 60, and at time 0930 hours in Figure 62.

This oil contamination accumulation and release effect has important implications for the use of ultrafine particles in oil contamination detection. Specifically, temporary increases in ultrafine particle concentrations, even to levels associated with substantial levels of oil contamination, do not necessarily indicate that contamination is occurring at that point in time. These increases could be from previously accumulated oil contamination released by a change in engine power or any other factor that produces an increase in bleed air temperature.

Whether or not the oil contamination released by bleed air temperature transients, as indicated by the elevated ultrafine particle concentrations, has an impact on airplane cabin air quality comparable to the impact when oil contamination is being injected, was not directly addressed in these experiments.

2.5.1.4 Ultrafine particle response to hydraulic fluid

Although the focus of ground-based, on-wing aircraft test runs was engine oil contamination, one experimental test run was conducted with hydraulic fluid, Skydrol PE5. The results with respect to ultrafine particle concentrations are depicted in Figure 62, Figure 63 and Figure 67. Unfortunately, it was not possible to conduct an elevated temperature cleanout of the bleed air system between the Mobil Jet Oil II test that preceded the Skydrol PE-5 test, and there was insufficient time for the ultrafine particle concentrations due to oil contamination to return to baseline values before the Skydrol PE-5 injection began. Thus, carry over of Mobil Jet Oil II into the Skydrol PE-5 hydraulic fluid test is a likely explanation for the unexpected data patterns witnessed. Figure 63 shows that Skydrol PE 5 resulted in little, if any increase in ultra fine particle concentrations over baseline values except for diameters less than about 50nm. However, it is suspected that this elevation in ultrafine particle concentration for diameters less than 50nm is due to oil carry over from the previous Mobil Jet Oil II test condition. While it cannot be proven from this one test condition, hydraulic fluid contamination may enhance the release of this accumulated contamination.

2.5.1.5 Ambient measurements of ultrafine particles

Concentration of ultrafine particles increased during oil injection in a number of cases. The “ambient” sample point was beneath the aircraft fuselage not far from the pack exit discharge. Depending on the wind condition, significant amounts of pack exit air may have been ingested by the ambient air sample line fan thereby accounting for elevated concentrations of fine particles seen in ambient air samples. In retrospect, ambient air sample collection at the inlet to the appropriate APU or #3 engine would have been beneficial, yet such sampling locations were not feasible. Therefore, the measurements identified as ambient air should not be considered engine inlet air. Unlike the ambient air sample line, the engine air intakes were well removed from the pack exit discharge air. Additionally, air flow rates through the engines, especially the #3 engine, are much larger than the pack discharge air flow rate. Consequently, contaminant ingestion by the #3 engine was minimal at most and, likely, non-existent.

Ambient Ultrafine particle data are presented in Figures 56 through 69:

- Figure 56. Total ultrafine particle concentration, SMPS, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)

- Figure 57. Particle size distribution, SMPS, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 58. Total ultrafine particle concentration, SMPS, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 59. Particle size distribution, SMPS, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 60. Total ultrafine particle concentration, SMPS, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)
- Figure 61. Particle size distribution, SMPS, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)
- Figure 62. Total ultrafine particle concentration, SMPS, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal) and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)
- Figure 63. Particle size distribution, SMPS, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal), and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)
- Figure 64. Total ultrafine particle concentration, Naneos Partector, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 65. Total ultrafine particle concentration, Naneos Partector, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 66. Total ultrafine particle concentration, Naneos Partector, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)
- Figure 67. Total ultrafine particle concentration, Naneos Partector, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal) and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)
- Figure 68. Total ultrafine particle concentration, Pegasor, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 69. Total ultrafine particle concentration, Pegasor, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)

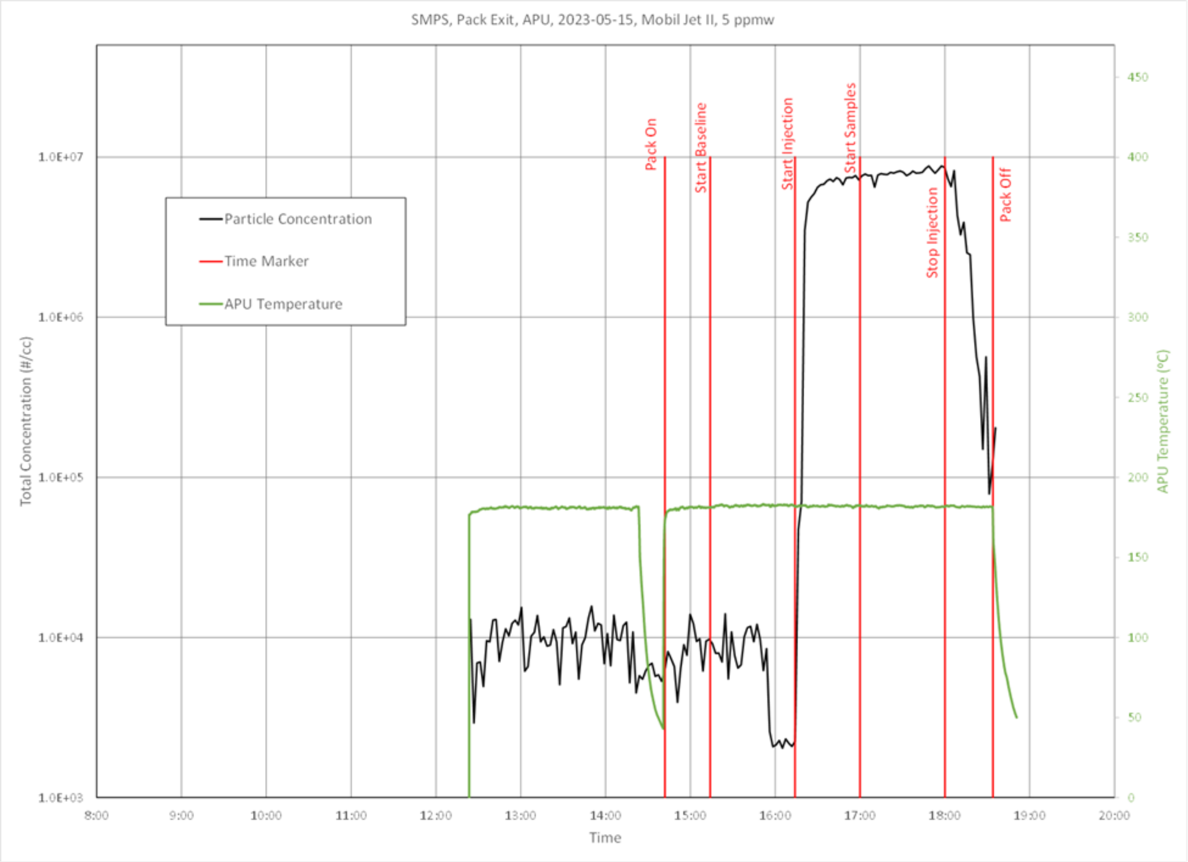


Figure 56. Total ultrafine particle concentration, SMPS, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)

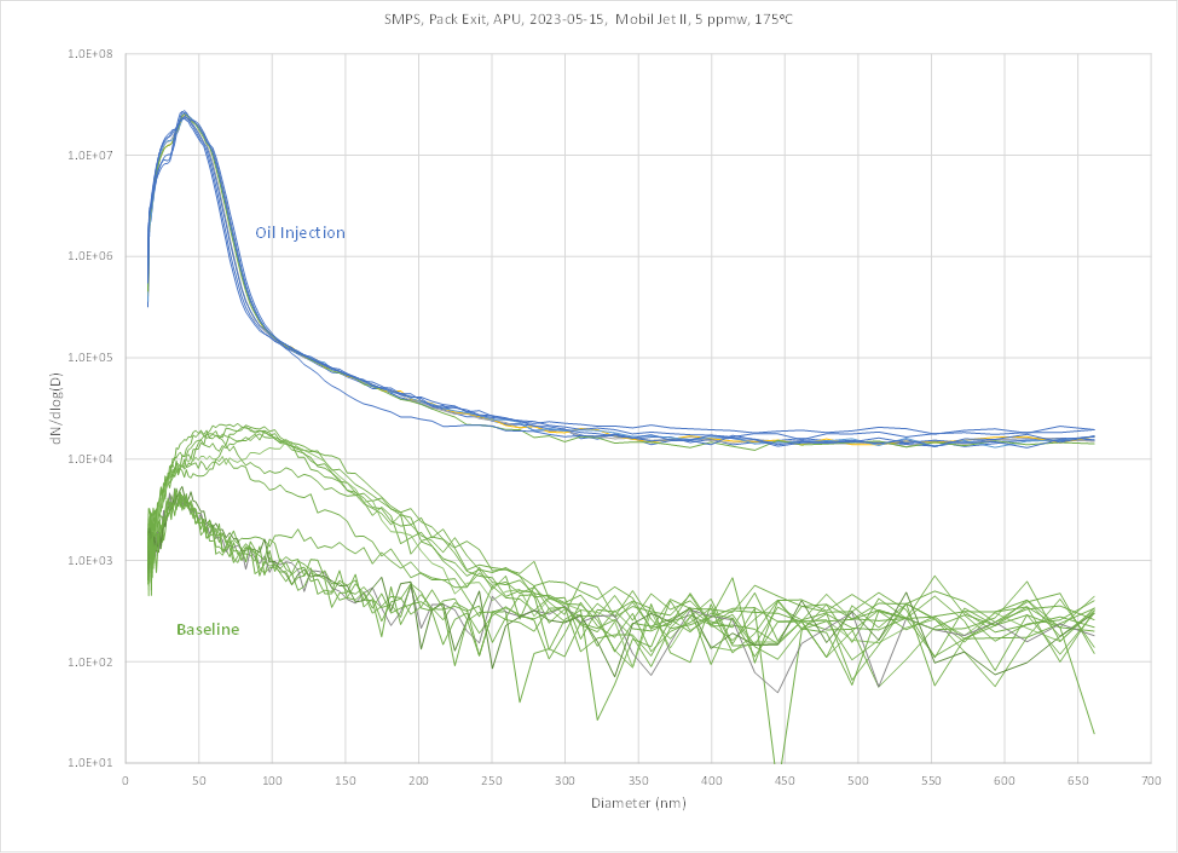


Figure 57. Particle size distribution, SMPS, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)

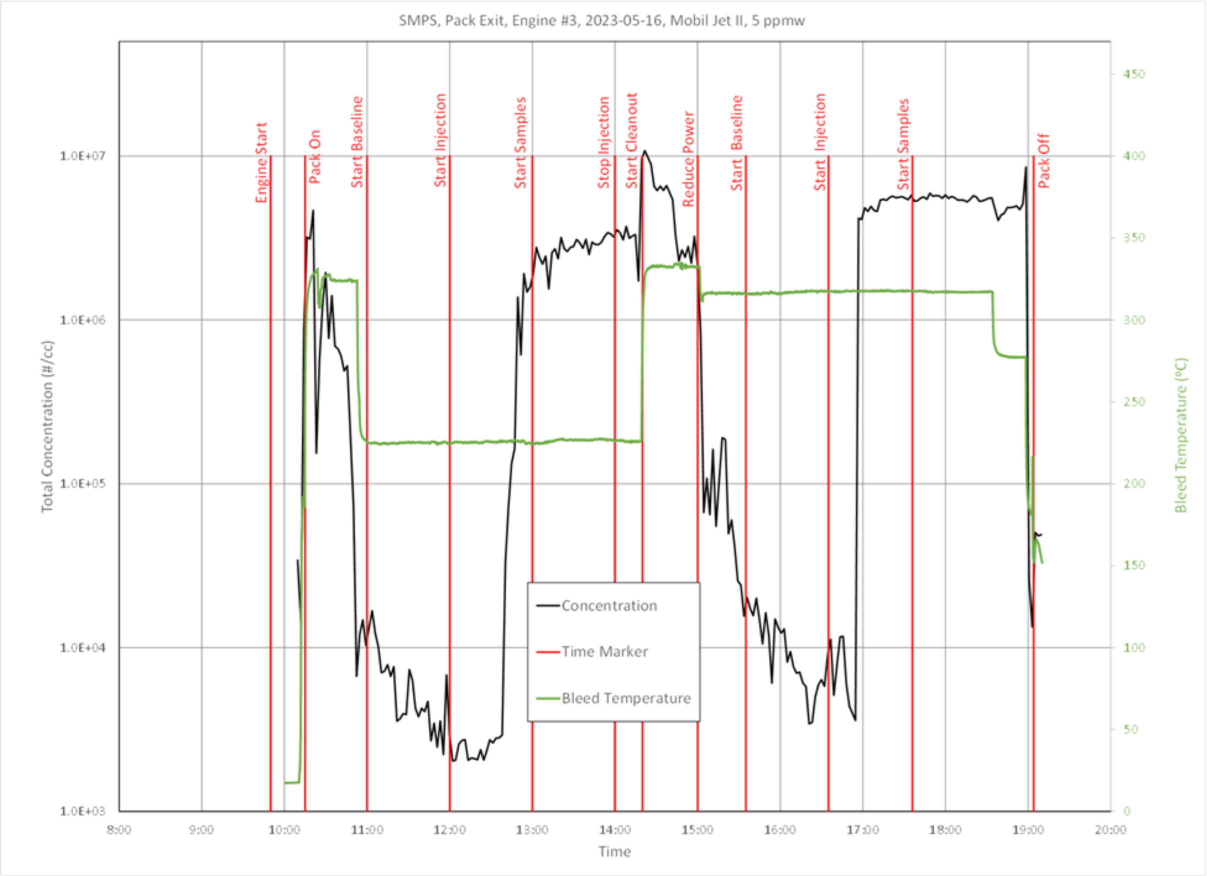


Figure 58. Total ultrafine particle concentration, SMPS, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)

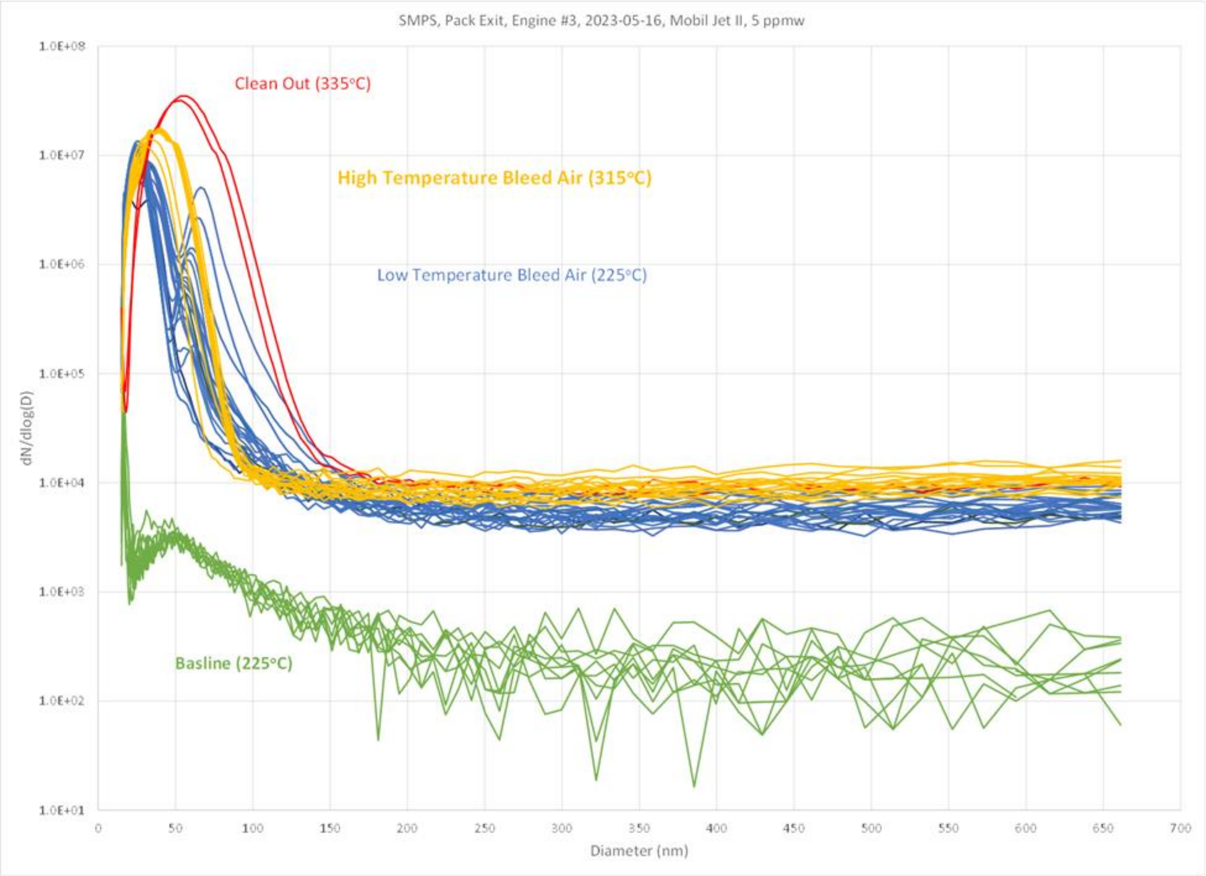


Figure 59. Particle size distribution, SMPS, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)

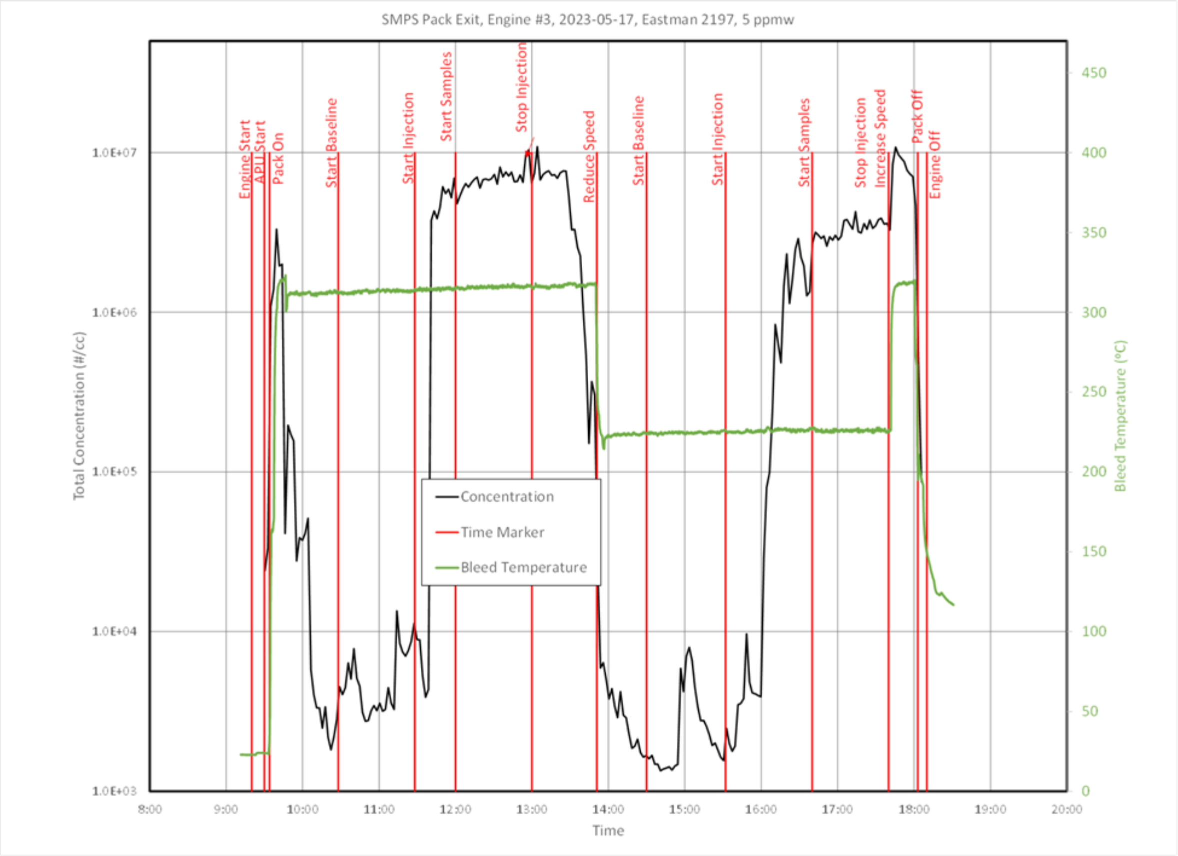


Figure 60. Total ultrafine particle concentration, SMPS, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)

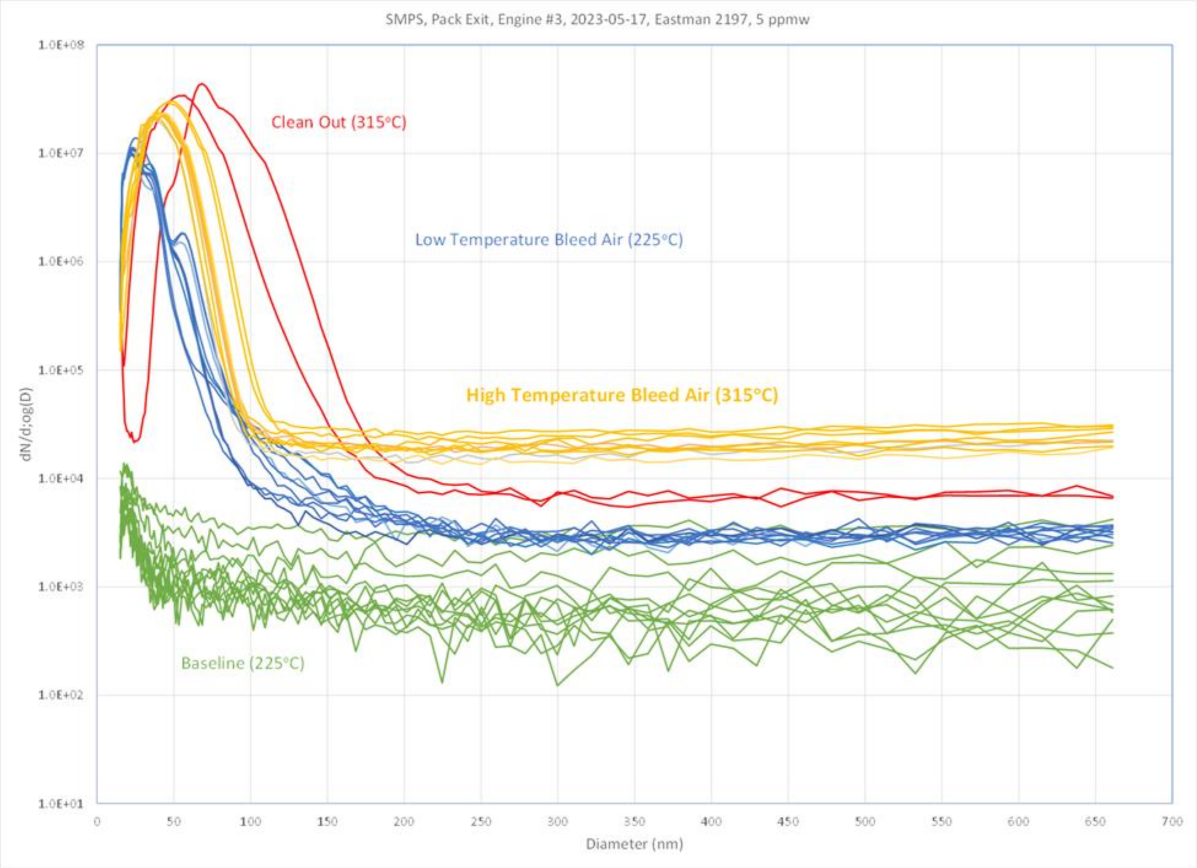


Figure 61. Particle size distribution, SMPS, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)

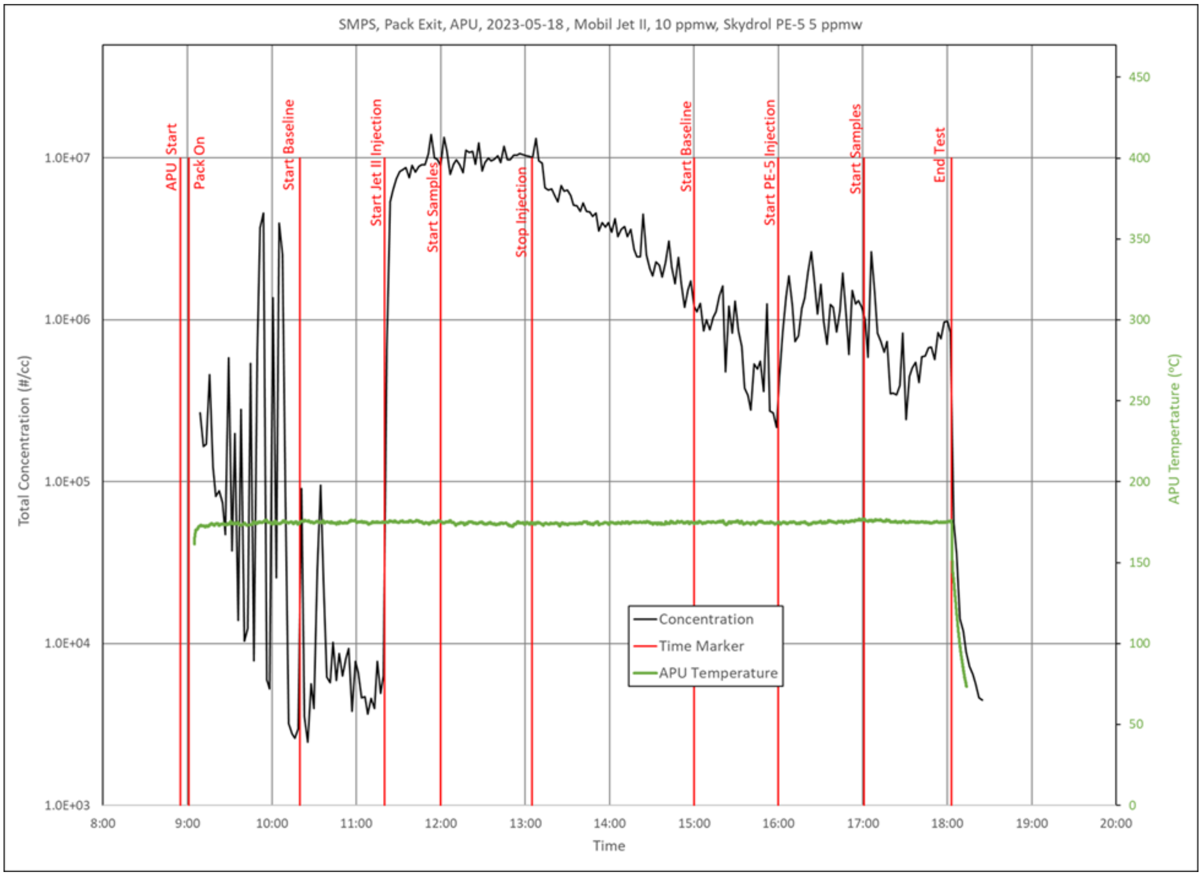


Figure 62. Total ultrafine particle concentration, SMPS, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal) and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)

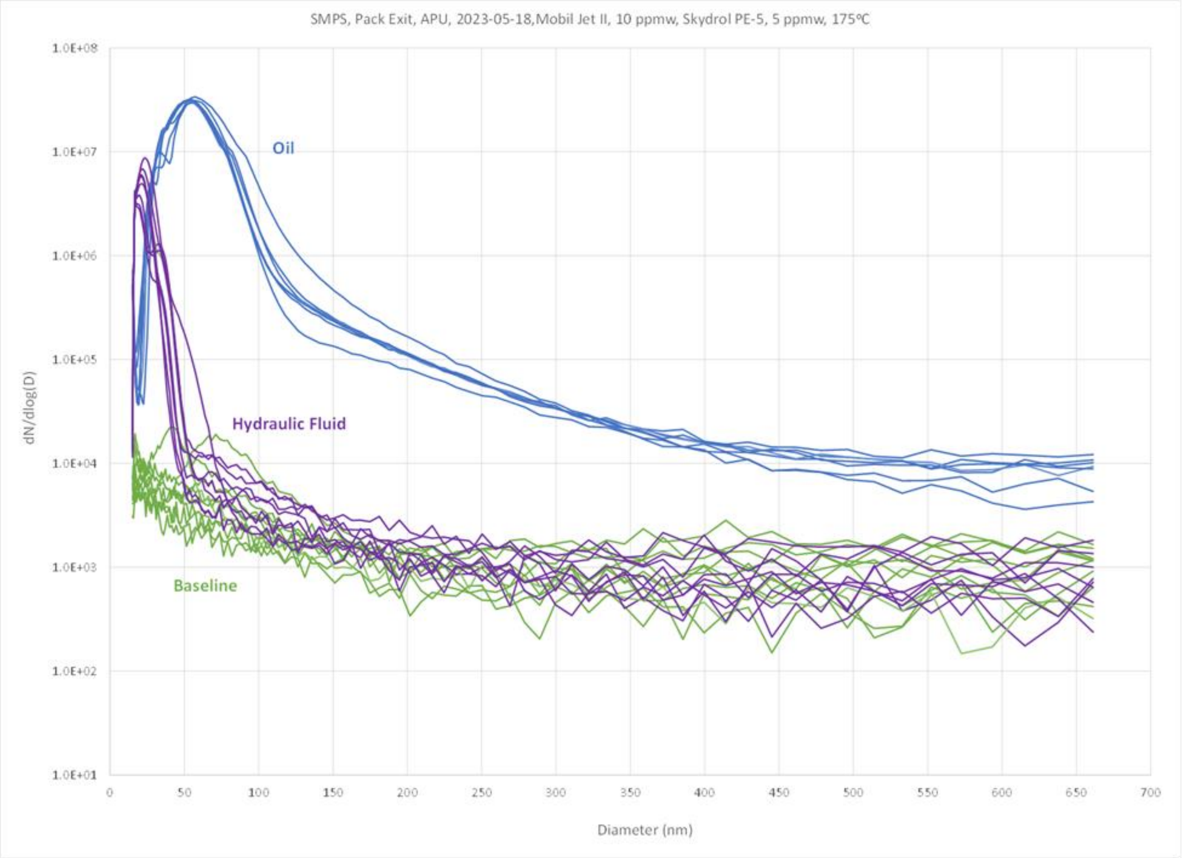


Figure 63. Particle size distribution, SMPS, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal), and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)

Figure 64. Total ultrafine particle concentration, Naneos Partector, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)

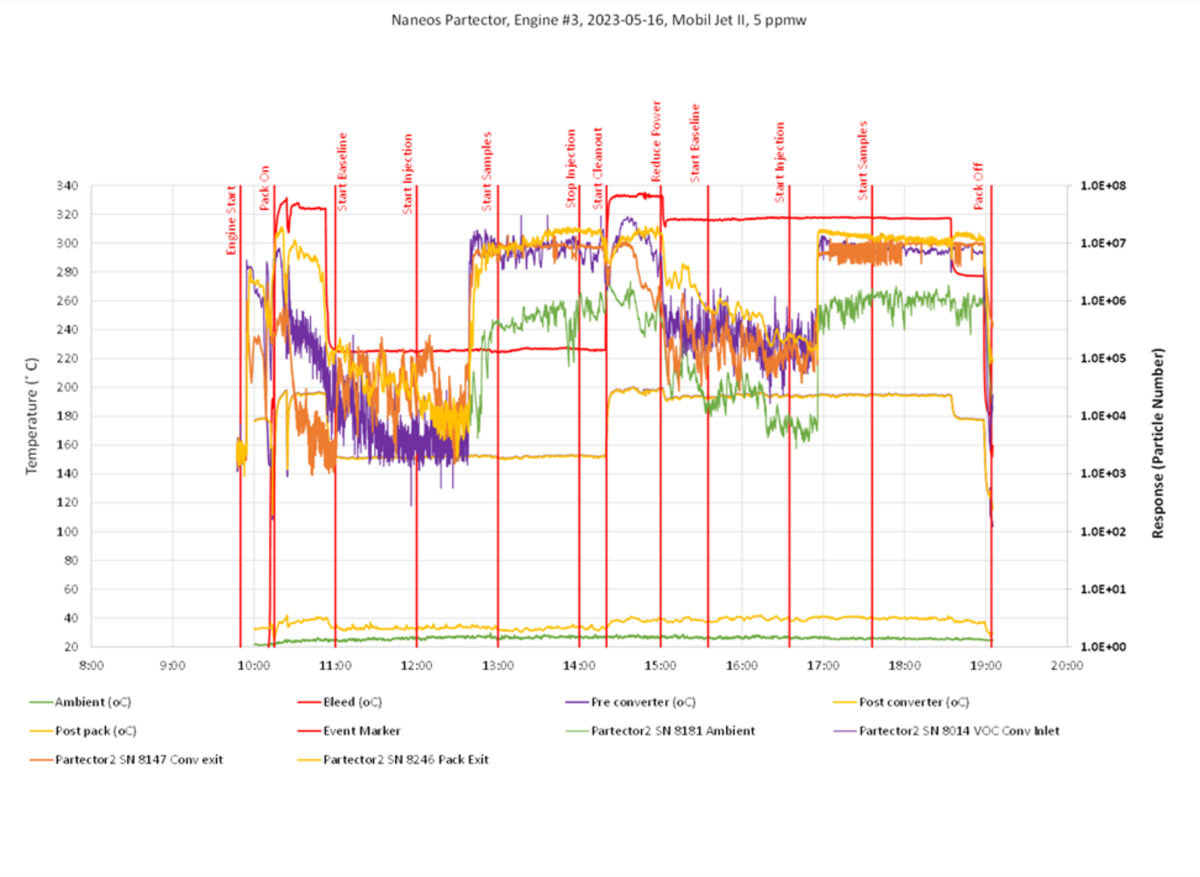


Figure 65. Total ultrafine particle concentration, Naneos Partector, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)

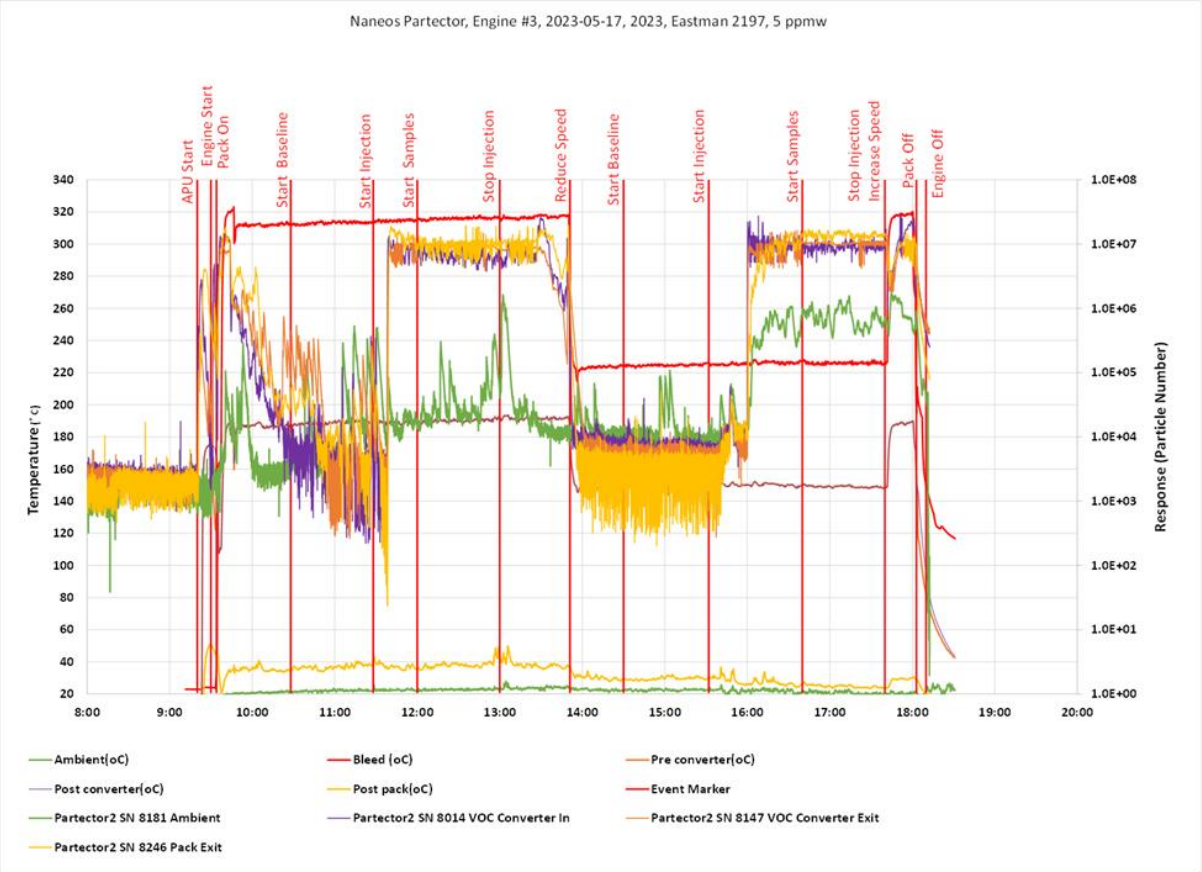


Figure 66. Total ultrafine particle concentration, Naneos Partector, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)

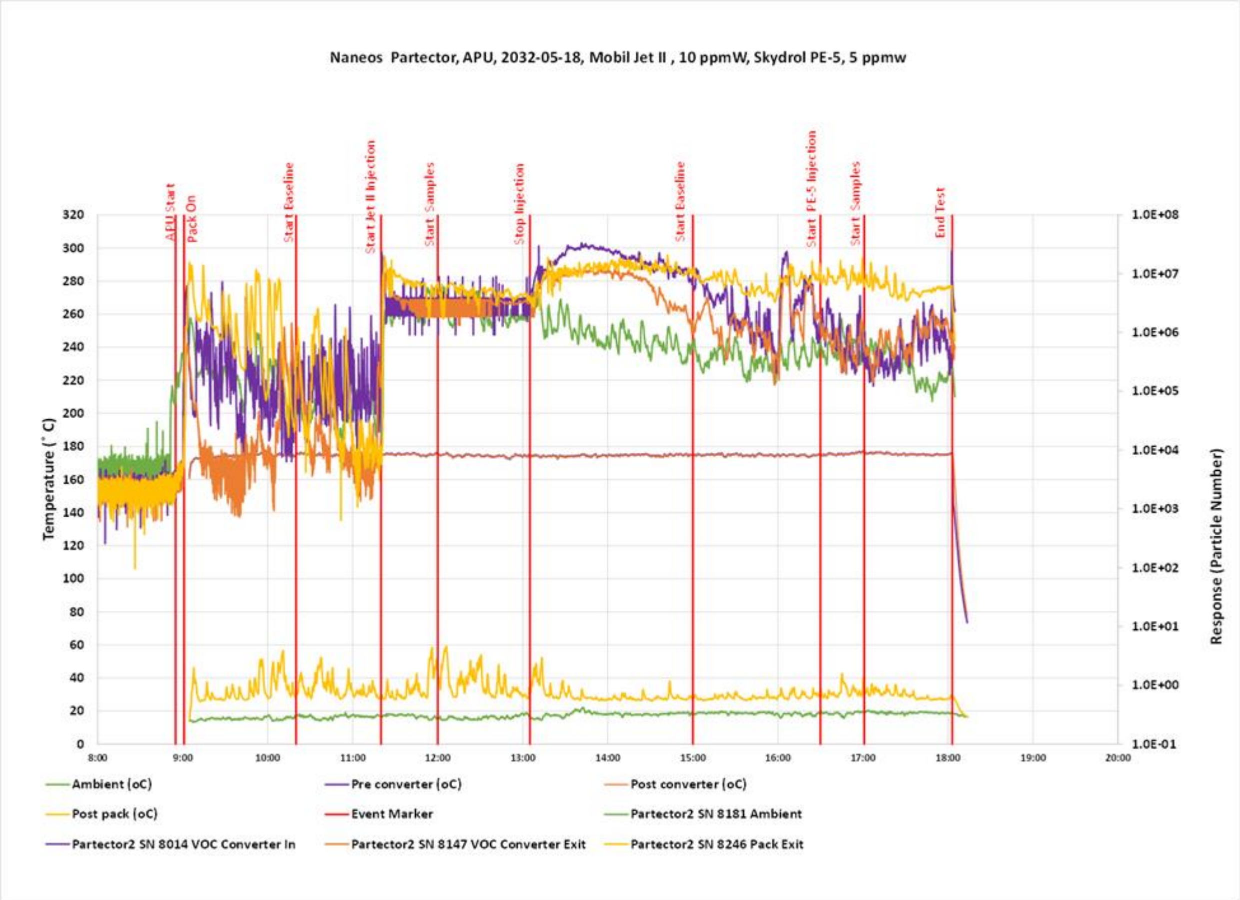


Figure 67. Total ultrafine particle concentration, Naneos Partector, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal) and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)

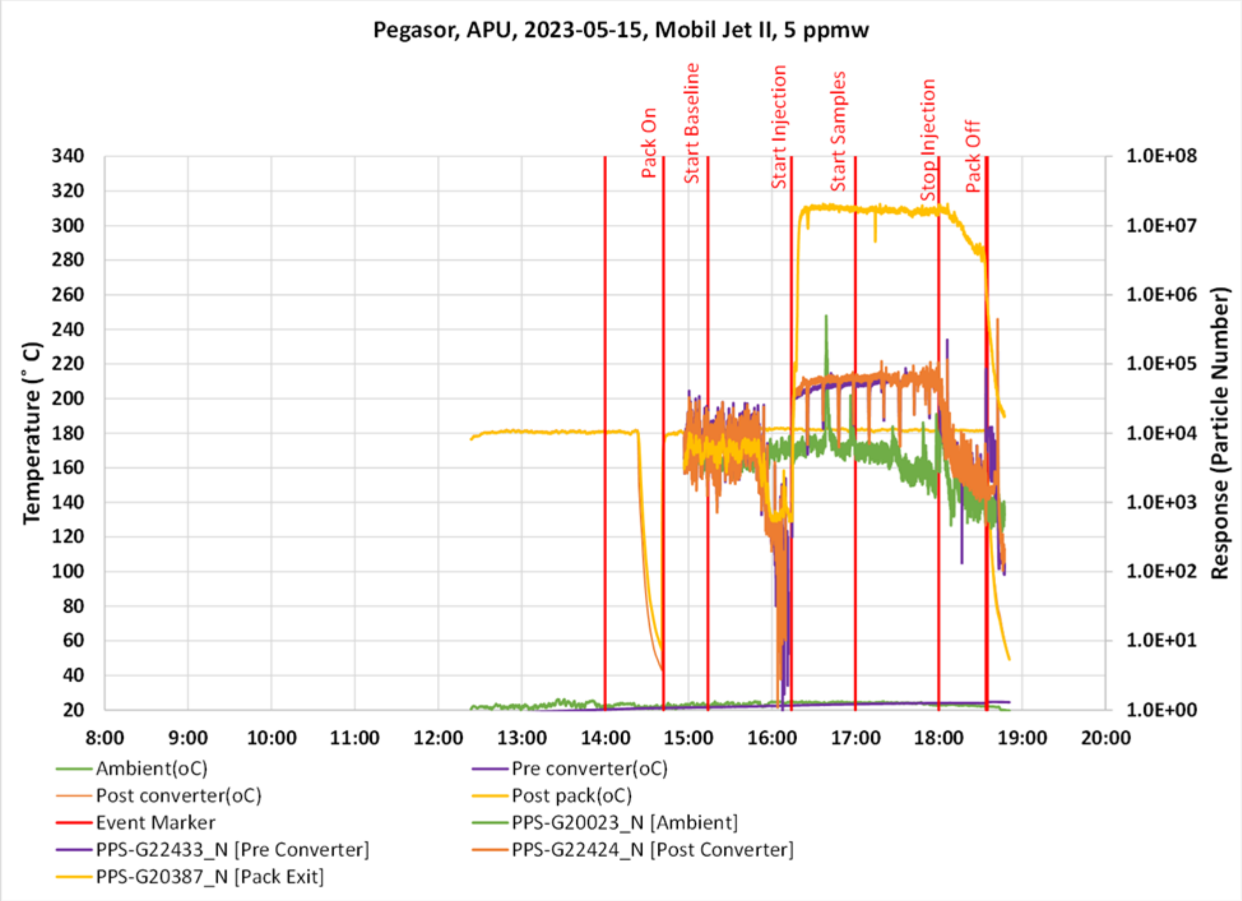


Figure 68. Total ultrafine particle concentration, Pegasor, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)

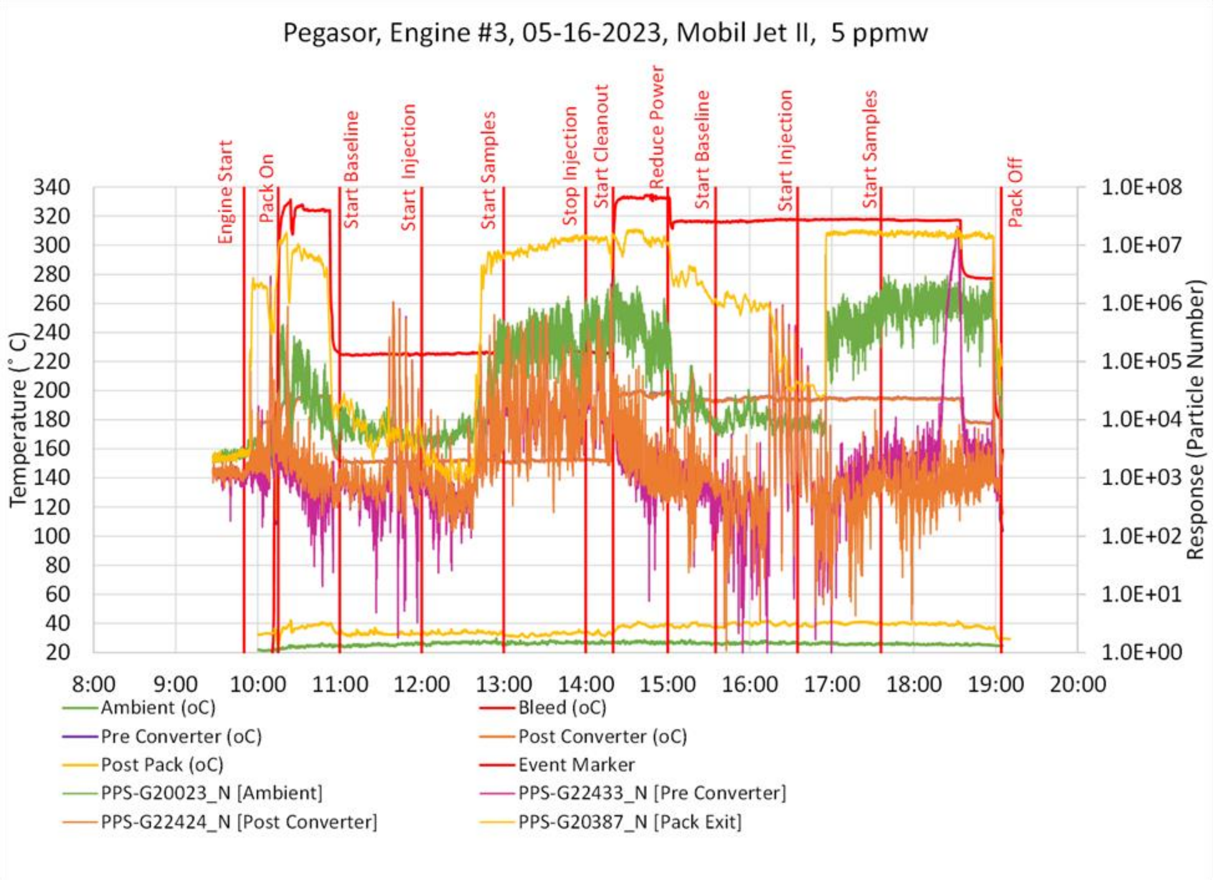


Figure 69. Total ultrafine particle concentration, Pegasor, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)

2.5.2 Assessment of fine particulate measurements

2.5.2.1 Fine particle response to oil contamination

Figures 70 through 80 summarize the fine particle concentrations and size distributions as measured by the aerodynamic particle sizer (APS):

- Figure 70. Total fine particle concentration, APS, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 71. Particle size distribution, APS, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 72. Total fine particle concentration, APS, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 73. Particle size distribution, APS, May 16, 2023, number 3 engine, 225^{o}C, Mobil Jet Oil II, 5 ppmm (nominal)

- Figure 74. Particle size distribution, APS, May 16, 2023, number 3 engine, 315°C, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 75. Total fine particle concentration, APS, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)
- Figure 76. Particle size distribution, APS, May 17, 2023, number 3 engine, 315°C, Eastman Oil 2197, 5 ppmm (nominal)
- Figure 77. Particle size distribution, APS, May 17, 2023, number 3 engine, 225 °C, Eastman Oil 2197, 5 ppmm (nominal)
- Figure 78. Total fine particle concentration, SMPS, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal) and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)
- Figure 79. Particle size distribution, APS, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal)
- Figure 80. Particle distribution, SMPS, May 18, 2023, APU, Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)

Except for one ambient air measurement, these measurements were all collected from a sample airstream connected to the pack exit. The APS counts total particles in the size range of 0.3 µm - 20 µm in diameter and provides size distributions for the size range of 0.5 µm -20 µm. The fine particle concentration consistently responded to oil injection for low temperature bleed air. This response includes both the APU (Figure 70 and Figure 78) and the propulsion engine (Figure 72 and Figure 75). The increase over baseline was about one and one-half orders of magnitude with 5ppmm of Mobil Jet Oil II with the APU (Figure 72) and about two orders of magnitude with 10ppmm with the APU (Figure 78). With the propulsion engine and lower temperature bleed air (225° C), the response was a bit less but still about an order of magnitude increase for both Mobil Jet Oil II and Eastman Oil 2197 (Figure 72 and Figure 75). However, there was essentially no response at the higher bleed air temperature (315° C) for Mobil Jet Oil II or Eastman Oil 2197 (Figure 72 and Figure 75). The somewhat higher response with the APU as compared to the propulsion engine at the lower bleed temperature may be due to the even lower 180° C temperature with the APU. The reason there are elevated fine particle concentrations at lower temperatures and not at higher temperatures is not apparent from the data.

In all cases, few, if any, particles larger than 2 µm were detected (Figure 71, Figure 73, Figure 74, Figure 76, Figure 77, Figure 79, and Figure 80). In comparison, there were particles larger than 3µm in the ambient air (Figure 71). Evidently, the engine compressors remove the larger particles. In all cases where there was a substantial increase in fine particle concentration with oil contamination, the bulk of the particles were smaller than one micron with peak concentration around 0.6 µm. The measurement range for the APS and the SMPS overlap. The SMPS measurements do not show the sharp drop off in concentration below 0. 6 µm seen with the APS. The drop off in concentration seen with the APS may be due to a drop off in measurement efficiency with the smaller diameters and not due to a true decrease in concentration.

In addition to the APS, fine particle concentrations were measured in sample airstreams from the pack exit and downstream of the ozone converter with the Piera Systems Canaree (pack exit) and Piera Systems 7100 (ozone out) sensors. These instruments use the same particle detection sensor. The Canaree is different in that it includes sensors for other parameters. The results of the Piera measurements are presented in Figure 81 through Figure 84. The Piera instruments provide data in units of particles per liter rather than particle per cubic centimeters as used with the APS. Thus, a factor of 1000 must be included when comparing the data between these two sensors. Even with this factor, the concentrations with the Piera instruments are higher than with the APS for the APU measurements (Figure 81 and Figure 84 compared to Figure 70 and Figure 78). However, the relative increase over baseline is similar. The higher concentrations measured with the Piera instruments may be due to differences in the size range detected.

As with the APS, the Piera instruments showed little if any discernable increase in concentration due to oil injection with the higher temperature bleed air with the propulsion engine (Figure 82 and Figure 83). The relative increase at the lower temperatures was similar to those seen with the APS; however, the baseline values are noisier which may limit the ability to detect the increase resulting from the contamination. As with the ultrafine particle measurements, the response for the pack exit was like the response at the ozone converter exit.

2.5.2.2 Fine particle response to hydraulic fluid contamination

General conclusions cannot be drawn from a single test with hydraulic fluid. Results from the one test that was conducted are presented in Figure 78, Figure 80, and Figure 84. This test was conducted with 5ppmm (nominal) of Skydrol PE-5 hydraulic fluid injected into the APU air inlet. These results can be compared to the results in Figure 70, Figure 71, and Figure 77 where 5ppmm (nominal) of Mobil Jet Oil II was injected into the APU. It is seen that, while there is an increase in fine particle concentration associated with the Skydrol PE-5 contamination, it is somewhat lower than measured with the Mobil Jet Oil II contamination, about one order of magnitude increase with the Skydrol PE-5 as compared to nearly two orders of magnitude increase with Mobil Jet Oil II. The two large concentration peaks after the start of Skydrol PE-5 injection in Figure 78 and Figure 84 are due to a malfunction of the injection pump resulting in a

10ppmm injection rate in one direction of the dual stroke pump. Comparing Figure 80 to Figure 71, it is seen that the particle sizes with the hydraulic fluid are larger than with the Mobil Jet Oil II which may be a reason why the number concentration is lower. Since no hydraulic fluid tests were conducted with the propulsion engine, it is not known if higher bleed air temperatures would have the same negative effect on fine particle concentrations seen with the oils.

The fine particle data show that establishing a fine particle concentration baseline can be a challenge. Without contamination, the fine particle concentration in the bleed air is lower than in the ambient air as seen in Figure 71. Not only does the engine compressor apparently remove the larger particles, as already noted, it removes a substantial fraction of the ambient particles across the full-size range of particle size as measured by the APS by as much as an order of magnitude. Thus, ambient air is not a valid reference condition for using fine particles to detect bleed air contamination. Additionally, the baseline is not always highly stable as seen in Figure 78 prior to the Mobil Jet Oil II injection for example. This baseline variation is even more pronounced with the Piera instruments (e.g., see Figure 81), where the variations are nearly an order of magnitude at times. Even though an order of magnitude or more increase in fine particle concentration seen with the APU and low temperature bleed air with the propulsion engine seems large, the difficulty in establishing a precise baseline may limit the ability to use fine particles as a reliable indicator of contamination. This limitation and the small or non-existent response to oil contamination at higher bleed air temperatures do not appear to be encouraging for using fine particles as the primary detection method for bleed air contamination. They may be useful when looking at bleed air provided by the APU.

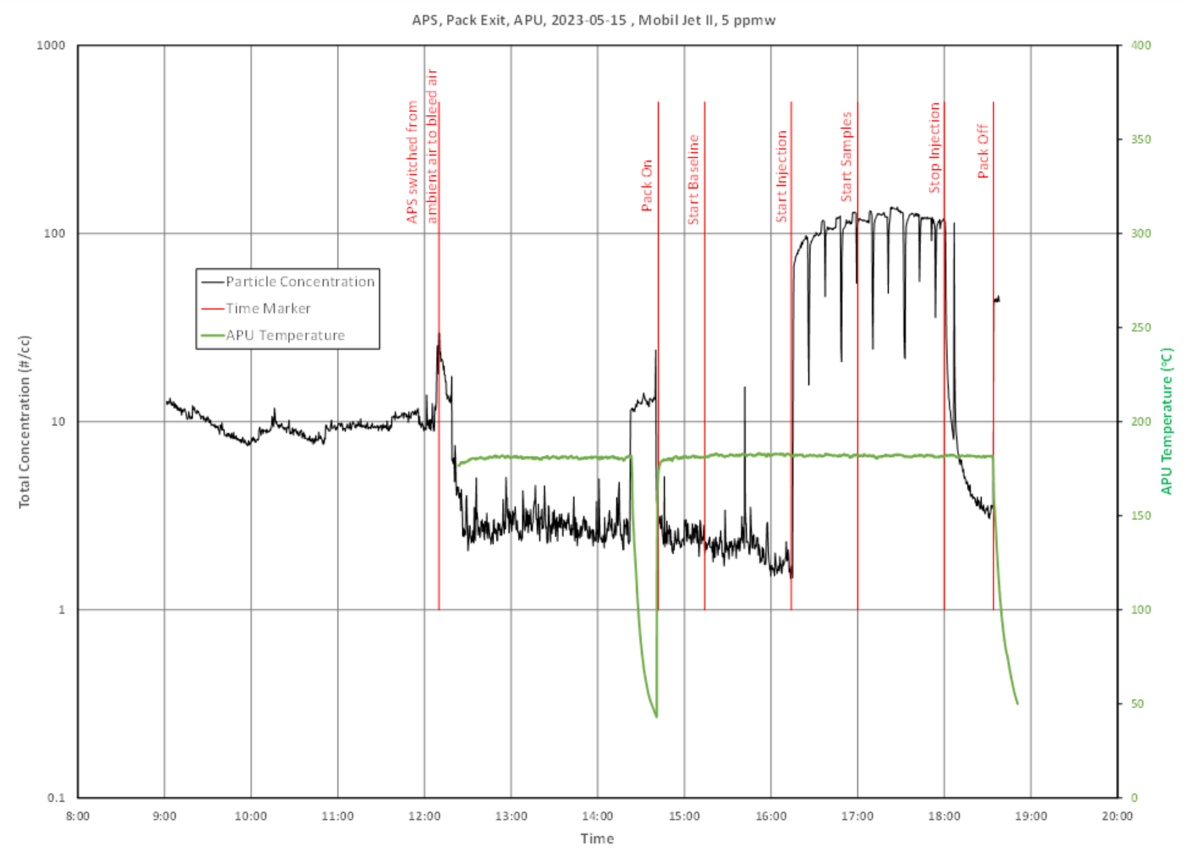


Figure 70. Total fine particle concentration, APS, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)

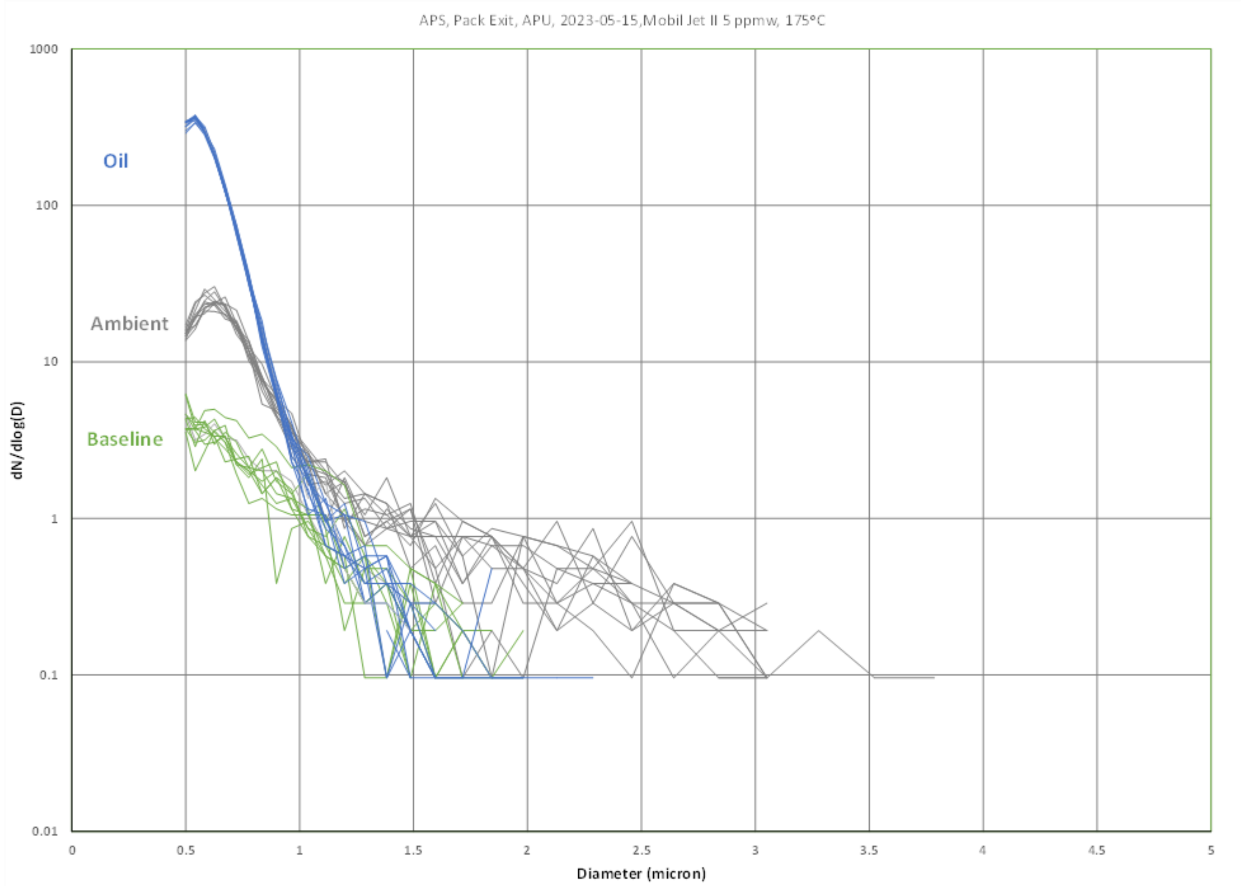


Figure 71. Particle size distribution, APS, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)

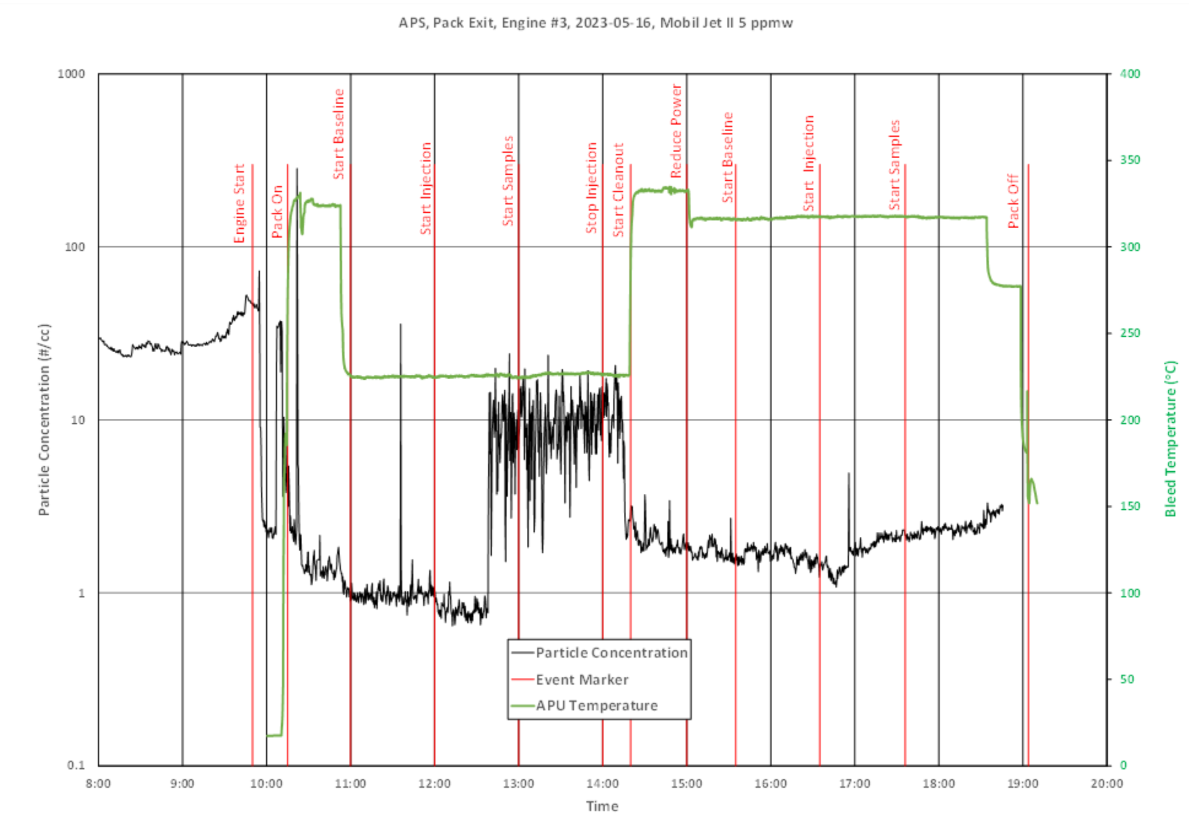


Figure 72. Total fine particle concentration, APS, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)

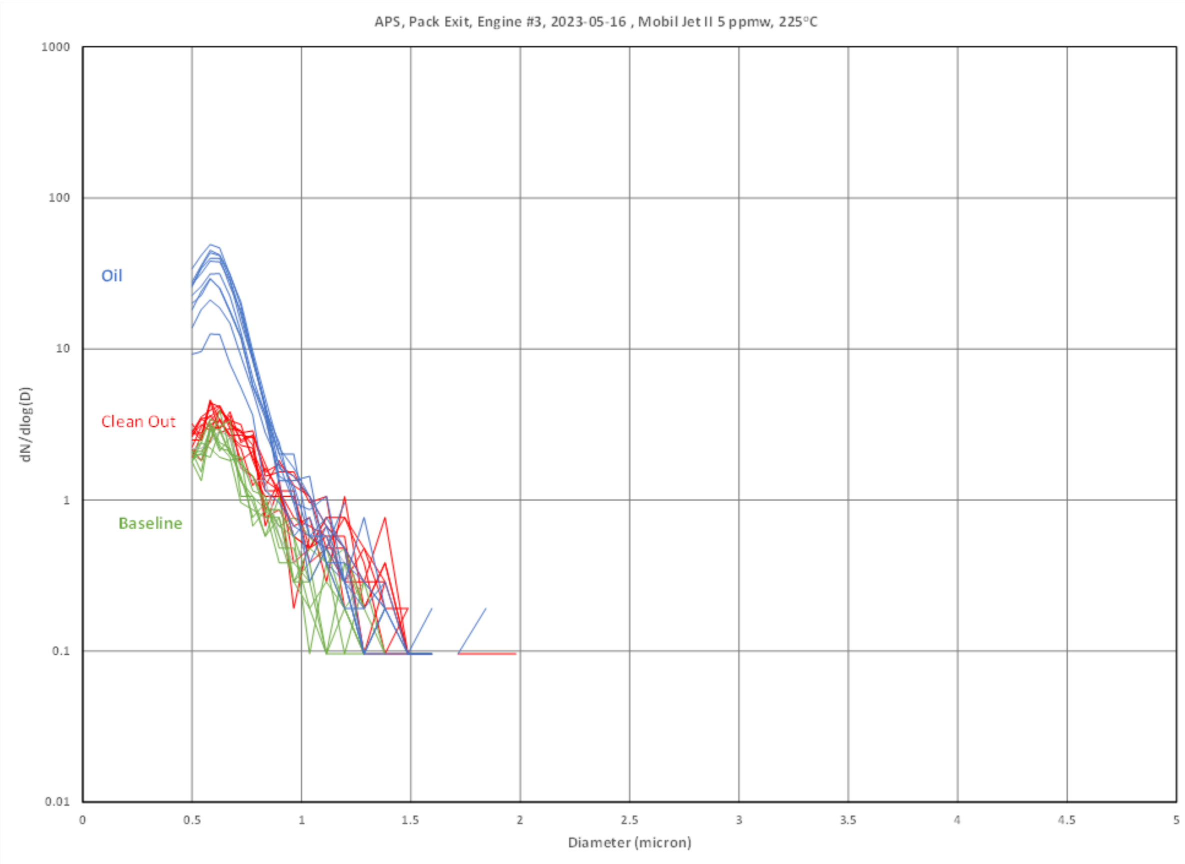


Figure 73. Particle size distribution, APS, May 16, 2023, number 3 engine, 225^{o}C, Mobil Jet Oil II, 5 ppmm (nominal)

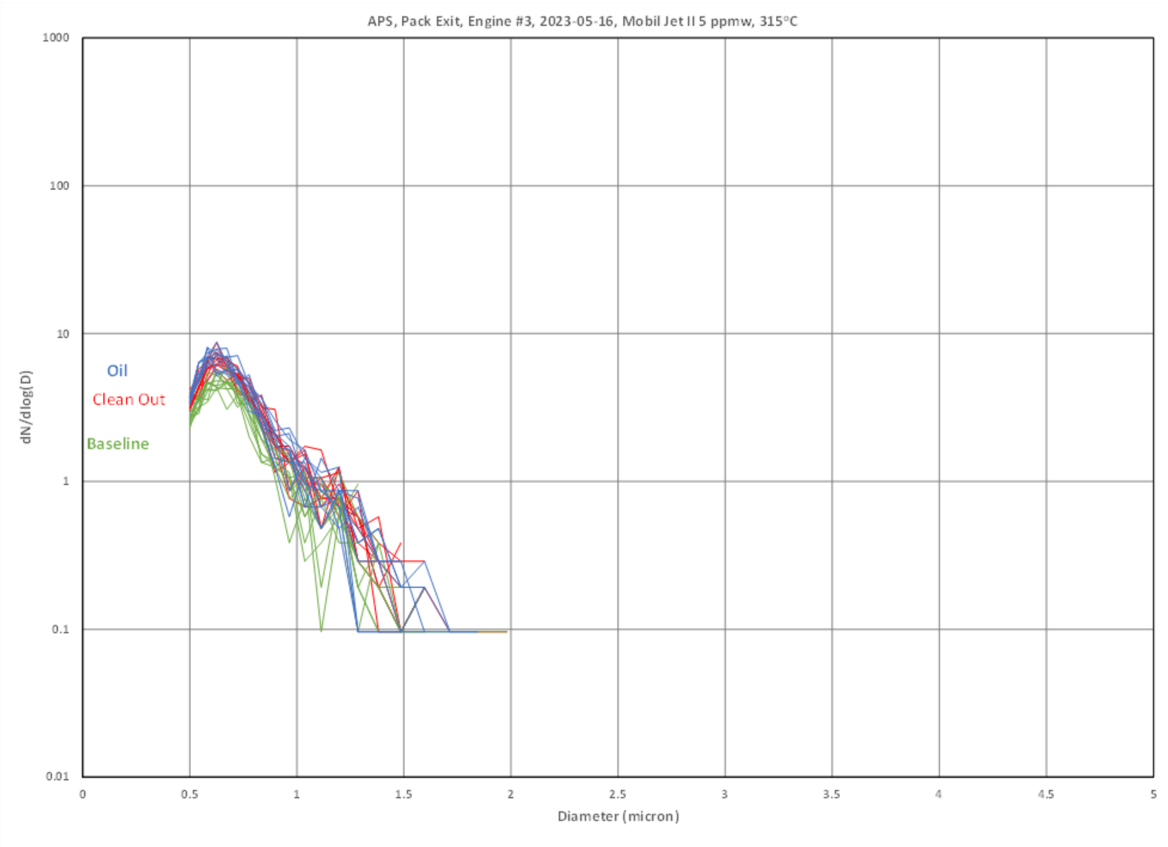


Figure 74. Particle size distribution, APS, May 16, 2023, number 3 engine, 315°C, Mobil Jet Oil II, 5 ppmm (nominal)

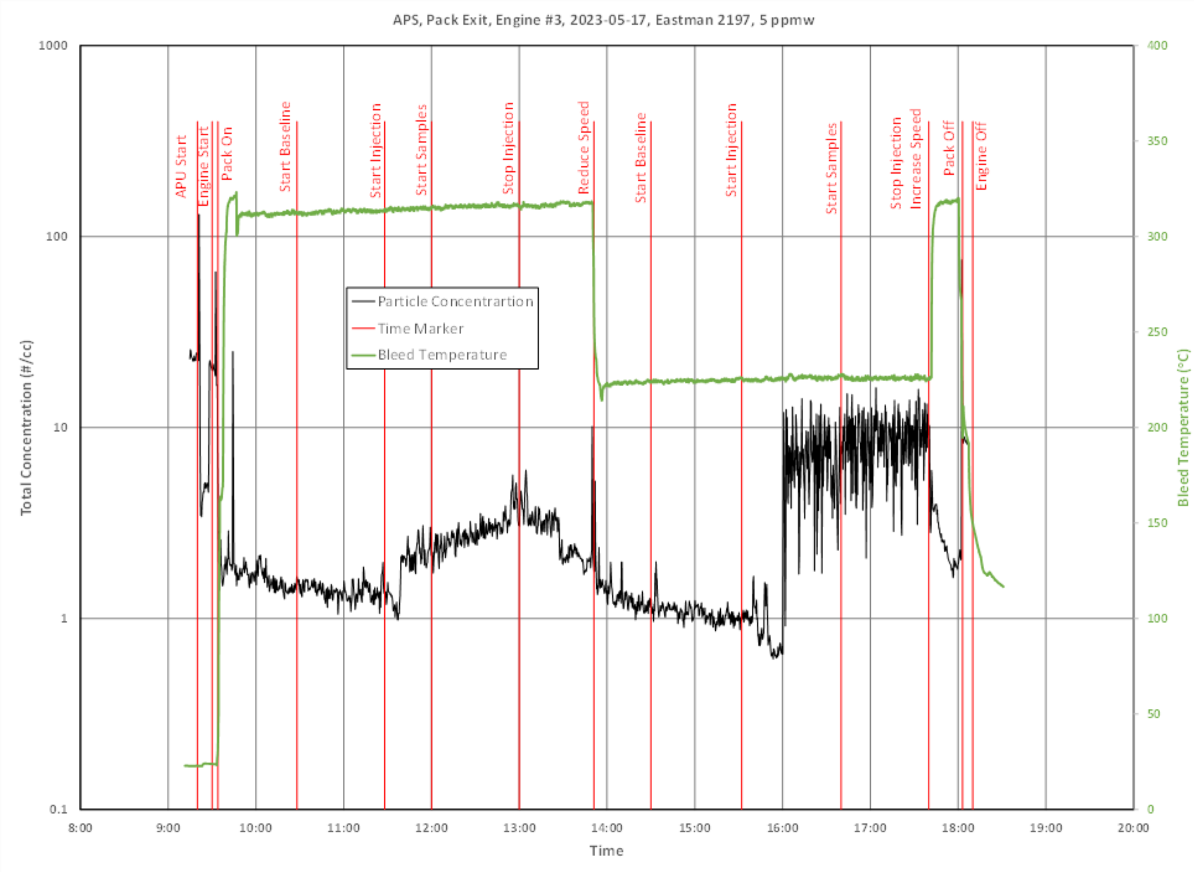


Figure 75. Total fine particle concentration, APS, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)

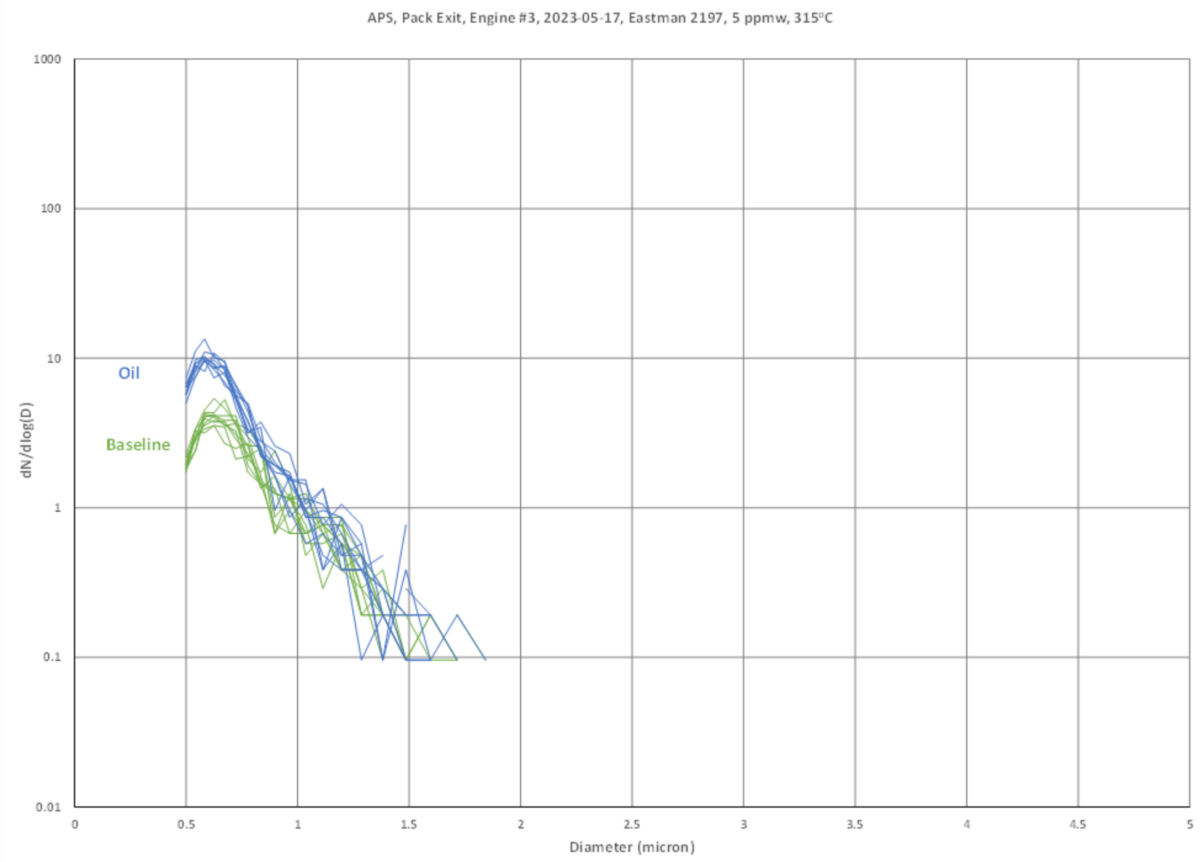


Figure 76. Particle size distribution, APS, May 17, 2023, number 3 engine, 315°C, Eastman Oil 2197, 5 ppmm (nominal)

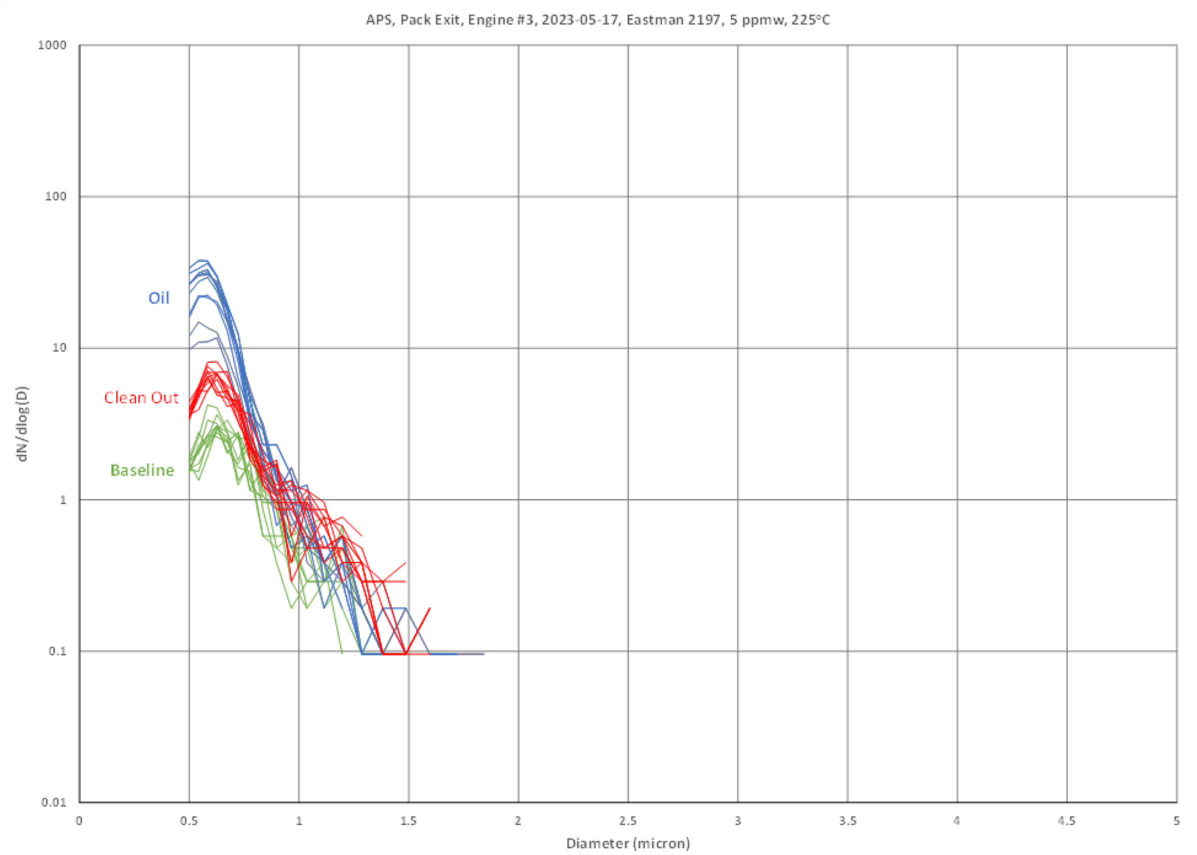


Figure 77. Particle size distribution, APS, May 17, 2023, number 3 engine, 225 ^{o}C, Eastman Oil 2197, 5 ppmm (nominal)

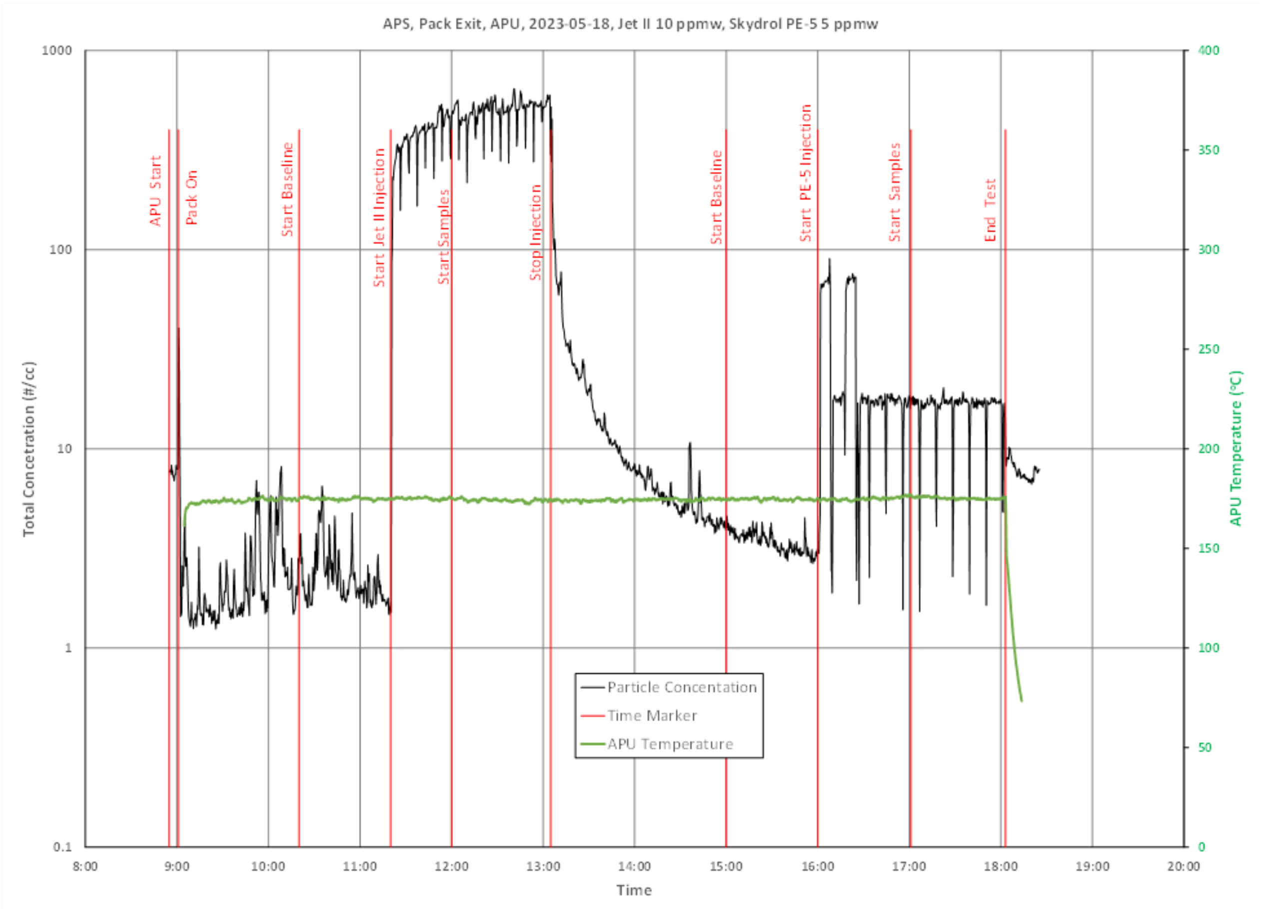


Figure 78. Total fine particle concentration, SMPS, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal) and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)

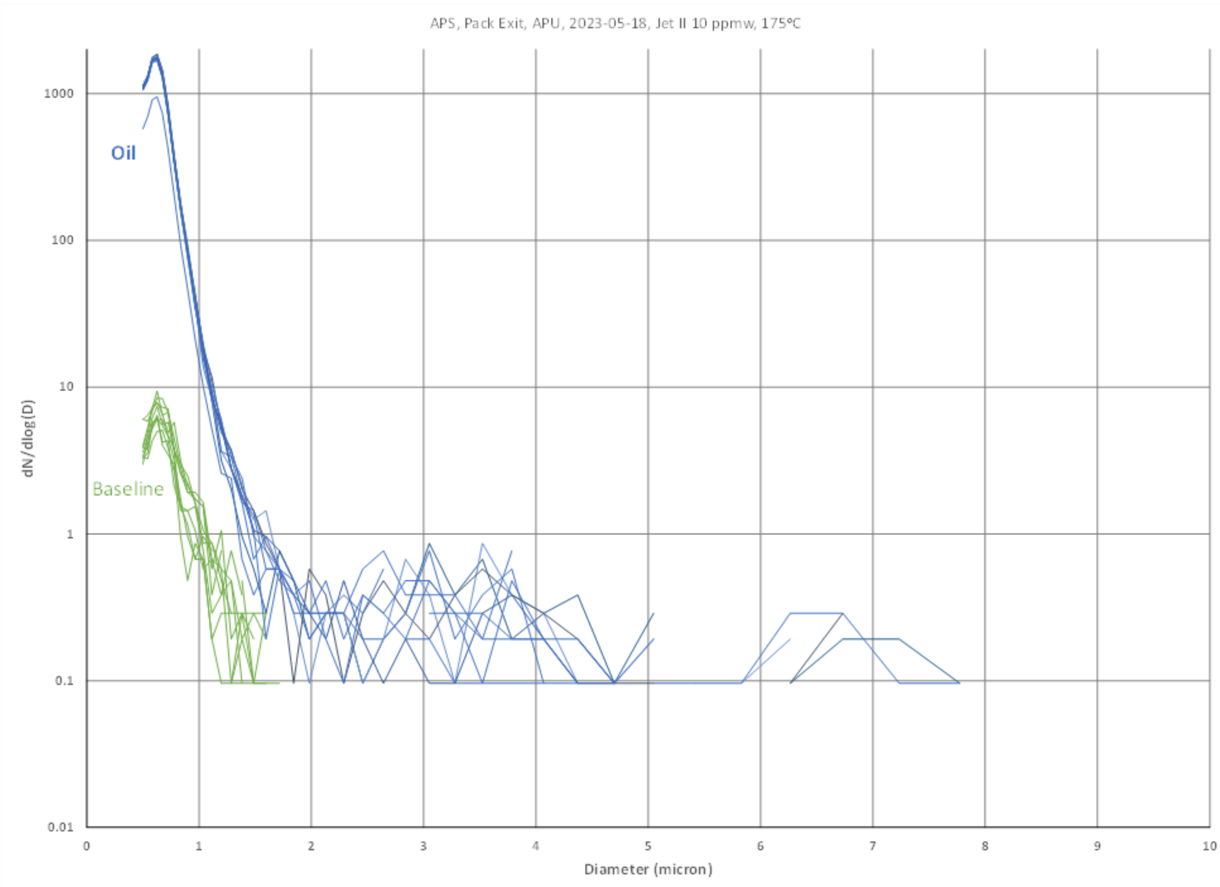


Figure 79. Particle size distribution, APS, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal)

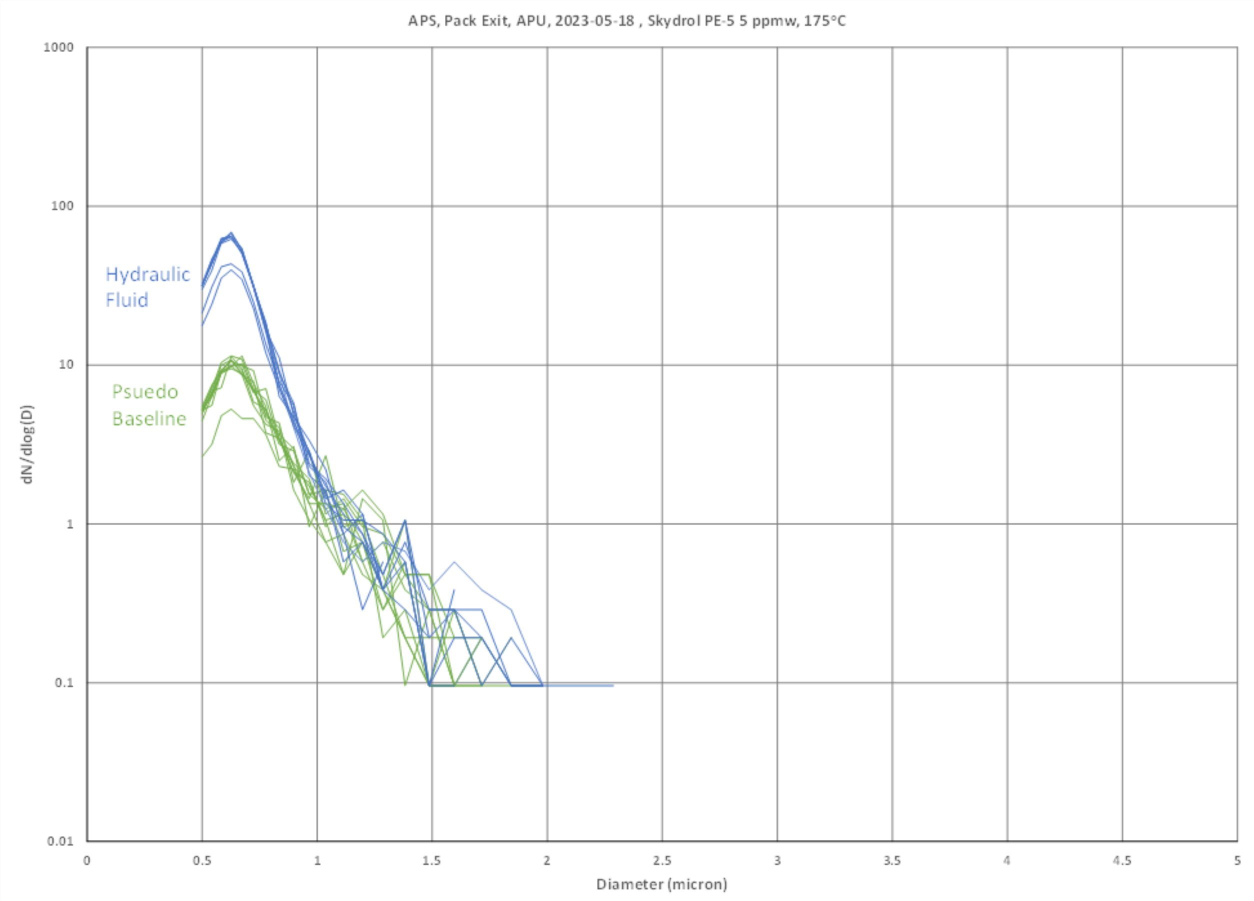


Figure 80. Particle distribution, APS, May 18, 2023, APU, Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)

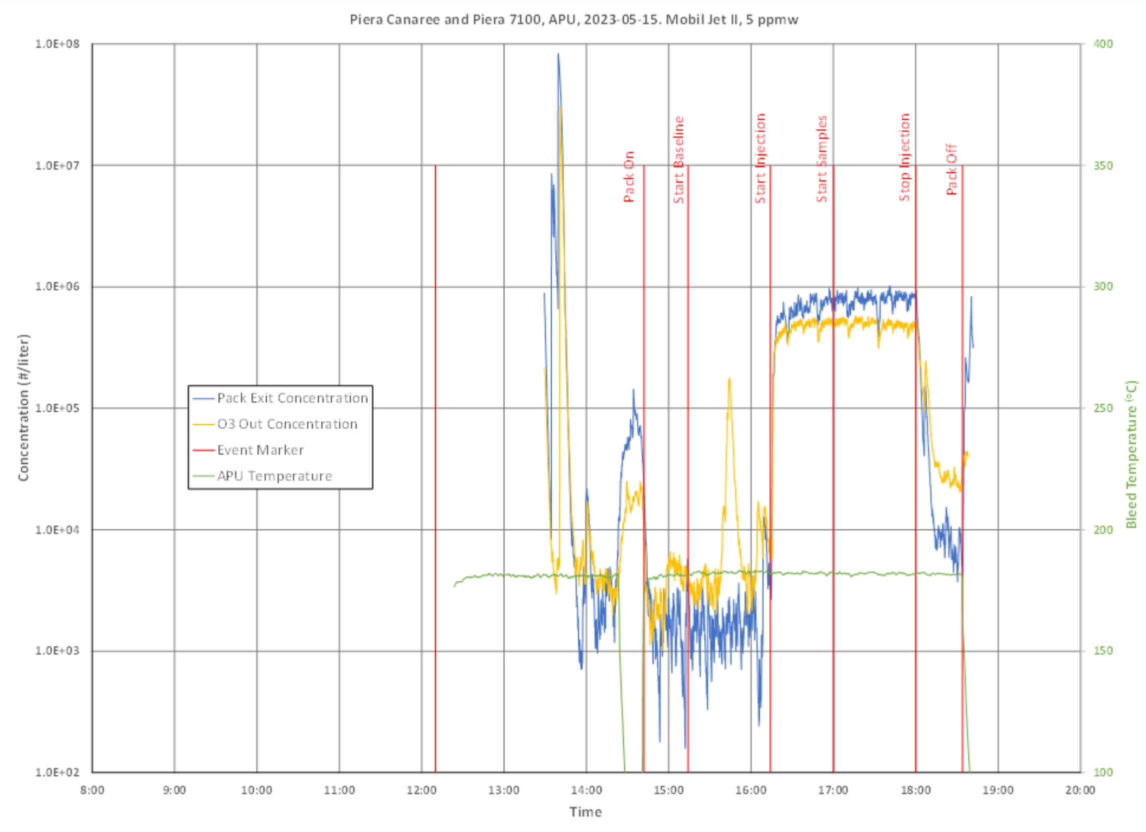


Figure 81. Total fine particle concentration, Piera Canaree and Piera 7100, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)

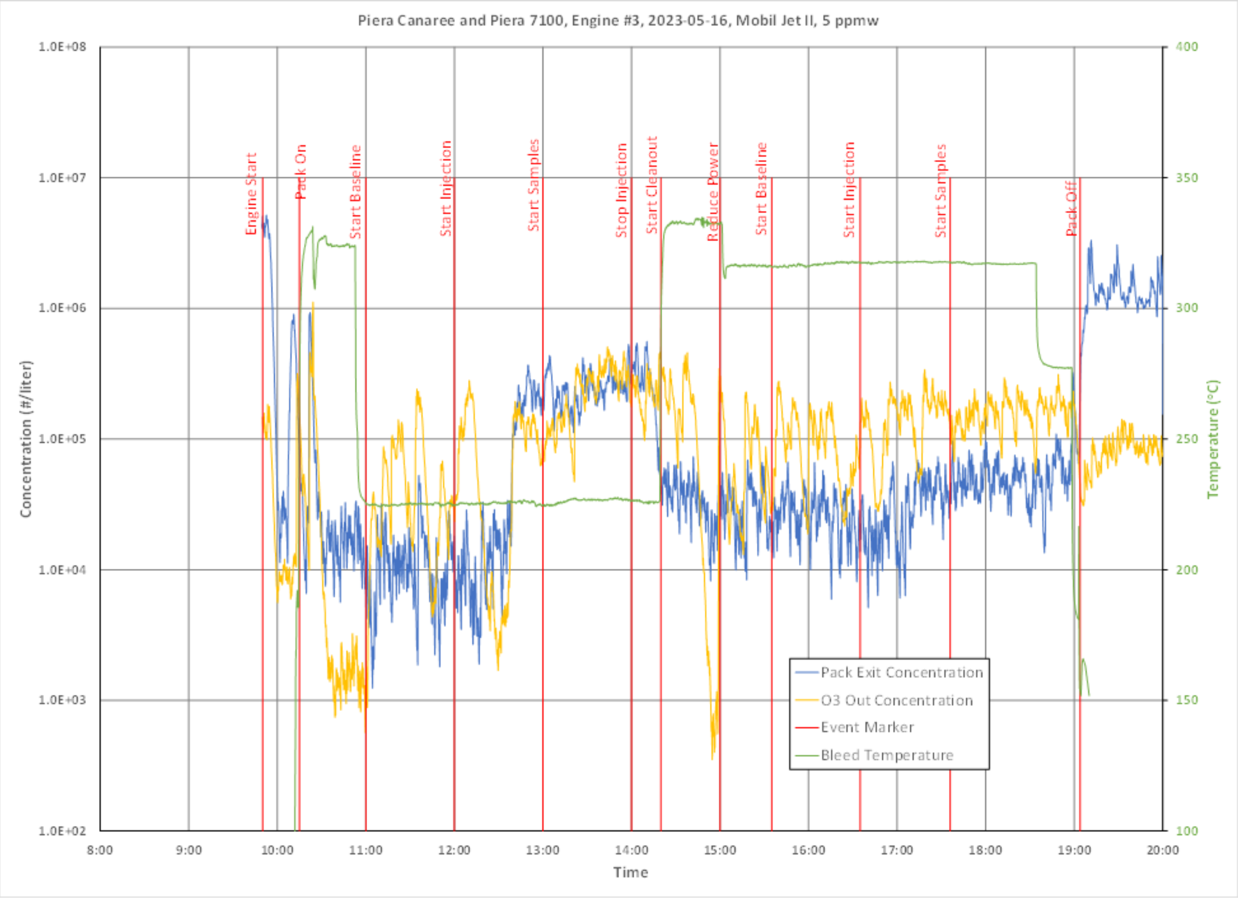


Figure 82. Total fine particle concentration, Piera Canaree and Piera 7100, May 16, 2023, number 3 engine, Mobil Jet Oil II, 5 ppmm (nominal)

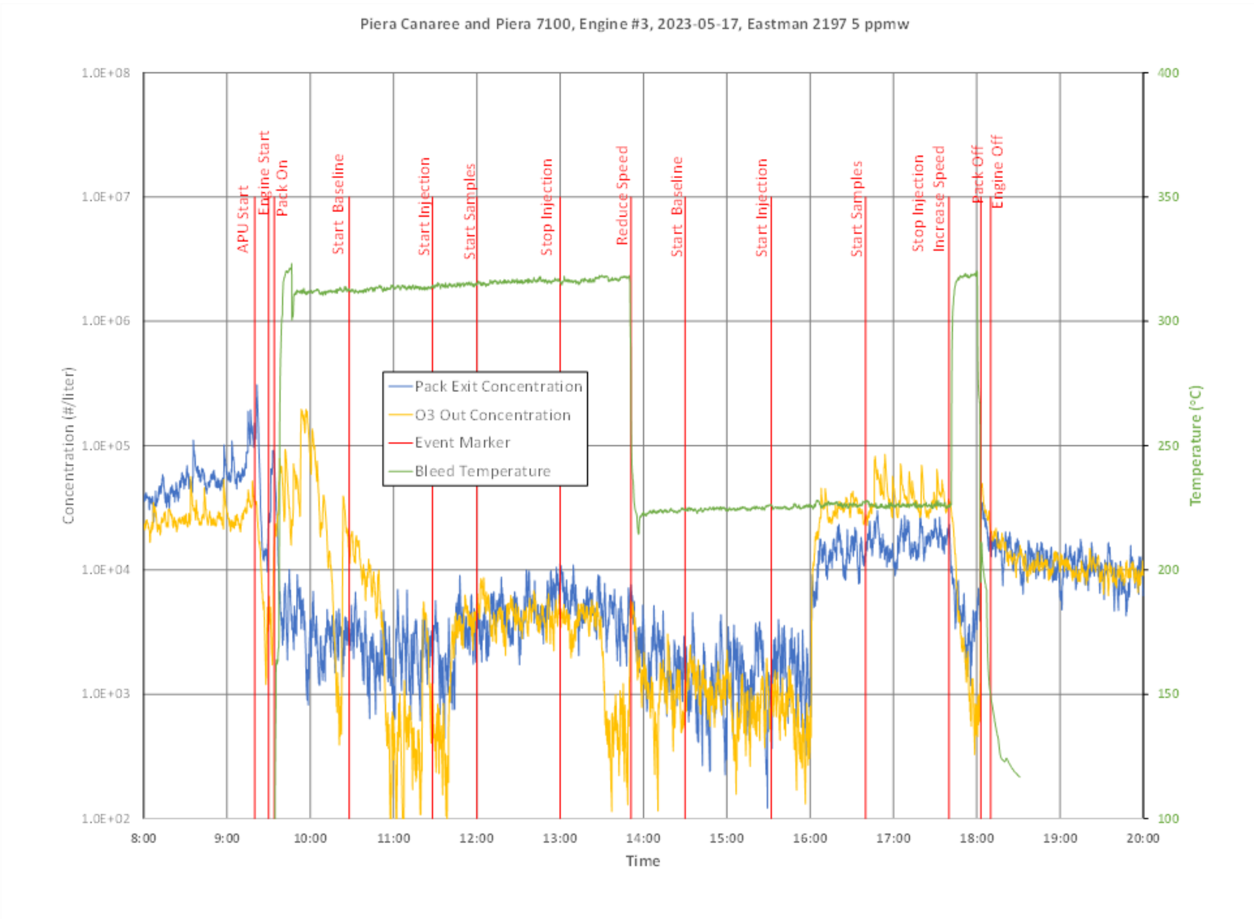


Figure 83. Total ultrafine particle concentration, Piera Canaree and Piera 7100, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmm (nominal)

Figure 84. Total fine particle concentration, Piera Canaree and Piera 7100, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal) and Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)

2.5.3 Assessment of carbon dioxide and carbon monoxide measurements

No significant changes were observed in concentrations of carbon dioxide and carbon monoxide above ambient levels, as shown in Figure 85, Figure 86, Figure 87, and Figure 88. These data substantiate the findings from the May 2022 engine test that carbon monoxide is not a good indicator of the presence of oil contamination.

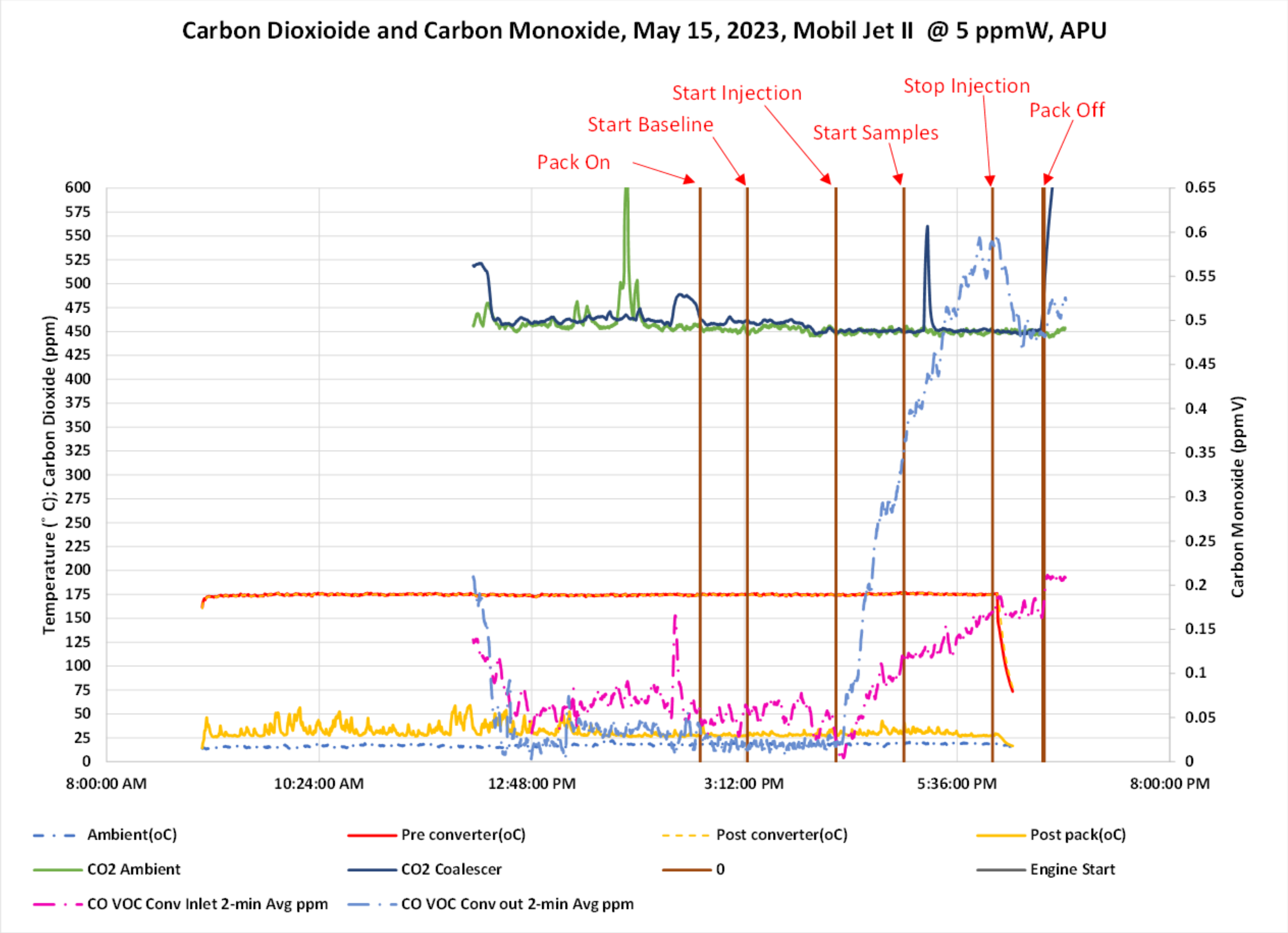


Figure 85. Carbon dioxide and carbon monoxide, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmW

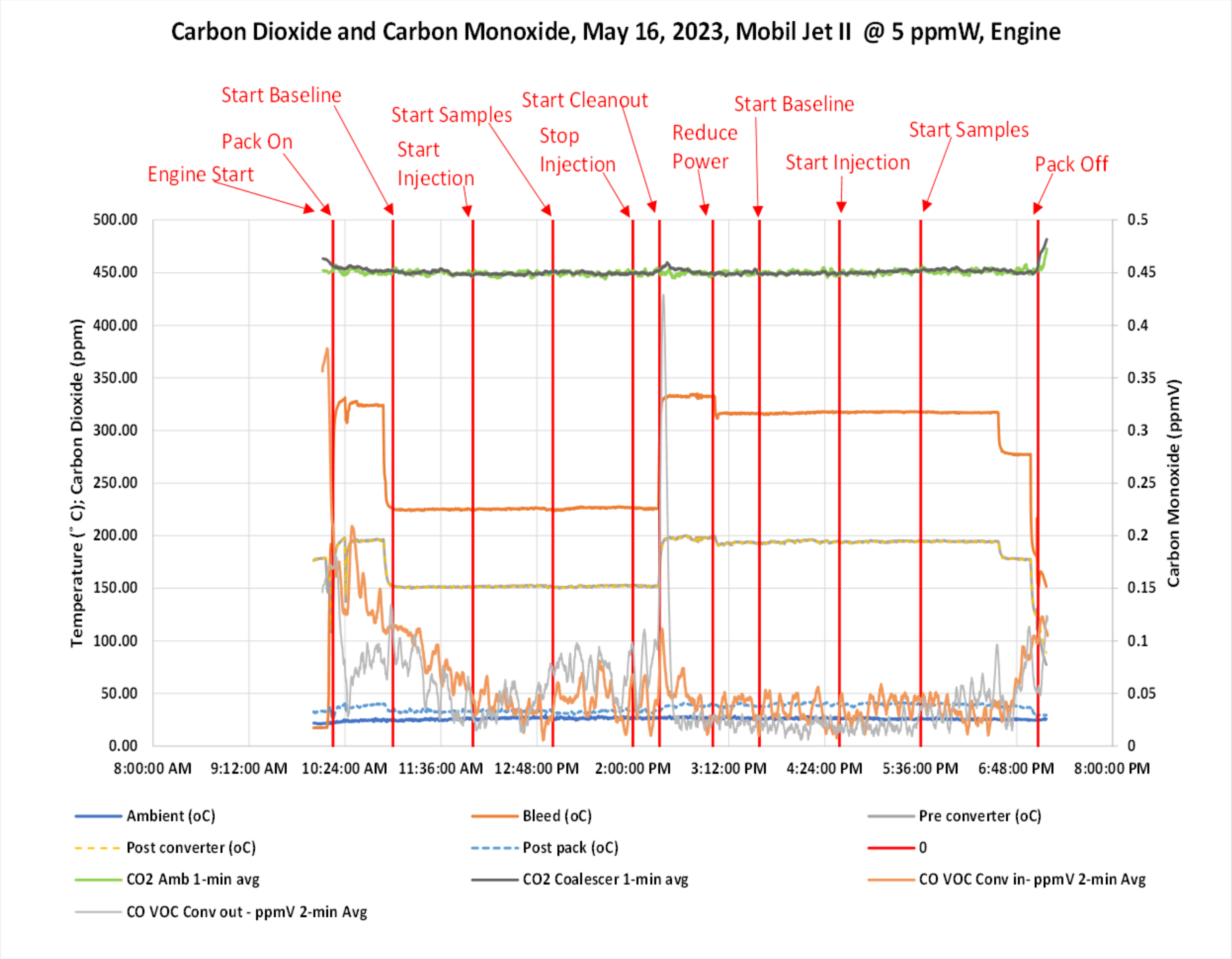


Figure 86. Carbon dioxide and carbon monoxide, May 16, 2023, number 3 engine, Mobile Jet Oil II, 5 ppmW

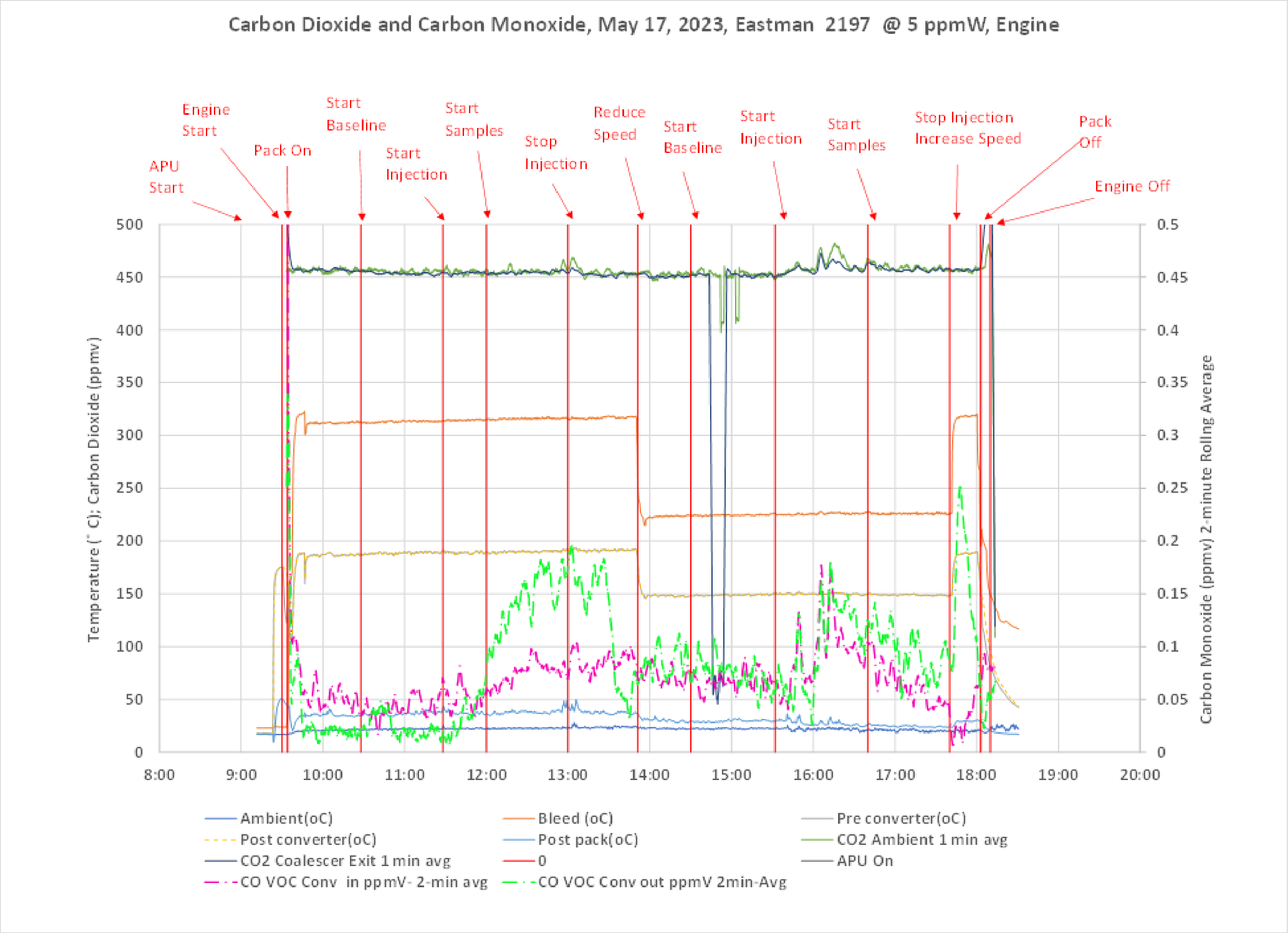


Figure 87. Carbon dioxide and carbon monoxide, May 17, 2023, number 3 engine, Eastman Oil 2197, 5 ppmW

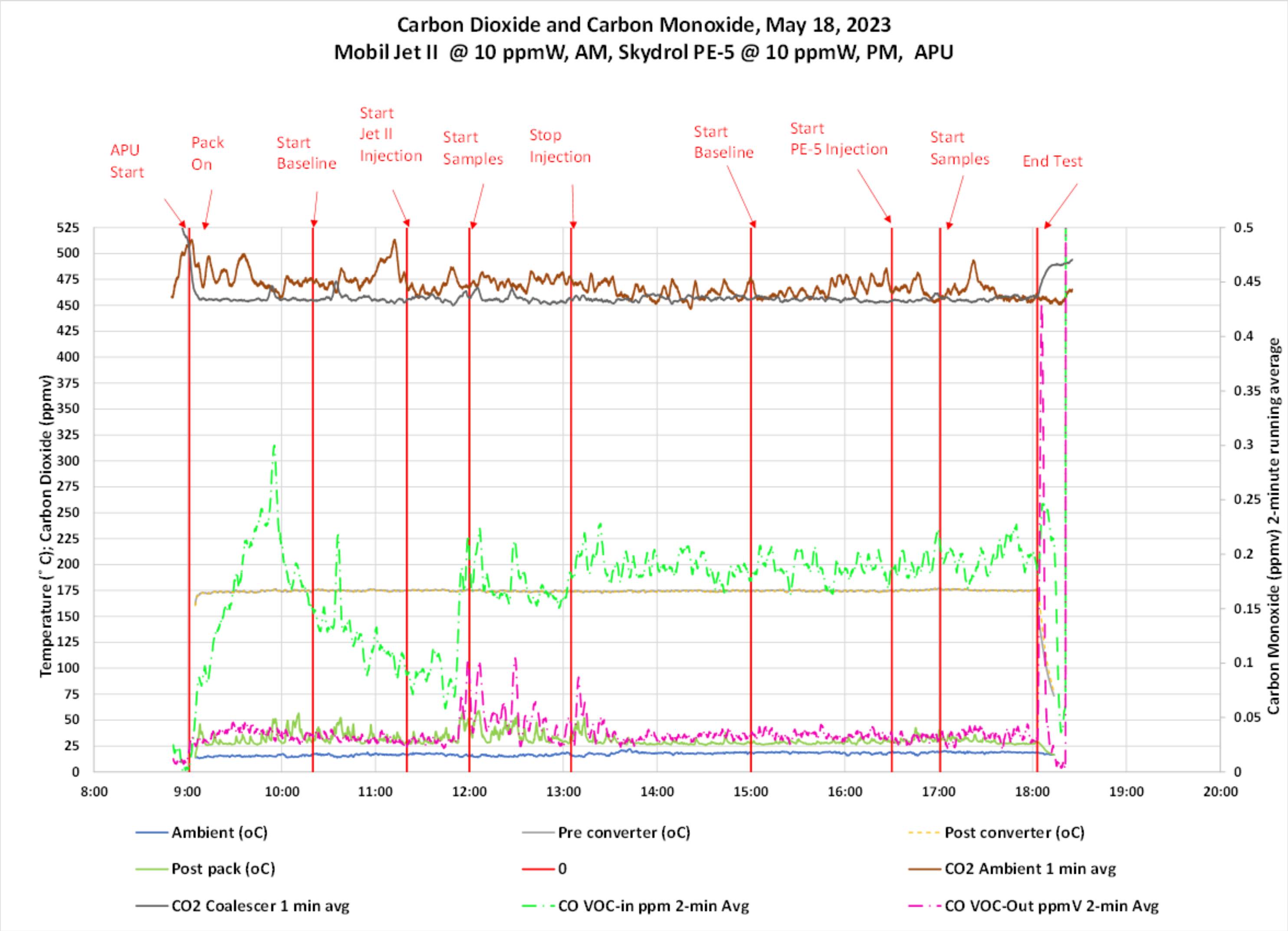


Figure 88. Carbon dioxide and carbon monoxide, May 18, 2023, APU, Mobile Jet Oil II, 10 ppmW (morning measurement) and Skydrol PE-5 hydraulic fluid, 10 ppmW (afternoon measurement)

2.5.4 Assessment of Honeywell hot bleed air sensor

The Honeywell high temperature instrument (HTTVOC) is a protype instrument that measured airstream samples immediately upstream of the ozone converter. This instrument is capable of operating with sample airstreams at high bleed air temperatures and, thus, the sample airstream was not cooled prior to being supplied to the instrument. The results from each day and each test condition are presented in Figures 89 through 95:

- Figure 89. TVOC, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 90. TVOC May 16, 2023, number 3 engine, 225°C, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 91. TVOC, May 16, 2023, number 3 engine, 315°C, Mobil Jet Oil II, 5 ppmm (nominal)
- Figure 92. TVOC, May 17, 2023, number 3 engine, 315° C, Eastman Oil 2197, 5 ppmm (nominal)
- Figure 93. TVOC, May 17, 2023, number 3 engine, 225° C, Eastman Oil 2197, 5 ppmm (nominal)
- Figure 94. TVOC, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal)
- Figure 95. TVOC, May 18, 2023, APU, Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)

The HTTVOC responded well to all injected fluid contaminants. It also tracked similarly to the UFP concentrations. However, it should be noted that the *HTTVOC data are presented on a linear scale and the UFP data are presented on a logarithmic scale*. The HTTVOC does not have the several orders of magnitude increase in response with contaminants as do the UFP. Even so, the HTTVOC generally shows a signal to noise ratio of about 10:1 in response to 5ppmm of contamination. Thus, there is a clear, well-defined response to contamination of this level.

The response differed from UFP in several respects. First, and perhaps most importantly, the HTTVOC responded well to hydraulic fluid. In fact, it appeared to respond more to hydraulic fluid than to engine oil. In Figure 95 with the APU and 5 ppmm of hydraulic fluid, the sensor is at the borderline of saturation, 305%. In comparison with the APU and 5 ppmm of engine oil in Figure 89, the response is just mid-range, 237%. The change in signal from baseline with hydraulic fluid was 150% in comparison to 110% with the oil.

In Figure 91, the response increased at the end of the test when the injection stopped and the bleed air temperature decreased. This behavior was not seen with UFP, and it is not clear why decreasing the bleed air temperature would lead to an increased response for the HTTVOC. At time 13:40 in Figure 94, 100mL of isopropyl alcohol (IPA) was injected into the inlet of the APU in an attempt to clean any residual engine oil from ECS surfaces. No response in UFP was seen at that time but there was a large response for the HTTVOC. The HTTVOC did respond positively to bleed air temperature increases as seen in Figure 90 and Figure 94 but the response was much briefer than with UFP.

The scale on the HTTVOC instrument was set at 100% to 300%, where 100% was intended to correspond to clean air and 300% to heavily contaminated air. As a result, the instrument output saturated at 300%. This limit is not inherent to the sensing technology but resulted from the way the instrument was set up to detect low levels of VOCs. It was possible to estimate readings above 300%; however, those readings are estimates and should be treated as such. The response appears to be more or less linear with increasing contaminant concentration but there is inadequate data to fully assess this linearity. The test shown in Figure 89 and Figure 94 are for the same engine and injected contaminant, but with twice the concentration in Figure 94. The change in response with 5ppmm was 111% and 217% with 10ppmm; however, the latter value is just an estimate due to sensor saturation.

The experiments were not designed to test lower detection limits of the HTTVOC. On the assumption of linearity of response and given the noise level observed, it is expected the lower limit would be about 1ppmm for oil and perhaps as low as 0.5ppmm for hydraulic fluid.

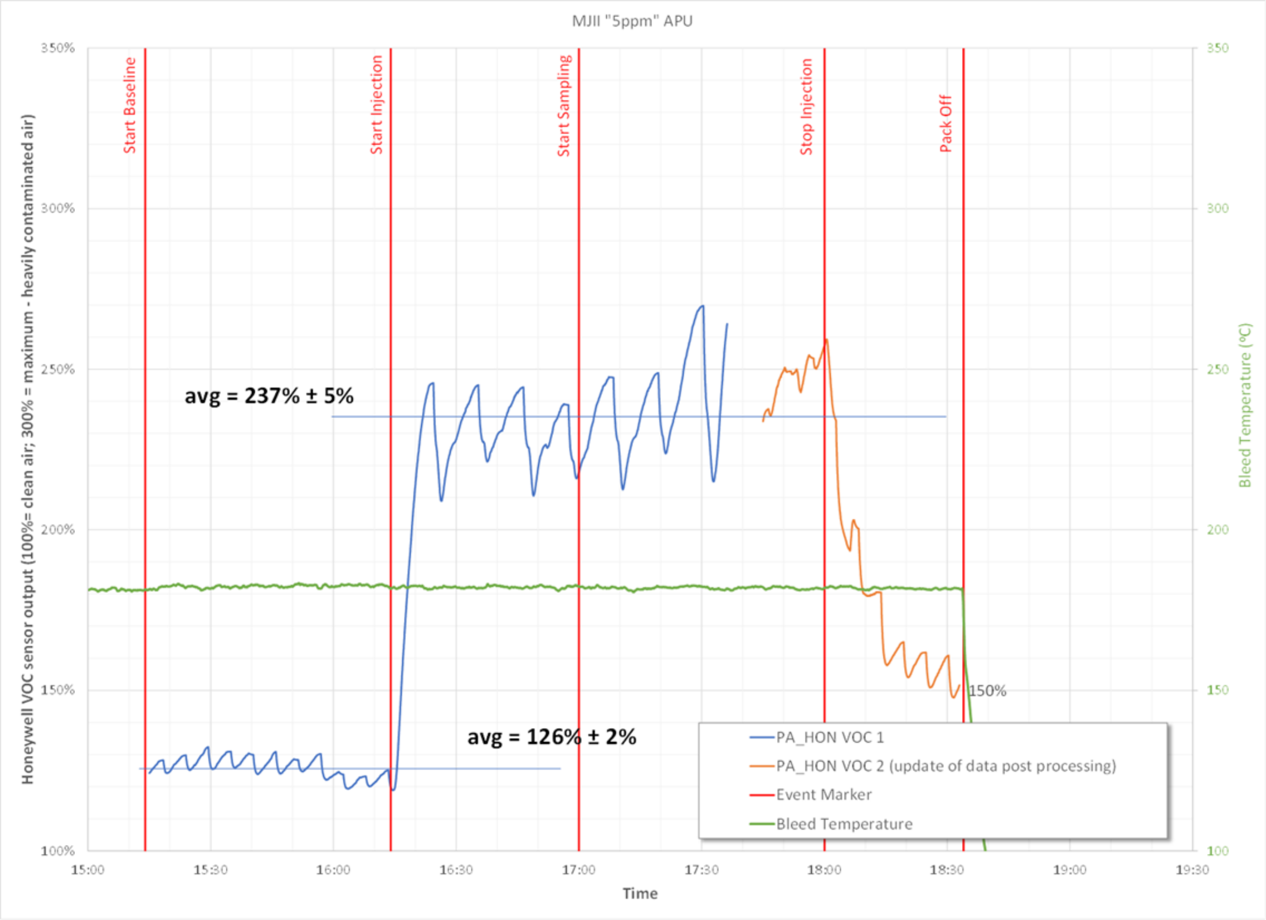


Figure 89. TVOC, May 15, 2023, APU, Mobil Jet Oil II, 5 ppmm (nominal)

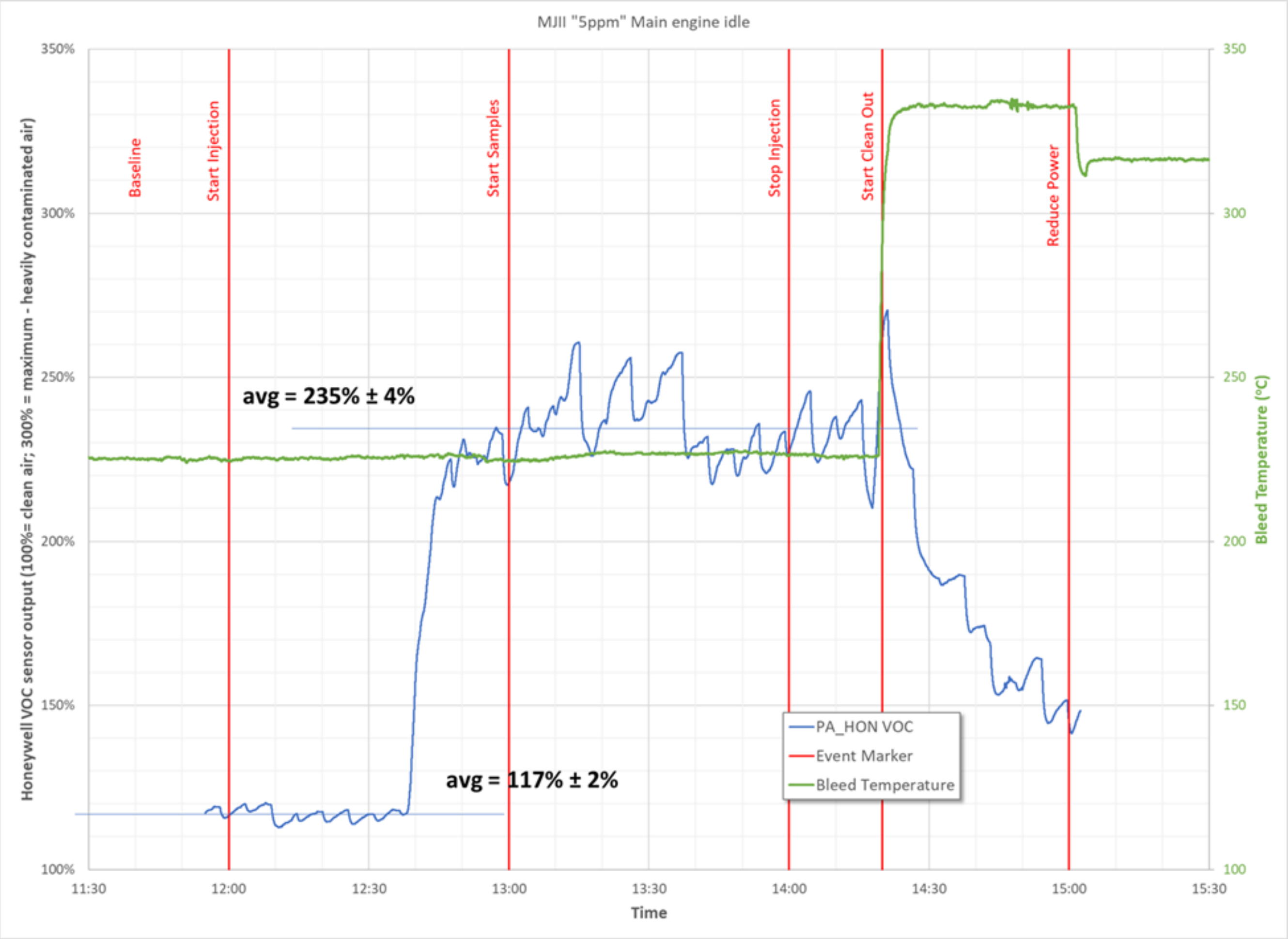


Figure 90. TVOC May 16, 2023, number 3 engine, 225ºC, Mobil Jet Oil II, 5 ppmm (nominal)

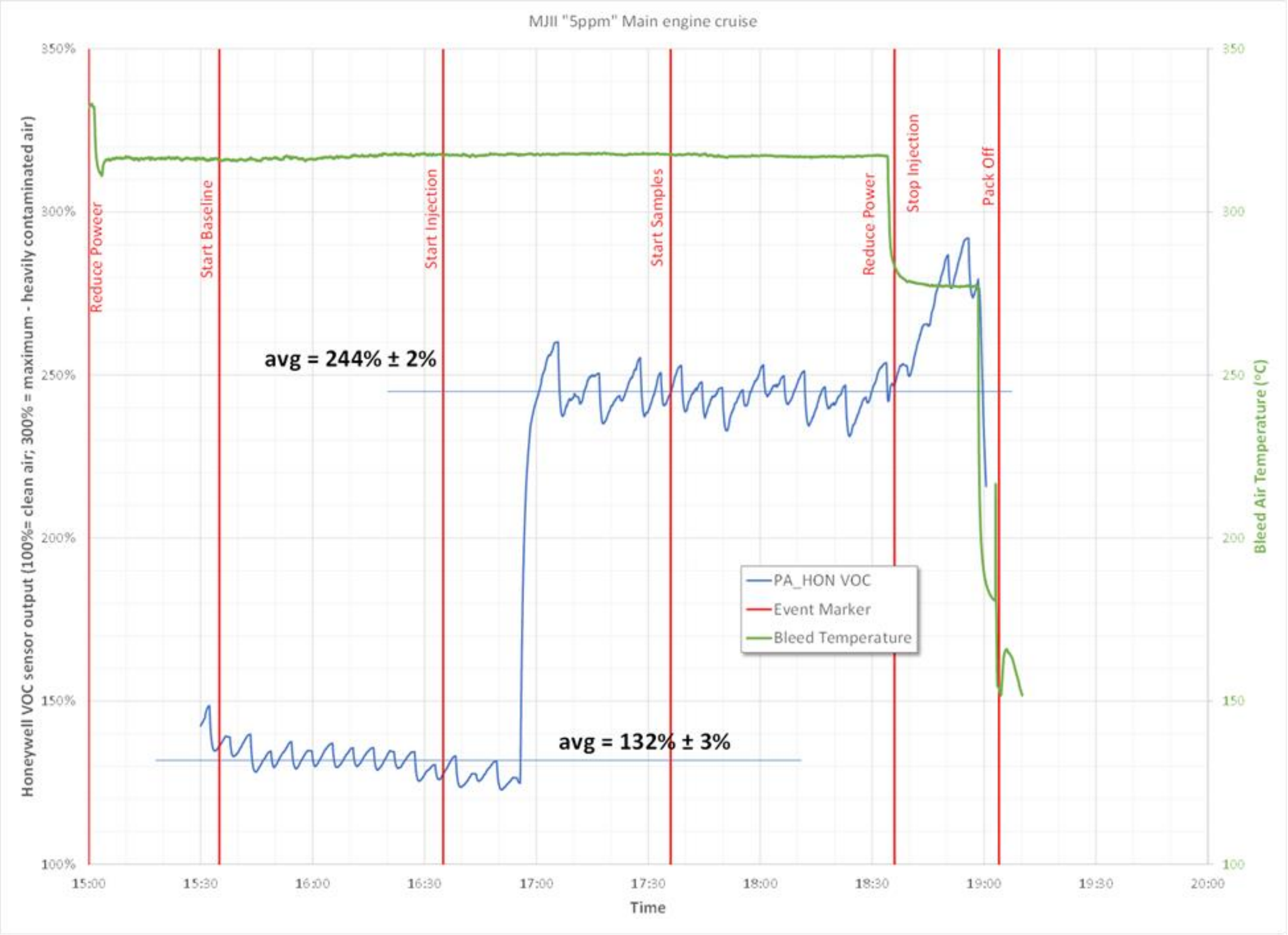


Figure 91. TVOC, May 16, 2023, number 3 engine, 315ºC, Mobil Jet Oil II, 5 ppmm (nominal)

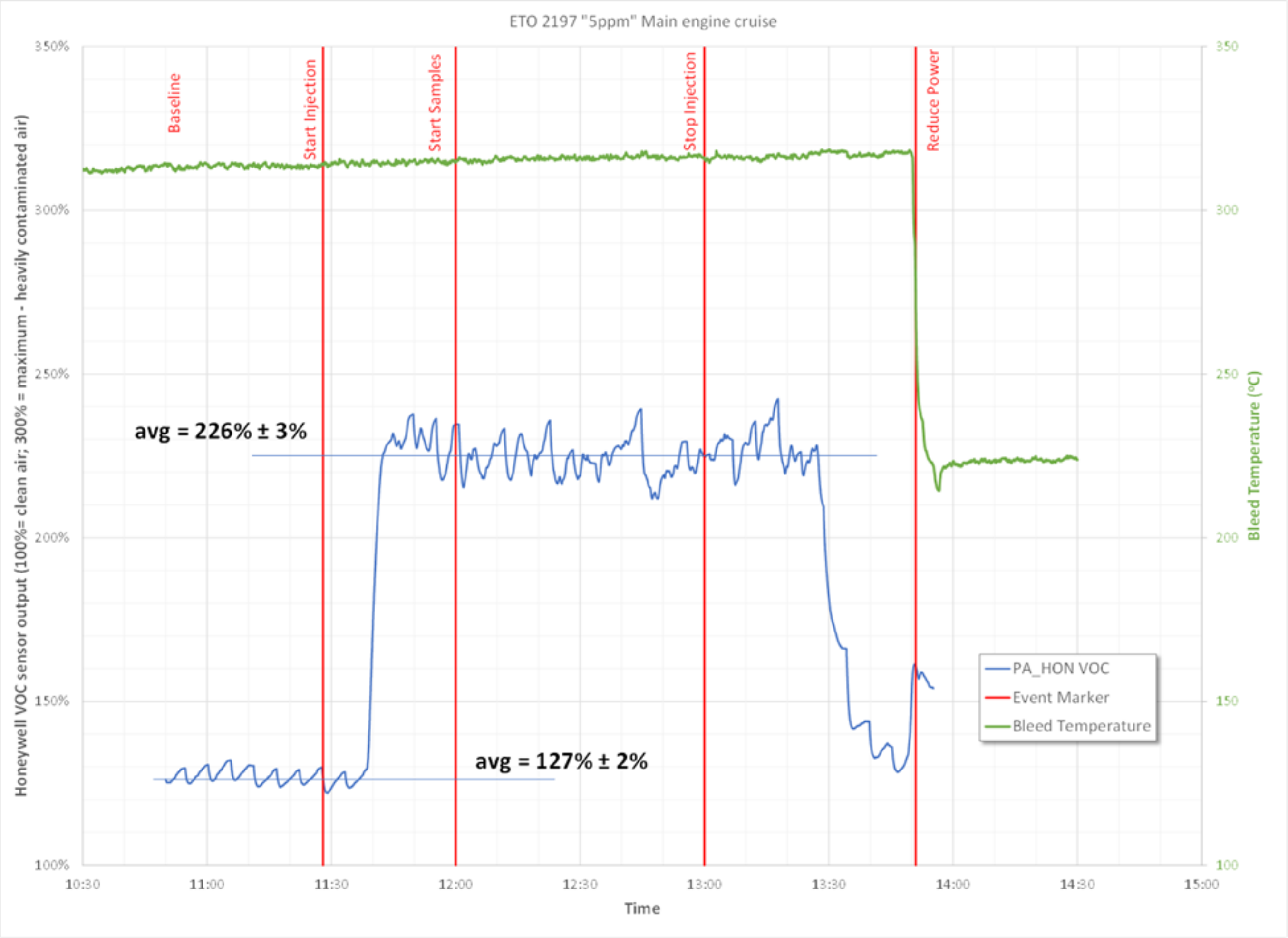


Figure 92. TVOC, May 17, 2023, number 3 engine, 315° C, Eastman Oil 2197, 5 ppmm (nominal)

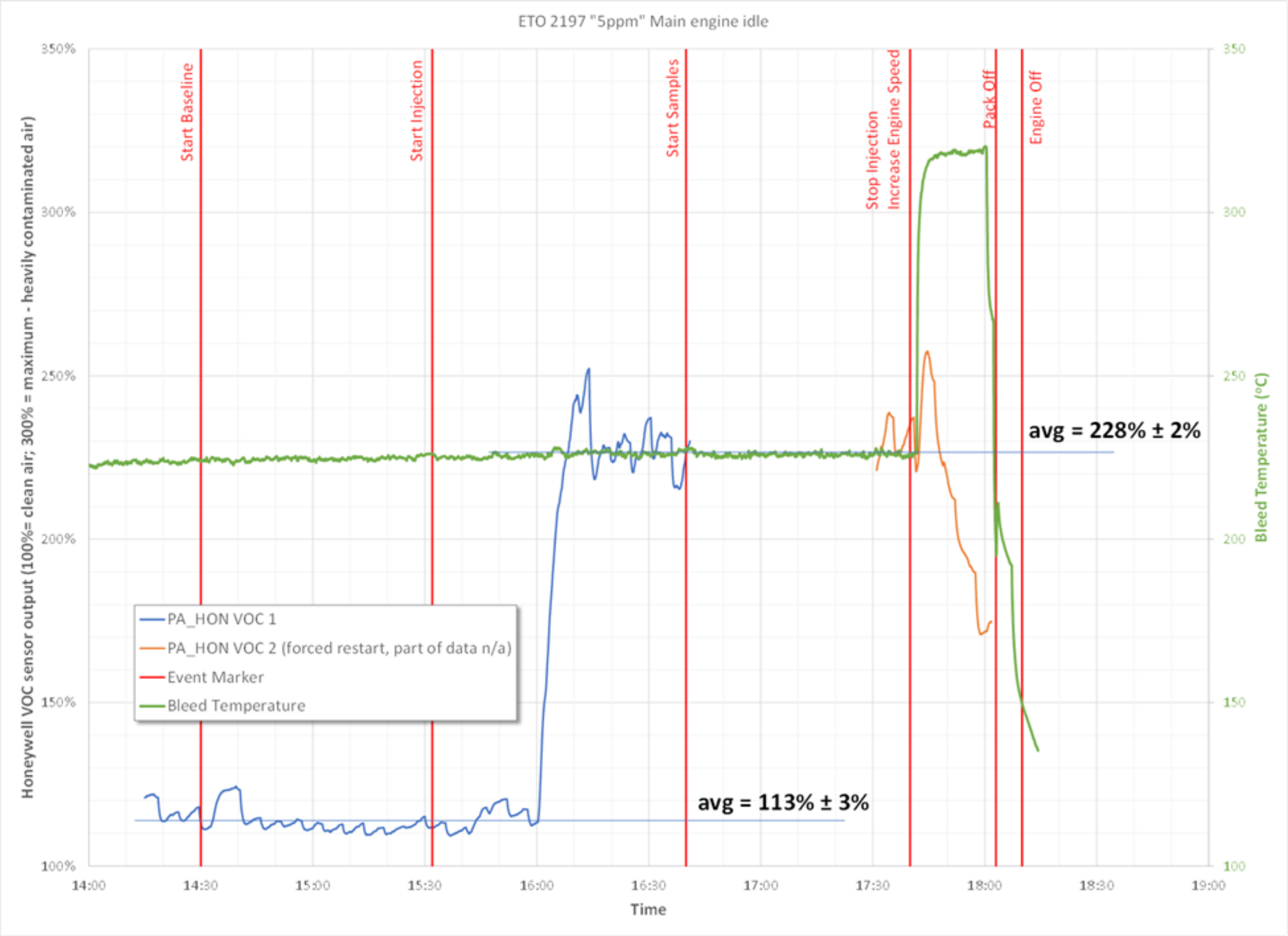


Figure 93. TVOC, May 17, 2023, number 3 engine, 225^{o} C, Eastman Oil 2197, 5 ppmm (nominal)

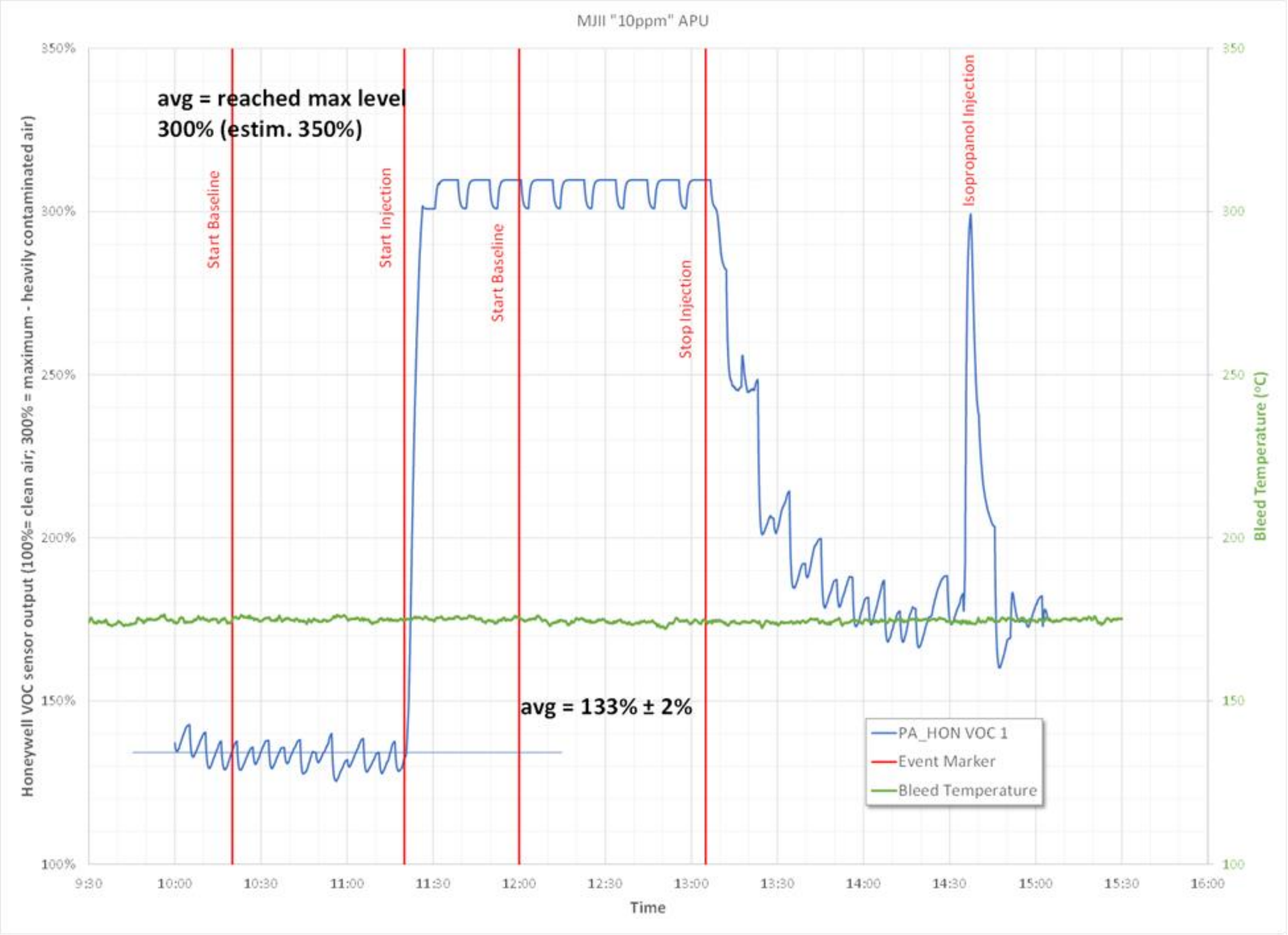


Figure 94. TVOC, May 18, 2023, APU, Mobil Jet Oil II, 10 ppmm (nominal)

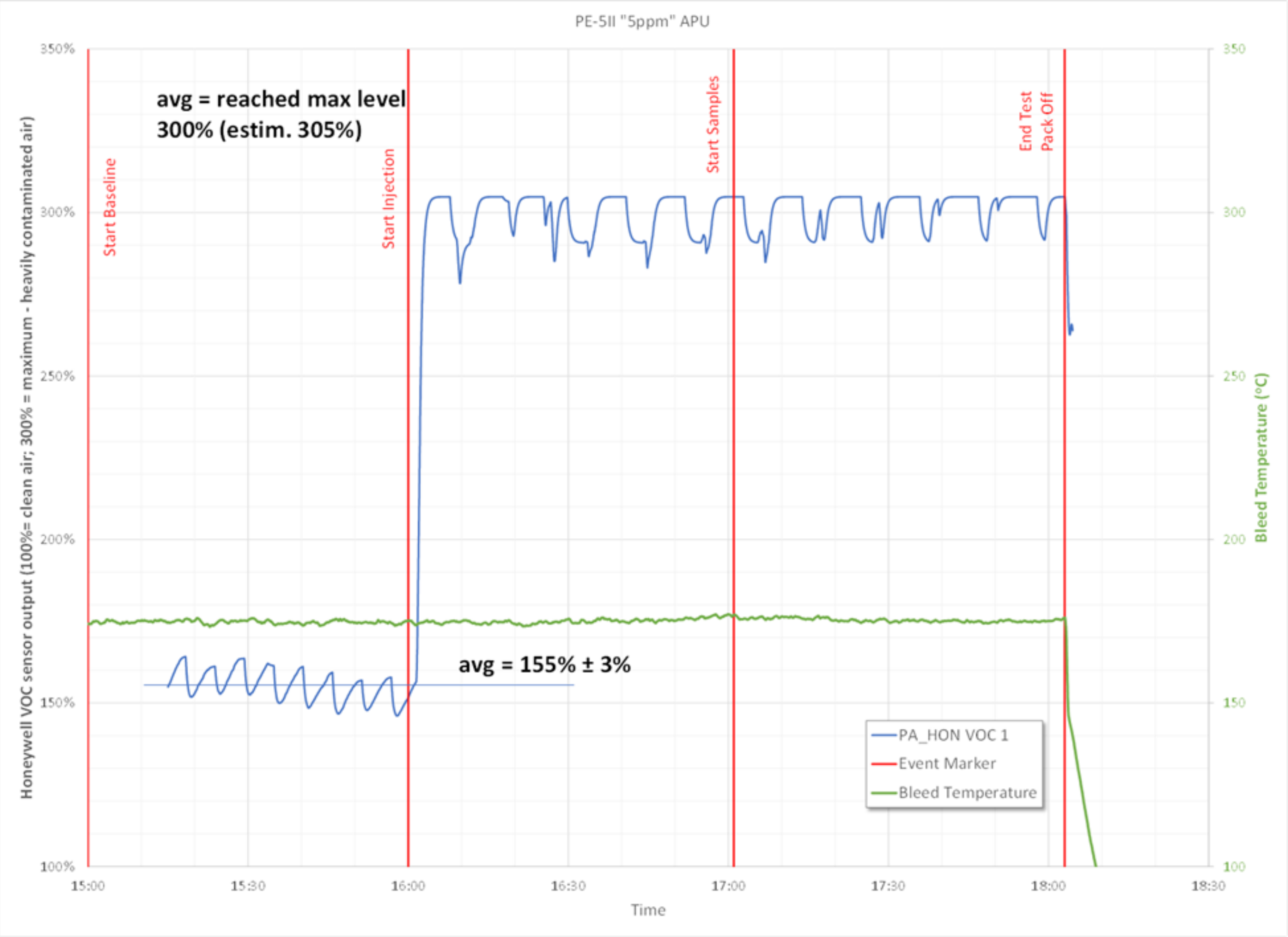


Figure 95. TVOC, May 18, 2023, APU, Skydrol PE-5 hydraulic fluid, 5 ppmm (nominal)

2.5.5 Assessment of airsense aerotracer ion mobility spectrometer

Ion mobility spectrometer response to oil contamination

The Aerotracer (AT) instrument from Airsense (Figure 96) was used to monitor and measure contamination in the bleed air. It was positioned inside of the cabin where four sampling probes were available in order to measure ambient air (position #1), bleed air upstream of the VOC/ozone converter (position #2), bleed air downstream of the VOC converter (position #3) and the pack exit (position #4).

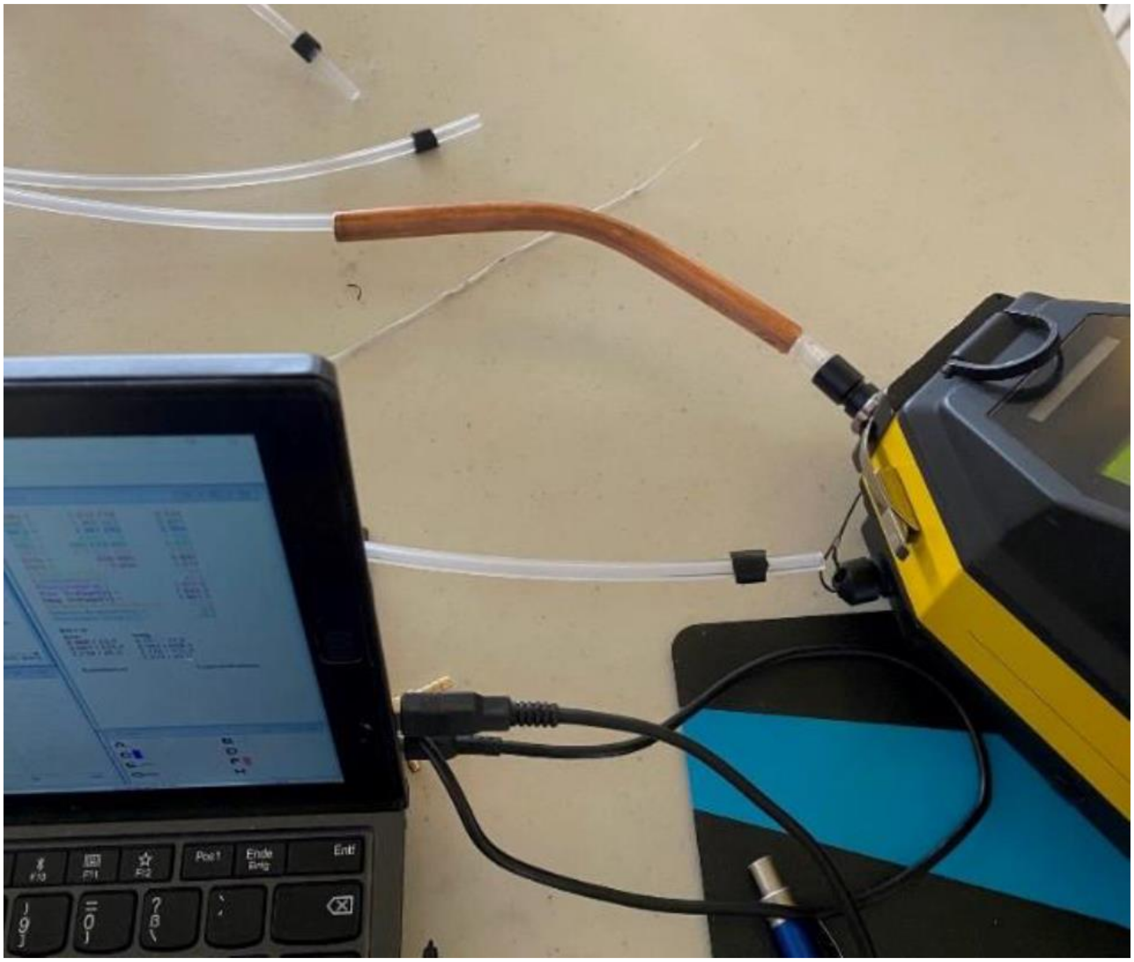


Figure 96. AT with 4 different sampling lines

Only one AT was available. Therefore, the bleed air upstream of the VOC converter was monitored most of the time (i.e., position #2). Position #3 and #4 were subsequently measured after the signal had stabilized at position #2. The AT was operated mainly with its standard library at setting A of the instrument panel, which delivers “Odor Units” if engine oil is identified.

2.5.5.1 Instrument

The AT is a portable instrument designed to identify chemicals and odors related to the aviation industry. It consists of a combination of an ion mobility spectrometer (IMS) with additional gas detectors such as a photo ionization detector (PID), an electro-chemical cell (EC), and two metal oxide sensors (MOS).

The AT was operated with its standard libraries, the “Odor Units” library at setting A of the instrument panel, which monitors only engine oil and delivers odor units based on an internal rating. A second library at position B, the “Maintenance” library, is mainly used to identify sources of odor from chemicals used in the aviation industry.

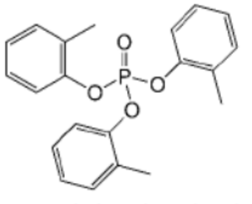
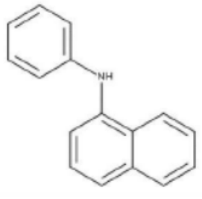
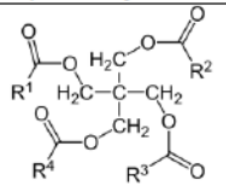
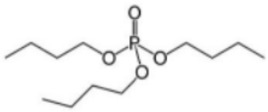
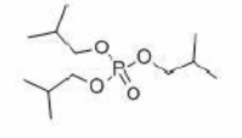
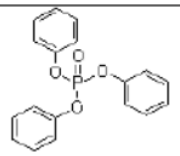
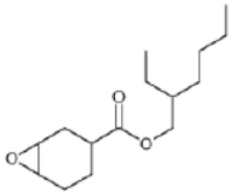
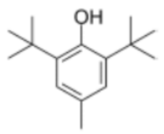
2.5.5.2 Chemicals

For the experiments, three different chemical mixtures were provided as possible contaminants of bleed air: the engine oils “Mobil Jet Oil II”, “Eastman Oil 2197” and “Skydrol PE-5 Hydraulic Fluid.” From the Safety Data Sheets (SDS), the chemical composition listed in Table 5 is known. Table 6 shows the chemical structures of the compounds in the fluids.

Table 5. Composition of the Chemical Mixtures used as Contaminants of Bleed Air

Name / Manufacturer	**Composition / Molecular Weight**	**Use/ Source of information**
Mobil Jet Oil II / ExxonMobil	1-3% Tricresylphosphate (TCP), (CAS 1330-78-5) / MW=368	SDS Mobil Jet Oil II (ExxonMobil, 2024)
Eastman 2197 / Eastman	▪ 1-<2% Tris (methylphenyl)phosphate (TCP), (CAS 1330-78-5) / MW=368 ▪ in Synthetic Lubricants	SDS Eastman Turbo Oil 2197 (Eastman, 2020)
Skydrol PE-5 / Eastman	▪ 58-68% Tributylphosphate (TBP), (CAS 126-73-8) / MW=266 ▪ 8-10% Triisobutyl phosphate, (CAS 126-71-6) / MW=266 ▪ 5-14% Phenol, isopropylated, phosphate (3:1) (CAS 68937-41-7) / MW=452 ▪ 1,3-1,9% Triphenylphosphine, (CAS 115-86-6) / MW=326 ▪ 5,5-6,5% 2-Ethylhexyl 7-oxabicyclo [4.1.0] heptane-3-carboxylate (CAS 62256-00-2) / MW = 254 ▪ 0.1-1% Butylated hydroxytoluene (CAS 128-37-0) / MW= 220	SDS Eastman Skydrol PE-5 (Eastman, 2023)

Table 6. Chemical structures of compounds in turbine oils and hydraulic fluid

 Tricresyl phosphate (TCP), CAS 1330-78-5 **Turbine Oil**	 N-Phenyl-1-Napththylamine CAS 90-30-2 **Turbine Oil**	 Polyolesters (base stock of the oil) **Turbine Oil**
 Tributyl phosphate (TBP) CAS 126-73-8 **Hydraulic Fluid**	 Triisobutyl phosphate CAS 126-71-6 **Hydraulic Fluid**	 Triphenylphosphate CAS 115-86-60 **Hydraulic Fluid**
 2-Ethylhexyl 7-oxabicyclo [4.1.0] heptane-3-carboxylate CAS 62256-00-2 **Hydraulic Fluid**	 Butylated hydroxytoluene CAS 128-37-0 **Hydraulic Fluid**	

2.5.5.3 Measurements & results (Part 1)

The following results were obtained by using the standard WinMuster Software, which is provided with the AT instrument. The graphics shown are screenshots from the Airsense WinMuster program and as such, may not display all graph axes correctly nor provide a time indication. The blue line is the integral of all peaks measured with the IMS.

Note: figures that reference samples collected at the coalescer are the same location as referenced to samples collected at the pack exit. Airsense AT screenshots are presented in Figures 97 through 111:

- Figure 97. Measurement of bleed air with the AT upstream of the VOC/ozone converter before injection of engine oil
- Figure 98. Measurement of bleed air upstream of VOC/ozone converter after injection of engine oil

- Figure 99. Negative spectra of IMS before and after injection of Mobil Jet Oil II upstream of VOC/ozone converter
- Figure 100. Negative spectra of IMS after injection of Mobil Jet Oil II downstream of VOC/ozone converter (4.0 Odor Units)
- Figure 101. Negative spectra of IMS after injection of Mobil Jet Oil II sampled at pack exit
- Figure 102. Measurement of bleed air with AT upstream of VOC/ozone converter before injection of engine oil at the number 3 engine
- Figure 103. Measurement of bleed air with AT at VOC/ozone converter inlet during injection of engine oil at number 3 engine, lower bleed air temperature
- Figure 104. Measurement of bleed air with AT at pack exit during injection of engine oil at the number 3 engine.
- Figure 105. Measurement of bleed air with AT upstream of VOC/ozone converter during injection of engine oil at number 3 engine
- Figure 106. Measurement of bleed air with AT upstream of VOC/ozone converter during injection of Eastman Oil 2197 at the number 3 engine. Hot bleed air condition
- Figure 107. Measurement of bleed air with AT upstream of VOC/ozone converter during injection of Eastman Oil 2197 at the number 3 engine
- Figure 108. Measurement of bleed air with the AT upstream of the VOC/ozone converter after injection of Mobil Jet Oil II at a higher concentration (10ppmm)
- Figure 109. Sensor signals upstream of VOC/ozone converter during cleaning with cooler bleed air and injection of isopropyl alcohol
- Figure 110. Sensor signals at VOC/ozone converter inlet during hydraulic fluid injection
- Figure 111. Positive (left) and Negative (right) IMS Spectra measured during Skydrol PE-5 hydraulic fluid injection upstream of VOC converter

Day 1 (APU), Monday, May 15, 2023

The APU was started at approximately 1400 hours to warm up and equilibrate the APU and aircraft systems. Figure 97 shows the response of the AT instrument at position #2 (bleed air upstream of VOC converter) before contaminant fluid injection. The nominal bleed air temperature was T=180° C. A very small engine oil peak was visible just before engine oil injection and the AT indicated an odor unit of around 1.4, which is close to the detection limit.

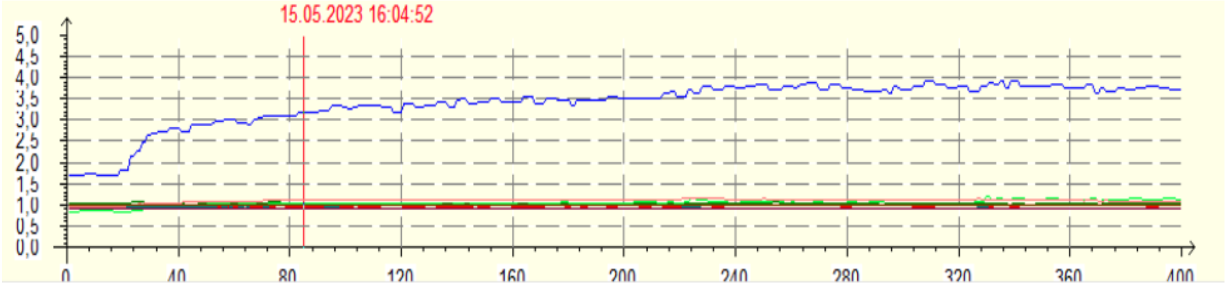


Figure 97. Measurement of bleed air with the AT upstream of the VOC/ozone converter before injection of engine oil

Engine Oil Indicated Several Seconds After Starting Measurement (1.4 Odor Units)

At 1614 hours, Mobil Jet Oil II was injected into the APU at a rate of 200mL/h in order to achieve an estimated concentration of 5 ppmm. The AT library identified it as engine oil and detected a signal increase after 2 minutes as shown in Figure 98. The instrument indicated odor units of 2.6 after 10 minutes and 2.7 units after an hour.

Besides the IMS, also one MOS sensor (channel F) and the PID (channel H) showed a small response.

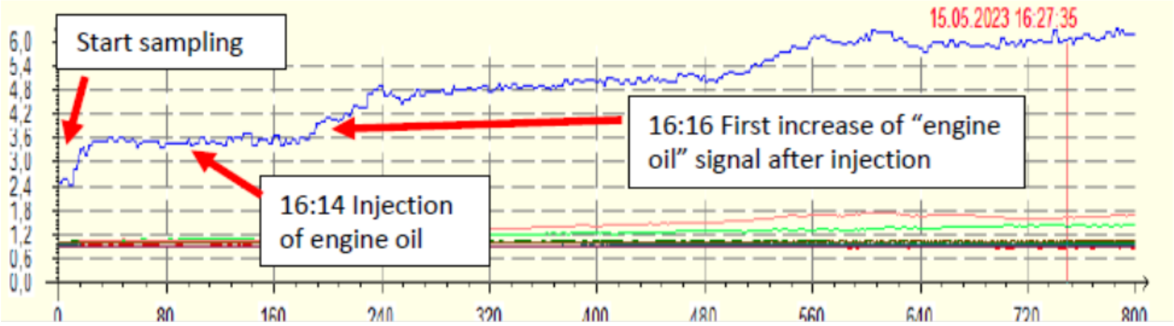
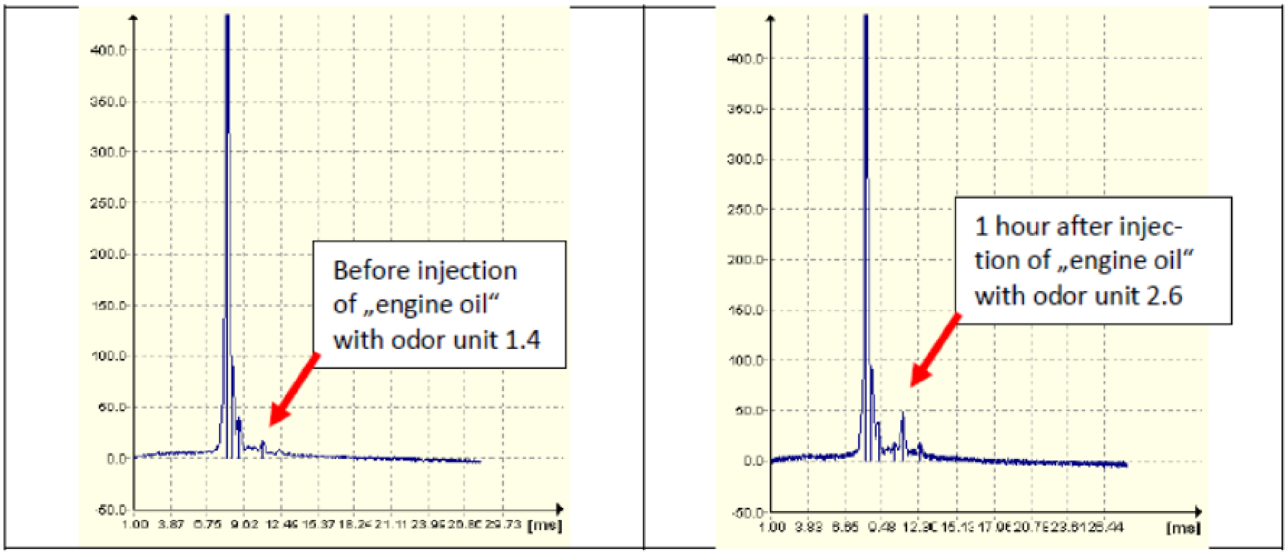


Figure 98. Measurement of bleed air upstream of VOC/ozone converter after injection of engine oil

Increase of "Engine Oil" signal detected several seconds after injection (odor units increased continuously)

The spectra of the ion mobility spectrometer (negative ions) before and after injection of engine oil is shown in Figure 99. Measurements after the VOC/ozone converter (position #3) showed significant changes in the positive ion and the negative ion spectra.

The AT indicated "Engine Oil", but it can be seen from the spectra that additional peaks appeared. Figure 100 shows the negative ion spectrum measured after the ozone filter. The AT displayed an odor unit of 4.0. Possible reasons are a catalytic conversion of the compounds in the oil by the VOC/ozone converter.



Before injection of „engine oil" with odor unit 1.4

1 hour after injection of „engine oil" with odor unit 2.6

Figure 99. Negative spectra of IMS before and after injection of Mobil Jet Oil II upstream of VOC/ozone converter

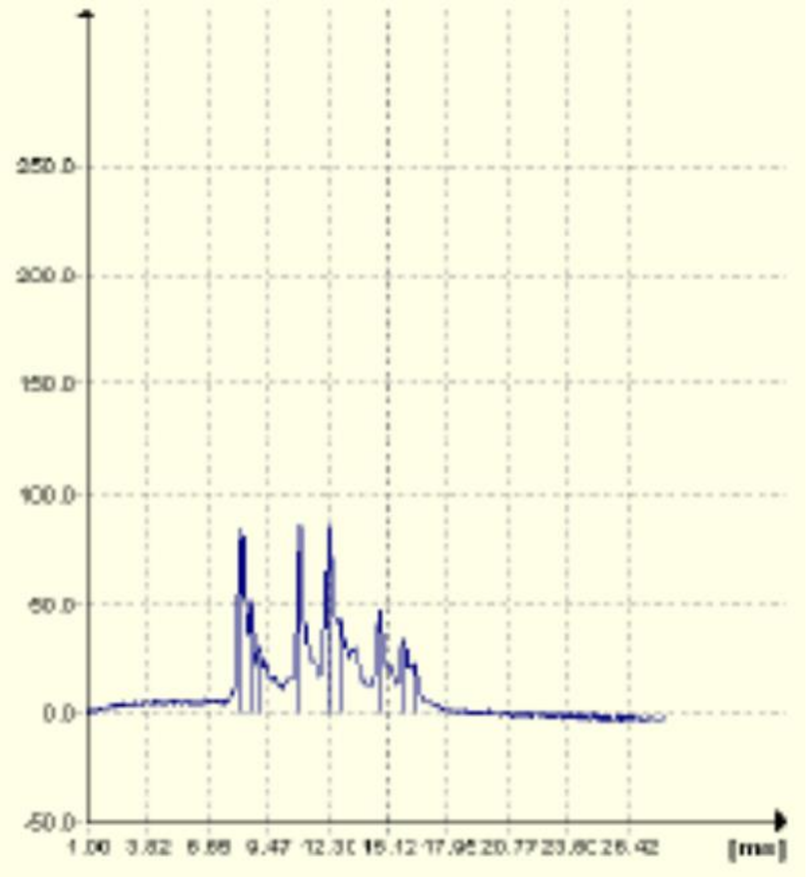


Figure 100. Negative spectra of IMS after injection of Mobil Jet Oil II downstream of VOC/ozone converter (4.0 Odor Units)
Unidentified peaks present in addition to "Engine Oil" peak in the spectrum

Measurements at the pack exit showed very similar spectra as shown in Figure 101. The AT indicated an odor unit of 4.1.

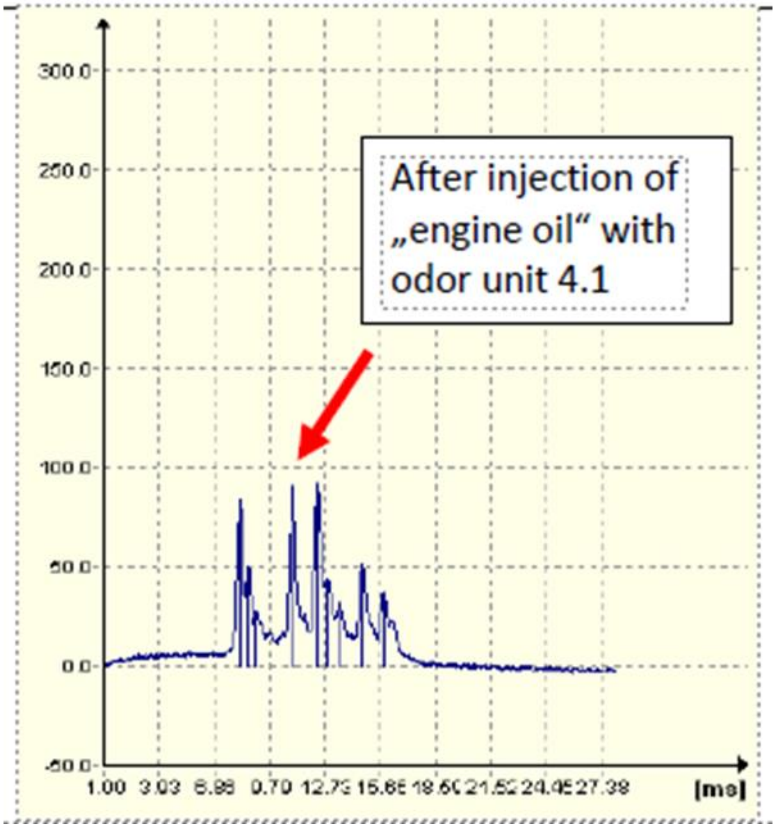


Figure 101. Negative spectra of IMS after injection of Mobil Jet Oil II sampled at pack exit
Unidentified peaks in the spectrum same as those downstream of the VOC/ozone converter

Due to the additional peaks in the spectrum, it can be assumed that the indicated concentration of "Engine Oil", which is based on the peak height of only one peak, is probably lower than the real concentration.

Day 2 (number 3 engine), Tuesday, May 16, 2023

The APU was started at 0950 hours. The #3 engine was started at 1009 hours and after a run-up to a nominal bleed temperature of T = 275° C and a stabilization time of about 30 minutes, the engine was operated to provide a nominal bleed air temperature of T = 231° C.

Figure 102 shows the response of the AT instrument at position #2 after about one hour of operation. A small engine oil peak was visible, and the AT indicated an odor unit of around 2.0, which was decreasing slowly with time. The indicated concentration of engine oil was decreasing until no "Engine Oil" signal was detected, just before the injection of Mobil Jet Oil II. Contaminants of the bleed gas were thermally desorbed and cleaned due to the long operation with the #3 engine.

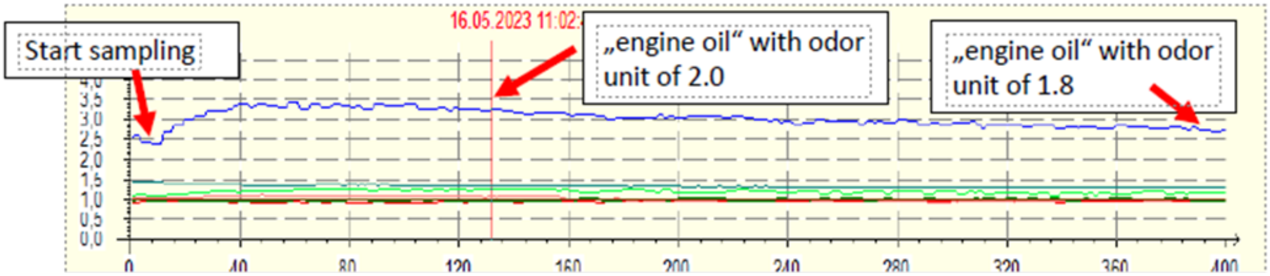


Figure 102. Measurement of bleed air with AT upstream of VOC/ozone converter before injection of engine oil at the number 3 engine
Contamination due to engine oil decreased with time

Figure 103 shows the sensor signals after injection of Mobil Jet Oil II into the #3 engine. At 1205 hours Mobil Jet Oil II was injected at a rate of 35ml/h to achieve an estimated concentration of 5 ppmm. Engine oil was detected after 30 minutes (see extended timeline in Figure 103), which is much longer compared to the measurements at the APU the day before. The engine oil concentration stabilized after an hour and reached an odor unit of 1.8. At 1315 hours the chemical sample collection started for about 60 minutes.

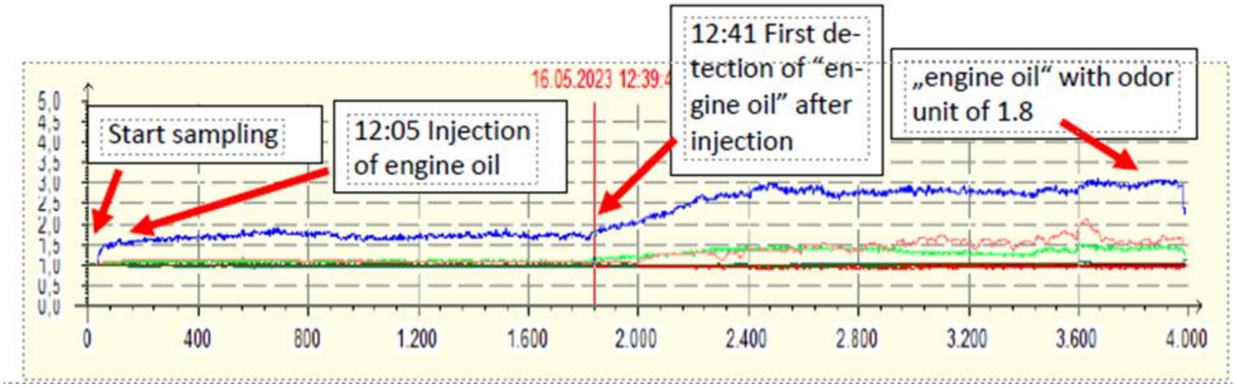


Figure 103. Measurement of bleed air with AT at VOC/ozone converter inlet during injection of engine oil at number 3 engine, lower bleed air temperature
Contamination with engine oil measured 30 minutes after injection

The bleed air sampled after the VOC/ozone converter was measured during the chemical sample collection and the AT indicated an odor unit of 4.7. Sampling point #4 (pack exit) was measured afterwards from 1344 hours until 1426 hours and the instrument displayed an odor unit of 5.7, but the concentration increased continuously. The concentration was high, and the IMS was working at its saturation limit. Figure 104 shows the pack exit measurement with the response of the instrument after increasing the power of the engine for the pack “burn out” from T = 231° C to T = 330° C (at 1418 hours). The additional heat released more compounds and led to a saturation of the IMS; therefore, no reliable quantitative results can be obtained. After a pack burn out and a stabilization time at T = 315° C, the next injection started with the higher nominal bleed air temperature.

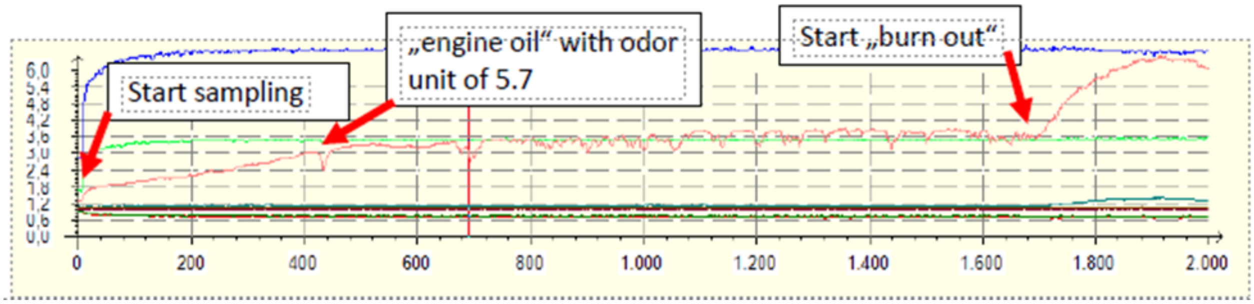


Figure 104. Measurement of bleed air with AT at pack exit during injection of engine oil at the number 3 engine

Contamination with engine oil increased slightly with time; at 1418 hours engine power increase led to even higher concentrations of engine oil in bleed air.

The second injection of Mobil Jet Oil II started at 1635 hours with the goal to achieve the same concentration of 5ppmm. Before injection, “engine oil” was detected with an odor unit of 1.4. Figure 105 shows the sensor signals after injection of Mobil Jet Oil II into the #3 engine at the higher operating temperature. An increased engine oil concentration was detected after 20 minutes, which was about 10 minutes faster than before, when operating the engine at colder temperatures.

The concentration of engine oil upstream of the VOC/ozone converter led to an odor unit of 3.5, which was higher than before when operating at lower temperatures. After a stabilization time, a chemical sample collection time of 90 minutes began.

The bleed air sampled after the VOC converter was measured during the chemical sample collection period, and the AT measured an odor unit of 4.4. The sampling point #4 (after the pack exit) was measured some minutes afterwards and the instrument displayed an odor unit of 4.2. As reported before, the concentration was very high for the instrument and the IMS was working at its saturation limit. After the chemical sample collection time the power was reduced at 1841 hours due to increasing vibrations of the engine. The nominal bleed air temperature was reduced to T = 279° C, sample collection and injection of the engine oil was stopped at 1856 hours.

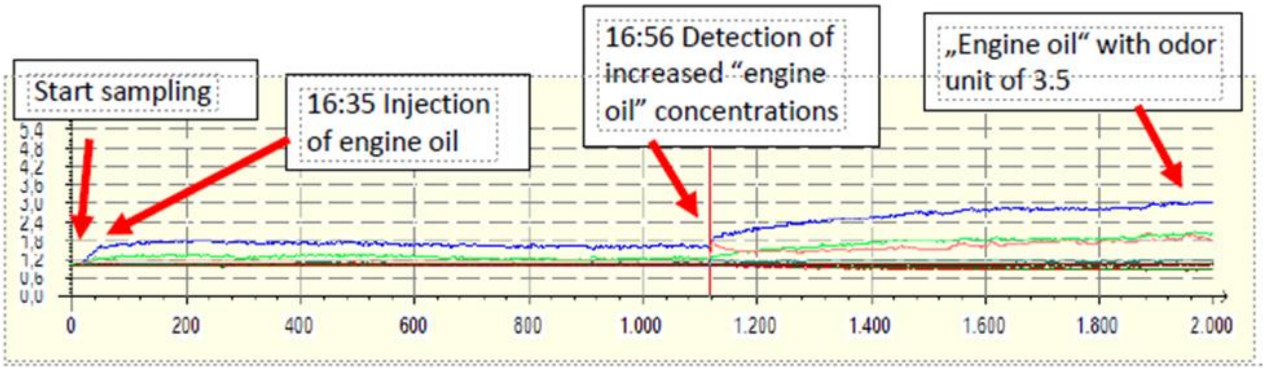


Figure 105. Measurement of bleed air with AT upstream of VOC/ozone converter during injection of engine oil at number 3 engine

Hot bleed air condition; Increase of engine oil signals detected at 1656 hours

Day 3 (number 3 engine), Wednesday, May 17, 2023

The APU started at 0917 hours. The #3 engine was started at 0932 hours and after several minutes, operated at a nominal bleed air temperature of T = 312 °C. After a stabilization time of about 30 minutes and an additional base-line period of 60 minutes, the injection of a different engine oil was started. Eastman Oil 2197 was now injected. The IMS spectra are identical.

The baseline period was not enough to reduce the background of the engine oil signals to zero in contrast to the day before. Therefore the "Engine Oil" signal indicated on the instrument display with an odor unit around 1.7 before injection.

The injection started at 1128 hours. The injection rate was 35 ml/h to achieve a calculated concentration of 5 ppmm. Chemical sampling for a duration of 60 minutes started at 1220 hours. "Engine Oil" indicated on the display and after 15 minutes with an odor unit around 3.7. The quantitative data were very similar to the data measured with Mobil Jet Oil II. The injection was stopped at 1326 hours.

Sensor data after injection of Eastman Oil 2197 into the #3 engine at the higher operating temperature are shown in Figure 106. The instrument identified the presence of engine oil contamination.

An odor unit of 4.5 was displayed when sampling downstream of the VOC converter. An odor unit of 4.0 was measured at the pack exit. In similar fashion to previous tests, the concentration was very high for the instrument and the IMS was working at its saturation limit.

After a burn out (clean-up procedure), the nominal temperature of the bleed air was reduced to T = 220 °C. The next injection of Eastman Oil 2197 at lower temperatures started at 1532 hours, just after a stabilization time. The nominal bleed air temperature was maintained at T = 221 °C and after stabilization a chemical sample collection period was started at 1640 hours.

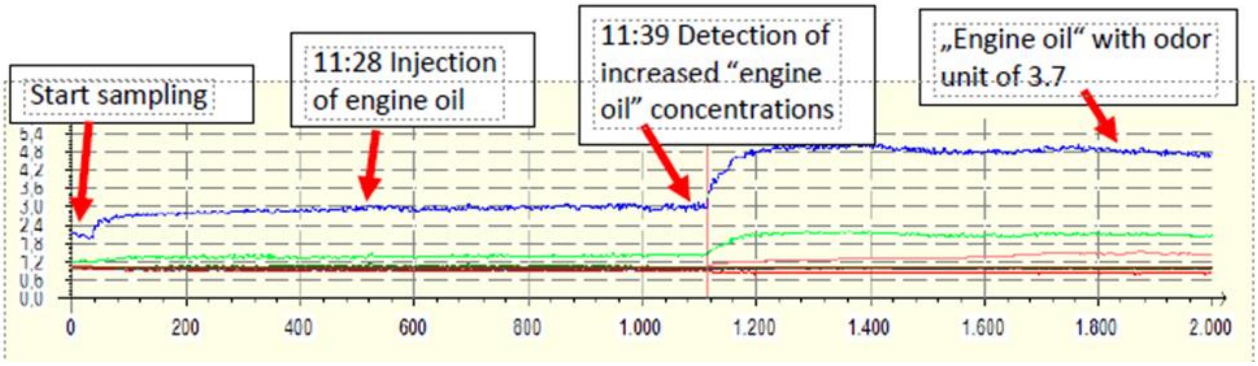


Figure 106. Measurement of bleed air with AT upstream of VOC/ozone converter during injection of Eastman Oil 2197 at the number 3 engine. Hot bleed air condition

Increase of engine oil signal detected at 1139 hours

Sensor signals after injection of Eastman Oil 2197 into the #3 engine at the lower operating temperature are shown in Figure 107. The instrument signaled the presence of "Engine Oil" prior to injection, yet a small increase in sensor signals about 35 minutes after injection also occurred. A similar delay between indicated phenomena was measured the day before. The AT displayed very low concentrations with an odor unit of 1.4 before injection and around 1.8 after injection. The AT displayed an odor unit of 7.6 when sampling after the VOC/ozone converter. An odor unit of 7.2 was measured when sampling after the pack exit.

Injection of the engine oil was stopped at 1740 hours. A pack burn out at T = 316 °C started just several minutes before an unplanned shut down of the #3 engine due to hydraulic pump mechanical failure.

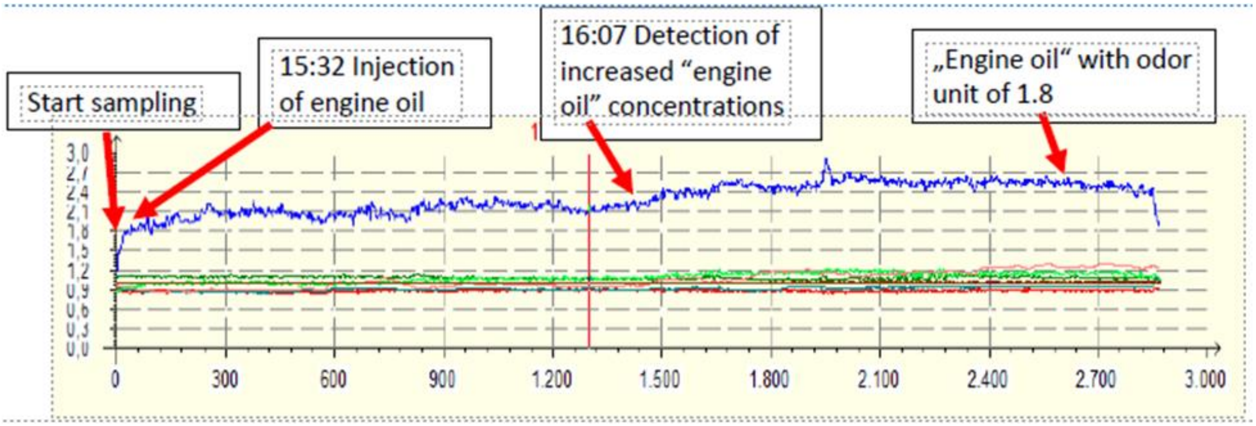


Figure 107. Measurement of bleed air with AT upstream of VOC/ozone converter during injection of Eastman Oil 2197 at the number 3 engine

Low bleed air temperature condition

Very small increase of engine oil signals detected at 1607 hours

Day 4 (APU), Thursday, May 18, 2023

For the final test day, only injections into the APU were planned. The APU was started at 0855 hours to warm up and to equilibrate the system. After an equilibrium time of ~ 60 minutes, the injection of Mobil Jet Oil II started at 1120 hours. The injection rate was increased to 400 mL/h in order to achieve a higher concentration of 10 ppmm. The chemical sampling period of 60 minutes started at 1200 hours.

The AT identified "Engine Oil" and detected an increase just after injection as shown in Figure 108. The instrument indicated odor units of around 4.0 after 10 minutes and around 3.2 after an hour. Besides the IMS, also one MOS sensor (channel F, red line) showed an intensive response.

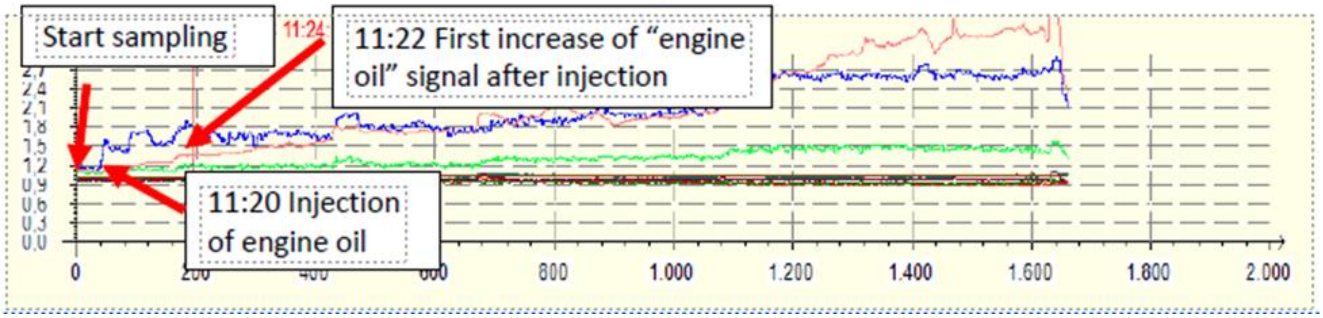


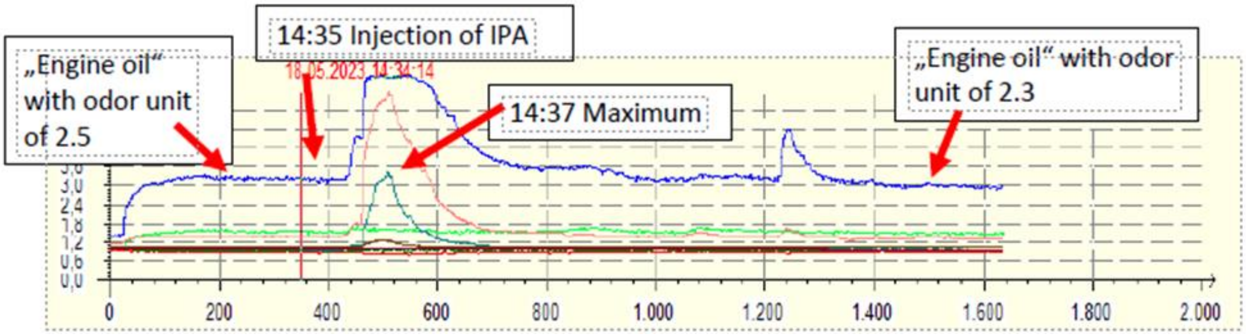
Figure 108. Measurement of bleed air with the AT upstream of the VOC/ozone converter after injection of Mobil Jet Oil II at a higher concentration (10ppmm)

Increase of the engine oil signal was detected some seconds after injection with odor units increasing continuously

An odor unit of 9.8 was displayed when sampling downstream of the VOC converter at 1220 hours. Twelve minutes later at 1232 hours, an odor unit of 10.3 was measured when sampling after the pack exit. As reported before, the concentration was very high for the instrument and the IMS was working at its saturation limit.

The ambient air was also monitored (position #1) and at 1315 hours, the instrument displayed the “Engine Oil” signal with an odor unit of 2.2. Additionally, the air in the cabin was also measured, showing a bigger peak in the positive spectrum. The reason is butanol, which is released from the condensation aerosol counters.

A pack burn-out using the #3 engine was not possible for the remaining test runs due to the engine hydraulic pump mechanical failure the day prior. System cleaning was possible only by operating the APU for an extended period and therefore the cleaning time was extended. At 1435 hours, a solvent (IPA = isopropyl alcohol) was injected with the intention to speed up the cleaning process. The two MOS sensors and the PID reacted due to the solvent with a delay of about 2.5 minutes after injection. But as can be seen in Figure 109, the intended clean up procedure did not help because the odor units did not change dramatically before and after IPA injection.


„Engine oil“ with odor unit of 2.5

14:35 Injection of IPA

18.05.2023 14:34:14

14:37 Maximum

„Engine oil“ with odor unit of 2.3

Figure 109. Sensor signals upstream of VOC/ozone converter during cleaning with cooler bleed air and injection of isopropyl alcohol

At 1601 hours the Skydrol PE-5 hydraulic fluid was injected at a rate of 200 mL/h with the intention to achieve a concentration of 5 ppmm in the bleed air (Figure 110). The bleed air was still contaminated with engine oil. The first identification of Skydrol PE-5 was not seen over the oil signature until 8 minutes after start of injection, as the response is slower compared to the injections of engine oil.

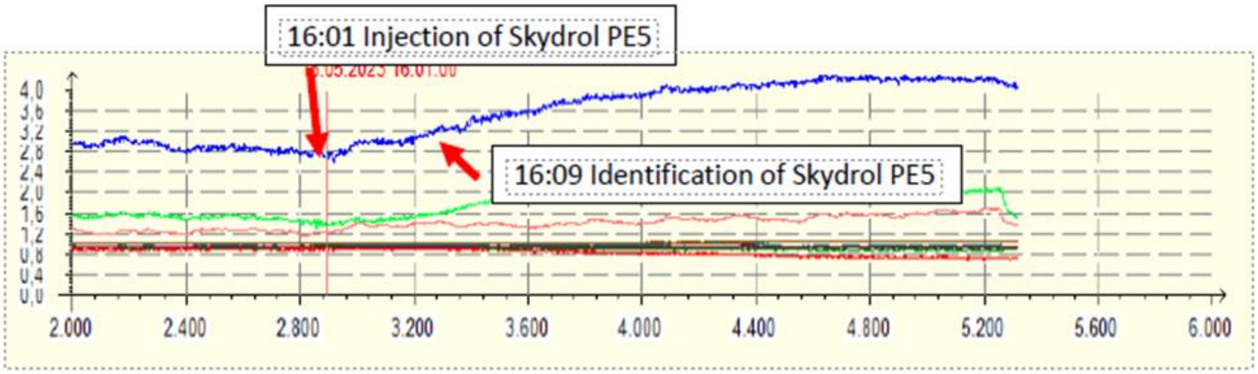


Figure 110. Sensor signals at VOC/ozone converter inlet during hydraulic fluid injection

Figure 111 shows the positive and negative spectra of the IMS at the beginning of the identification at 1601 hours and about 40 minutes later. Skydrol PE-5 appears mainly in the positive spectrum of the IMS. Quantitative information was not available on-site due to a missing entry in the AT instrument library for Skydrol PE-5 hydraulic fluid.

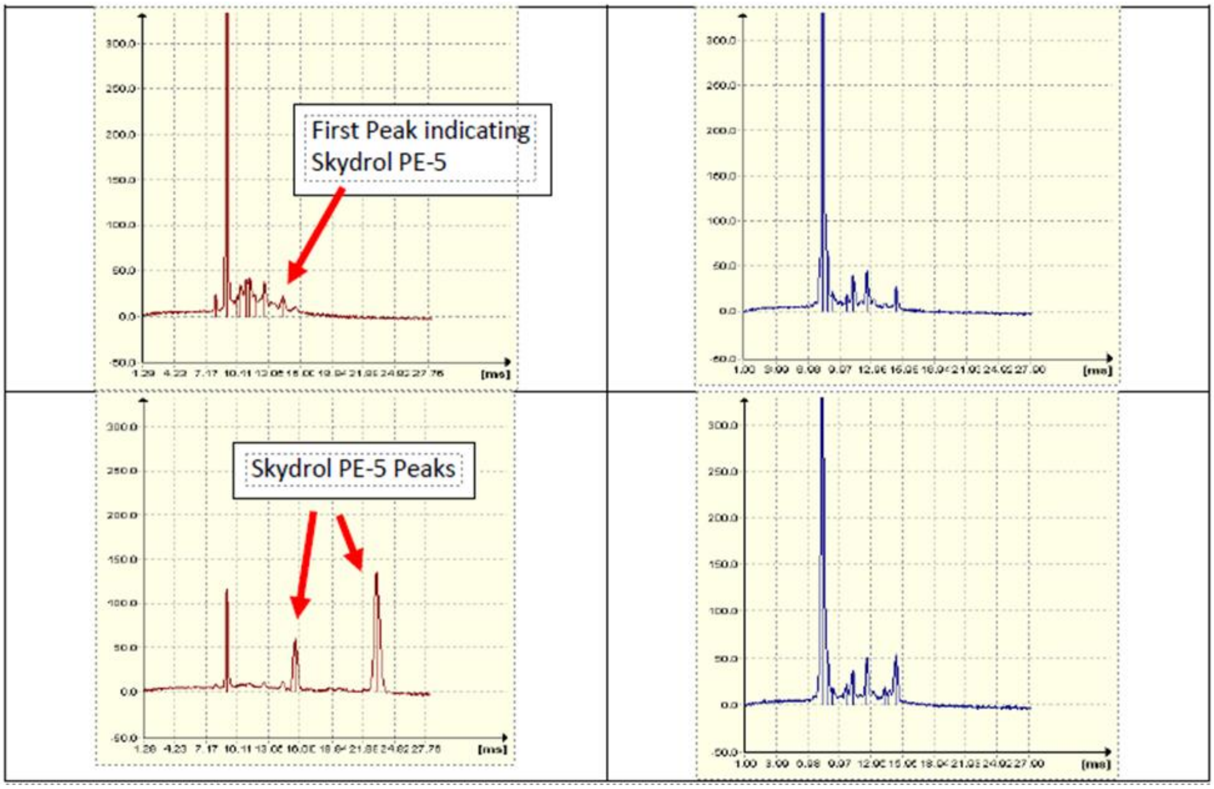


Figure 111. Positive (left) and Negative (right) IMS Spectra measured during Skydrol PE-5 hydraulic fluid injection upstream of VOC converter

Upper spectra - first peaks appeared at beginning of lower concentration

Lower spectra show IMS peaks after 40 minutes of injection

The Skydrol PE-5 spectra of the positive ions upstream and downstream of the VOC converter are very similar. The major differences observed upstream and downstream of the VOC converter with engine oil were not seen with the hydraulic oil. The peak heights of the Skydrol PE-5 measured when monitoring the air after the pack exit were very similar to the peak heights after the ozone filter. The chemical sample collection started at 1701 hours for a duration of 60 minutes. At 1801 hours the injection was stopped and the APU turned off.

Day 5 (Contingency Day), Friday, May 19, 2023

Day 5 was used to dismantle the instrumentation and related tools. No further data was recorded.

2.5.5.4 Additional data interpretation (Part 2)

The following results are based on special software tools, which offer the possibility to export all data in Excel format. As mentioned above, the concentrations were very high for the AT, sometimes working at its saturation limit.

Especially at higher concentrations, quantitative or semi-quantitative data can be improved when monitoring not only the height of a single peak but the sum of all relevant peaks. Therefore, the main peaks height data were exported to Excel for processing. The following figures display the sum of all relevant compound specific peaks as a function of time:

- Figure 112. Measurement of bleed air from APU with AT upstream and downstream of VOC/ozone converter and at pack exit during injection of Mobil Jet Oil II, 5 ppmm
- Figure 113.Measurement of Bleed Air from the Number 3 Engine Upstream and Downstream of VOC/ozone Converter and at Pack Exit During Injection of Mobil Jet Oil II, 5 ppmm with Bleed Air Temperature of T = 231° C.
- Figure 114. Measurement of bleed air from the number 3 engine upstream and downstream of VOC/ozone converter at pack exit during injection of Mobil Jet Oil II
- Figure 115. Measurement of bleed air from the number 3 engine upstream and downstream of VOC/ozone converter and at pack exit during injection of Eastman Oil 2197
- Figure 116. Measurement of bleed air from number 3 engine upstream and downstream of VOC/ozone converter and at pack exit during injection of Eastman Oil 2197, 5 ppmm with bleed air temperature of T = 230 °C
- Figure 117. Measurement of bleed air from APU with AT upstream and downstream of VOC/ozone converter and at pack exit during injection of Mobil Jet Oil II (10ppmm)

- Figure 118. Measurement of bleed air from APU with AT upstream and downstream of VOC/ozone converter and at pack exit during injection of Skydrol PE-5 hydraulic fluid, 5 ppmm

The graphics of Part 1 of the AT results do display the sum of all ions and not just the sum of all compound-specific peaks.

Day 1 (APU), Monday, May 15, 2023

Figure 112 shows the compilation of all measurements of the contaminated bleed air (Mobil Jet Oil II, 5 ppmm) from the APU. To better illustrate, only the data during active sampling (no cleaning periods of the instrument) and after some minutes of monitoring (first period of the response time of the instrument is not shown) are displayed at the various different sampling positions. Instead of one peak (which is usually used for the calculation of the odor units), the sum of the intensity of five peaks was used for displaying the concentration of engine oil. For the hydraulic fluid, only the sum of two peaks (monomer and 2x dimer) is used. This procedure will be used for Figures 112 to 118 on the following pages.

Day 2 (Engine 3), Tuesday, May 16, 2023

Figure 113 shows the compilation of measurements of the bleed air from the #3 propulsion engine being contaminated with Mobil Jet Oil II (5 ppmm). The nominal bleed “cold” air temperature was T = 231 °C

Figure 114 shows a compilation of measurements of the bleed air from the same engine with identical contamination but with a nominal bleed air temperature of T = 320 °C.

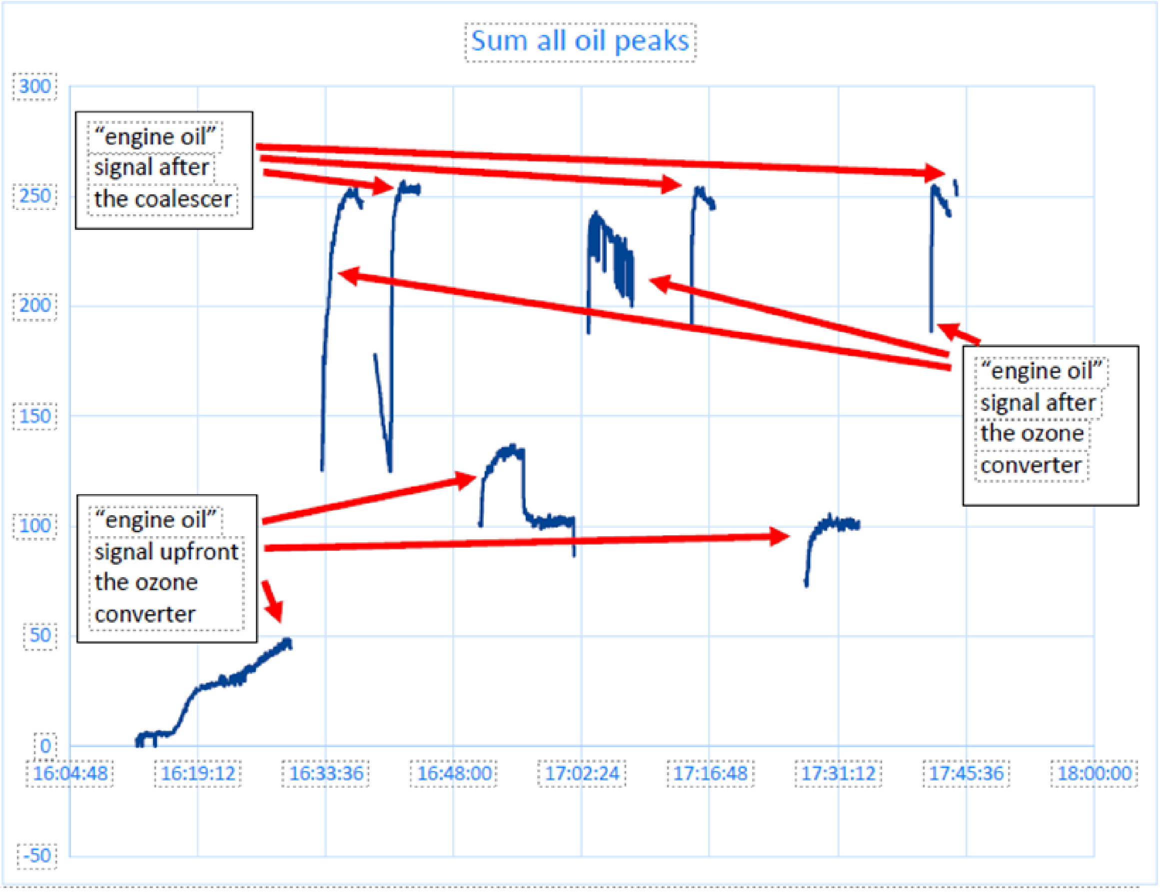


Figure 112. Measurement of bleed air from APU with AT upstream and downstream of VOC/ozone converter and at pack exit during injection of Mobil Jet Oil II, 5 ppmm

Day 3 (engine 3), Wednesday, May 17, 2023

Figure 115 shows the compilation of measurements of the bleed air from the #3 propulsion engine being contaminated with Eastman Oil 2197 (5 ppmm). The nominal bleed air temperature was T = 330 °C. Figure 116 shows the measurements with identical contamination but with a "cold" nominal bleed air temperature of T = 230 °C.

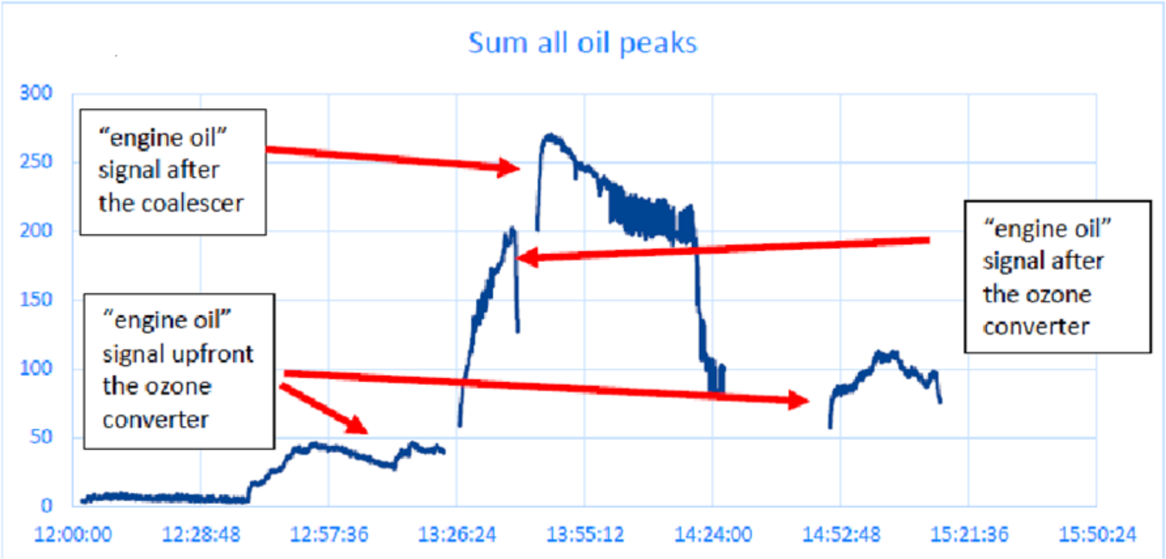


Figure 113. Measurement of bleed air from the number 3 engine upstream and downstream of VOC/ozone converter and at pack exit during injection of Mobil Jet Oil II
5 ppmm with bleed air temperature of T = 231° C

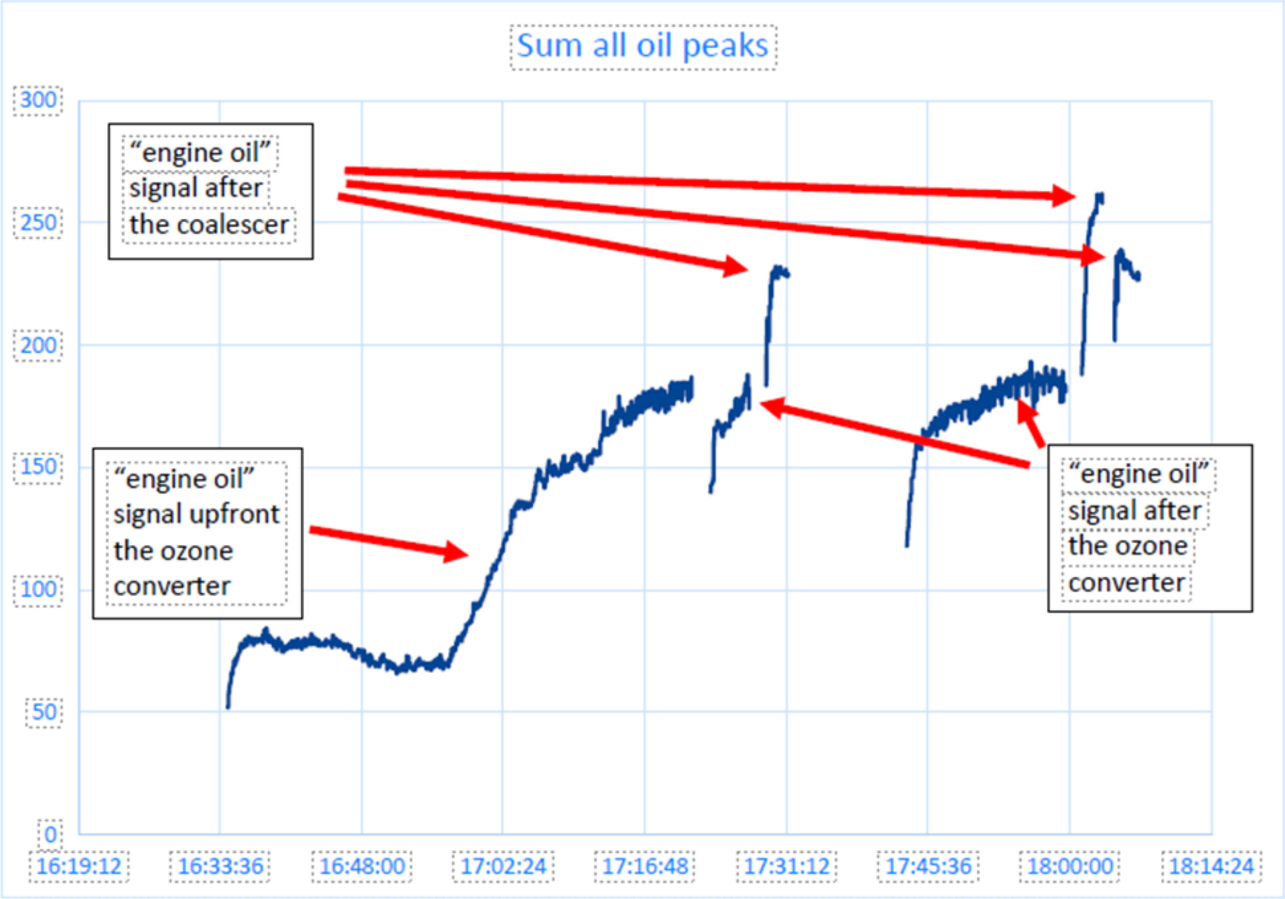


Figure 114. Measurement of bleed air from the number 3 engine upstream and downstream of VOC/ozone converter at pack exit during injection of Mobil Jet Oil II
5 ppmm with bleed air temperature of T = 320 °C

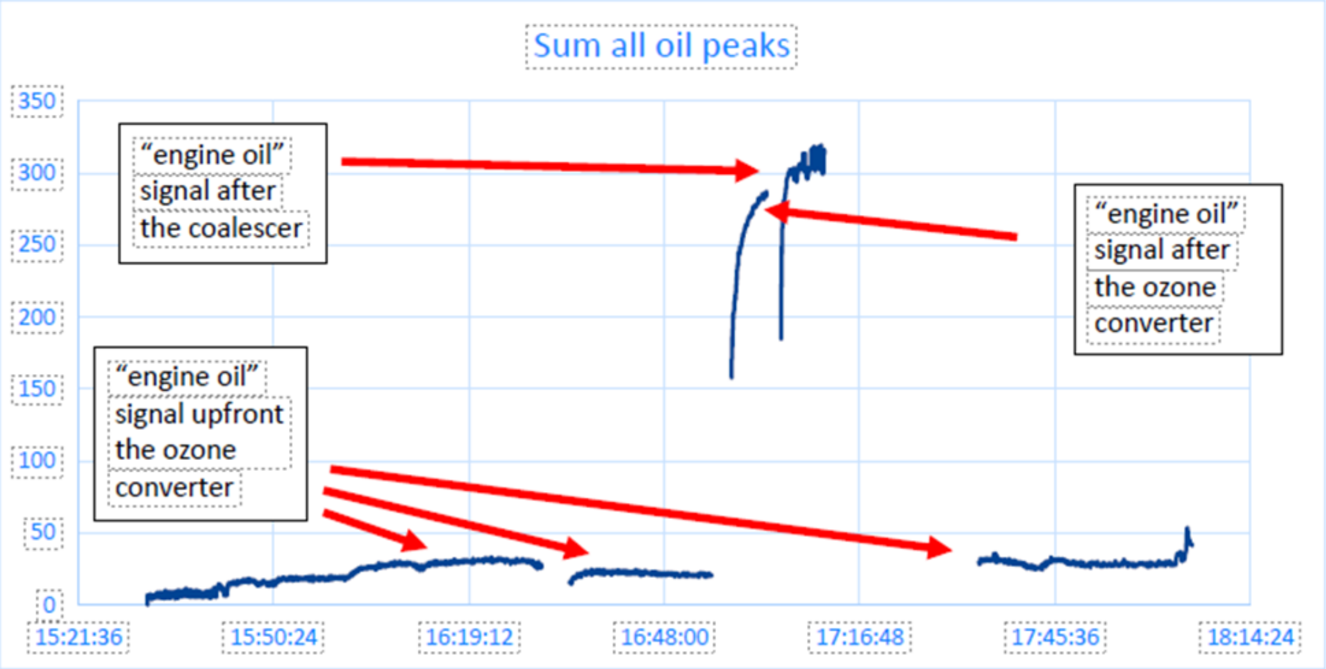


Figure 115. Measurement of bleed air from the number 3 engine upstream and downstream of VOC/ozone converter and at pack exit during injection of Eastman Oil 2197
5 ppmm with Bleed Air Temperature of T = 33 ℃

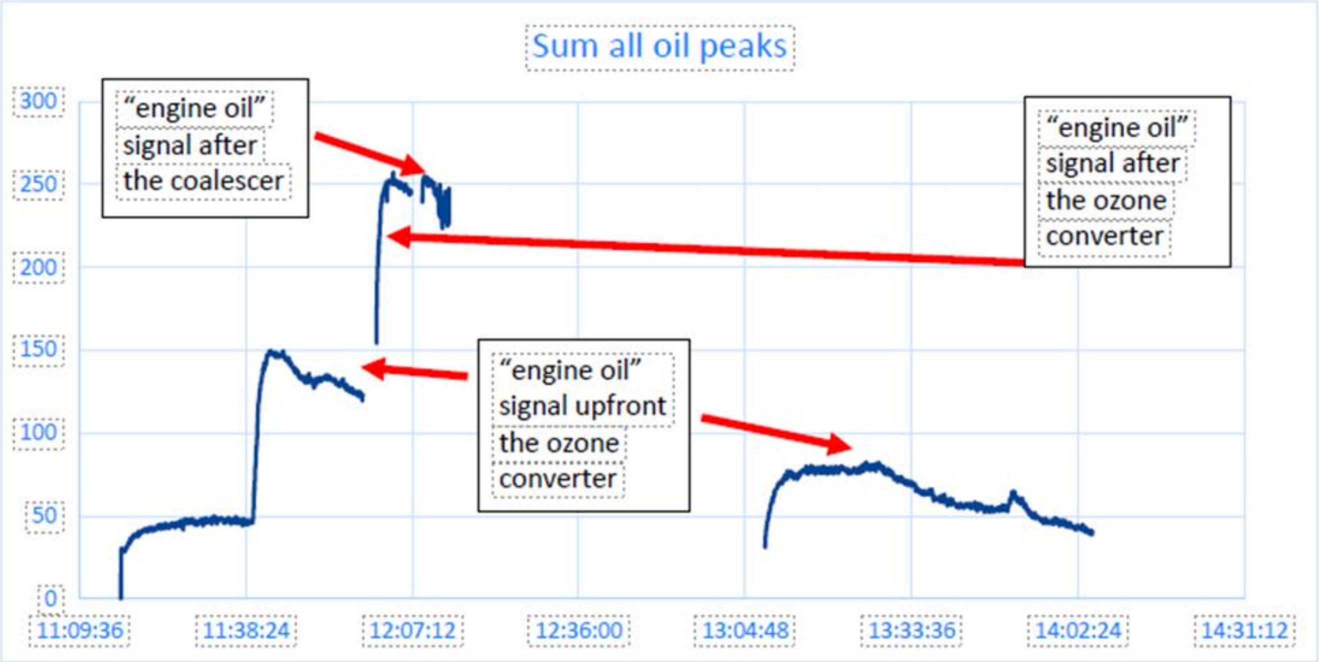


Figure 116. Measurement of bleed air from number 3 engine upstream and downstream of VOC/ozone converter and at pack exit during injection of Eastman Oil 2197
5 ppmm with bleed air temperature of T = 230 °C

Day 4 (APU), Thursday, May 18, 2023

Figure 117 shows the compilation of all measurements of the bleed air from the APU being contaminated with Mobil Jet Oil II with a higher concentration (10 ppmm).

Figure 118 shows the compilation of all measurements of the bleed air from the APU being contaminated with Skydrol PE-5 hydraulic fluid (5 ppmm).

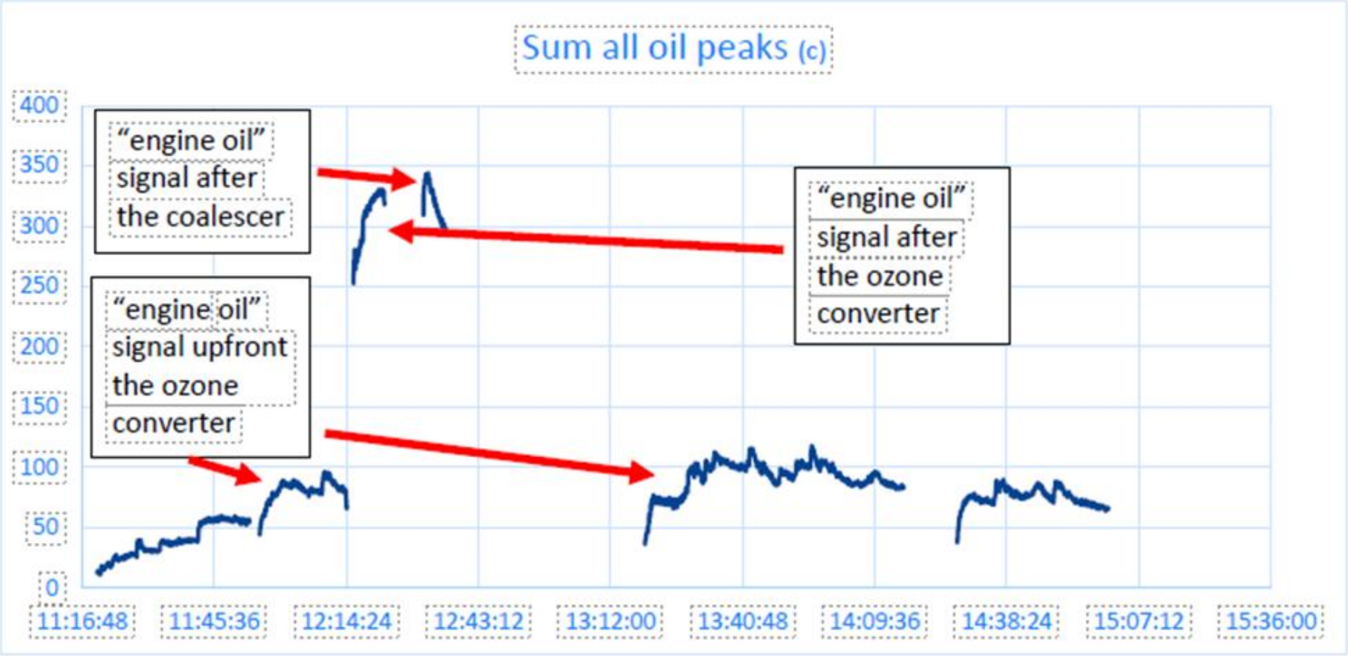


Figure 117. Measurement of bleed air from APU with AT upstream and downstream of VOC/ozone converter and at pack exit during injection of Mobil Jet Oil II (10ppmm)

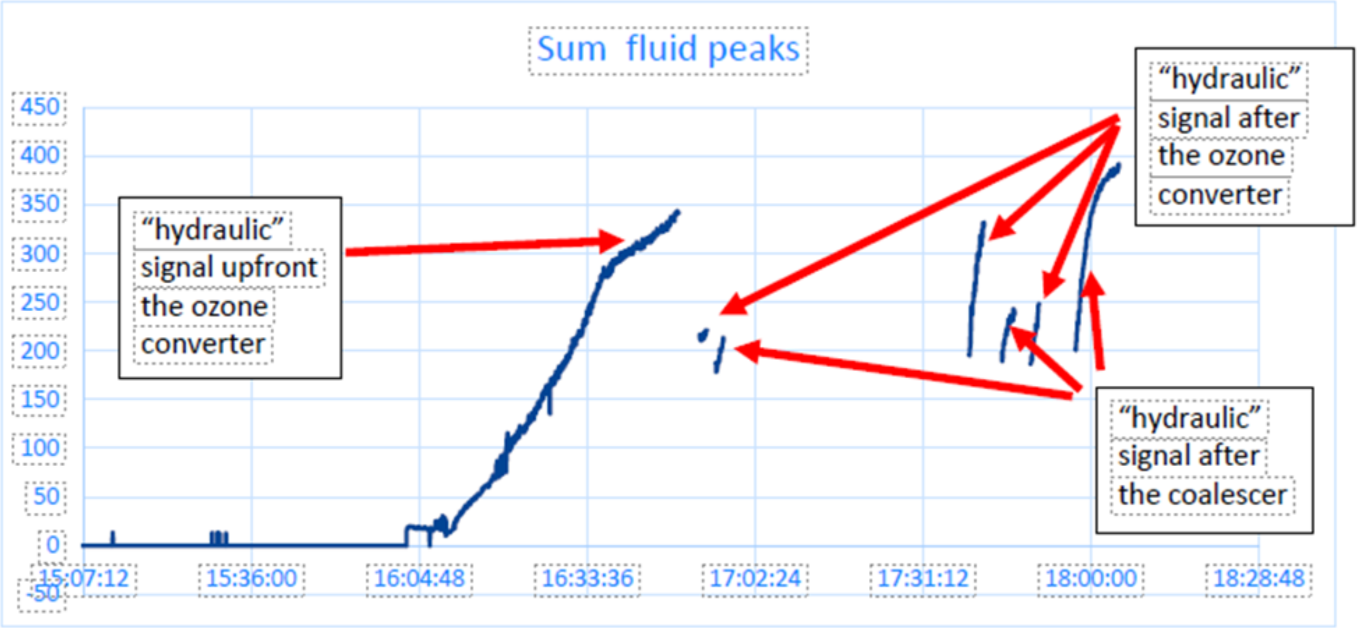


Figure 118. Measurement of bleed air from APU with AT upstream and downstream of VOC/ozone converter and at pack exit during injection of Skydrol PE-5 hydraulic fluid, 5 ppmm

Summary of AT instrument results:

The measurements of contaminated bleed air showed that relative high concentrations were obtained onsite. The AT was operating close to the saturation level. Additional peaks appearing on the spectra of the IMS during the engine oil measurements after the VOC/ozone converter showed that chemical reactions are occurring, probably mainly on the catalytic surface of the VOC/ozone converter. Therefore, the AT instrument library had to be adapted. This phenomenon was not observed when the bleed air was contaminated with the Skydrol PE-5 hydraulic fluid. Nevertheless, the AT was able to detect and to identify the contamination on-site.

The measurements also showed that the concentrations of the engine oils or hydraulic fluids depend on many factors such as the residual contamination of the ducting from the past, the temperature of the ducting, the flow rate of the bleed air, and the position where the bleed air is monitored. Doubling the nominal concentration of contamination with engine oil does not lead to a much higher intensity of the peak heights (Figure 112 compared with Figure 117). There are no major differences between the contamination behavior of the engine oils Mobil Jet Oil II and Eastman Oil 2197 (Figure 113 compared to Figure 116). Higher bleed air temperatures increase the concentration of contaminants in front of the VOC/ozone converter (it is less relevant after the VOC/ozone converter).

2.5.6 SIFT-MS results

The Syft company provided on-site testing at no cost to Kansas State University. The selected-ion flow-tube mass spectrometer (SIFT-MS) is most capable of providing quantitative results when the compounds of interest are known. Syft was requested to review its test results and provide quantitation for Formaldehyde, Acetaldehyde, and Pentanoic Acid from the ground-based, on-wing aircraft tests. Table 7 contains a summary of the data from the SIFT-MS instrument. This is a background-subtracted dataset, utilizing the sample collection data with a subtraction of the data collected during baseline.

Table 7. Carbonyl and Carboxylic Acid results from SIFT-MS

		ppbv	**ppbv**	
	Mobil-II	**Formaldehyde**	**Acetaldehyde**	**Pentanoic Acid**
Pre VOC/ozone converter	24297	6	126	4
post VOC/ozone converter	24298	6	310	3
pack exit	24299	26	167	1
ambient	24300	22	113	2
	Skydrol			
Pre VOC/ozone converter	24421	322	45	93
post VOC/ozone converter	24424	0	66	33
pack exit	24423	0	45	51
ambient	24422	251	37	61

Syft chose to analyze data obtained during the Skydrol PE-5 hydraulic fluid test run as the concentration of that infusion was the highest by far of the experimental test sets and provided the best signal intensity. Skydrol PE-5 carbonyls from a baseline sample and during injection of 5 ppmm Skydrol PE-5 are presented in Figure 119. Carbonyls from Mobil Jet Oil II injection are presented in Figure 120.

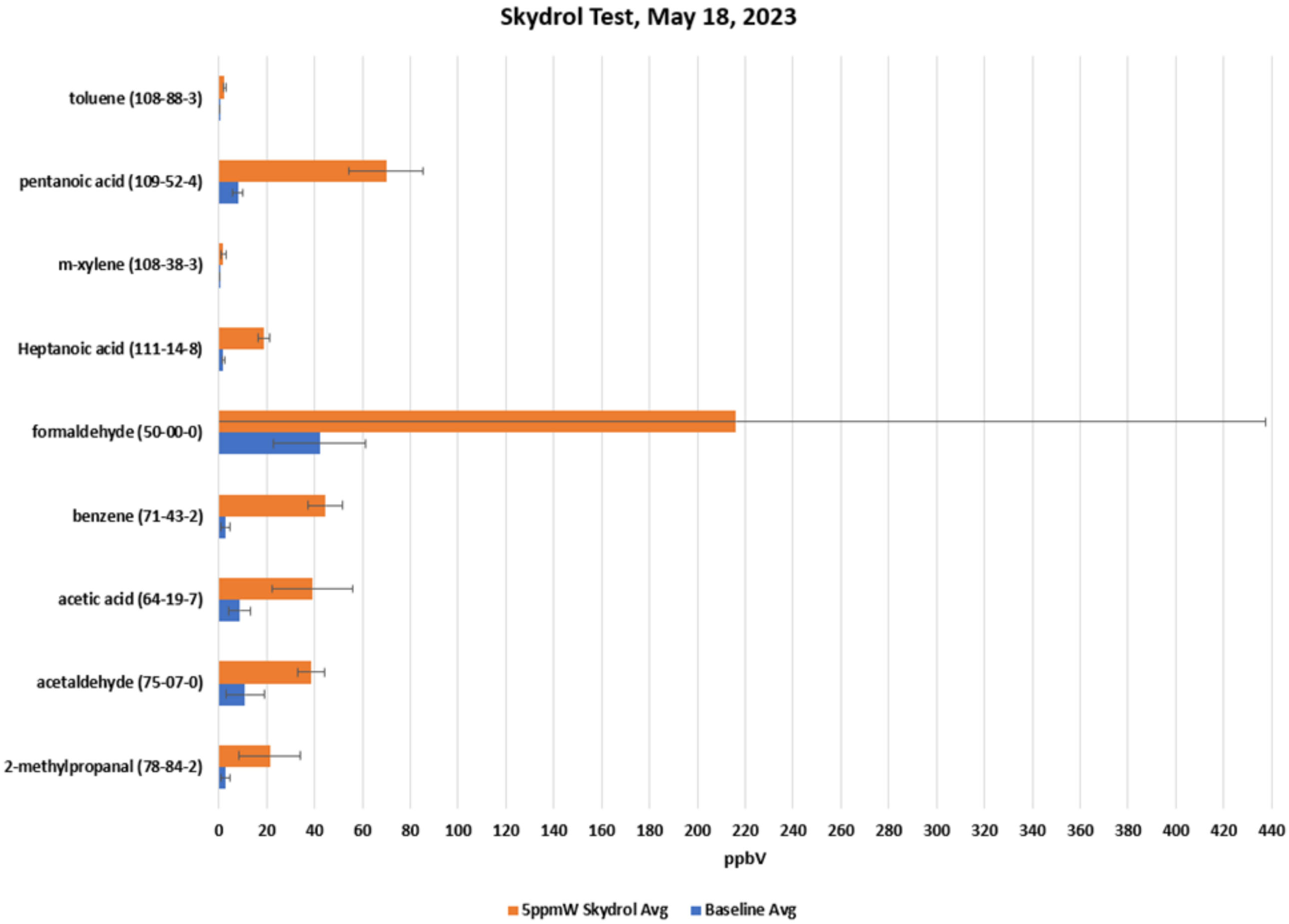


Figure 119. Skydrol PE-5 hydraulic fluid carbonyls by SIFT-MS

According to Syft interpretation, the majority of identified compounds are carbonyls:

- Acids or esters: CnH2nO2 (n = 2 to 12)
- Ketones (and at lower MW some aldehydes): CnH2nO (ketones: n = 3 to 11; aldehydes: n = 1 to 7)
- Unsaturated ketones/aldehydes: CnH2n-2O (n = 3 to 10)

Because:

- NO+: almost all features in the mass spectrum can be matched with a proton transfer peak in H3O+ at 29 mass units lower (i.e., dominated by association) hence indicating carbonyls above (and simpler than H3O+ - reduced water secondary chemistry).
- H3O+: assignment in parallel with NO+; additional features

- O2+: almost all larger carbonyls are fractured (especially greater than C6), so most features are m/z < 100 and can be assigned to a single compound (many common fragments).
- The +14 patterns, especially visible in H3O+, correspond to homologous series adding CH2 groups

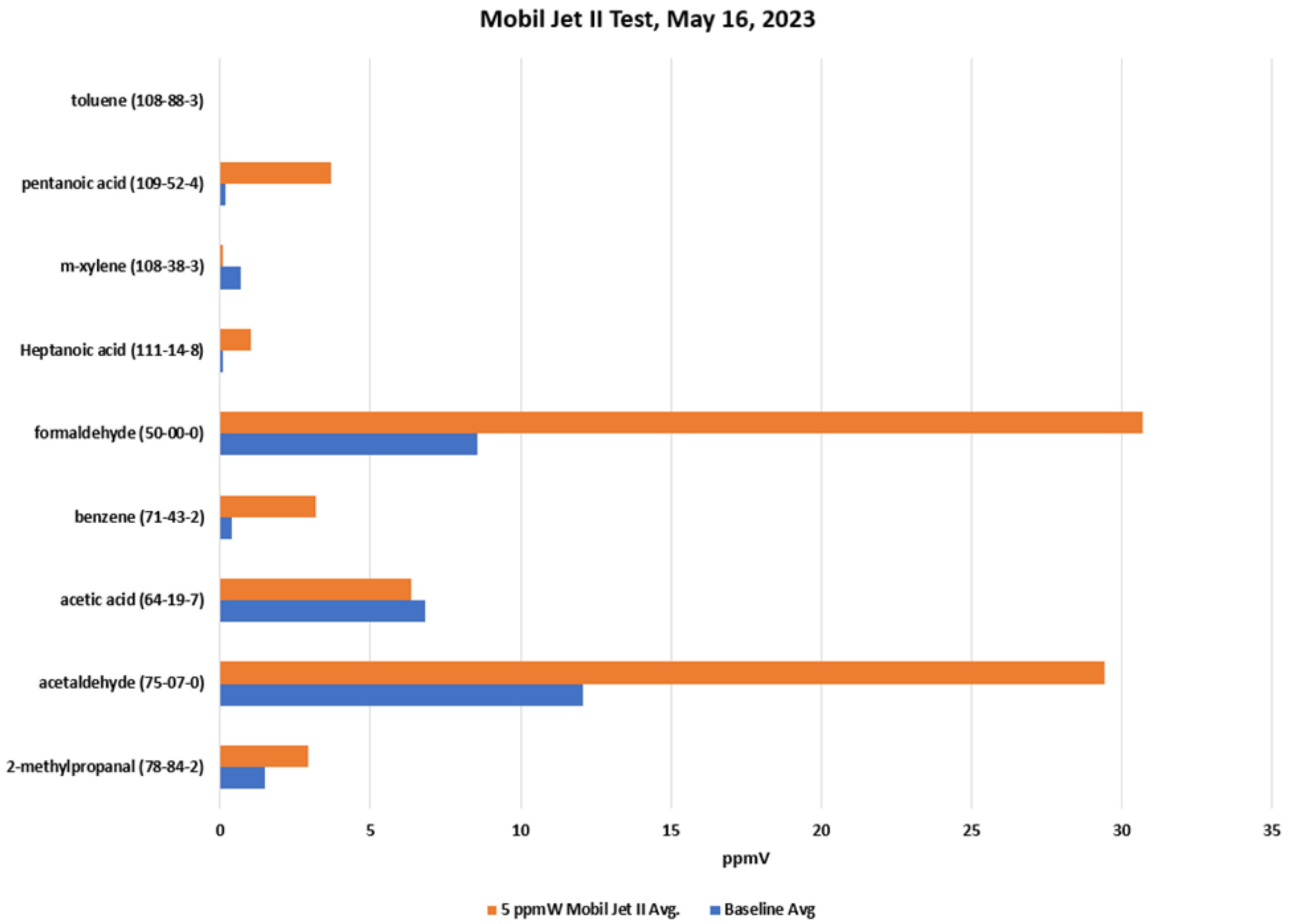


Figure 120. Mobil Jet Oil II carbonyls by Syft

The remainder of the data signal is due to instrument noise level. Qualitative rather than quantitative differences were observed between the different sampled ports.

2.6 Chemical sampling laboratory results

Chemical sampling result summaries are presented in the body of this report. The reader should visit the accompanying dataset information (KSU, 2024) to obtain the complete laboratory reports, the full data sets (i.e., electronic data deliverables [EDD] files, quality control information, and chromatograms for each chemical species). A list of the laboratory reports, their chronological revision histories, and the EDD datasets are summarized in Table 8.

Table 8. Laboratory reports, report revision histories, and data sets for the Volume 2 report

Report File Name	**Brief Contents Summary**	**Date Issued**
AAC Laboratory		
230962AAC Rev2 EPA TO-11.pdf	Carbonyls; EPA TO-11A results, (Field Blanks subtracted); 18 samples; 12 pages. Chemical sample location nomenclature corrected in chain of custody forms	December 20, 2023
230962 AAC Rev-2 EPA TO-11-EDD.xlsx	Carbonyls Electronic Data Deliverable, EPA TO-11A	December 20, 2023
230962 Revision History AAC TO-11.docx		March 14, 2024
RJ Lee Laboratory		
W305169, Rev 1 Report TO-13A Phosphates-Rev 240717.pdf	EPA TO-13A, OP TICs, SVOC TICs; 39 samples; 235 pages	July 17, 2024
W305169 Chromatograms.pdf	39 samples, July 24 - 28, 2023. 42 pages	October 9, 2023
W305169 EDD Final 2024-07-17.xlsx	OP TIC; EPA TO-13A Results,	July 17, 2024
W305169 Revision History TO-13A.docx		March 14, 2024
RJ Lee Laboratory		
W305170 TO-13A PAH Rev 240717- RevB.pdf	PAHs and OP Isomers; 33 Samples; EPA TO-13A; 139 pages	July 17,2024
W305170 EDD Final 2024-07-17.xlsx	PAHs and OP Isomers; Electronic Data Deliverable; 33 Samples; EPA TO-13A;	July 17, 2024

Report File Name	Brief Contents Summary	Date Issued
W305170 Revision History EPA TO13A PAH.docx		March 14, 2024
RJ Lee Laboratory		
W305171_Final Report_Rev.3-1 EPA TO-17.pdf	VOCs; EPA TO-17 (one broken tube reported as less than the reporting limit); 34 samples; 206 pages	May 1, 2024
W305171 EDD TO-17 List Rev4.xlsx	VOCs; EPA TO-17 Electronic Data Deliverable, TIC without CAS numbers removed	May 1, 2024
W305171 Revision History EPA TO-17.docx		March 14, 2024
Fraunhofer Institute		
Fraunhofer Atlantic City 2023 Analysis Report_corr.pdf	2023 Analysis Report, chemical sample locations corrected (CA, OP/Oil, and Tenax,)	August 30, 2023

2.6.1 Dinitrophenyl hydrazine (DNPH) cartridge samples for EPA TO-11A analysis (carbonyls)

Carbonyl analyses from AAC Laboratory Report Number 230962, Revision 2, is presented in bar chart format in Figure 121.

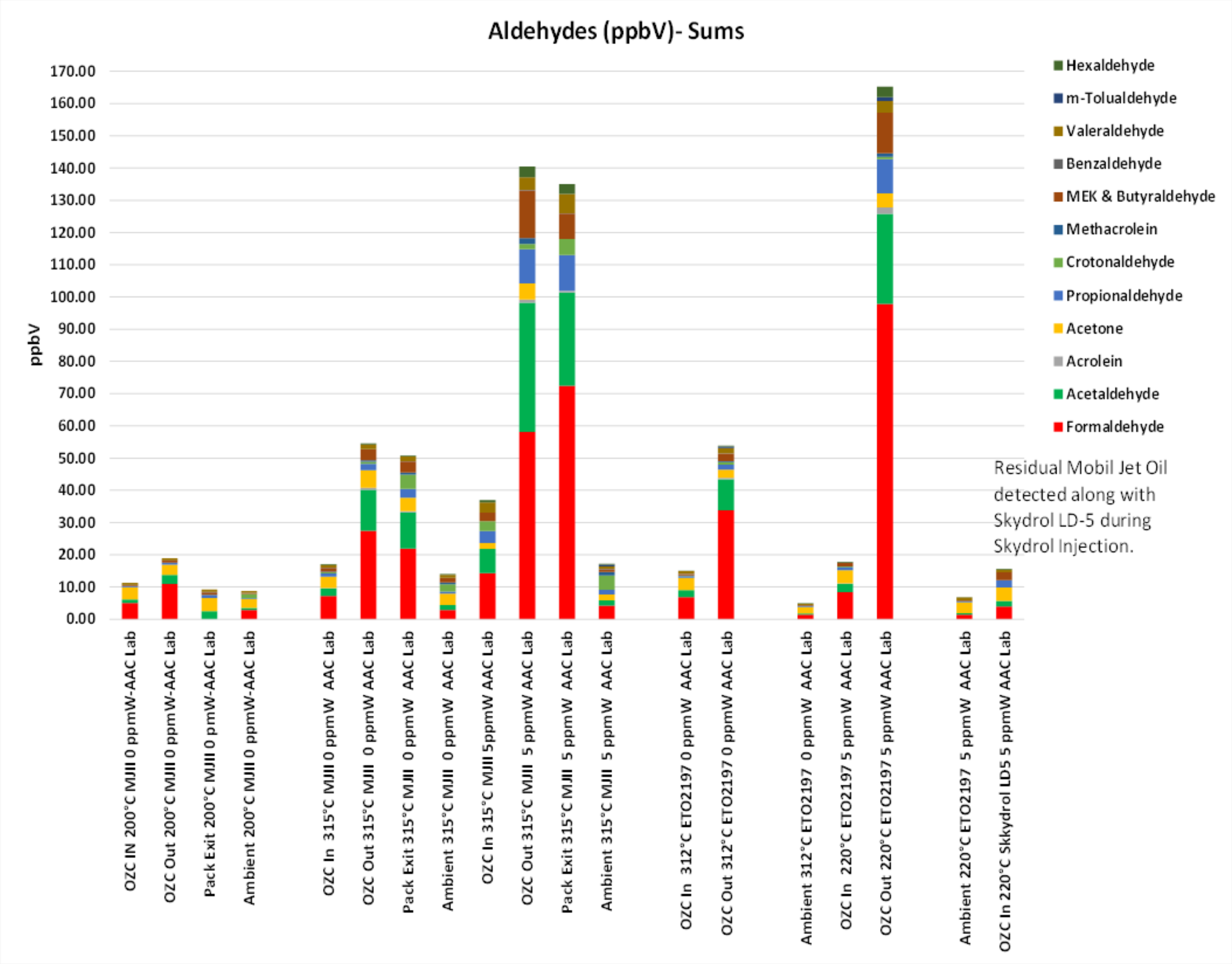


Figure 121. EPA TO-11A background-subtracted carbonyls results by AAC Laboratory

2.6.2 Polyaromatic hydrocarbons (PAHs) EPA Method TO-13A

EPA TO-13A analyses were reported in RJ Lee Reports W305169 and W305170. The results are compiled into four representative bar charts (Figures 122 through 125), sorted by molecular weight (MW):

- Figure 122. EPA TO-13A, molecular weights 85 - 198 SIM Mode
- Figure 123. EPA TO-13A molecular weights 202 - 295 SIM Mode
- Figure 124. EPA TO-13 A, molecular weights 296-348 SIM Mode
- Figure 125. EPA TO-13A, molecular weights 350-526 SIM Mode

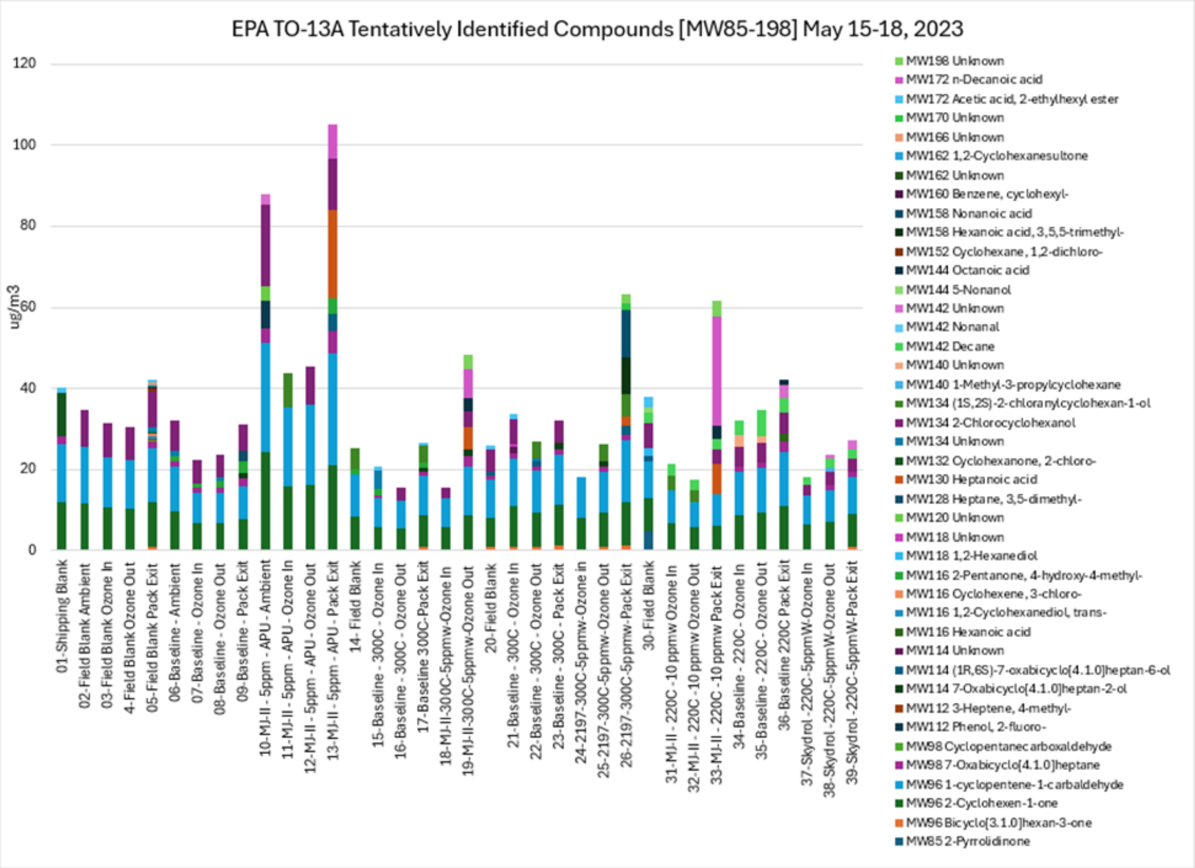


Figure 122. EPA TO-13A, molecular weights 85 - 198 SIM Mode

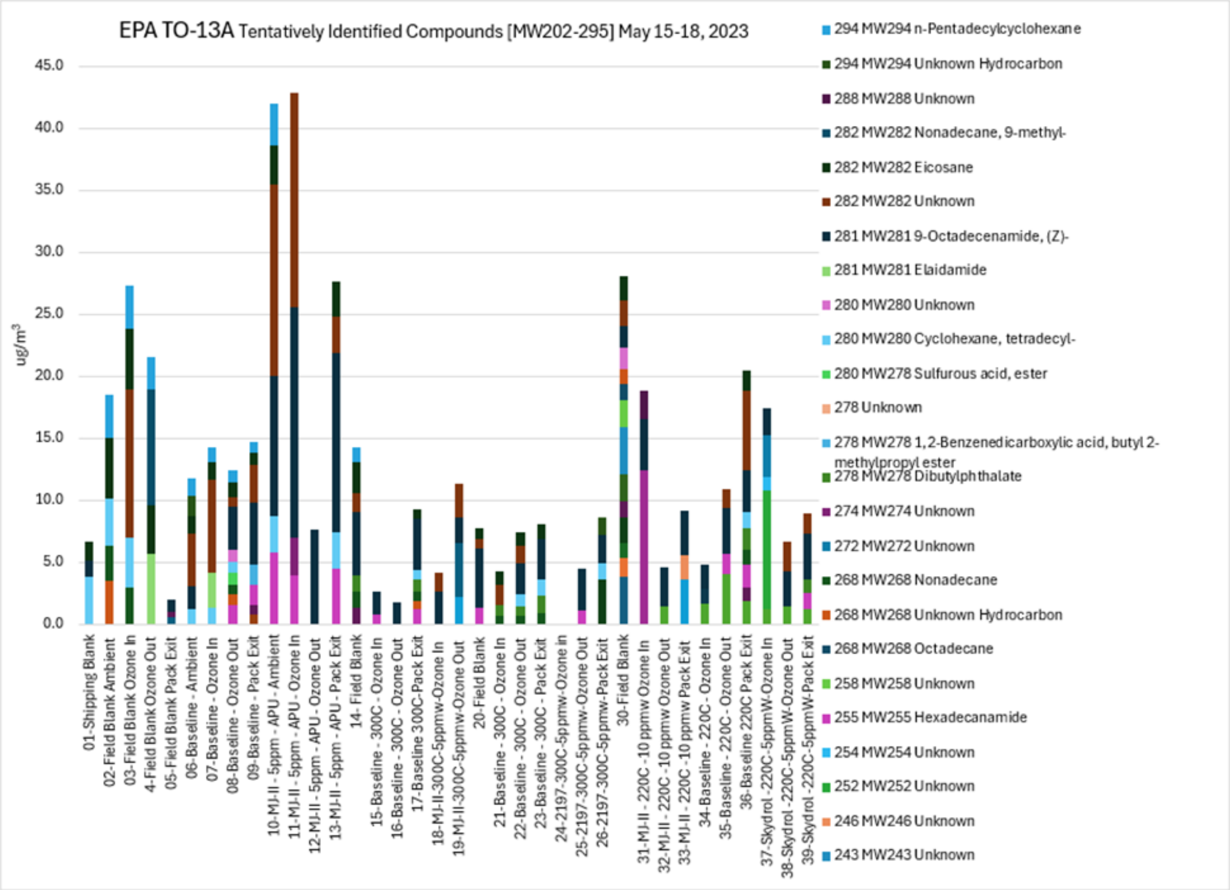


Figure 123. EPA TO-13A molecular weights 202 - 295 SIM Mode

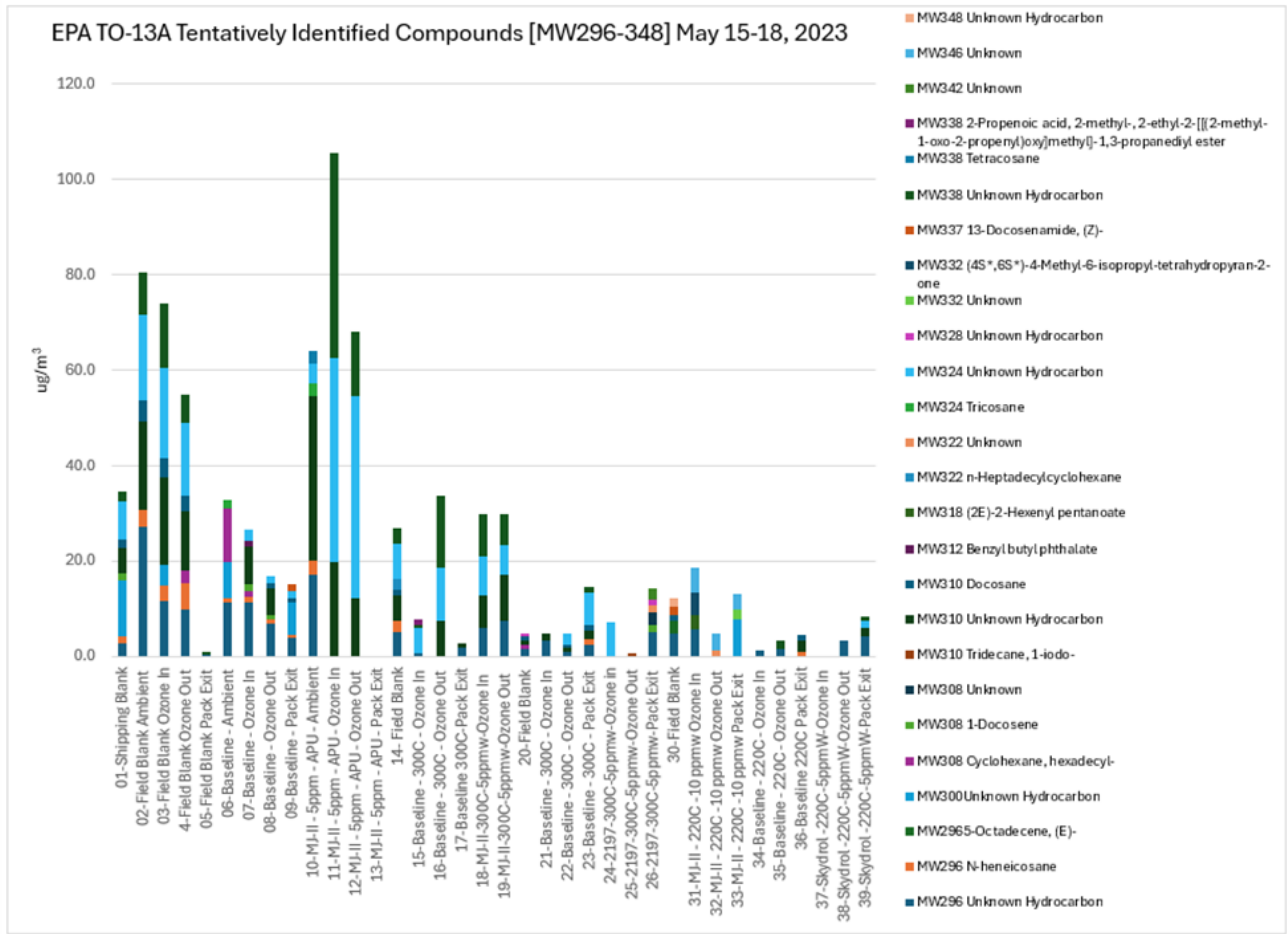


Figure 124. EPA TO-13 A, molecular weights 296-348 SIM Mode

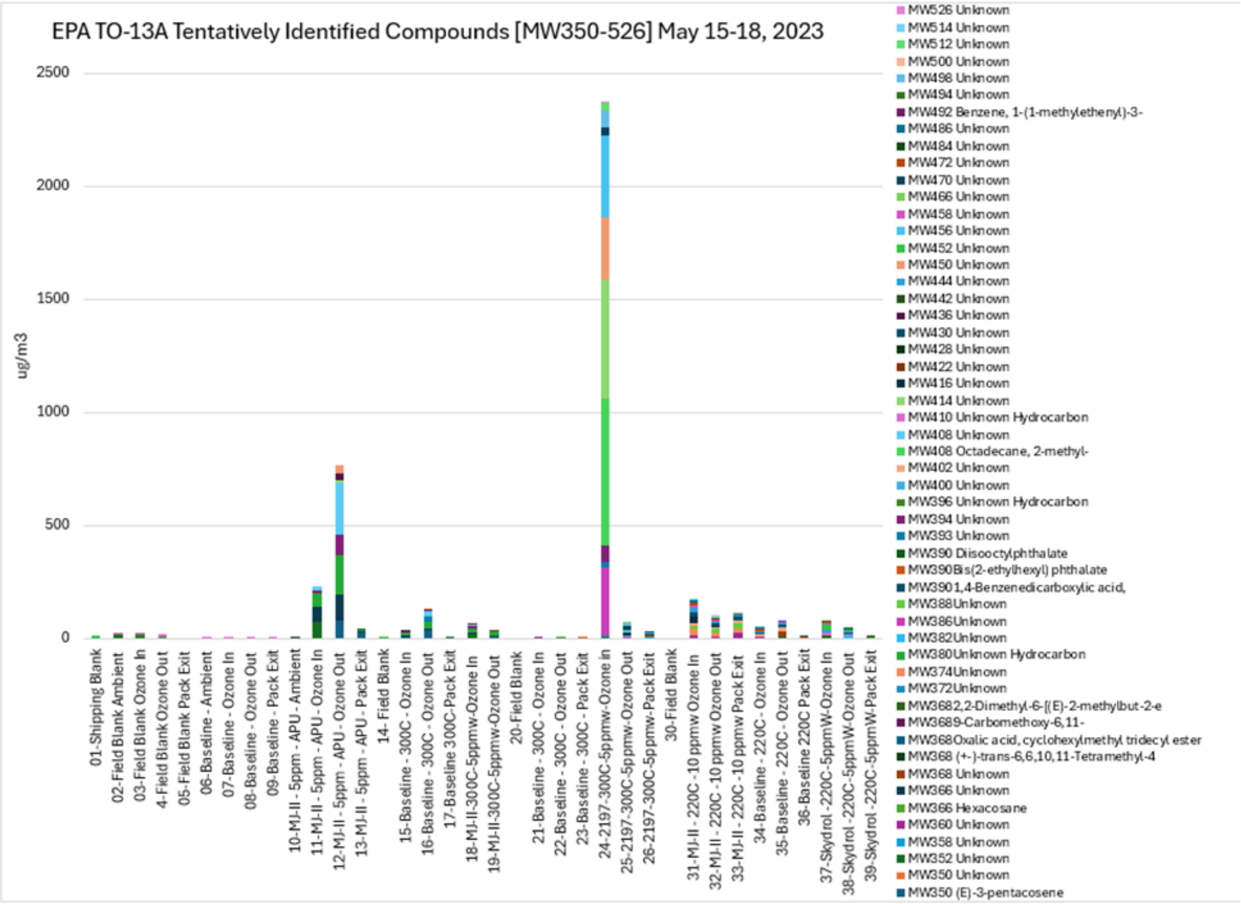


Figure 125. EPA TO-13A, molecular weights 350-526 SIM Mode

2.6.3 Organophosphorous (OP) Compounds

2.6.3.1 Fraunhofer OP compound results

Fraunhofer OP compounds results are summarized in Figure 126.

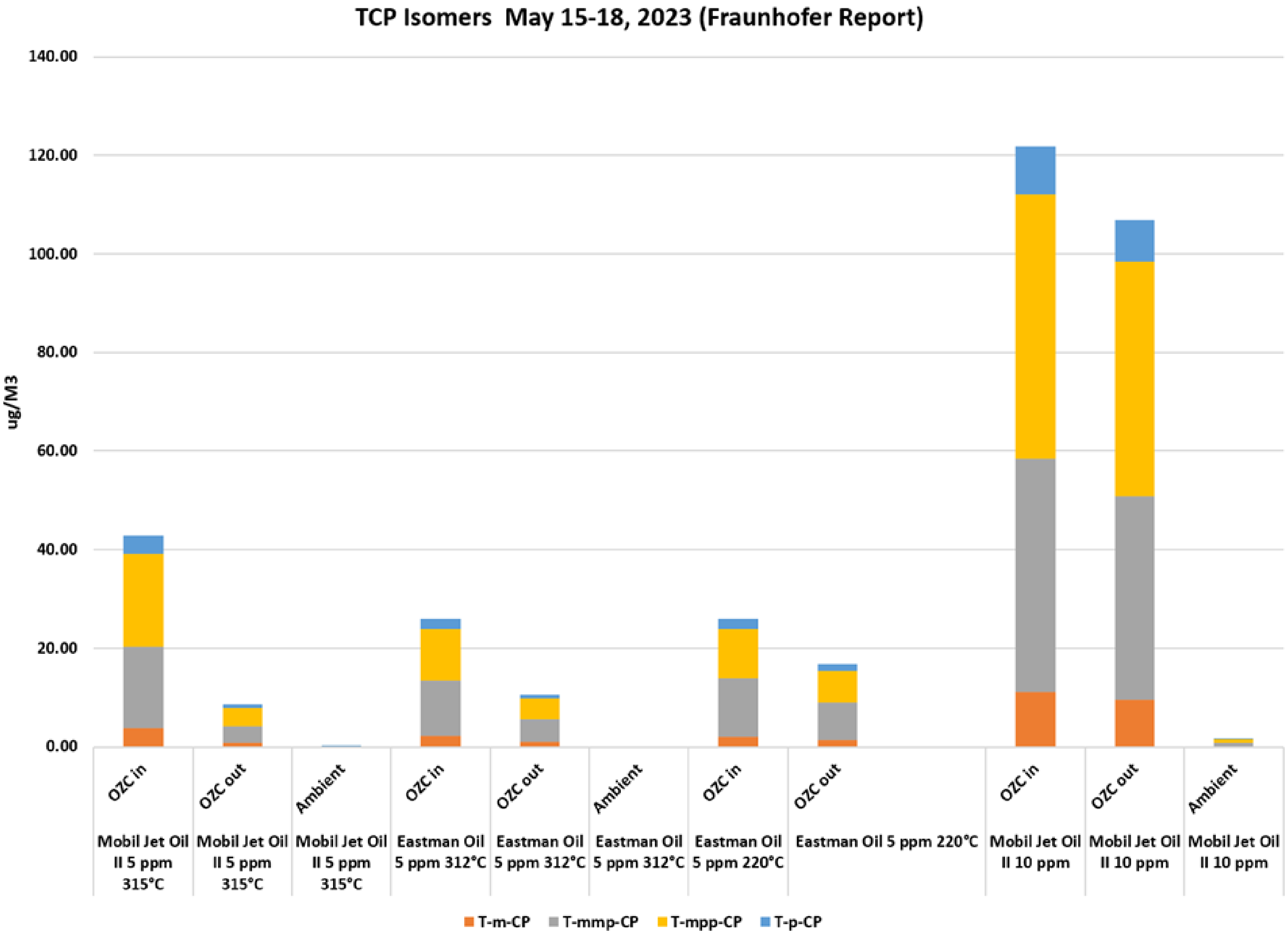


Figure 126. TCP isomers summary by Fraunhofer ITEM

2.6.3.2 RJ Lee OP compounds by EPA TO-13A

Data from RJ Lee Report Number W305169, Revision 1 and W305169 EDD are presented in Figure 127. The figure presents the total OP compounds summed as bar charts for each test condition.

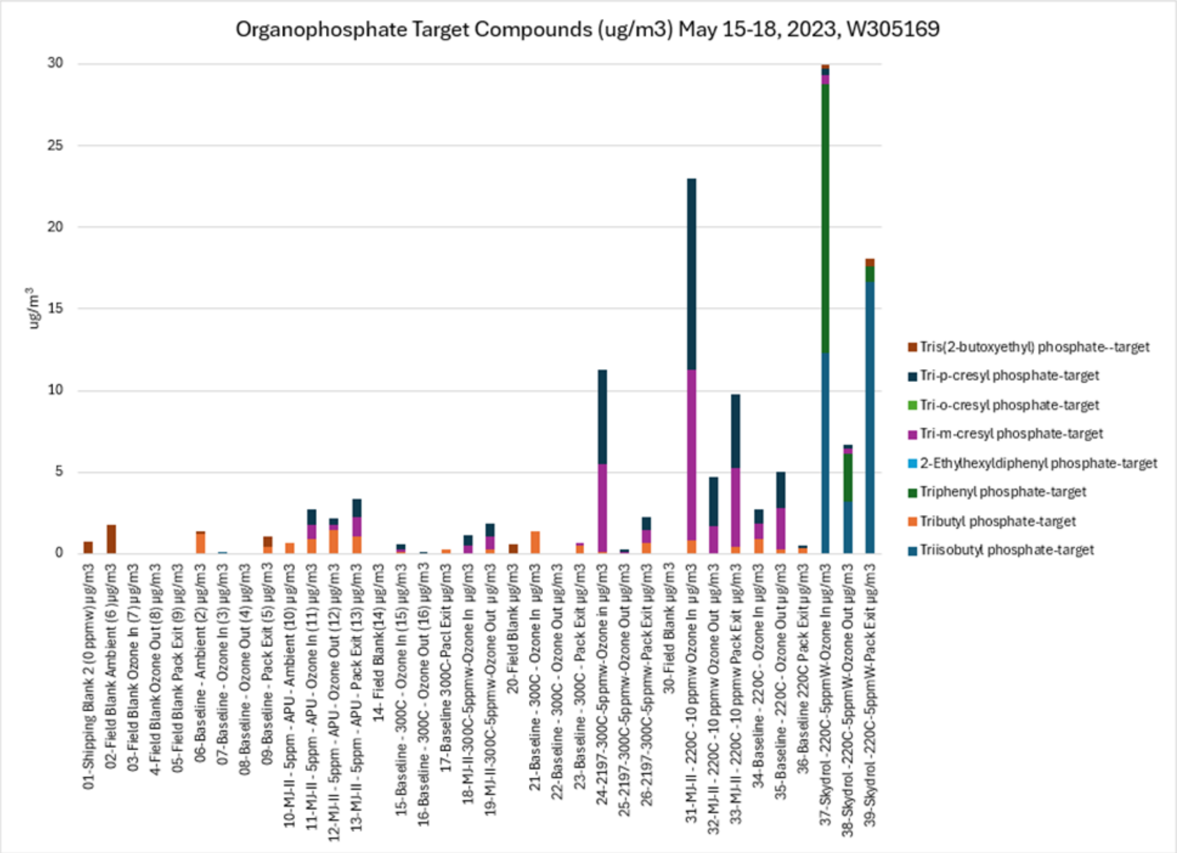


Figure 127. OP Compounds detected by EPA TO-13A

2.6.4 Fraunhofer volatile organic compounds (VOCs) report

Fraunhofer VOCs results are summarized in Figure 128.

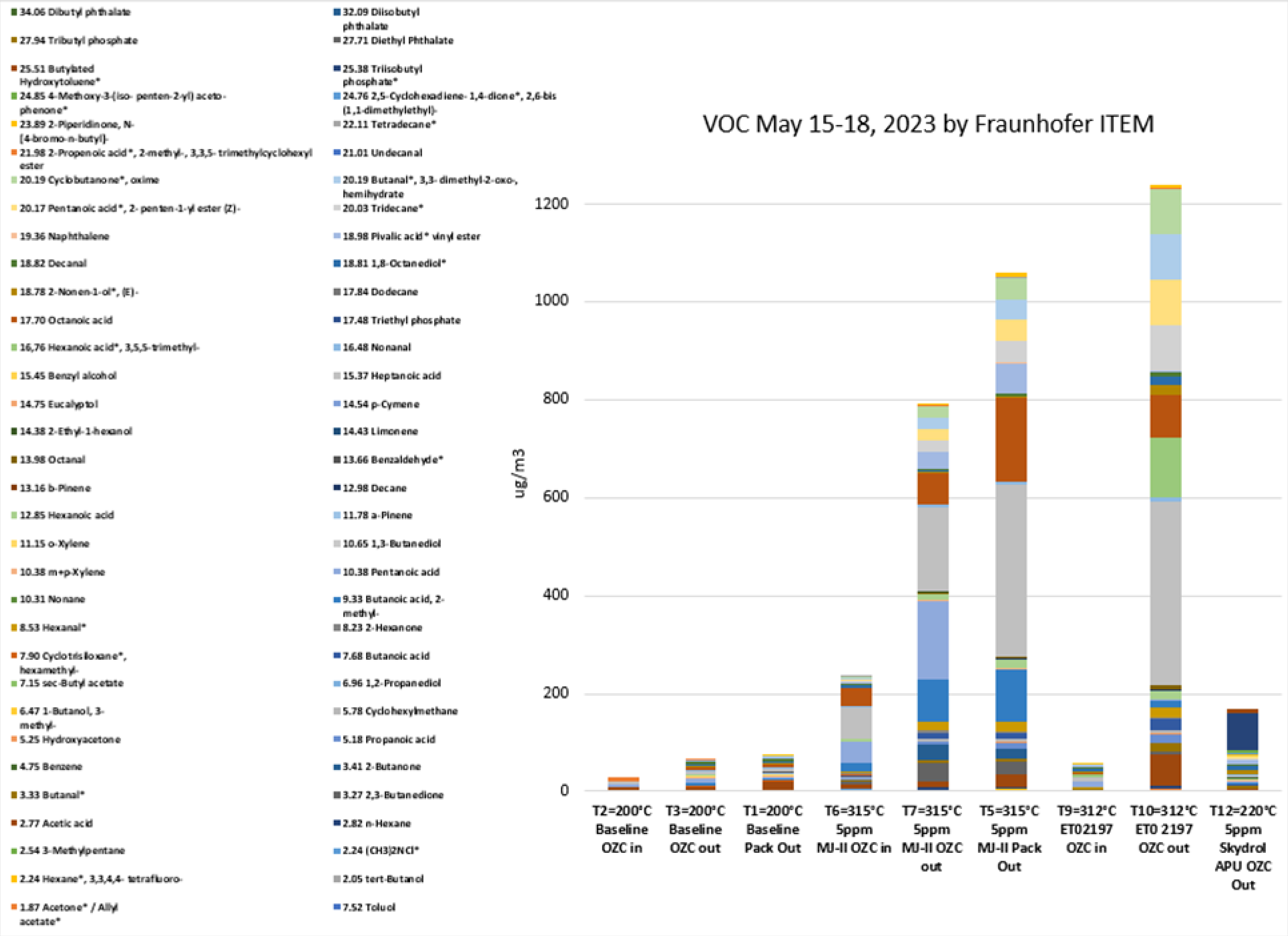


Figure 128. Volatile organic compounds (VOCs) test results by Faunhofer ITEM

2.6.5 Volatile organic compounds (VOCs) by EPA TO-17

2.6.5.1 Assessment of laboratory identified potential sampling line reversal between ambient and pack exit sample lines

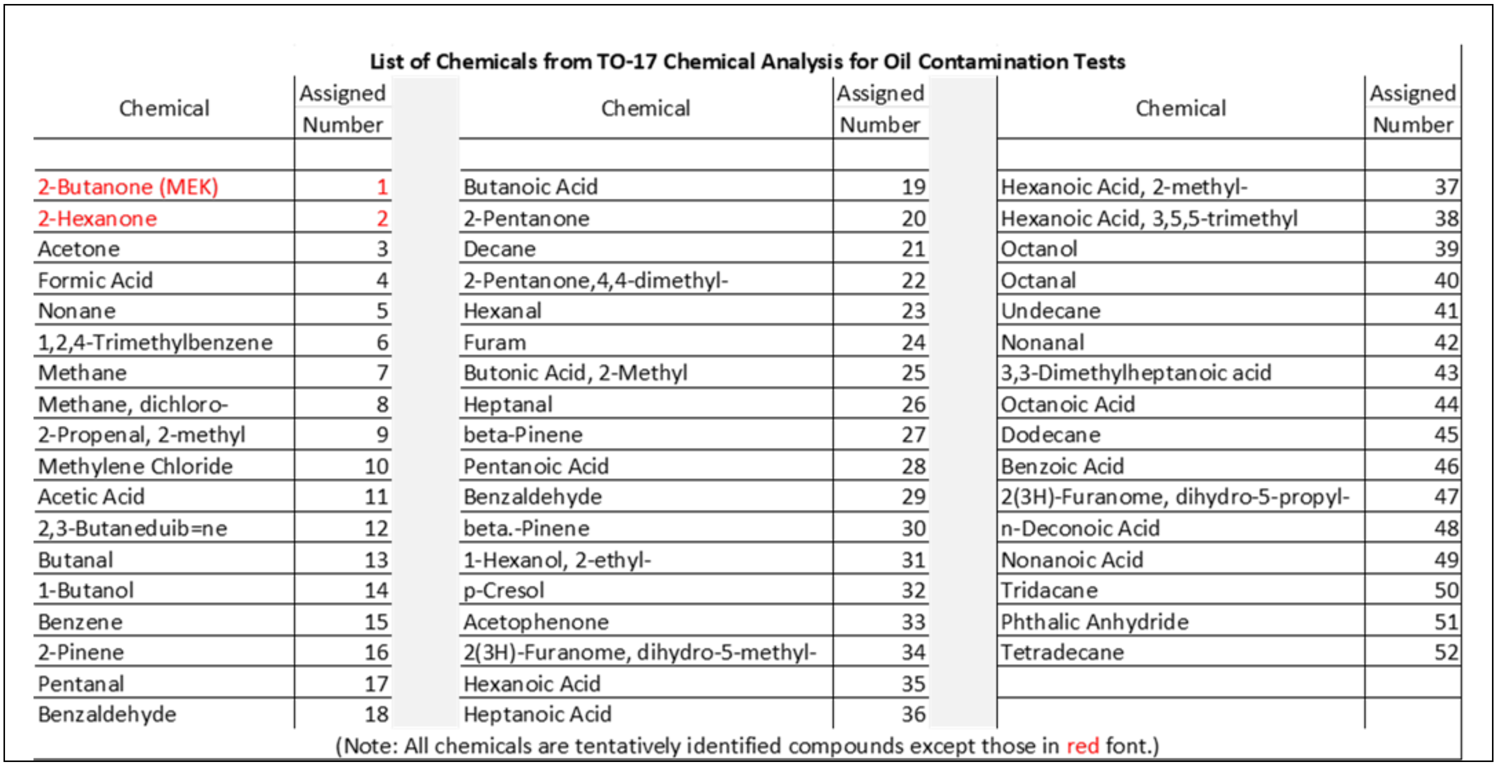
Initial review of the analytical laboratory results raised questions as to whether or not sample lines in the aircraft cabin had been correctly identified. In particular, it appeared that some of the lines between the distribution boxes and the chemical sample stations may have been inadvertently reversed. At that point in time, the experimental setup had been dismantled so it was not possible to conduct a physical examination of the sample lines. Instead, an in-depth investigation of the chemical data was conducted to address this question and assure data integrity.

The RJ Lee Group (RJLG) Laboratory used EPA TO-17 for VOC analyses. EPA TO-17 data were reviewed to determine if the sample lines to the chemical sampling station in the aircraft cabin had been inadvertently reversed. There was good certainty that the lines labeled as being connected to the VOC/ozone converter were indeed connected to the VOC/ozone converter due to the high pressure at the VOC/ozone converter which had to be accommodated at the sampling station. However, it is possible that the identification of the VOC/ozone converter inlet and outlet lines were reversed. Similarly, the lines identified as ambient and pack exit could have been reversed as well.

The first task was to identify which chemicals would be used in the assessment. Data for the baseline conditions and the oil injection were reviewed. The minimum reporting threshold varies somewhat from chemical to chemical and typically is in the range of 0.15 - 0.20 ppbv. The data were reviewed test-condition by test-condition and those chemicals with at least one entry of 0.3 ppbV were identified. After several test conditions and associated baseline data were reviewed, and the list was nearing 50 chemicals, the limit was increased to 0.5 ppbV. In the end, 52 chemicals were identified for the list and are presented in Table 9 for VOC in engine oil and Table 10 for VOC in hydraulic fluid.

Values for chemicals listed in red were quantified using internal standards. Values for chemicals listed in black were quantified using surrogate standards.

Table 9. Dominant VOCs in engine oil as determined by EPA TO-17

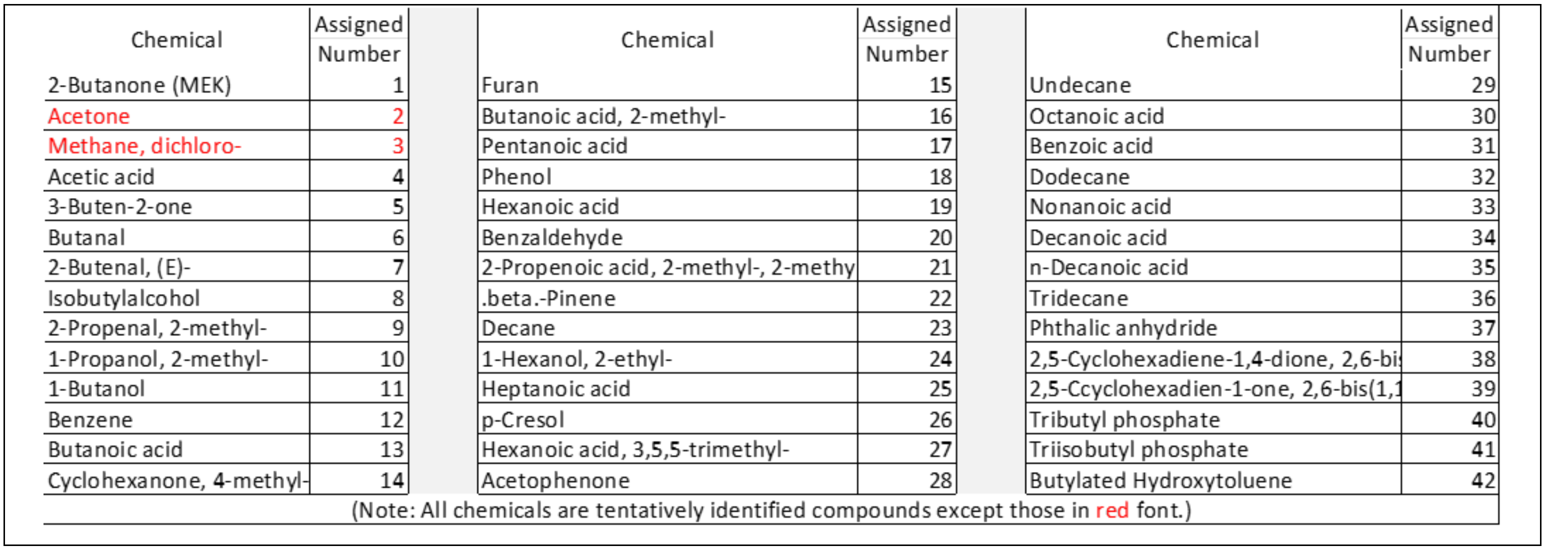


List of Chemicals from TO-17 Chemical Analysis for Oil Contamination Tests

Chemical	Assigned Number	Chemical	Assigned Number	Chemical	Assigned Number
2-Butanone (MEK)	1	Butanoic Acid	19	Hexanoic Acid, 2-methyl-	37
2-Hexanone	2	2-Pentanone	20	Hexanoic Acid, 3,5,5-trimethyl	38
Acetone	3	Decane	21	Octanol	39
Formic Acid	4	2-Pentanone,4,4-dimethyl-	22	Octanal	40
Nonane	5	Hexanal	23	Undecane	41
1,2,4-Trimethylbenzene	6	Furam	24	Nonanal	42
Methane	7	Butonic Acid, 2-Methyl	25	3,3-Dimethylheptanoic acid	43
Methane, dichloro-	8	Heptanal	26	Octanoic Acid	44
2-Propenal, 2-methyl	9	beta-Pinene	27	Dodecane	45
Methylene Chloride	10	Pentanoic Acid	28	Benzoic Acid	46
Acetic Acid	11	Benzaldehyde	29	2(3H)-Furanome, dihydro-5-propyl-	47
2,3-Butaneduib=ne	12	beta.-Pinene	30	n-Deconoic Acid	48
Butanal	13	1-Hexanol, 2-ethyl-	31	Nonanoic Acid	49
1-Butanol	14	p-Cresol	32	Tridacane	50
Benzene	15	Acetophenone	33	Phthalic Anhydride	51
2-Pinene	16	2(3H)-Furanome, dihydro-5-methyl-	34	Tetradecane	52
Pentanal	17	Hexanoic Acid	35		
Benzaldehyde	18	Heptanoic Acid	36		

(Note: All chemicals are tentatively identified compounds except those in red font.)

Table 10. Dominant VOCs in hydraulic fluid as determined by EPA TO-17



Chemical	Assigned Number	Chemical	Assigned Number	Chemical	Assigned Number
2-Butanone (MEK)	1	Furan	15	Undecane	29
Acetone	2	Butanoic acid, 2-methyl-	16	Octanoic acid	30
Methane, dichloro-	3	Pentanoic acid	17	Benzoic acid	31
Acetic acid	4	Phenol	18	Dodecane	32
3-Buten-2-one	5	Hexanoic acid	19	Nonanoic acid	33
Butanal	6	Benzaldehyde	20	Decanoic acid	34
2-Butenal, (E)-	7	2-Propenoic acid, 2-methyl-, 2-methy	21	n-Decanoic acid	35
Isobutylalcohol	8	.beta.-Pinene	22	Tridecane	36
2-Propenal, 2-methyl-	9	Decane	23	Phthalic anhydride	37
1-Propanol, 2-methyl-	10	1-Hexanol, 2-ethyl-	24	2,5-Cyclohexadiene-1,4-dione, 2,6-bi	38
1-Butanol	11	Heptanoic acid	25	2,5-Ccyclohexadien-1-one, 2,6-bis(1,1	39
Benzene	12	p-Cresol	26	Tributyl phosphate	40
Butanoic acid	13	Hexanoic acid, 3,5,5-trimethyl-	27	Triisobutyl phosphate	41
Cyclohexanone, 4-methyl-	14	Acetophenone	28	Butylated Hydroxytoluene	42

(Note: All chemicals are tentatively identified compounds except those in red font.)

The baseline tests were used to verify which sample line identification was associated with the ambient air and which sample line identification was associated with the pack exit sampling location. The chemicals in the ambient air could have some variations during the course of the experiments. However, when comparing baseline conditions to contaminant injection conditions, the concentrations of chemicals in the ambient air should be relatively insensitive to the contaminant injection. Conversely, the concentrations of chemicals at the pack exit sampling location would be expected to be quite sensitive to the presence of injected oil.

Comparative data are plotted in Figures 129 through 135.

- Figure 129. Comparison of chemical concentrations for baseline and Mobil Jet Oil II, 350 ˚C
- Figure 130. Comparison of chemical concentrations for baseline and Eastman Oil 2197, 312 ˚C
- Figure 131. Comparison of chemical concentrations for ambient, ozone in, and pack exit, Mobil Jet Oil II, 315 ˚C
- Figure 132. Eastman Oil 2197, 312 ˚C high temperature test
- Figure 133. Eastman Oil 2197, 220 ˚C low temperature test
- Figure 134. Mobil Jet Oil II APU test
- Figure 135. Skydrol PE-5 hydraulic fluid APU test

Figure 129 compares the Mobil Jet Oil II high temperature test to its baseline while Figure 130 compares the Eastman Oil 2197 high temperature test to its baseline. The concentrations for all 52 chemicals are plotted. It is seen that there are some very large changes from baseline to injection test in both cases for the sample sources identified as pack exit but small or minimal changes for sample sources identified as ambient. Figures 129 through 135 use the correct identification.

The data in Figure 129 made it clear which sample source was the ambient air as the concentration for the samples from that line changed minimally from baseline to contamination injection conditions. The sample sources in Figure 129 are correctly identified. However, in the original data, **the sampling lines from the ambient air inlet and pack exit had been inadvertently reversed** during the adsorbent tube sample acquisition. This reversal is corrected in all figures, tables, files, and text in this report.

However, there still remained the possibility that the sample lines identified as *inlet to* and *outlet from* the VOC/ozone converter were inadvertently reversed. To assess this question, the chemical concentrations for each sample source and each contamination test condition were plotted. The results of this pos-hoc analysis are presented in Figure 131 through Figure 135. The trends are consistent in all cases. The concentrations of all chemicals are all relatively low in the ambient air, except possibly for methane (numbers 7 and 8). There is a modest increase in the concentrations of some chemicals at the inlet to the VOC/ozone converter and then a large increase for select chemicals at the exit of the VOC/ozone converter. The concentrations at the pack exit are similar to those at the VOC/ozone converter exit. It appears the oxidation process in the VOC/ozone converter results in the generation of a number of chemical byproducts. Since there is no basis for expecting the pack to generate these chemicals, it is clear that the sample sources for the VOC/ozone converter inlet and VOC/ozone converter exit are correctly identified. The researchers had assumed prior to the test that VOC/ozone converter should eliminate VOC exiting the VOC/ozone converter. It was a revelation to the researchers that VOC/ozone converters generate secondary VOC. The VOC levels are elevated compared to the VOC/ozone converter inlet. On an ozone converter, the VOC levels are elevated even higher (Fox, 2024).

Although this post-hoc assessment was conducted to confirm or correct the sampling line source identification, it also provides insights into what chemicals may be useful for contaminant detection. First, it needs to be noted that concentrations of all of the chemicals measured by the TO-17 analysis are very low with the highest concentrations in the range of 10 - 30 ppbV range. Nevertheless, there is a clear indication of pentanoic acid (number 28) and heptanoic acid (number 36) in the presence of either Mobile Jet Oil II or Eastman Oil 2197 contamination. Lesser, but clearly increased concentrations of octanoic acid (number 44) were observed following injection of Mobile Jet Oil II and hexanoic acid (number 38) following injection of Eastman Oil 2197.

For the Skydrol PE-5 hydraulic fluid, butanol (number 11) was generated and is clearly due to the hydraulic fluid injection since it is not present in elevated concentrations for either Mobil Jet Oil II or Eastman Oil 2197 (number 14 for oil tests). The same is true for tributyl phosphate/triisobutyl phosphate (numbers 40 and 41) – the OPCs were present for the hydraulic fluid test runs, but not the engine oil runs (per data from the Aerotracer). Pentanoic acid (number 17), heptanoic acid (number 25), octanoic acid (number 30) were also present with the Skydrol PE-5 hydraulic fluid; however, it is unclear if these chemicals are due to carryover from the previous oil test runs or from the hydraulic fluid. It is also possible that the Skydrol PE-5 hydraulic fluid acted as a solvent to release the oil coating from ECS internal surfaces.

Summary of assessment and results of potential chemical sampling line(s) reversal:

The RJ Lee Laboratory EPA TO-17 results for VOC analyses helped the researchers determine if sample lines at the chemical sampling station in the cabin had been inadvertently reversed. The following was determined:

- Some of the sampling lines running within the aircraft interior between the distribution boxes and the chemical sampling/ media table were inadvertently reversed. (Refer to Appendix Figure D- 4) In particular, the **ambient air inlet line and the pack exit lines were inadvertently reversed** during chemical sample collection.
- The ambient air inlet and pack exit lines reversal **affected the following chemical samples** (i.e., chemical species):
  - Carbonyls chemical sampling (DNPH, EPA TO-11A results; AAC Report 230962, Rev. 2)
  - VOCs chemical sampling (EPA TO-17 results; RJL Report W305171-Final)
  - Fraunhofer VOC, organophosphate, and carboxylic acids (CA) chemical sampling
- The **ambient air inlet and pack exit lines reversal was corrected** on the Chain of Custody Forms, in the results of the AAC, RJ Lee, and Fraunhofer laboratory reports and accompanying electronic data deliverable (EDD) files, and in the body of this report.
- The ambient air inlet and pack exit lines reversal **DID NOT affect** the following chemical sampling:
  - OP TICS, SVOC TICs, and PAHs chemical sampling (EPA TO-13A results; RJL Report W305169, Rev. 1).
- The **VOC/ozone converter inlet and the VOC/ozone converter exit sampling lines WERE NOT reversed** (i.e., the chemical sampling sources/lines were correctly identified) and thus no corrections are needed for the Chain of Custody Forms, the results of laboratory reports, nor to accompanying electronic data files.

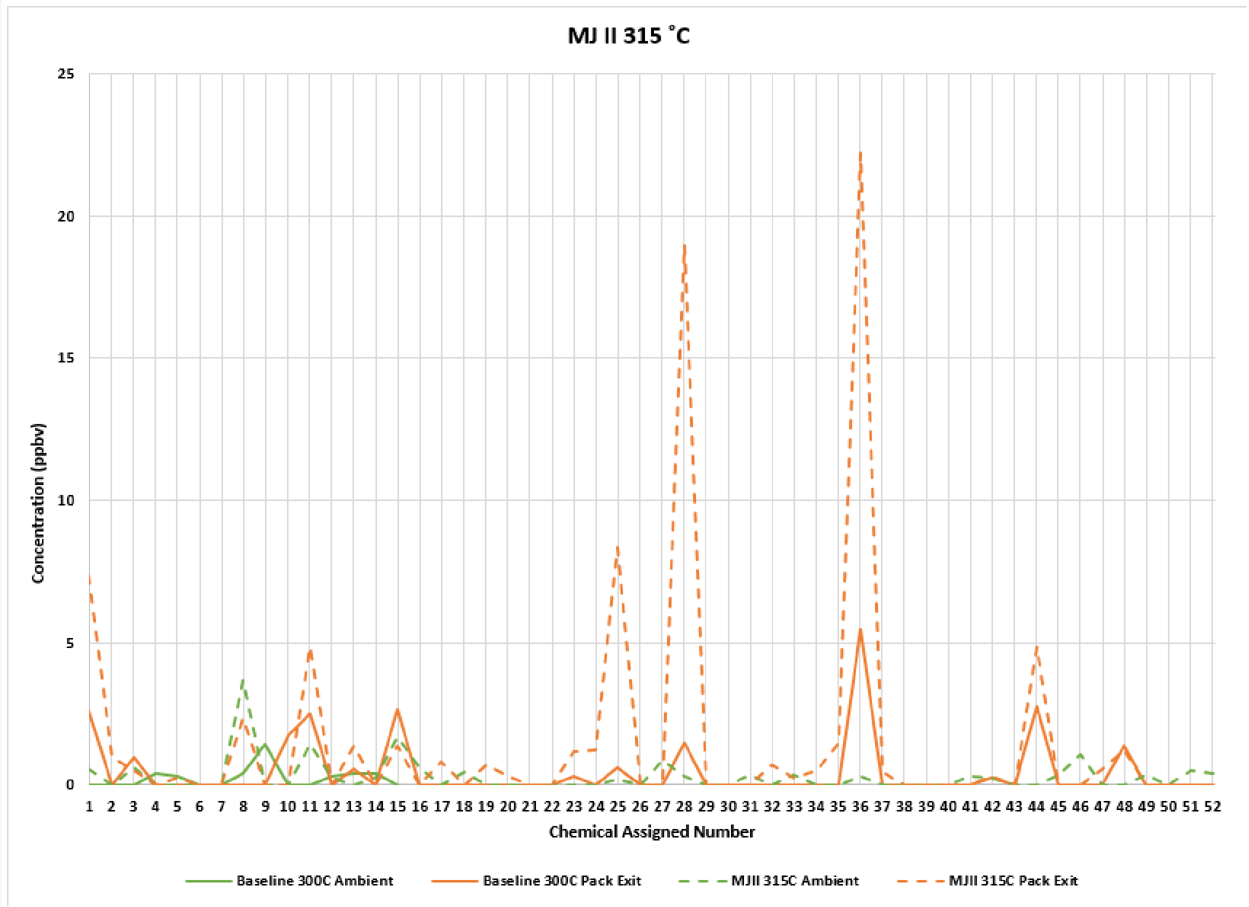


Figure 129. Comparison of chemical concentrations for baseline and Mobil Jet Oil II, 350 ˚C

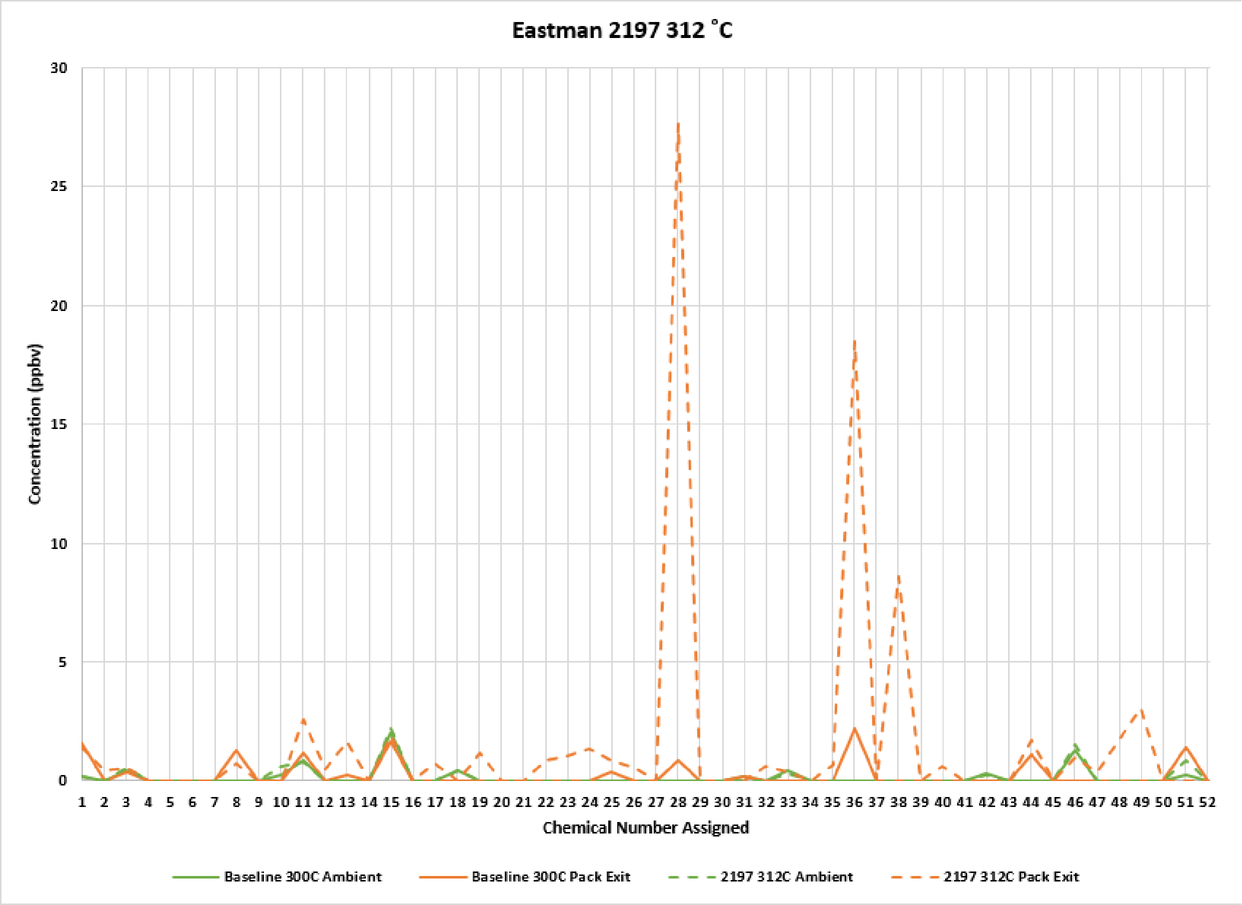


Figure 130. Comparison of chemical concentrations for baseline and Eastman Oil 2197, 312 ˚C

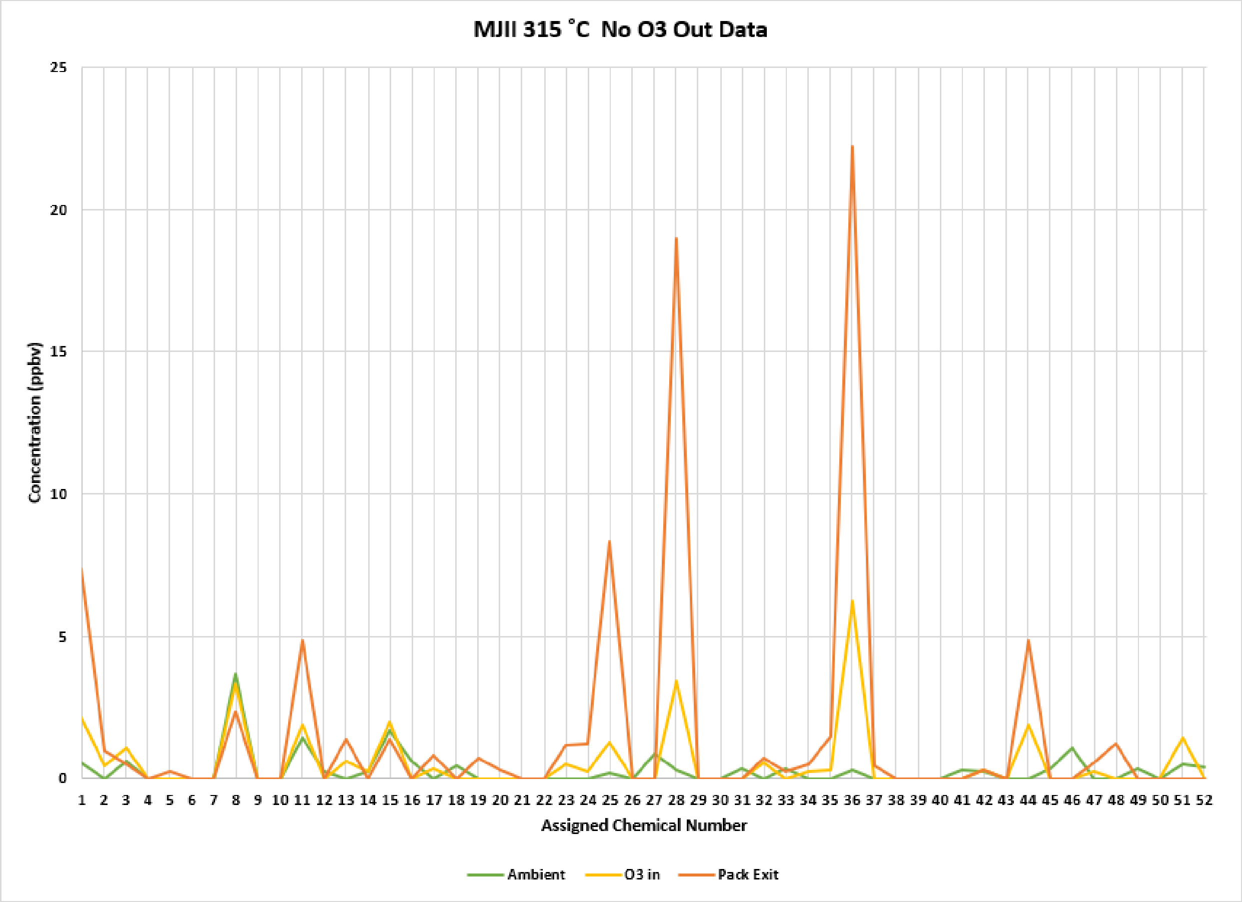


Figure 131. Comparison of chemical concentrations for ambient, ozone in, and pack exit, Mobil Jet Oil II, 315 ˚C

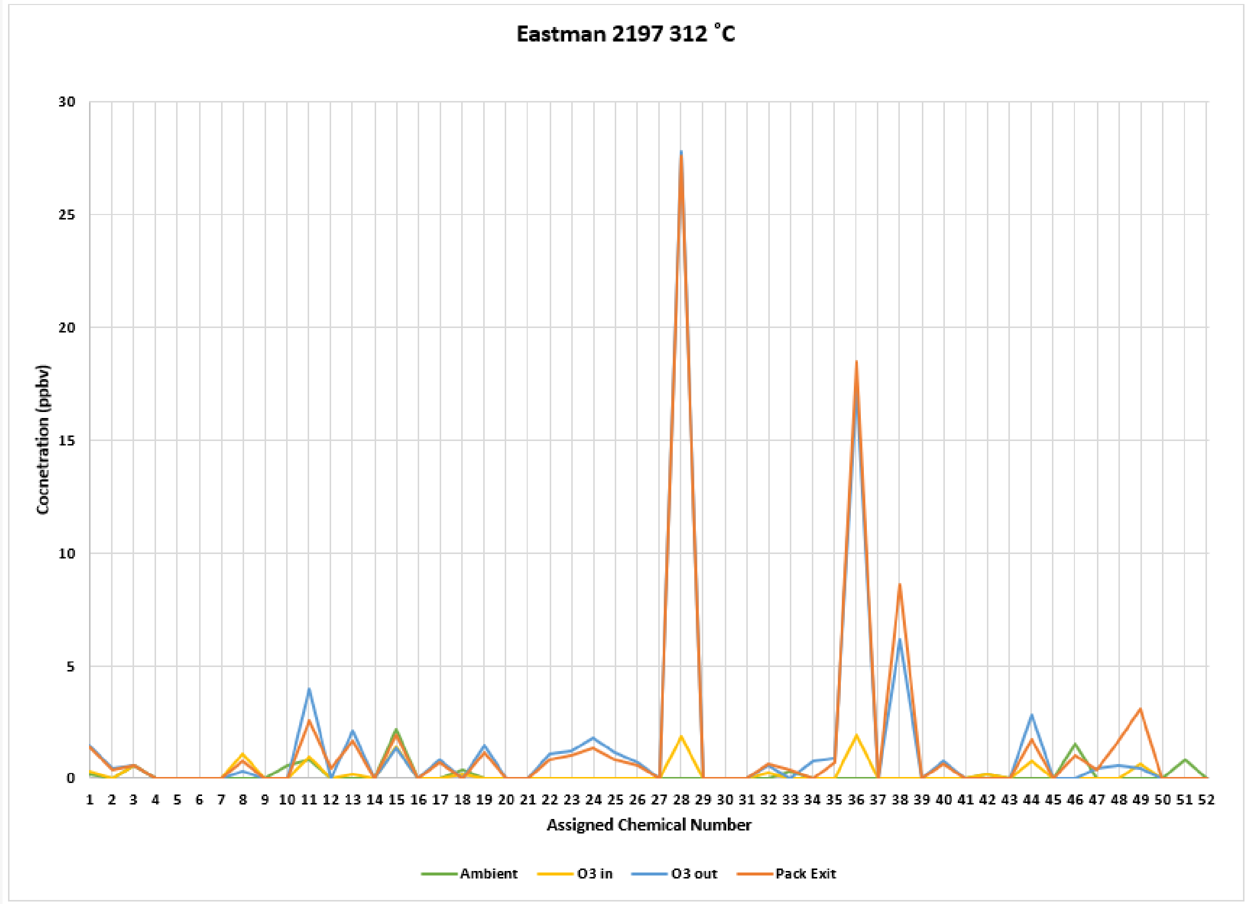


Figure 132. Eastman Oil 2197, 312 ˚C high temperature test

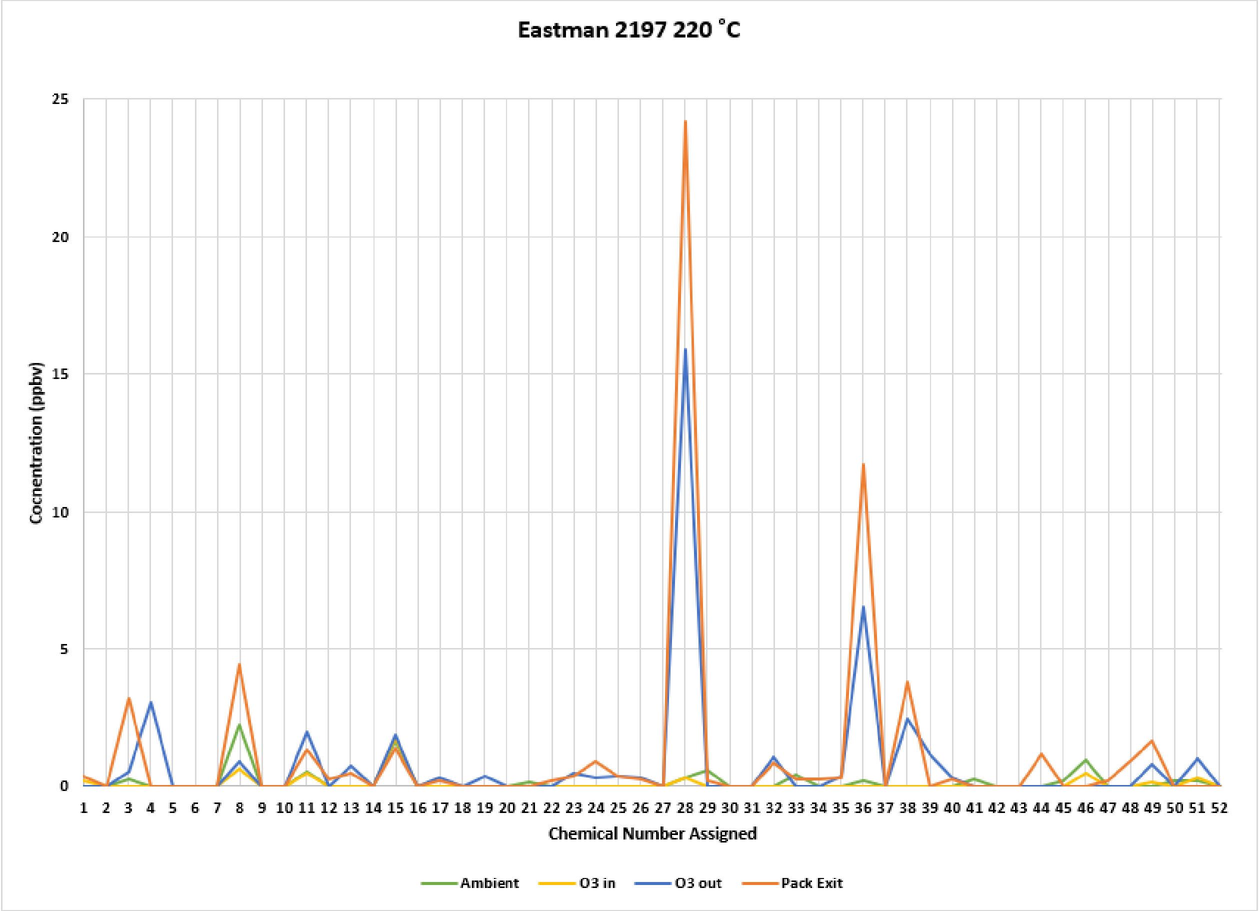


Figure 133. Eastman Oil 2197, 220 ˚C low temperature test

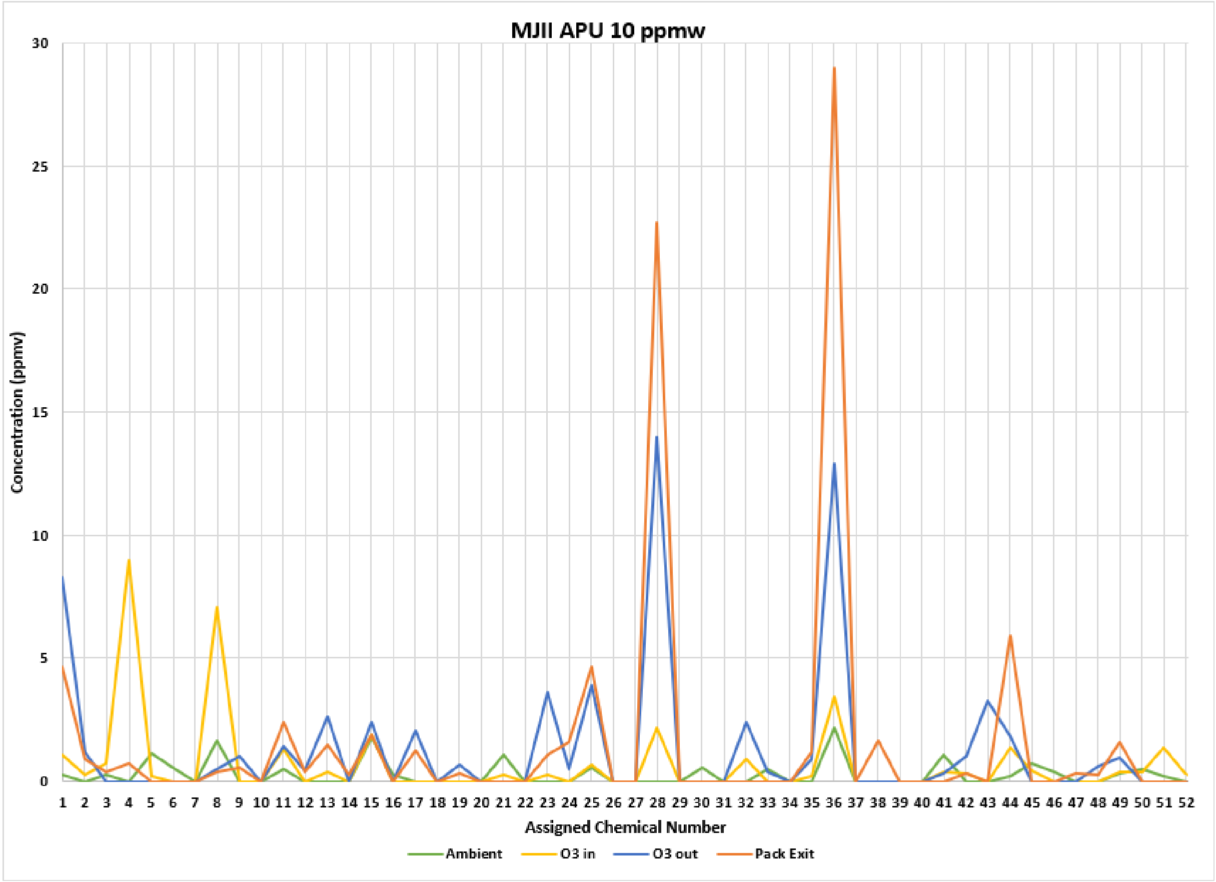


Figure 134. Mobil Jet Oil II APU test

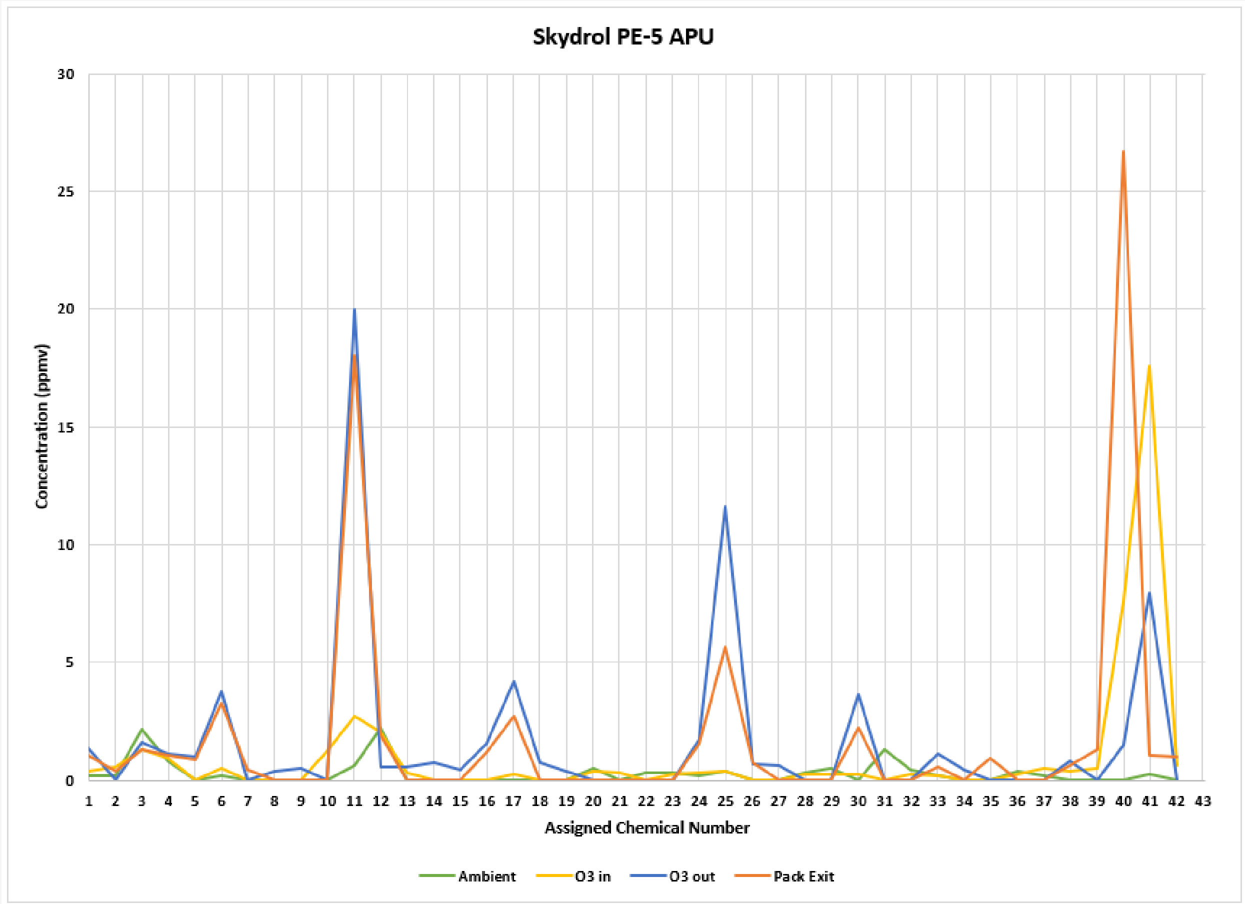
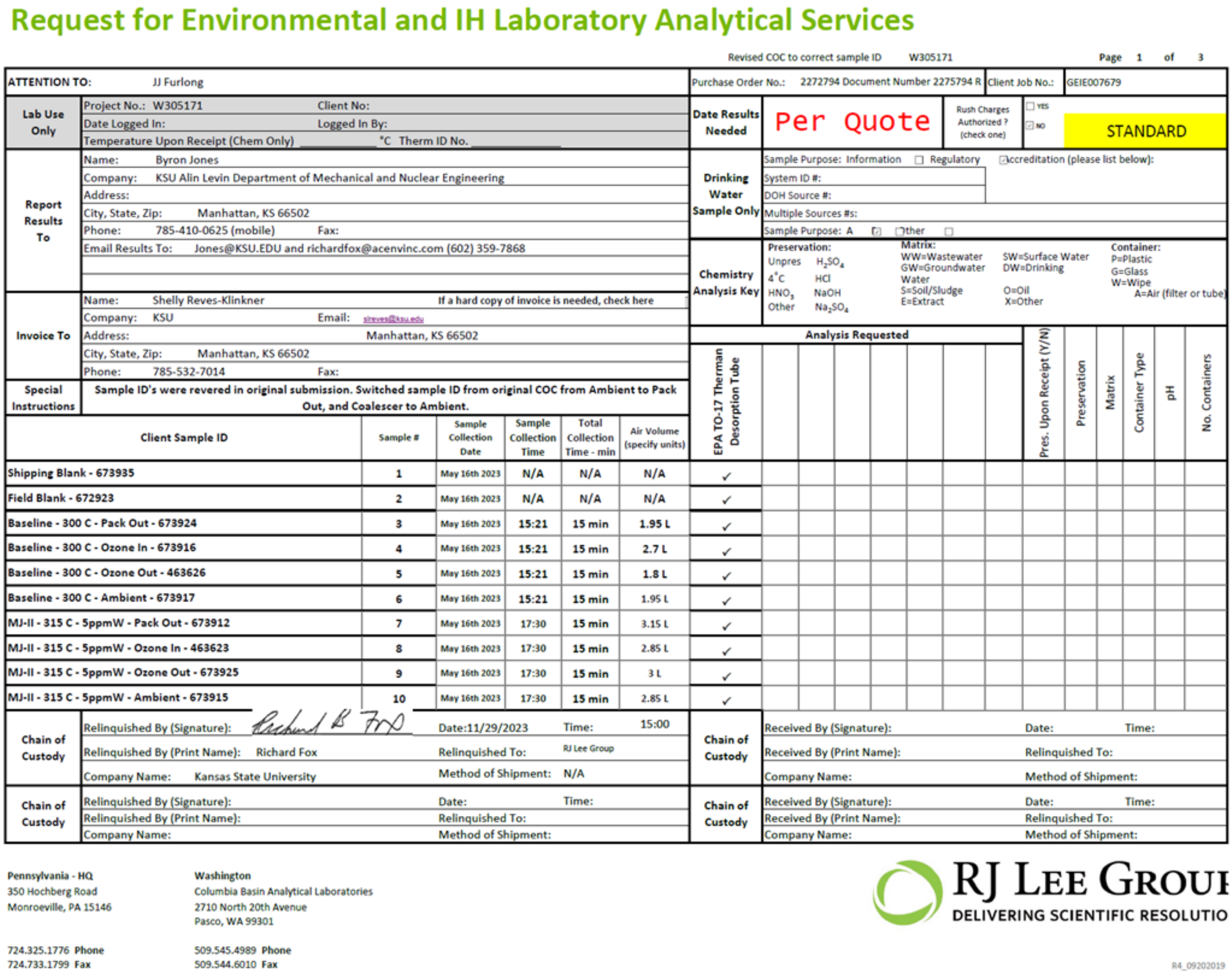


Figure 135. Skydrol PE-5 hydraulic fluid APU test

The corrected chain of custody forms are presented in Figure 136, Figure 137, Figure 138, Figure 139, and Figure 140.



Request for Environmental and IH Laboratory Analytical Services

Revised COC to correct sample ID W305171 Page 1 of 3

ATTENTION TO: JJ Furlong

Purchase Order No.: 2272794 Document Number 2275794 R
Client Job No.: GEIE007679

Lab Use Only
Project No.: W305171 Client No:
Date Logged In: Logged In By:
Temperature Upon Receipt (Chem Only) ____________ °C Therm ID No. ____________

Date Results Needed Per Quote
Rush Charges Authorized ? (check one) ☐ YES ☑ NO
STANDARD

Report Results To
Name: Byron Jones
Company: KSU Alin Levin Department of Mechanical and Nuclear Engineering
Address:
City, State, Zip: Manhattan, KS 66502
Phone: 785-410-0625 (mobile) Fax:
Email Results To: Jones@KSU.EDU and richardfox@acenvinc.com (602) 359-7868

Drinking Water Sample Only
Sample Purpose: Information ☐ Regulatory ☑Accreditation (please list below):
System ID #:
DOH Source #:
Multiple Sources #s:
Sample Purpose: A ☑ ☐Other ☐

Chemistry Analysis Key
Preservation: Unpres, H_2SO_4, 4°C, HCl, HNO_3, NaOH, Other, Na_2SO_4
Matrix: WW=Wastewater, GW=Groundwater Water, S=Soil/Sludge, E=Extract, SW=Surface Water, DW=Drinking, O=Oil, X=Other
Container: P=Plastic, G=Glass, W=Wipe, A=Air (filter or tube)

Invoice To
Name: Shelly Reves-Klinkner If a hard copy of invoice is needed, check here
Company: KSU Email: slreves@ksu.edu
Address: Manhattan, KS 66502
City, State, Zip: Manhattan, KS 66502
Phone: 785-532-7014 Fax:

Special Instructions Sample ID's were revered in original submission. Switched sample ID from original COC from Ambient to Pack Out, and Coalescer to Ambient.

Analysis Requested

Client Sample ID	Sample #	Sample Collection Date	Sample Collection Time	Total Collection Time - min	Air Volume (specify units)	EPA TO-17 Therman Desorption Tube	Pres. Upon Receipt (Y/N)	Preservation	Matrix	Container Type	pH	No. Containers
Shipping Blank - 673935	1	May 16th 2023	N/A	N/A	N/A	✓						
Field Blank - 672923	2	May 16th 2023	N/A	N/A	N/A	✓						
Baseline - 300 C - Pack Out - 673924	3	May 16th 2023	15:21	15 min	1.95 L	✓						
Baseline - 300 C - Ozone In - 673916	4	May 16th 2023	15:21	15 min	2.7 L	✓						
Baseline - 300 C - Ozone Out - 463626	5	May 16th 2023	15:21	15 min	1.8 L	✓						
Baseline - 300 C - Ambient - 673917	6	May 16th 2023	15:21	15 min	1.95 L	✓						
MJ-II - 315 C - 5ppmW - Pack Out - 673912	7	May 16th 2023	17:30	15 min	3.15 L	✓						
MJ-II - 315 C - 5ppmW - Ozone In - 463623	8	May 16th 2023	17:30	15 min	2.85 L	✓						
MJ-II - 315 C - 5ppmW - Ozone Out - 673925	9	May 16th 2023	17:30	15 min	3 L	✓						
MJ-II - 315 C - 5ppmW - Ambient - 673915	10	May 16th 2023	17:30	15 min	2.85 L	✓						

Chain of Custody
Relinquished By (Signature): Richard B Fox Date:11/29/2023 Time: 15:00
Relinquished By (Print Name): Richard Fox Relinquished To: RJ Lee Group
Company Name: Kansas State University Method of Shipment: N/A

Chain of Custody
Received By (Signature): Date: Time:
Received By (Print Name): Relinquished To:
Company Name: Method of Shipment:

Chain of Custody
Relinquished By (Signature): Date: Time:
Relinquished By (Print Name): Relinquished To:
Company Name: Method of Shipment:

Chain of Custody
Received By (Signature): Date: Time:
Received By (Print Name): Relinquished To:
Company Name: Method of Shipment:

Pennsylvania - HQ
350 Hochberg Road
Monroeville, PA 15146

724.325.1776 **Phone**
724.733.1799 **Fax**

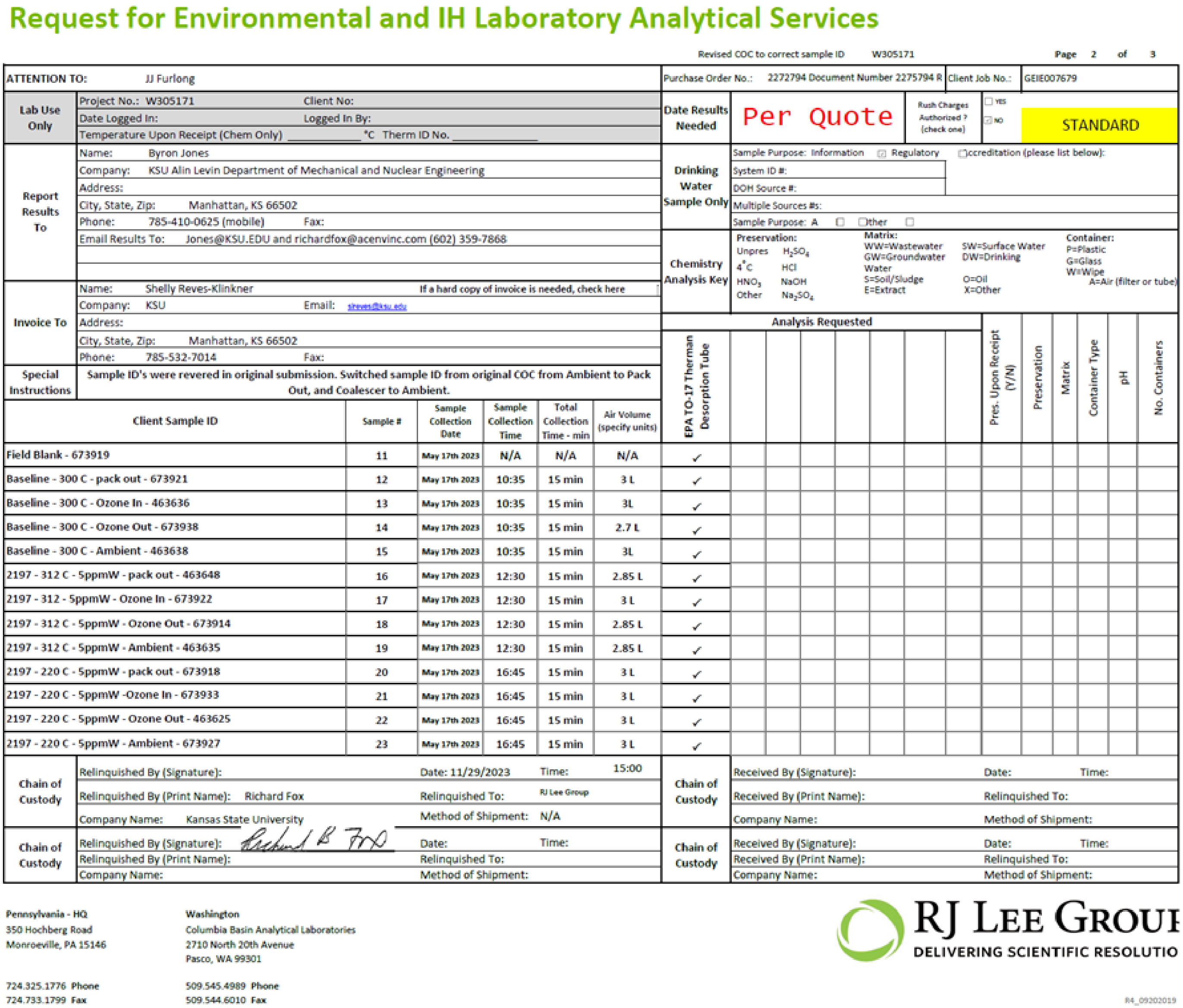
Washington
Columbia Basin Analytical Laboratories
2710 North 20th Avenue
Pasco, WA 99301

509.545.4989 **Phone**
509.544.6010 **Fax**

RJ LEE GROU
DELIVERING SCIENTIFIC RESOLUTIO

R4_09202019

Figure 136. Corrected chain of custody form for RJ Lee laboratory samples (1 of 3)



Request for Environmental and IH Laboratory Analytical Services

Revised COC to correct sample ID W305171 Page 2 of 3

ATTENTION TO: JJ Furlong	Purchase Order No.: 2272794 Document Number 2275794 R	Client Job No.:	GEIE007679

Lab Use Only	Project No.: W305171 Client No: Date Logged In: Logged In By: Temperature Upon Receipt (Chem Only) ______ °C Therm ID No. ______
Date Results Needed	Per Quote
Rush Charges Authorized ? (check one)	☐ YES ☑ NO
	STANDARD
Report Results To	Name: Byron Jones Company: KSU Alin Levin Department of Mechanical and Nuclear Engineering Address: City, State, Zip: Manhattan, KS 66502 Phone: 785-410-0625 (mobile) Fax: Email Results To: Jones@KSU.EDU and richardfox@acenvinc.com (602) 359-7868
Drinking Water Sample Only	Sample Purpose: Information ☑ Regulatory ☐ccreditation (please list below): System ID #: DOH Source #: Multiple Sources #s: Sample Purpose: A ☐ ☐ther ☐
Invoice To	Name: Shelly Reves-Klinkner If a hard copy of invoice is needed, check here Company: KSU Email: sreves@ksu.edu Address: City, State, Zip: Manhattan, KS 66502 Phone: 785-532-7014 Fax:
Chemistry Analysis Key	Preservation: Unpres, H_2SO_4, 4°C, HCl, HNO_3, NaOH, Other, Na_2SO_4 Matrix: WW=Wastewater, GW=Groundwater Water, S=Soil/Sludge, E=Extract, SW=Surface Water, DW=Drinking, O=Oil, X=Other Container: P=Plastic, G=Glass, W=Wipe, A=Air (filter or tube)
Special Instructions	Sample ID's were revered in original submission. Switched sample ID from original COC from Ambient to Pack Out, and Coalescer to Ambient.

						Analysis Requested													
Client Sample ID	Sample #	Sample Collection Date	Sample Collection Time	Total Collection Time - min	Air Volume (specify units)	EPA TO-17 Therman Desorption Tube								Pres. Upon Receipt (Y/N)	Preservation	Matrix	Container Type	pH	No. Containers
Field Blank - 673919	11	May 17th 2023	N/A	N/A	N/A	✓													
Baseline - 300 C - pack out - 673921	12	May 17th 2023	10:35	15 min	3 L	✓													
Baseline - 300 C - Ozone In - 463636	13	May 17th 2023	10:35	15 min	3L	✓													
Baseline - 300 C - Ozone Out - 673938	14	May 17th 2023	10:35	15 min	2.7 L	✓													
Baseline - 300 C - Ambient - 463638	15	May 17th 2023	10:35	15 min	3L	✓													
2197 - 312 C - 5ppmW - pack out - 463648	16	May 17th 2023	12:30	15 min	2.85 L	✓													
2197 - 312 - 5ppmW - Ozone In - 673922	17	May 17th 2023	12:30	15 min	3 L	✓													
2197 - 312 C - 5ppmW - Ozone Out - 673914	18	May 17th 2023	12:30	15 min	2.85 L	✓													
2197 - 312 C - 5ppmW - Ambient - 463635	19	May 17th 2023	12:30	15 min	2.85 L	✓													
2197 - 220 C - 5ppmW - pack out - 673918	20	May 17th 2023	16:45	15 min	3 L	✓													
2197 - 220 C - 5ppmW -Ozone In - 673933	21	May 17th 2023	16:45	15 min	3 L	✓													
2197 - 220 C - 5ppmW - Ozone Out - 463625	22	May 17th 2023	16:45	15 min	3 L	✓													
2197 - 220 C - 5ppmW - Ambient - 673927	23	May 17th 2023	16:45	15 min	3 L	✓													

Chain of Custody	Relinquished By (Signature):	Date: 11/29/2023 Time: 15:00	**Chain of Custody**	Received By (Signature): Date: Time:
	Relinquished By (Print Name): Richard Fox	Relinquished To: RJ Lee Group		Received By (Print Name): Relinquished To:
	Company Name: Kansas State University	Method of Shipment: N/A		Company Name: Method of Shipment:
Chain of Custody	Relinquished By (Signature): Richard B Fox	Date: Time:	**Chain of Custody**	Received By (Signature): Date: Time:
	Relinquished By (Print Name):	Relinquished To:		Received By (Print Name): Relinquished To:
	Company Name:	Method of Shipment:		Company Name: Method of Shipment:

Pennsylvania - HQ
350 Hochberg Road
Monroeville, PA 15146

724.325.1776 Phone
724.733.1799 Fax

Washington
Columbia Basin Analytical Laboratories
2710 North 20th Avenue
Pasco, WA 99301

509.545.4989 Phone
509.544.6010 Fax

RJ LEE GROU
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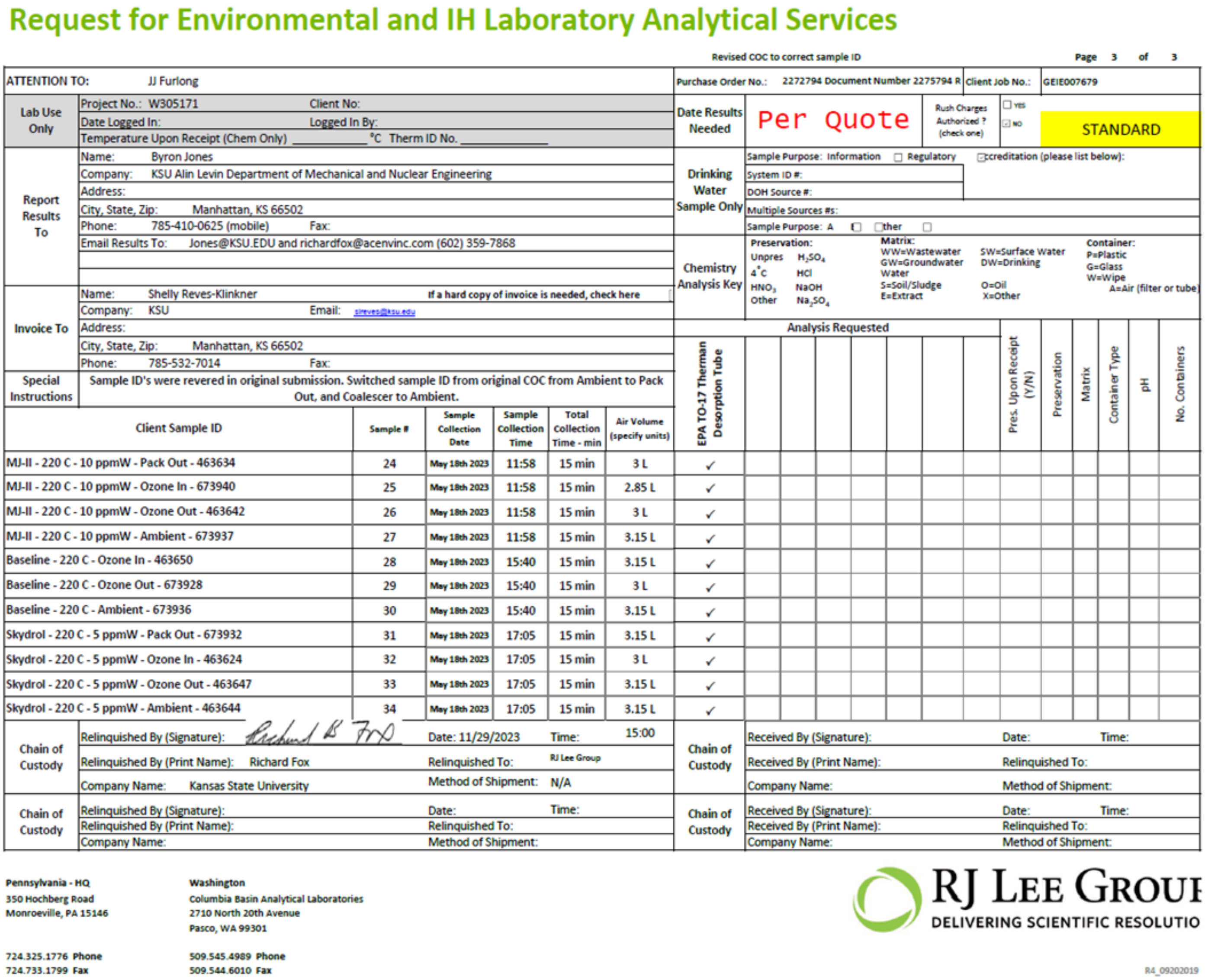
R4_09202019

Figure 137. Corrected chain of custody form for RJ Lee laboratory samples (2 of 3)



Request for Environmental and IH Laboratory Analytical Services

Revised COC to correct sample ID

Page 3 of 3

ATTENTION TO: JJ Furlong

Purchase Order No.: 2272794 Document Number 2275794 R

Client Job No.: GEIE007679

Lab Use Only

Project No.: W305171 Client No:

Date Logged In: Logged In By:

Temperature Upon Receipt (Chem Only) ____________ °C Therm ID No. ______________

Date Results Needed Per Quote

Rush Charges Authorized ? (check one) ☐ YES ☑ NO

STANDARD

Report Results To

Name: Byron Jones

Company: KSU Alin Levin Department of Mechanical and Nuclear Engineering

Address:

City, State, Zip: Manhattan, KS 66502

Phone: 785-410-0625 (mobile) Fax:

Email Results To: Jones@KSU.EDU and richardfox@acenvinc.com (602) 359-7868

Drinking Water Sample Only

Sample Purpose: Information ☐ Regulatory ☐ccreditation (please list below):

System ID #:

DOH Source #:

Multiple Sources #s:

Sample Purpose: A ☐ ☐ther ☐

Invoice To

Name: Shelly Reves-Klinkner If a hard copy of invoice is needed, check here ☐

Company: KSU Email: sireves@ksu.edu

Address:

City, State, Zip: Manhattan, KS 66502

Phone: 785-532-7014 Fax:

Chemistry Analysis Key

Preservation: Unpres H_2SO_4 4°C HCl HNO_3 NaOH Other Na_2SO_4

Matrix: WW=Wastewater GW=Groundwater Water S=Soil/Sludge E=Extract SW=Surface Water DW=Drinking O=Oil X=Other

Container: P=Plastic G=Glass W=Wipe A=Air (filter or tube)

Special Instructions Sample ID's were revered in original submission. Switched sample ID from original COC from Ambient to Pack Out, and Coalescer to Ambient.

Analysis Requested

Client Sample ID	Sample #	Sample Collection Date	Sample Collection Time	Total Collection Time - min	Air Volume (specify units)	EPA TO-17 Therman Desorption Tube	Pres. Upon Receipt (Y/N)	Preservation	Matrix	Container Type	pH	No. Containers
MJ-II - 220 C - 10 ppmW - Pack Out - 463634	24	May 18th 2023	11:58	15 min	3 L	✓						
MJ-II - 220 C - 10 ppmW - Ozone In - 673940	25	May 18th 2023	11:58	15 min	2.85 L	✓						
MJ-II - 220 C - 10 ppmW - Ozone Out - 463642	26	May 18th 2023	11:58	15 min	3 L	✓						
MJ-II - 220 C - 10 ppmW - Ambient - 673937	27	May 18th 2023	11:58	15 min	3.15 L	✓						
Baseline - 220 C - Ozone In - 463650	28	May 18th 2023	15:40	15 min	3.15 L	✓						
Baseline - 220 C - Ozone Out - 673928	29	May 18th 2023	15:40	15 min	3 L	✓						
Baseline - 220 C - Ambient - 673936	30	May 18th 2023	15:40	15 min	3.15 L	✓						
Skydrol - 220 C - 5 ppmW - Pack Out - 673932	31	May 18th 2023	17:05	15 min	3.15 L	✓						
Skydrol - 220 C - 5 ppmW - Ozone In - 463624	32	May 18th 2023	17:05	15 min	3 L	✓						
Skydrol - 220 C - 5 ppmW - Ozone Out - 463647	33	May 18th 2023	17:05	15 min	3.15 L	✓						
Skydrol - 220 C - 5 ppmW - Ambient - 463644	34	May 18th 2023	17:05	15 min	3.15 L	✓						

Chain of Custody

Relinquished By (Signature): Richard B Fox Date: 11/29/2023 Time: 15:00

Relinquished By (Print Name): Richard Fox Relinquished To: RJ Lee Group

Company Name: Kansas State University Method of Shipment: N/A

Chain of Custody

Received By (Signature): Date: Time:

Received By (Print Name): Relinquished To:

Company Name: Method of Shipment:

Chain of Custody

Relinquished By (Signature): Date: Time:

Relinquished By (Print Name): Relinquished To:

Company Name: Method of Shipment:

Chain of Custody

Received By (Signature): Date: Time:

Received By (Print Name): Relinquished To:

Company Name: Method of Shipment:

Pennsylvania - HQ
350 Hochberg Road
Monroeville, PA 15146

724.325.1776 Phone
724.733.1799 Fax

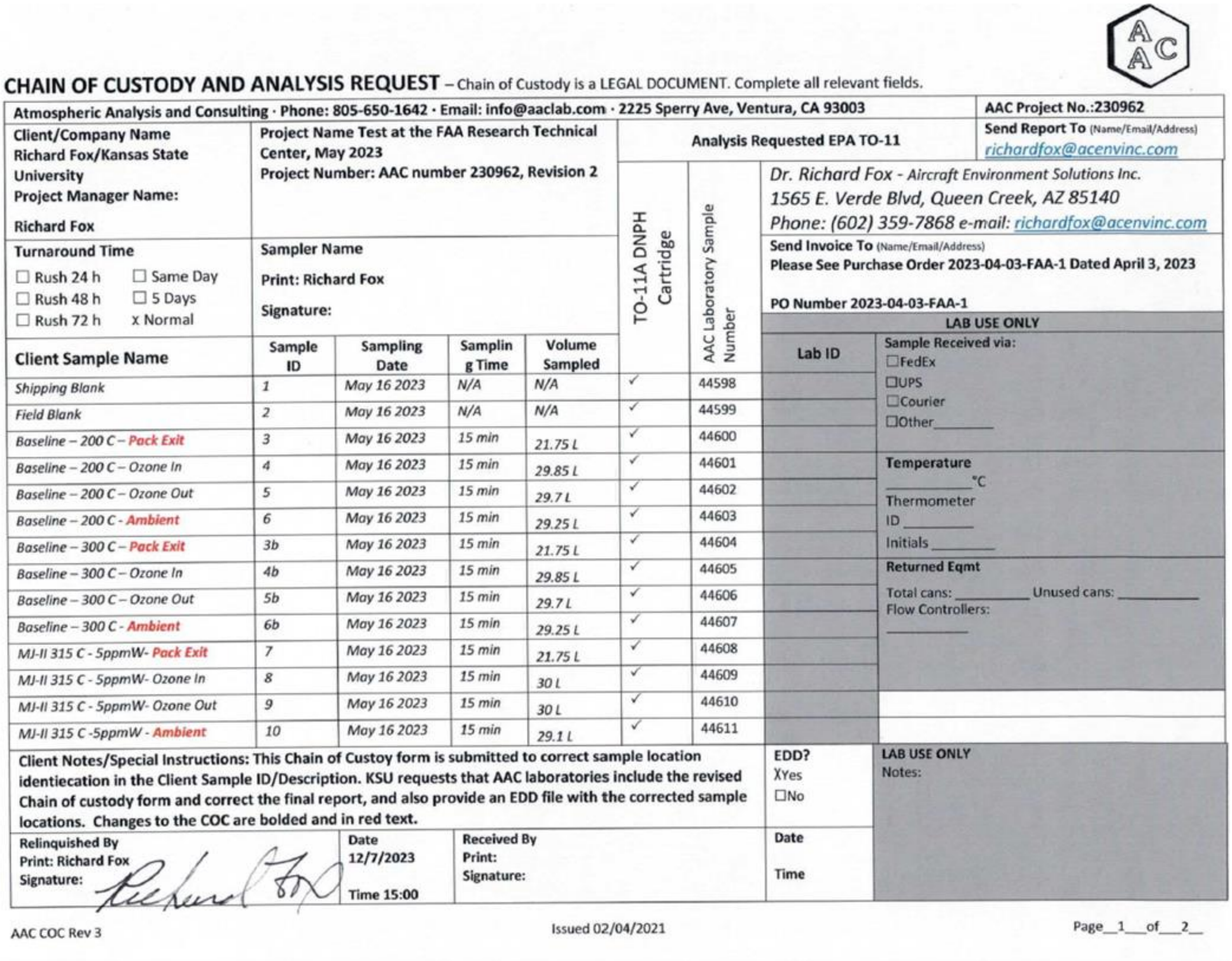
Washington
Columbia Basin Analytical Laboratories
2710 North 20th Avenue
Pasco, WA 99301

509.545.4989 Phone
509.544.6010 Fax

RJ LEE GROU
DELIVERING SCIENTIFIC RESOLUTIO

R4_09202019

Figure 138. Corrected chain of custody form for RJ Lee laboratory samples (3 of 3)



CHAIN OF CUSTODY AND ANALYSIS REQUEST – Chain of Custody is a LEGAL DOCUMENT. Complete all relevant fields.

Atmospheric Analysis and Consulting · Phone: 805-650-1642 · Email: info@aaclab.com · 2225 Sperry Ave, Ventura, CA 93003

AAC Project No.:230962

Client/Company Name Richard Fox/Kansas State University

Project Manager Name: Richard Fox

Project Name Test at the FAA Research Technical Center, May 2023

Project Number: AAC number 230962, Revision 2

Analysis Requested EPA TO-11

Send Report To (Name/Email/Address) richardfox@acenvinc.com

Dr. Richard Fox - Aircraft Environment Solutions Inc.
1565 E. Verde Blvd, Queen Creek, AZ 85140
Phone: (602) 359-7868 e-mail: richardfox@acenvinc.com

Send Invoice To (Name/Email/Address)
Please See Purchase Order 2023-04-03-FAA-1 Dated April 3, 2023

PO Number 2023-04-03-FAA-1

Turnaround Time

☐ Rush 24 h ☐ Same Day
☐ Rush 48 h ☐ 5 Days
☐ Rush 72 h x Normal

Sampler Name

Print: Richard Fox

Signature:

Client Sample Name	Sample ID	Sampling Date	Sampling Time	Volume Sampled	TO-11A DNPH Cartridge	AAC Laboratory Sample Number	Lab ID
Shipping Blank	*1*	*May 16 2023*	*N/A*	*N/A*	✓	44598	
Field Blank	*2*	*May 16 2023*	*N/A*	*N/A*	✓	44599	
Baseline – 200 C – ***Pack Exit***	*3*	*May 16 2023*	*15 min*	*21.75 L*	✓	44600	
Baseline – 200 C – Ozone In	*4*	*May 16 2023*	*15 min*	*29.85 L*	✓	44601	
Baseline – 200 C – Ozone Out	*5*	*May 16 2023*	*15 min*	*29.7 L*	✓	44602	
Baseline – 200 C - ***Ambient***	*6*	*May 16 2023*	*15 min*	*29.25 L*	✓	44603	
Baseline – 300 C – ***Pack Exit***	*3b*	*May 16 2023*	*15 min*	*21.75 L*	✓	44604	
Baseline – 300 C – Ozone In	*4b*	*May 16 2023*	*15 min*	*29.85 L*	✓	44605	
Baseline – 300 C – Ozone Out	*5b*	*May 16 2023*	*15 min*	*29.7 L*	✓	44606	
Baseline – 300 C - ***Ambient***	*6b*	*May 16 2023*	*15 min*	*29.25 L*	✓	44607	
MJ-II 315 C - 5ppmW- ***Pack Exit***	*7*	*May 16 2023*	*15 min*	*21.75 L*	✓	44608	
MJ-II 315 C - 5ppmW- Ozone In	*8*	*May 16 2023*	*15 min*	*30 L*	✓	44609	
MJ-II 315 C - 5ppmW- Ozone Out	*9*	*May 16 2023*	*15 min*	*30 L*	✓	44610	
MJ-II 315 C -5ppmW - ***Ambient***	*10*	*May 16 2023*	*15 min*	*29.1 L*	✓	44611	

LAB USE ONLY

Sample Received via:
☐FedEx
☐UPS
☐Courier
☐Other________

Temperature
__________°C
Thermometer ID ________
Initials ________

Returned Eqmt
Total cans: __________ Unused cans: ___________
Flow Controllers: ___________

Client Notes/Special Instructions: This Chain of Custoy form is submitted to correct sample location identiecation in the Client Sample ID/Description. KSU requests that AAC laboratories include the revised Chain of custody form and correct the final report, and also provide an EDD file with the corrected sample locations. Changes to the COC are bolded and in red text.

EDD?
X Yes
☐No

LAB USE ONLY
Notes:

Relinquished By
Print: Richard Fox
Signature: Richard Fox

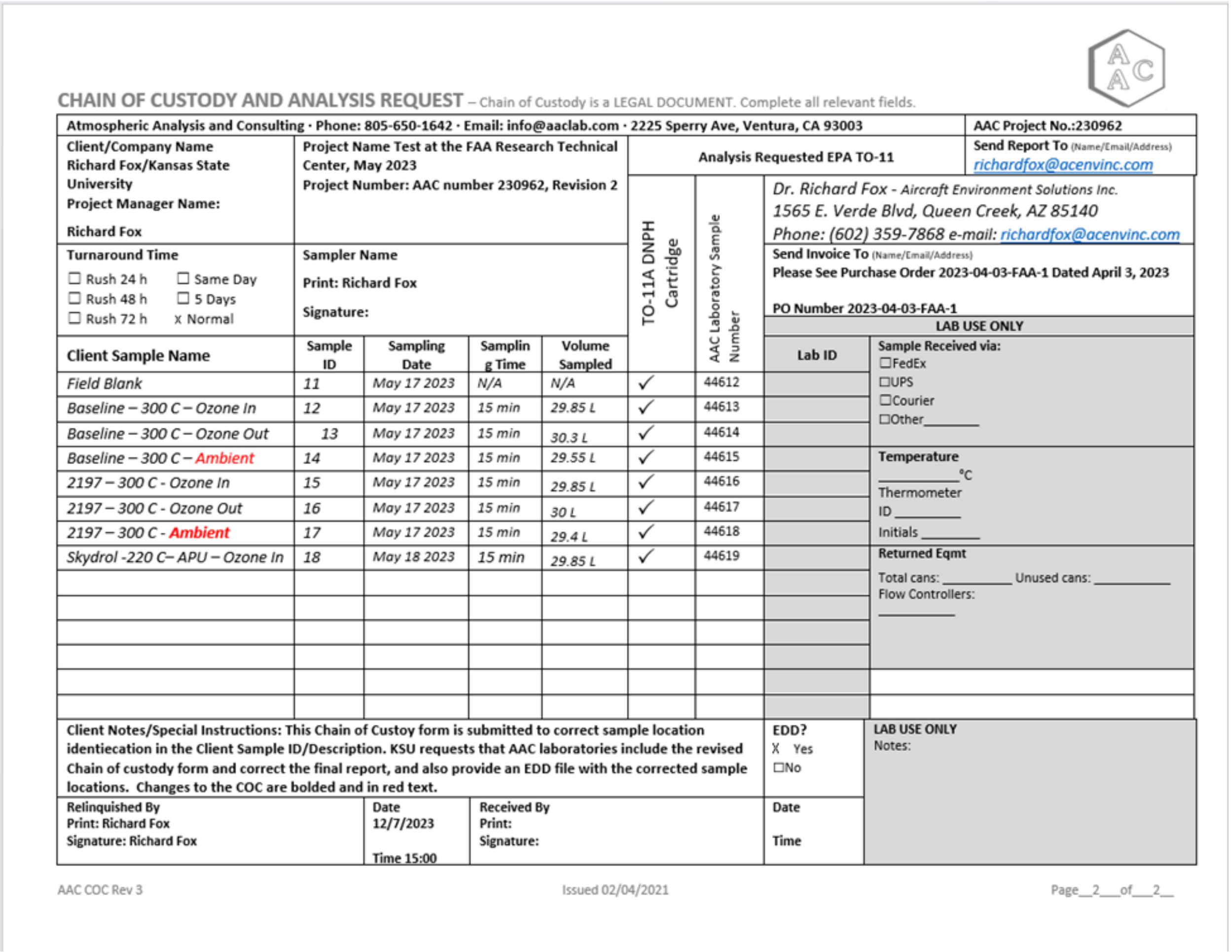
Date
12/7/2023
Time 15:00

Received By
Print:
Signature:

Date
Time

AAC COC Rev 3 Issued 02/04/2021 Page_1__of__2_

Figure 139. Corrected chain of custody form for AAC laboratory samples (1 of 2)



CHAIN OF CUSTODY AND ANALYSIS REQUEST – Chain of Custody is a LEGAL DOCUMENT. Complete all relevant fields.

Atmospheric Analysis and Consulting · Phone: 805-650-1642 · Email: info@aaclab.com · 2225 Sperry Ave, Ventura, CA 93003

AAC Project No.:230962

Client/Company Name
Richard Fox/Kansas State University
Project Manager Name:
Richard Fox

Project Name Test at the FAA Research Technical Center, May 2023
Project Number: AAC number 230962, Revision 2

Analysis Requested EPA TO-11

Send Report To (Name/Email/Address)
richardfox@acenvinc.com

Dr. Richard Fox - Aircraft Environment Solutions Inc.
1565 E. Verde Blvd, Queen Creek, AZ 85140
Phone: (602) 359-7868 e-mail: richardfox@acenvinc.com

Send Invoice To (Name/Email/Address)
Please See Purchase Order 2023-04-03-FAA-1 Dated April 3, 2023

PO Number 2023-04-03-FAA-1

Turnaround Time
☐ Rush 24 h ☐ Same Day
☐ Rush 48 h ☐ 5 Days
☐ Rush 72 h x Normal

Sampler Name
Print: Richard Fox
Signature:

LAB USE ONLY

Client Sample Name	Sample ID	Sampling Date	Sampling Time	Volume Sampled	TO-11A DNPH Cartridge	AAC Laboratory Sample Number	Lab ID
Field Blank	*11*	*May 17 2023*	*N/A*	*N/A*	✓	44612	
Baseline – 300 C – Ozone In	*12*	*May 17 2023*	*15 min*	*29.85 L*	✓	44613	
Baseline – 300 C – Ozone Out	*13*	*May 17 2023*	*15 min*	*30.3 L*	✓	44614	
Baseline – 300 C – Ambient	*14*	*May 17 2023*	*15 min*	*29.55 L*	✓	44615	
2197 – 300 C - Ozone In	*15*	*May 17 2023*	*15 min*	*29.85 L*	✓	44616	
2197 – 300 C - Ozone Out	*16*	*May 17 2023*	*15 min*	*30 L*	✓	44617	
2197 – 300 C - ***Ambient***	*17*	*May 17 2023*	*15 min*	*29.4 L*	✓	44618	
Skydrol -220 C– APU – Ozone In	*18*	*May 18 2023*	*15 min*	*29.85 L*	✓	44619	

Sample Received via:
☐FedEx
☐UPS
☐Courier
☐Other________

Temperature
___________°C
Thermometer
ID _________
Initials _________

Returned Eqmt
Total cans: __________ Unused cans: ___________
Flow Controllers:
____

Client Notes/Special Instructions: This Chain of Custoy form is submitted to correct sample location identiecation in the Client Sample ID/Description. KSU requests that AAC laboratories include the revised Chain of custody form and correct the final report, and also provide an EDD file with the corrected sample locations. Changes to the COC are bolded and in red text.

EDD?
X Yes
☐No

LAB USE ONLY
Notes:

Relinquished By
Print: Richard Fox
Signature: Richard Fox

Date
12/7/2023
Time 15:00

Received By
Print:
Signature:

Date
Time

AAC COC Rev 3 Issued 02/04/2021 Page__2___of___2__

Figure 140. Corrected chain of custody form for AAC laboratory samples (2 of 2)

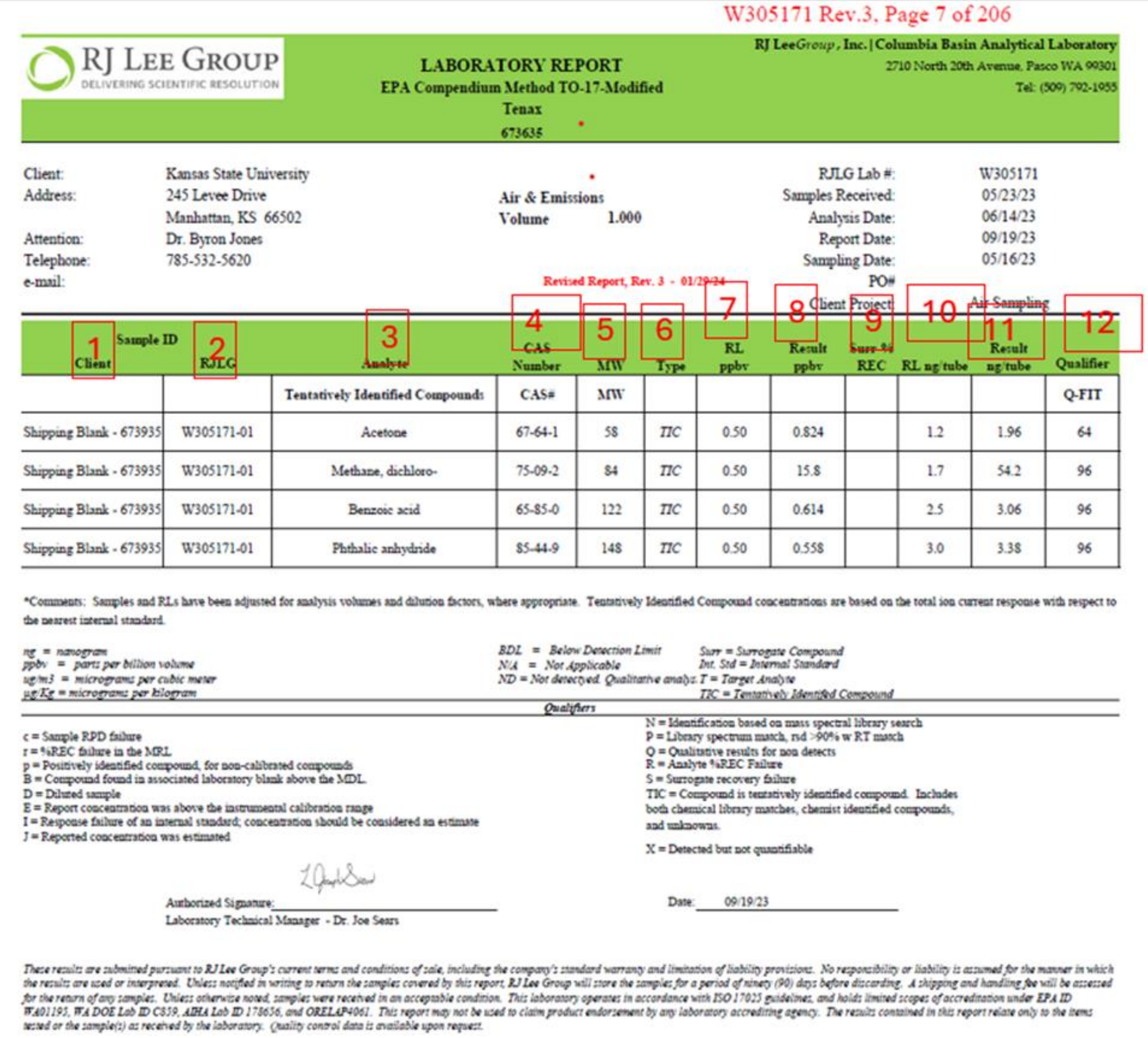
2.6.5.2 Assessment of total VOC quantities from EPA TO-17

The R. J. Lee Group (RJLG) Laboratory Report #W305171, Revision 2 (dated December 5, 2023) provides information on the VOC species captured on adsorbent media from three aircraft sampling locations (i.e., VOC/ozone converter inlet, VOC/Ozone converter exit, and Pack Exit). The ambient sample was collected using a blower under the aircraft and experienced some exhaust ingestion from the system providing air conditioning to the aircraft cabin during the testing. The VOC samples were first evaluated by first converting the data in the report to an excel file. Total VOC quantities which were presented in both ppbV and ug/M^3 were assessed by summing the quantities of the individual chemical species for each test condition. These data are summarized in stacked bar charts with species reported as ppbv. The stacked bar charts provide a compilation of information regarding the mixtures of VOCs that were reported in the RJLG laboratory report. The sample identification key below each chart contains information that enables the reader to search RJLG Report #W305171 to find specific information for each analysis (e.g., sample #, experimental condition, fluid contaminant, engine temperature, fluid injection rate, and sample collection location).

Sample #01 (shipping blank) from the EPA TO-17 VOCs report (RJLG report ID W305171, Rev. 3) is used as an example to show the reader how to work across the report table columns to decode and interpret key sample identification information in the report table(s) and accompanying electronic data deliverable (EDD) files / Excel spreadsheet datasets (KSU, 2024a).

1. “Client”:the KSU sample name and the Markes Tube Serial Number (Shipping Blank – 673935).
2. “RJLG”:the RJLG sample number (# assigned by RJLG when sample was received) (W305171-01). Subsequent samples are listed as [lab report ID #] - 02; [lab report ID #] - 03, etc.
3. “Analyte”:the Target Analyte for the EPA TO-17 method, or the Tentatively identified sample identification
4. “CAS Number”:unique Chemical Abstract Service Number, if known
5. “MW”:analyte molecular weight (if known)
6. “Type”:sample type, with identification key listed below the table.
    a. “Int. Std’:internal calibration standard
    b. ‘T’:target compound for the EPA TO-17 method
    c. ‘Surr’:surrogate standard that is near the gas chromatographic retention time, with a peak area or peak height that may be representative of similar compounds
    d. ‘TIC’:Tentatively Identified Compound which is not on the EPA TO-17 hit list but has sufficient chemical characteristics that it may be potentially identified.
7. “RL ppbv”: Reporting Limit, the smallest concentration of a compound in ppbv units that can be reported by the laboratory, based on sample volume.
8. “Results”:sample compound concentrations in ppbv, **not corrected for blanks.**
9. “**Surr % REC**”:method recovery efficiency for the surrogate standards.
10. “RL ng/tube”: Reporting Limit, the smallest concentration of a compound in ng/tube units that can be reported by the laboratory.

11. Results”:sample compound concentrations in ng/tube, **not corrected for blanks.**
12. ““‘**Qualifier**”:notes and/or remarks relevant to an individual sample; see “Qualifiers” identification key listed below the table (i.e., below the double line).



W305171 Rev.3. Page 7 of 206

RJ LEE GROUP
DELIVERING SCIENTIFIC RESOLUTION

LABORATORY REPORT
EPA Compendium Method TO-17-Modified
Tenax
673635

RJ LeeGroup, Inc.|Columbia Basin Analytical Laboratory
2710 North 20th Avenue, Pasco WA 99301
Tel: (509) 792-1955

Client: Kansas State University
Address: 245 Levee Drive
Manhattan, KS 66502
Attention: Dr. Byron Jones
Telephone: 785-532-5620
e-mail:

Air & Emissions
Volume 1.000

RJLG Lab #: W305171
Samples Received: 05/23/23
Analysis Date: 06/14/23
Report Date: 09/19/23
Sampling Date: 05/16/23
PO#
Client Project: Air Sampling

Revised Report, Rev. 3 - 01/29/24

Sample ID Client	RJLG	Analyte	CAS Number	MW	Type	RL ppbv	Result ppbv	Surr % REC	RL ng/tube	Result ng/tube	Qualifier
		Tentatively Identified Compounds	CAS#	MW							Q-FIT
Shipping Blank - 673935	W305171-01	Acetone	67-64-1	58	TIC	0.50	0.824		1.2	1.96	64
Shipping Blank - 673935	W305171-01	Methane, dichloro-	75-09-2	84	TIC	0.50	15.8		1.7	54.2	96
Shipping Blank - 673935	W305171-01	Benzoic acid	65-85-0	122	TIC	0.50	0.614		2.5	3.06	96
Shipping Blank - 673935	W305171-01	Phthalic anhydride	85-44-9	148	TIC	0.50	0.558		3.0	3.38	96

*Comments: Samples and RLs have been adjusted for analysis volumes and dilution factors, where appropriate. Tentatively Identified Compound concentrations are based on the total ion current response with respect to the nearest internal standard.

ng = nanogram
ppbv = parts per billion volume
ug/m3 = micrograms per cubic meter
µg/Kg = micrograms per kilogram

BDL = Below Detection Limit
N/A = Not Applicable
ND = Not detected. Qualitative analys.

Surr = Surrogate Compound
Int. Std = Internal Standard
T = Target Analyte
TIC = Tentatively Identified Compound

Qualifiers

c = Sample RPD failure
r = %REC failure in the MRL
p = Positively identified compound, for non-calibrated compounds
B = Compound found in associated laboratory blank above the MDL.
D = Diluted sample
E = Report concentration was above the instrumental calibration range
I = Response failure of an internal standard; concentration should be considered an estimate
J = Reported concentration was estimated

N = Identification based on mass spectral library search
P = Library spectrum match, rsd >90% w RT match
Q = Qualitative results for non detects
R = Analyte %REC Failure
S = Surrogate recovery failure
TIC = Compound is tentatively identified compound. Includes both chemical library matches, chemist identified compounds, and unknowns.

X = Detected but not quantifiable

Authorized Signature:
Laboratory Technical Manager - Dr. Joe Sears

Date: 09/19/23

These results are submitted pursuant to RJ Lee Group's current terms and conditions of sale, including the company's standard warranty and limitation of liability provisions. No responsibility or liability is assumed for the manner in which the results are used or interpreted. Unless notified in writing to return the samples covered by this report, RJ Lee Group will store the samples for a period of ninety (90) days before discarding. A shipping and handling fee will be assessed for the return of any samples. Unless otherwise noted, samples were received in an acceptable condition. This laboratory operates in accordance with ISO 17025 guidelines, and holds limited scopes of accreditation under EPA ID WA01195, WA DOE Lab ID C859, AIHA Lab ID 178656, and ORELAP4061. This report may not be used to claim product endorsement by any laboratory accrediting agency. The results contained in this report relate only to the items tested or the sample(s) as received by the laboratory. Quality control data is available upon request.

Figure 141. Typical RJ Lee report page

The EPA TO-17 data are presented as stacked bar charts. Each figure depicts a portion of the molecular weight range to better enable the reader to differentiate between the numerous compounds, as follows:

- Figure 142. EPA TO-17, tentatively identified compounds with molecular weights 41 - 90
- Figure 143. EPA TO-17, tentatively identified compounds with molecular weights 92 - 120
- Figure 144. EPA TO-17, tentatively identified compounds with molecular weights 121 - 142
- Figure 145. EPA TO-17, tentatively identified compounds with molecular weights 143 - 266

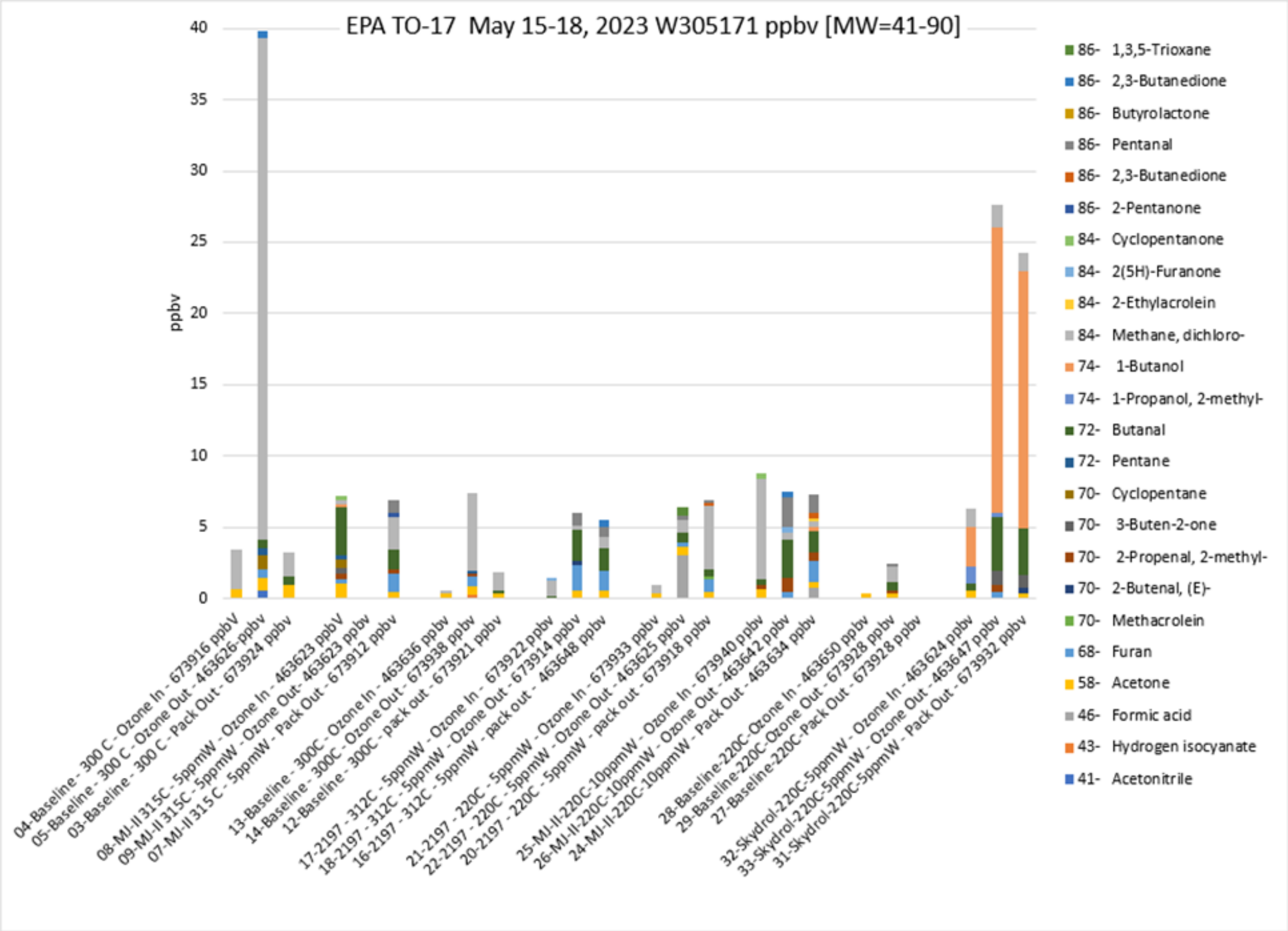


Figure 142. EPA TO-17, tentatively identified compounds with molecular weights 41 - 90

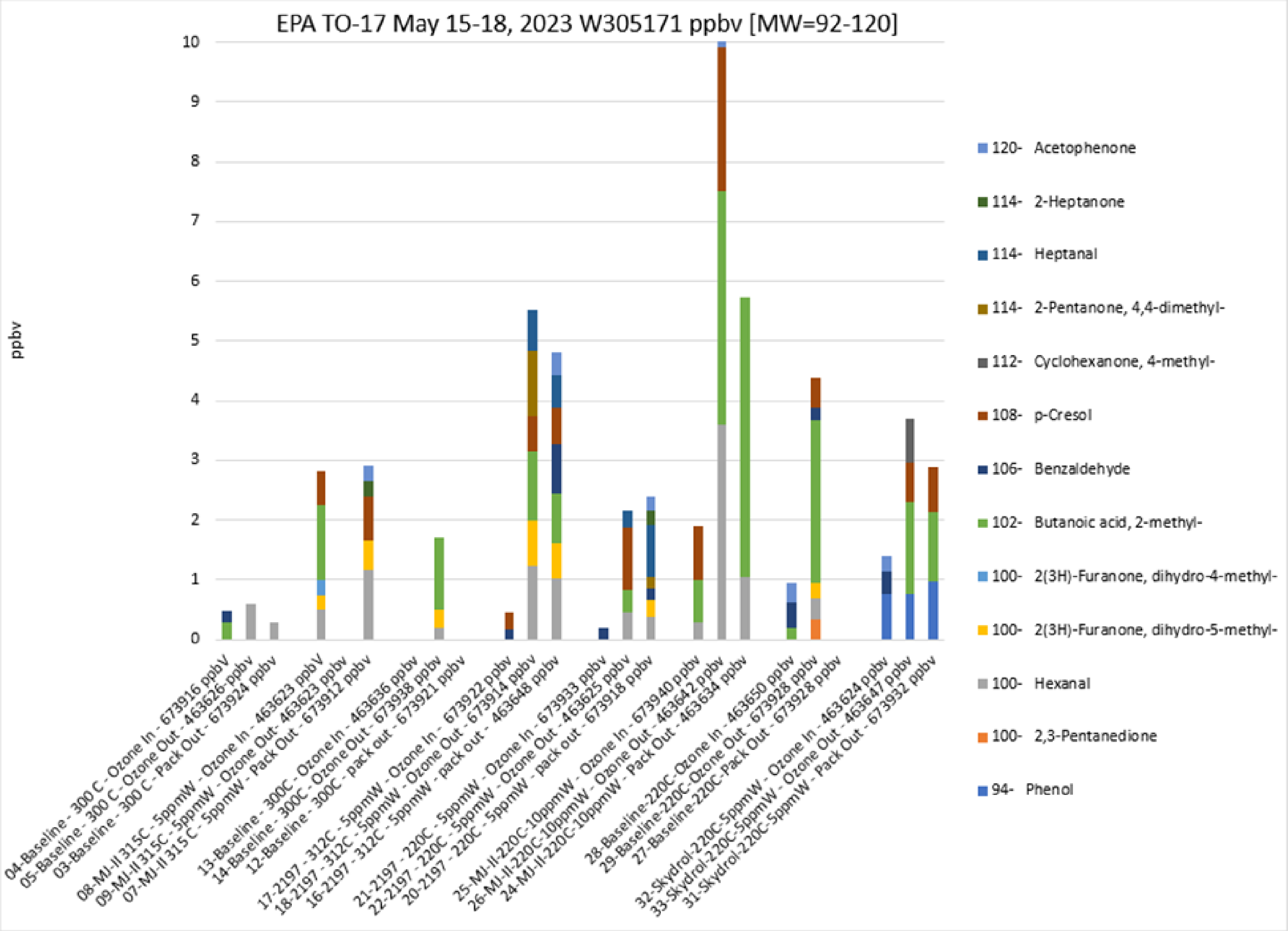


Figure 143. EPA TO-17, tentatively identified compounds with molecular weights 92 - 120

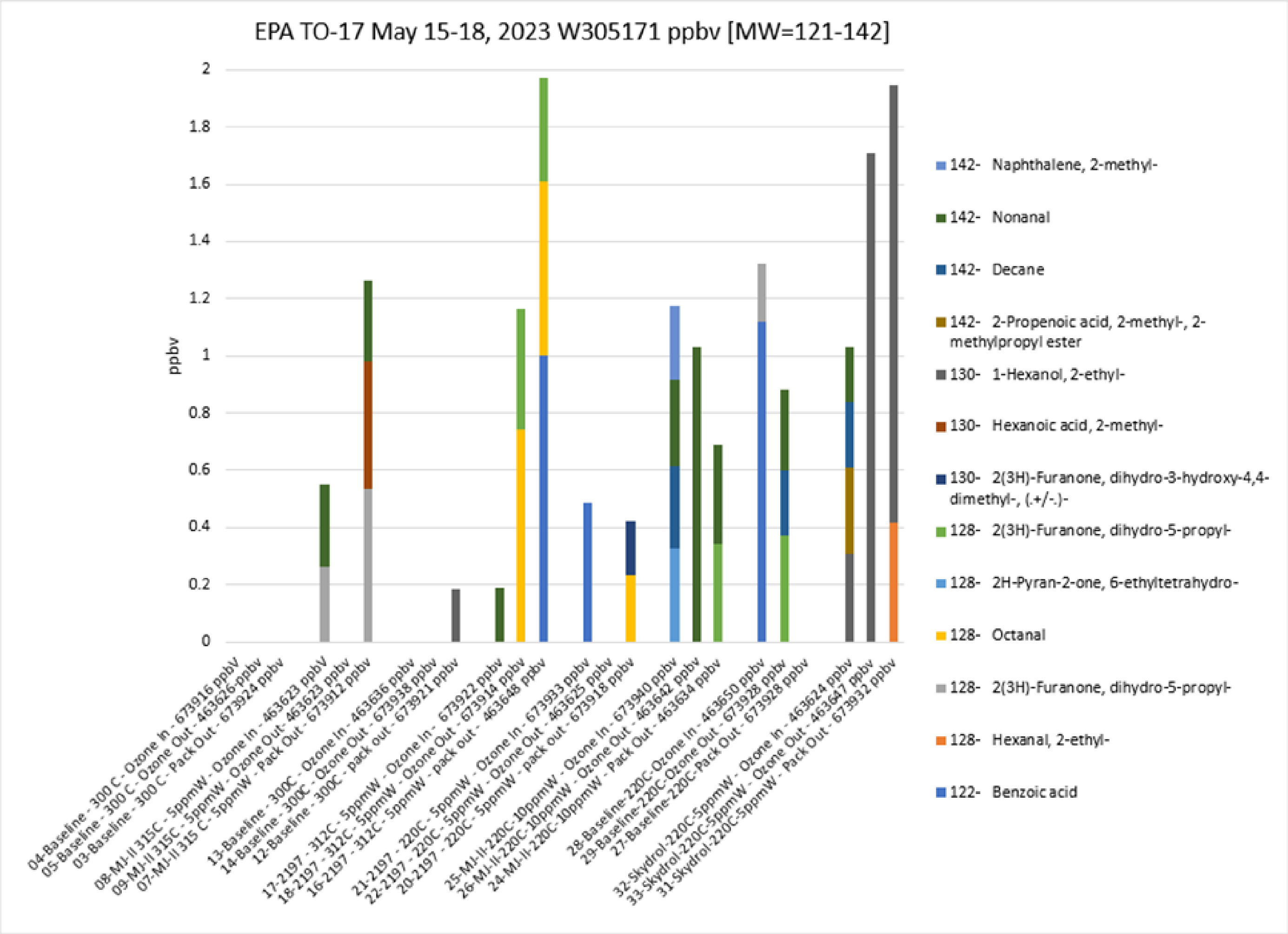


Figure 144. EPA TO-17, tentatively identified compounds with molecular weights 121 - 142

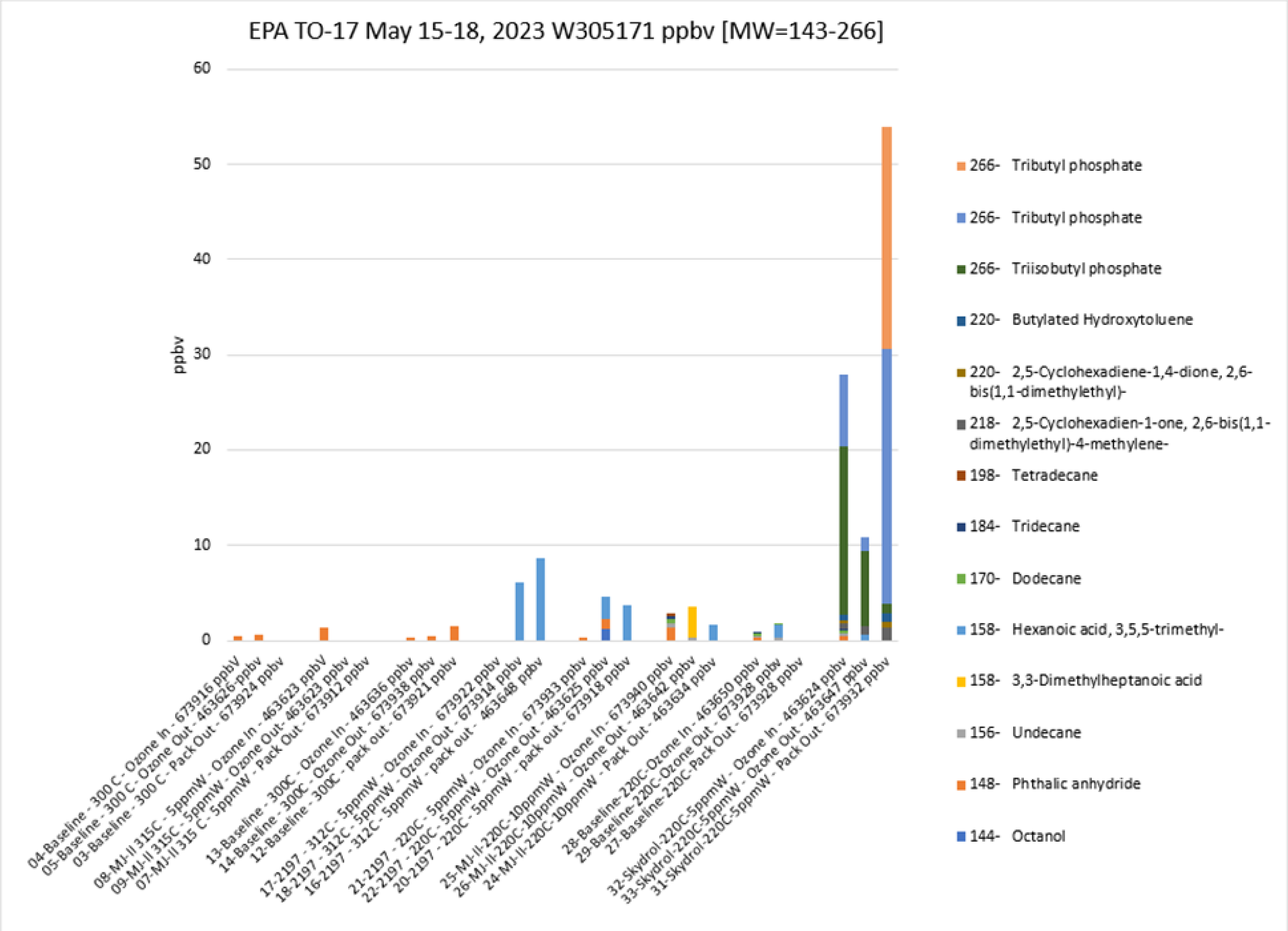
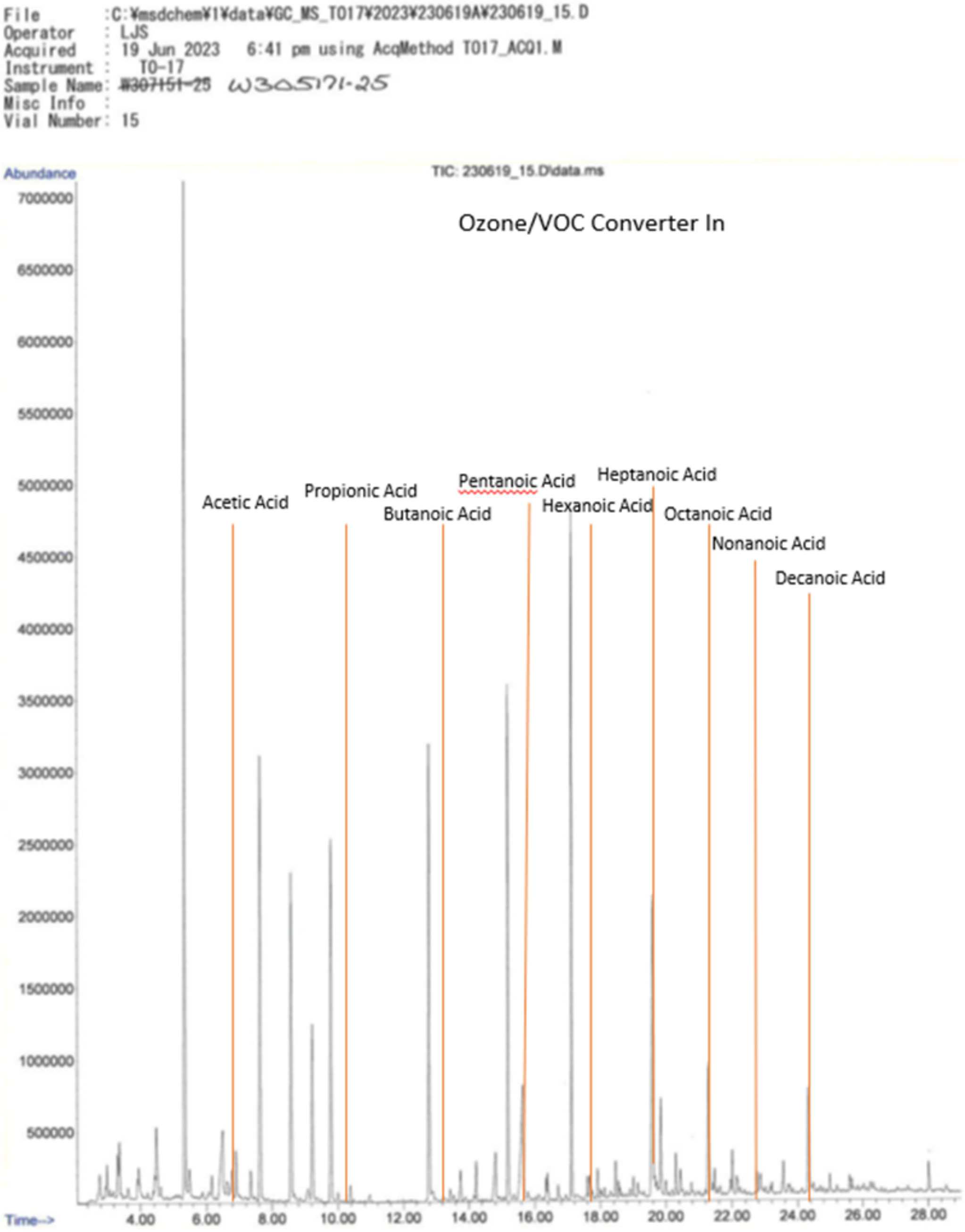


Figure 145. EPA TO-17, tentatively identified compounds with molecular weights 143 - 266

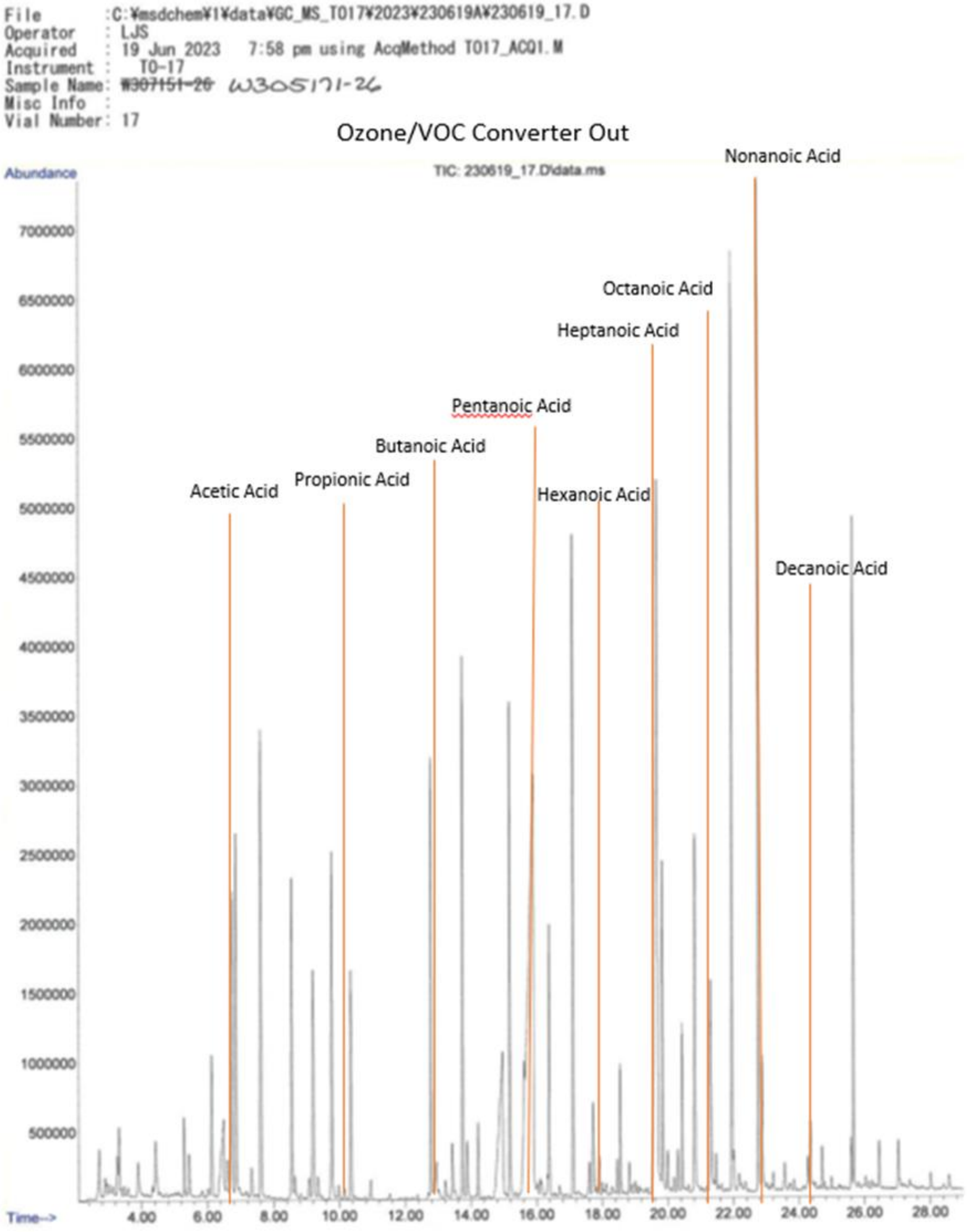
2.6.5.3 Carboxylic acids using SIM mode

There was sufficient signal to utilize the Selective Ion Mode and Internal Standards to quantify carboxylic acids. Figure 146 and Figure 147 indicate well separated peaks for the carboxylic acids. This enabled re-running the samples against internal standards, the results of which are plotted in Figure 148. Pentanoic and heptanoic acid stood out in the stacked bar charts.



File :C:¥msdchem¥1¥data¥GC_MS_T017¥2023¥230619A¥230619_15.D
Operator : LJS
Acquired : 19 Jun 2023 6:41 pm using AcqMethod T017_ACQ1.M
Instrument : TO-17
Sample Name: ~~W307151-25~~ W305171-25
Misc Info :
Vial Number: 15

Figure 146. SIM mode analysis: carboxylic acids at ozone converter inlet



File :C:¥msdchem¥1¥data¥GC_MS_T017¥2023¥230619A¥230619_17.D
Operator : LJS
Acquired : 19 Jun 2023 7:58 pm using AcqMethod T017_ACQ1.M
Instrument : TO-17
Sample Name: ~~W307151-26~~ W305171-26
Misc Info :
Vial Number: 17

Figure 147. SIM mode analysis: carboxylic acids at ozone converter exit

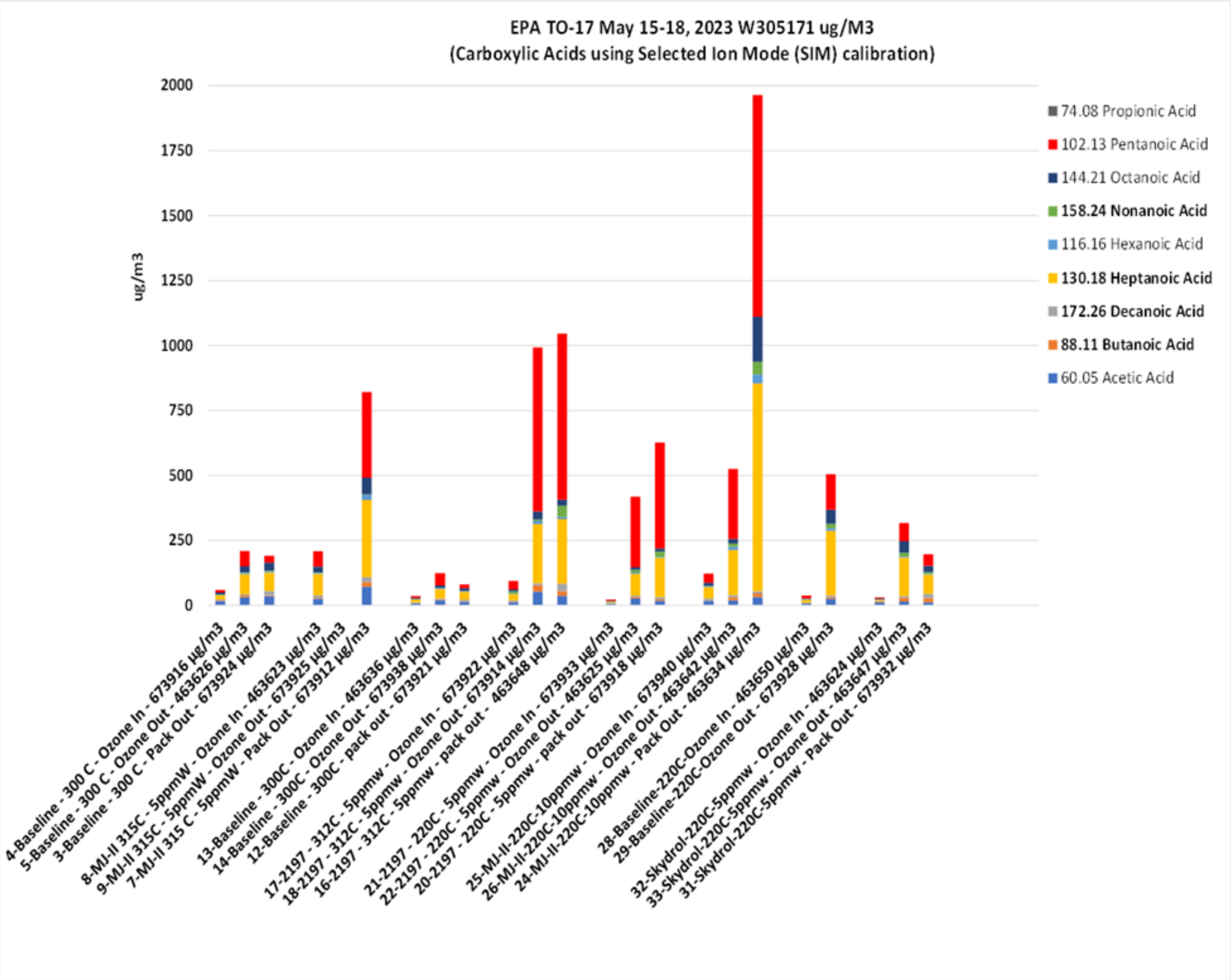


Figure 148. RJLG SIM mode analysis using internal standards: carboxylic acids by EPA TO-17

2.6.5.4 Carboxylic acids (German Method VDI 4301)

Table 11 summarizes the carboxylic acid data obtained using German Method VDI 4301

Table 11. Concentrations in ug/m3 of detected carboxylic acids of C1 to C12 samples

	Propanoic Acid	**2-Methyl-butyric Acid**	**Pentanoic Acid**	**Hexanoic Acid**	**Heptanoic Acid**	**Octanoic Acid**	**Nonanoic Acid**	**Decanoic Acid**
[μg/m^3]								
Tuesday May 16, 2023, #3 Engine								
C1-Pack Out	0.6	0.2	4.7	2.7	5.5	5.2	1.8	1.5
C2-VOC/ozone converter inlet	0.4	0	1.5	1.3	2.4	2.1	0.8	0.3
C3-VOC/ozone converter exit	0.5	2.4	6.4	1.3	3.5	2.2	0.6	0.2
C4-Ambient	0*	0	0.1	0.9	1.6	0.4	0	0
C5-VOC/ozone converter inlet	2.4	12.9	32.2	2.3	17.7	13.7	0	4.1
C6-VOC/ozone converter exit	13.2	152.4	280.5	15.8	113.6	65.8	0	17.5
C7-Ambient	0.5	1.1	5.9	1.7	3.6	2.7	0	0
Wednesday May 17, 2023., #3 Engine								
C8-VOC/ozone converter inlet	0.2	0.2	17.3	1.8	6.9	4.2	6.1	3.2
C9-VOC/ozone converter exit	12.6	11.6	520.8	8.7	95.5	25.7	19.2	7.7
C10-Ambient	0	0	3.6	0.5	1.7	0.3	0	0
Thursday, May 18, 2023, APU								
C11-VOC/ozone converter inlet	0.5	4.0	14.7	1.9	7.3	0.3	0	0
C12-VOC/ozone converter exit	3.5	105.2	272.1	10.0	117.5	39.5	25.1	9.8
* A value of zero (0) = not detected								

The carboxylic acids comparative results from Fraunhofer ITEM and RJ Lee Group, presented in Figure 149 indicate that pentanoic acid and heptanoic acid are the dominant carboxylic acids present.

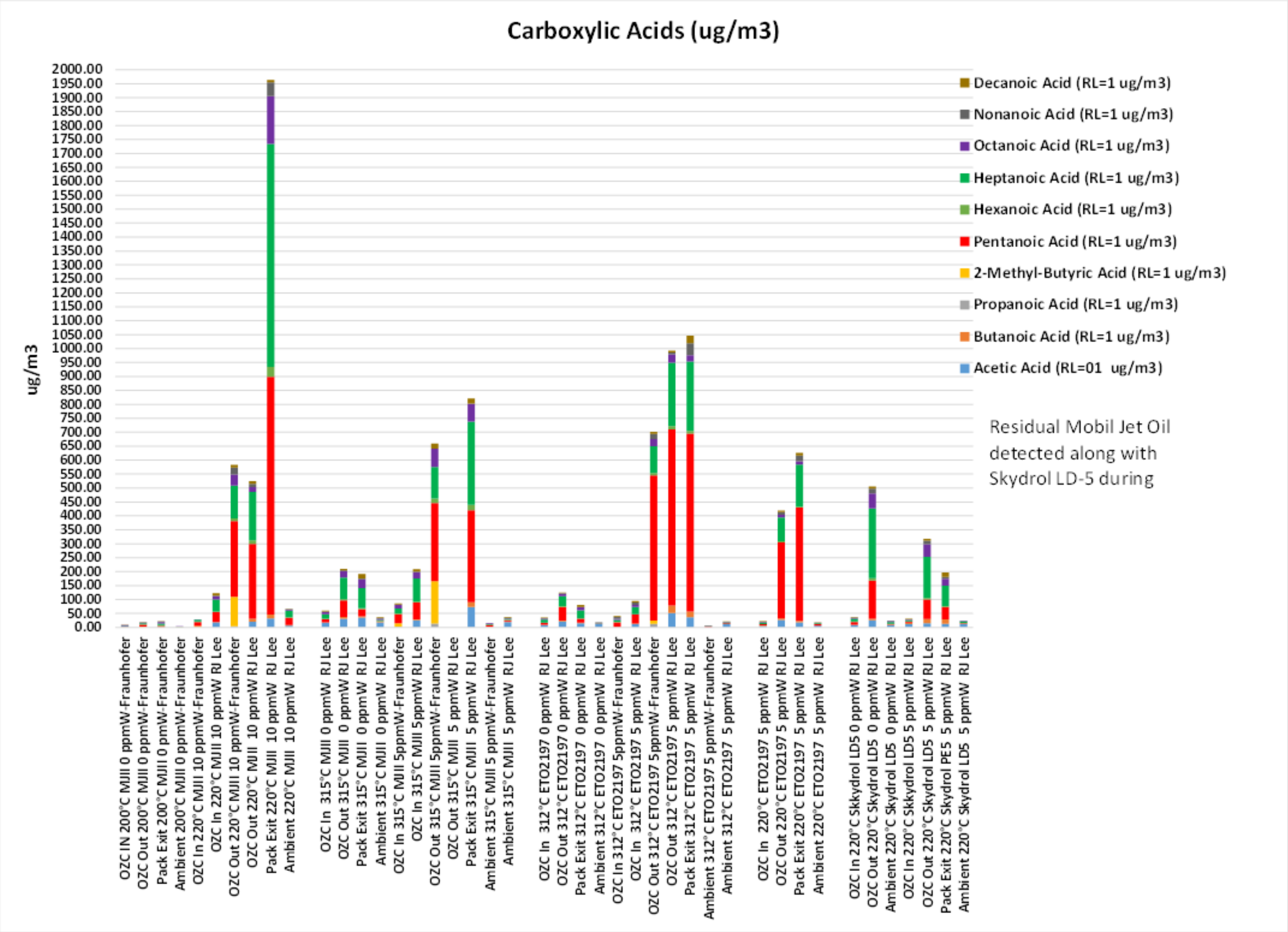


Figure 149. Dominant carboxylic acids are pentanoic and heptanoic acids

3 Executive discussion

This executive discussion addresses results from the Phase 2, Volume 1 Report (i.e., May 2022 engine stand tests conducted at KSU) and the Phase 2, Volume 2 (May 2023 ground-based, on-wing aircraft tests conducted at the FAA's WJHTC). Thus, the intent of this executive discussion is to summarize the overall results of the entire 30-month project.

3.1 Ultrafine particles

Ultrafine particles (UFP) have been proven to be a reliable and sensitive indicator of engine oil contamination in bleed air. This reliability has been demonstrated through a number of different experiments including test stand engines and on-aircraft engines as follows:

NASA- Vehicle Integrated Propulsion Research (VIPR)

- P&W 2000 C17 Aircraft Propulsion Engine (on aircraft)
- Allison C18 Helicopter Engine (on test stand)
- Allison C28B Helicopter Engine (on test stand)

FAA Phase 1-ASHRAE

- Garrett 85-98DHF APU (on test stand)
- Alison C28 Helicopter Engine (on test stand)

FAA Phase 2

- Honeywell 131-9A APU (on aircraft)
- Allison C28B Helicopter Engine (on test stand)
- P&W JT9D 747 Aircraft Propulsion Engine May 2023 (on aircraft)
- Honeywell 660-4x APU May 2023 (on aircraft)

In addition to this variety of engines, four different methods on introducing contaminating engine oil into the engine were employed:

- Atomized and injected into engine intake air.
- Not atomized and injected into engine air inlet.
- Atomized and injected into engine compressor through inspection port.
- Not atomized and injected into bleed air immediately downstream of the compressor.

In all cases, UFP increased by multiple orders of magnitude with oil contamination rates down to 1 ppmm and with bleed air temperatures above 150^{o} C. In addition to UFP being a reliable indicator of oil contamination, it was demonstrated that there are reasonable cost (<$10,000) sensor technologies that may be suitable for aircraft applications already in the marketplace including the Pegasor G2 and the Naneos Partector II.

Not only have UFP been reliably present with oil contamination, but they have also clearly been the best real time indicator of oil contamination when compared to other options including fine particles and various gas sensors. The one exception in this regard may be the Honeywell high temperature total volatile organic compound (HTTVOC) instrument which also performed well in the May 2023 experiments but has not had the extensive evaluation of prior experiments like UFP.

At this point, a strong recommendation that UFP is a good option, and likely the preferred option, for sensing engine oil contamination of bleed air can be made with one caveat -- all the experiments noted were conducted with new engine oil straight out of a freshly opened can. None of the experiments utilized used or aged engine oil as it would exist in the engine in the case of an actual contamination event on an aircraft.

The FAA Phase 2, engine test stand experiments (conducted in May 2022) indicated that the UFP seen with oil contamination were likely due to condensation in the bleed air as it is cooled to approximately room temperature. The FAA Phase 2 ground-based, on-wing aircraft experiments with a Boeing 747 airplane (conducted in May 2023) clearly confirmed this expectation. For this condensation to occur, components of the oil first had to be vaporized so they could then be condensed. The question then arises as to whether or not used engine oil will respond similarly.

There is one experiment that indicates that engine oil, as it exists in the engine, does generate large concentrations of UFP when it contaminates bleed air. The FACTS (Houtzager, 2020) program conducted an experiment where a compressor seal leak was artificially generated by dry cranking an engine. Figures 5.9 – 5.11 of that report show that the resulting contamination of bleed air resulted in UFP concentrations in excess of 10^7 particles/cc. This result is similar to concentrations reported in the listed experiments. Size distributions were also similar. These results are encouraging but do not provide definitive proof that used engine oil will generate elevated concentrations of UFP just as new oil does, because the dry cranking experiments were uncontrolled – the engine oil was introduced into the bleed air in unknown quantities.

The next steps in the research program, if conducted, will be costly. It would be wise to conduct experiments to verify if used and/or aged aircraft engine oil generates UFP similar to the new engine oil. Extensive testing is not needed, rather only a limited number of experiments need to be conducted at the lower end of the temperature range (e.g. ~ 200^{o}C). If UFP are generated with used oil at this temperature, then one can be reasonably confident that they will be generated at higher temperatures but not vice versa. Thus, the tests could be conducted with an APU or test stand engine where it is very easy to inject the contaminant. Additionally, the May 2023 experiments show that bleed air samples can be drawn from anywhere in the bleed air path, wherever convenient. Also, extensive instrumentation would not be needed. All that is needed is an injection pump and a scanning mobility particle sizer (SMPS) or other UFP instrument (at least two devices for redundancy).

Oil taken from an engine during servicing could be used and only a modest quantity (e.g., 1 liter) would be needed. It would be a good idea to collect samples from several aircraft and, preferably for aircraft using different oils. Since chemical sampling is not involved, long, steady-state test periods are not needed. Several days for test setup and teardown, and one to two days of testing (one week overall) is probably all that would be required. All testing could be done at 5 ppmm of injected fluid contaminant since extensive data are available for that condition for comparison. A detailed project plan and cost estimate were not developed but a rough estimate is that such testing would cost in the range of $100K to $300K if a suitable test engine is available.

If these tests show the used engine oil does not generate high levels of UFP when it contaminates bleed air, it would be necessary to reevaluate the recommended method for detecting engine oil contamination.

3.2 Temperature transients and system cleaning

The engine test stand experiments reviewed and conducted in the Phase 1 project, as well as the engine test stand experiments conducted in this FAA project (i.e., Phase 2, Vol. 1; May 2022 experiments) both provide strong evidence that contaminants could be released for heat exchanger surfaces and possible other surfaces in the bleed air system. With prior engine oil contamination of the bleed air, an increase in the bleed air temperature resulted in elevated UFP and VOCs even though the engine may have run for some time with no injected contamination. The resulting UFP concentrations were comparable to those measured with the injected engine oil contamination. This phenomenon was seen clearly in the May 2023 ground-based, on-wing aircraft experiments. Clean out cycles of approximately 45 minutes with elevated bleed air temperature were employed. Typically, the concentrations would start to drop off after about 10 minutes at the elevated temperature and would decay exponentially to baseline values. Concentrations could remain above baseline values for 30 minutes or more. If the bleed air temperature was reduced following a period of elevated bleed air temperature, the concentration would drop much more rapidly. Presumably, this response to temperature increase is due to engine oil aerosol depositing on bleed air system surfaces and volatile components being driven off with the increased temperature. As the deposited contamination is depleted, the concentration in the bleed air drops off. Similarly, when the bleed temperature is reduced, contaminants are no longer driven off.

This response to transients has important consequences for practical application in aircraft with regard to interpreting output sensor data intended to detect bleed air contamination. Temperature transients may generate particles or increase concentrations of bleed air contaminants, thereby falsely indicating a leak at the time of measurement. These temperature transients can occur in response to increases in engine power which in turn increases engine speed and bleed air temperature. They can also result from the automatic switch over from the low-pressure bleed air exit port to the high-pressure bleed air exit port. In this case, a decrease in engine power can result in an increase in bleed air temperature. Also, the switch over from cooling to heating mode can result in increased temperature in some parts of the bleed air system. Similarly, when cooling requires operation of the pack compressor, the increased cooling requirement can result in increased temperature in some parts of the system. Thus, it is difficult to predict when temperature increases will occur in the bleed air system without detailed bleed air system and air-conditioning pack knowledge and detailed information about its operating mode at a given time. Thus, any indication of transient bleed air contamination needs to be interpreted carefully and does not necessarily indicate a seal leak or ingestion at that specific point in time.

The May 2023 ground-based, on-wing aircraft experiments incorporated a “cleanout” between some of the experimental conditions where the bleed air temperature was increased to the maximum feasible value for a period. This cleaning process was included for the purpose of data quality and was not designed to evaluate the effectiveness of the elevated temperature for cleaning purposes. However, sensors were operated throughout the cleaning period and the data provide some insights into the cleaning process. As noted in the preceding paragraph, the elevated temperature did help return UFP concentrations to baseline values, especially once the bleed temperature was again lowered. Also, decline in UFP concentrations is rather slow and operation for a short period of time at the elevated temperature is unlikely to effectively clean deposited engine oil contamination. Many questions remain as to temperatures required for cleaning engine oil contamination from the bleed air system and the effectiveness of elevated bleed air temperature for cleaning this contamination from the system. It is clear, however, that leak repair may not prevent a future bleed air quality event. Residual contamination may persist leading to a future event that will result primarily as a result of temperature transients. It is apparent that effective cleaning of the bleed air system is important following engine oil contamination. A program to evaluate the effectiveness of cleaning procedures and to establish standardized methods and processes for cleaning bleed air systems that have been documented to be effective is recommended.

3.3 Ultrafine particle generation by elevated ozone concentrations

Previous research (Bekö G, 2015) has shown that UFP concentrations in the aircraft cabin are elevated in response to elevated ozone (O_3) concentrations in the cabin. It is believed the UFP are the byproducts of chemical reactions between ozone and organic compounds on surfaces in the cabin, but the details of the chemistry have not been verified. It is not known if elevated O_3 concentrations in the ambient air will also result in elevated particulate concentrations in bleed air. Recent research has also found that oil contamination of simulated bleed air resulted in an ozone sensor giving a false indication of elevated ozone concentration (Mayer, 2024). Ozone sensors work on the principle of light absorption by ozone. Ultraviolet (UV) light with a wavelength of 253.7 nm is highly absorbed by O3 and by measuring the amount of this light absorbed (light attenuation), the concentration of O_3 can be determined. It is believed the ozone sensor compromised specificity (to include sensing engine oil) is due to light scattering and/or absorption by the aerosol generated by the engine oil contamination, but this cause has not been verified.

These two phenomena have a potential for confounding both O_3 measurements and bleed air engine oil contamination detection. That is, elevated O_3 concentrations could give a false indication of bleed air contamination due to the increased UFP. Likewise, engine oil contamination could result in a false indication of elevated O_3 concentration due to the sensitivity of the O_3 sensor to UFP generated by the engine oil contamination.

The basic physics for light scattering and absorption by UFP are complex but have been understood for some time. See, for example, van de Hulst discussion on the subject (van de Hulst, 1981, p. 360 and 405). To simplify, light scattering effects are limited to particles at least one-half the wavelength of the light – or about 127 nm for the light used in O_3 sensors. Thus, scattering of light by the UFP generated oil contamination aerosols is not likely to be a major factor. Oil contamination, however, increases concentrations of particles up to about 1 µm – 2 µm in diameter. These larger particles could be responsible for the sensitivity of the O_3 sensors to engine oil contamination. Also, light absorption by particles less than one-half the wavelength can occur. The exact phenomenon that causes the O_3 sensor to respond to oil contamination is not so important as is the fact that it apparently does occur.

UFP concentrations may increase due to the presence of elevated O_3 concentrations. It may be desirable to also include an O_3 sensor in a bleed air contamination detection instrument package. The ultraviolet ozone sensor can differentiate an increase in UFP as a result of O_3 from an increase in UFP due to oil contamination. This application is similar to the use of a CO_2 sensor used to differentiate an increase in UFP for exhaust ingestion from an increase due to engine oil contamination. However, if the ultraviolet O_3 sensor is also responsive to UFP due to ability to sense UFP at the lamp wavelength, then it cannot be used to discriminate between O_3 generated UFP and engine oil generated UFP.

Given the very limited data available both for O_3 sensor response to engine oil contamination in bleed air and for UFP generation in bleed air by elevated ozone, it may be wise to investigate this question further. It may not be a problem at all as the elevated UFP concentration in response to elevated O_3 measured by Bekö et al. (2015) are at least two orders of magnitude below those typically seen with engine oil contamination but those measurements were for cabin air, not bleed air. Bleed air response is most likely to be lower, but no data exists to verify this expectation. A limited series of experiments should be able to make this determination. If O3 levels, consistent with the maxima encountered with the more at-risk flights at **high altitudes and high latitudes,** are shown to result in UFP concentrations in bleed air at levels sufficient to be mistaken for engine oil contamination, then it may be necessary to identify O3 sensing technology that is not sensitive to UFP. It may also be beneficial to design sensing methods that eliminate the problem such as high efficiency particulate air (HEPA) filtration of the sample air supplied to the sensor. The first step would be to introduce sufficient O_3 into engine intake air to be representative of the worst-case exposure and determine if any increase in UFP sufficient to be a concern result in the bleed air. If not, then no further investigation should be needed. If they are of concern, then a second step to identify O_3 sensing or sampling methods that are not sensitive to engine oil contamination would be needed. A detailed test plan and cost estimate is outside the scope of this Phase 2 project, but if a suitable aircraft is available for the test, then a rough estimate is that it would cost $200K to $500K to make the evaluation. Given the low concentrations of UFP seen by Bekö et al. (2015), this concern is reasonably low risk and not a reason to hold up development of a prototype bleed air contamination detection instrument package.

3.4 Recommendations for continuing the research program

There are some questions about used oil and O3 that may need answering. However, the next major research step towards establishing the viability of bleed air contamination detection is to design a prototype instrument package based on the knowledge gained to date and instrument routine revenue flights for data collection. At this point, there is good knowledge as to what needs to be measured to detect engine oil contamination and, to a lesser extent, hydraulic fluid. Similarly, there is good knowledge as to what sensors and instruments are available to make the appropriate measurements. In addition to the technical challenges of designing the actual package of equipment that would be installed and operated, there is the added challenge of the apparent infrequency of major air quality events on aircraft of any kind and not all events are caused by bleed air contamination (Anderson, 2021). The exact frequency is a matter of debate but may be in the range of 1 in 1000 flights to 1 in 10,000 flights (Shehadi, 2015). Thus, any research program intended to evaluate the viability and usefulness of bleed air contamination will likely require a large number of instrumented aircraft and many flights in order to make that evaluation. Initially, the focus needs to be on selecting the instruments and sensors, designing the instrument packaging, and integration with aircraft systems. It would be desirable, but not necessarily feasible, to have a package that can be readily moved from aircraft to aircraft easily and quickly so that a single instrument package can be evaluated on a number of aircraft. Additionally, data management, statistical structure and analysis will need to be addressed. Questions such as how the data will be downloaded, how will the data be stored, how will the data be analyzed, who will have access to the data, etc., will need to be addressed and is no small task. The sensors envisioned can generate data as frequently as one datum per second and modern electronic storage media can store tremendous volumes of data which would allow sensors to record continuously for many flights between downloads. Managing this data will be a daunting challenge in the research phase as well as in any practical application that may follow.

Once these questions are addressed, then multiple sensor packages should be deployed to make it feasible to capture a few air quality events and evaluate the usefulness of the bleed air contamination detection. It is estimated that a minimum of 10 sensor packages deployed and moved at least monthly from aircraft to aircraft for a year would be needed to have a good probability of capturing enough events to evaluate the usefulness of the detection.

Clearly, extensive cooperation with one or more major airline and one or more aircraft manufacturer will be needed to implement such a research program. Researchers would need to have access to aircraft and the installed instrumentation. They would need to work closely with airline maintenance personnel to install and move instrument packages from aircraft to aircraft and download data. They would also need to have access to aircraft records to know when reported events occurred and to follow up on those events. Detailed knowledge of aircraft bleed air systems for different makes, models, and aircraft type will be required. Regulatory approvals will need to be sought and obtained.

The experiments that have been conducted provide a sound basis for beginning the design of a prototype instrument package to detect bleed air contamination that could be installed on aircraft flying revenue flights. Ultrafine particles (UFP) have been proven to be a reliable and sensitive indicator of engine oil contamination of bleed. Since oil contamination appears to be the primary contaminant of concern, UFP detection should be the focus of detection instruments. Instruments utilizing corona discharge detection technology have proven to be capable of measuring UFP concentrations when engine oil contamination is present in bleed air. This detection technology is desirable as it has no moving parts and does not require the use of condensation liquids as does the alternate technology, condensation particle counters. Also, they are capable of measuring the high concentrations of UFP on the order of 10^7 UFP /cc that are associated with engine oil contamination.

A UFP sensor alone sampling bleed air may be a useful instrument for engine oil contamination detection; however, experiments have shown that UFP from exhaust ingestion can mimic the UFP seen with engine oil contamination. Exhaust ingestion should not be a problem once an aircraft is airborne and away from the airport environment. On the ground however, there are certainly opportunities for exhaust ingestion both from other aircraft and from service vehicles. Whether or not exhaust ingestion will lead to problems with false indications of engine oil contamination will not be known until bleed air UFP detection instrumentation is deployed and operated extensively in the aircraft environment. Exhaust ingestion sufficient to generate UFP concentrations that could be confused with engine oil contamination have also been shown to generate elevated carbon dioxide (CO_2) levels above background values. Thus, it is recommended that, at least initially, a bleed air contamination detection instrument package include CO_2 sensors. If data collected for the initial installation of these packages indicate these sensors provide little value, then they could be eliminated in future packages. Non-dispersive infra-red (NDIR) CO_2 sensors are recommended for this purpose as they have adequate sensitivity, range, and stability. However, these sensors require regular calibration.

Other instruments, the Airsense Aerotracer (AT) and the Honeywell High Temperature TVOC sensor specifically, have been shown to be able to detect engine oil contamination in bleed air. The AT, in its current configuration, is not suitable for the envisioned bleed air contamination detection instrument package as it requires a skilled individual to operate it when measurements are being conducted. The results from May 2023 ground-based, on-wing aircraft experiments for the Honeywell instrument were promising, but that instrument is a proprietary prototype instrument and is not currently on the market. Little is known about the details of the technology employed and its operation. However, both instruments and their future versions, and perhaps other instruments as well, may prove to be effective for on-aircraft bleed air contamination detection. However, they are not recommended for the design of the initial detection packages. If deemed beneficial for inclusion, both instruments are able to detect hydraulic fluid.

Fine particle (FP) instruments do not always indicate oil contamination. In particular, there was minimal response by FP instruments when the bleed air temperature was at 315^{o} C during the May 2023 ground-based, on-wing aircraft experiments. Additionally, there is difficulty in establishing a valid baseline for FP. The concentrations of FP in bleed air without contamination are typically well below the concentrations in ambient air. The concentrations of FP with engine oil or hydraulic fluid contamination can be nearly equal to the concentrations in ambient air. An order of magnitude increase in FP concentration during aircraft operation could be recognized as a bleed air contamination event but an elevated reading that begins with engine start may not be recognized. Nevertheless, it is recommended that an FP detector be included in at least the initial instrument package. These sensors are low cost (~ $100), simple to operate, rugged and reliable. For example, the same Piera Systems 7100 sensor was used over several years in experiments conducted for bleed air contamination detection without servicing. Also, FP measurement may help detect hydraulic fluid since UFP are not sensitive to it. Since the temperature of air from APUs is well below the temperature where no FP response was observed, FP sensors may be useful for detecting contamination in air from this source. If FP concentration measurements are found to provide no added detection value in initial detection instrument packages, then they could be dropped from future packages. Given the minimal cost to include them, it makes sense to do so initially.

Carbon monoxide (CO) appears to have no value for detection of bleed air contamination by engine oil, hydraulic fluid, or deicing fluid. Increases in CO concentration in response to these contaminants was typically 1 ppmv or less. Accurately measuring this level of CO increase requires expensive instrumentation. Additionally, background variations can be well above this amount which would make it difficult, if not impossible, to distinguish between bleed air contamination and ambient air variations, especially on the ground. Some engine exhaust ingestion did result in more measurable concentrations of CO. However, CO_2 is a much more sensitive and reliable indicator of engine exhaust ingestion and would be a much better choice for detecting exhaust ingestion and distinguishing it from engine oil contamination. All combustion engines, internal combustion engines, and turbine engines, generate large amounts of CO_2. This CO_2 generation is inherent to the combustion processes on which they are based. Many combustion engines generate very little CO and, even for those engines that do generate measurable amounts of CO, the concentration is typically two orders of magnitude less than the amount of CO_2 generated. Thus, it is recommended that CO sensors not be included in the initial instrument packages.

There may be value to having CO monitors in aircraft cabins given that there are other potential sources of CO and there have been cases of apparent CO exposure by crew. All of the experiments conducted to date have shown that CO concentrations from engine oil contamination of bleed air are not sufficient to create an exposure concern even with engine oil concentrations that are large enough to create a quite noticeable air quality event. Based on these results, sources other than engine oil contamination of bleed air should be suspected when there are indications of crew or passenger exposure to CO, but the source is not obvious.

It would be desirable to include a volatile organic compound (VOC) sensor of some kind in the instrument package. However, no suitable instrument has been identified to date other than the Honeywell High Temperature TVOC sensor which has already been discussed. The chemical analyses have shown that the concentrations are very low, and sensors need to be able to measure at the ppbV level to be useful. Such sensitivity is challenging in a real time instrument. The Honeywell ppbRAE TVOC sensor did respond to engine oil and hydraulic fluid contamination; however, the instrument required frequent cleaning and more or less continuous attention from a trained individual. Its stability was also questionable. Thus, it is not suitable for the extended, stand-alone operation needed. The Honeywell High Temperature TVOC instrument was promising, as already mentioned, but is not yet available for adoption. None of the other VOC sensors tested had a reliable response to engine oil or hydraulic fluid. Thus, no VOC sensor is recommended for the initial instrument package.

Developing a detailed plan for future potential investigations and conducting detailed cost estimates for such an investigation are outside the scope of the current project. However, rough cost estimate for a somewhat similar investigation was made in a previous project. Overfelt and Jones (Overfelt & Jones, 2013). That proposed investigation was directed at capturing and evaluating actual bleed air contamination events as opposed to evaluating instrumentation to detect such events. However, the methods were similar and involved using multiple instrument packages designed to measure bleed air contamination events which can be moved from aircraft to aircraft in order to measure over a large number of aircraft and flights. In that previous plan, 10 instrument packages would be employed with the goal of conducting measurements on 100 flights on each of 100 different aircraft. That research program was estimated to cost $2.9M in 2013. Adjusting for inflation brings it to $3.9M in spring of 2024.

The previously proposed 2013 project included the introduction of a cabin air quality event reporting system which would not be needed in the recommended next step. On the other hand, that project was addressed at monitoring cabin air quality events and not specifically bleed air contamination events. Consequently, the instrumentation could be located in the cabin, which would make it much easier to move from aircraft to aircraft. Also, the challenges of on-wing aircraft measurements are much better understood now and were not fully appreciated in the previous cost estimate. The inflation adjusted estimate of $3.9M is then a reasonable, rough order of magnitude estimate for developing, building, and deploying 10 prototype instrumentation packages for one year.

4 Conclusions

The observations and conclusions presented here come from the test stand engine results conducted at KSU in May 2022 and from the ground-based, on-wing aircraft test results conducted at the FAA's WJHTC in May 2023.

- Ultrafine particles (UFP) are a good indicator of engine oil contamination in aircraft engine bleed air.
    - UFP has been evaluated for a variety of turbine engine oils and has consistently provided a large response when present in bleed air regardless of engine oil type.
    - UFP has been evaluated for multiple auxiliary power units, multiple test-stand small turbine engines, multiple airliner propulsion engines and have consistently shown a large response with the presence of engine oil.
    - UFP have been evaluated with multiple engine oil injection techniques, including downstream of the engine, and have consistently shown a large response with the presence of engine oil.
    - Very limited data is available for the response of UFP with used or aged engine oil.
    - Readily measurable UFP responses with oil concentrations as low as 1 ppmm have been demonstrated.
    - While the presence of engine oil can elevate particle concentrations for particles as large as 1µm, the large increases are generally for sizes less 100 nm.
    - The diameter for the peak concentration of UFP decreases with decreasing concentrations of oil contamination and can be as low as 20 nm when measured with a long differential mobility analyzer that was utilized by KSU. A recently presented study in which Arnold Engineering Development Center utilized a short differential mobility analyzer and a Cambustion 500 fast ultrafine particle analyzer indicated the peak shifted to 3 to 5nm (Fox, 2024).
    - Instruments intended for detection of engine oil in bleed air by measuring UFP should respond to particles over at least the 10 – 100 nm diameter range.
    - Moderately priced (< $10K), off-the-shelf instruments utilizing corona discharge measurement techniques were shown to respond reliably to the UFP generated by engine oil contamination of bleed air.

    - Exhaust from some turbine and reciprocating engines can contain UFP similar in size as resulting from engine oil contamination. The presence of engine exhaust can be readily identified by the presence of elevated carbon dioxide concentrations.
    - UFP is generated by condensation of volatile components of engine oil and are not generated in high concentrations in the engine.
    - UFP can be measured anywhere along the bleed air path from the engine to the pack exit, as long as the air is cooled to near room temperature prior to the sensors.
    - There is minimal elevation of UFP concentration when measured in un-cooled bleed air.
    - UFP is not a good indicator of hydraulic fluid contamination of bleed air.
    - UFP is not a good indicator of deicing fluid contamination.
    - The lack of UFP concentration increases in response to hydraulic fluid and deicing fluid contamination has a positive aspect as the presence of elevated UFP is then more contaminant specific.
- Fine particles (FP) are not a reliable indicator of engine oil contamination in aircraft engine bleed air.
    - FP have measurable responses to engine oil contamination at concentrations of 5 ppmm and higher with bleed air temperatures of 250^{o} C and lower.
    - FP have little or no response to engine oil contamination with higher bleed air temperatures (315^{o} C). This observation is true even if the bleed air is cooled.
    - FP has measurable responses to hydraulic fluid contamination at temperatures of 250^{o} C and lower. They have not been evaluated at higher temperatures.
    - FP does not respond to deicing fluid contamination of bleed air.
    - Elevated concentrations of FP in response to engine oil contamination in un-cooled bleed indicate the FP are generated in the engine compressor.
    - Baseline concentrations of FP are generally well below ambient FP concentrations as seen in Figure 71. Elevated concentrations with engine oil contamination can be similar to ambient air concentrations as seen in Figure 73 and Figure 77. Even

    less as seen in Figure 74 and Figure 76 when compared to the ambient concentration in Figure 71.

    - Establishing the correct baseline FP concentration is important and potentially difficult if FP are to be used as an indicator of engine oil contamination.
    - FP in bleed air generally have sizes less than 2 µm with concentration increasing as diameter decreases.
    - Detection limits for engine oil with FP are not as well established as for UFP but are probably within the range of 2 - 3 ppmm with lower temperature bleed air.
    - While not nearly as sensitive as UFP, FP measurement may still have some application in low temperature bleed air.

- Carbon dioxide (CO_2) is not a useful indicator of bleed air contamination by engine oil, hydraulic fluid, or deicing fluid.
    - No measurable increases in CO2 above background levels were detected with engine oil, hydraulic fluid, or deicing fluid at concentrations up to 10 ppmm.
    - Increases in CO2 concentrations above background levels were measured with ingestion of engine exhaust from turbine engines and reciprocating engines.
    - CO2 concentration increases associated with ingestion of engine exhaust can differentiate this source from engine oil, hydraulic fluid, or deicing fluid.
- Carbon monoxide (CO) is not a useful indicator of bleed air contamination by engine oil, hydraulic fluid, or deicing fluid.
    - Increases with contaminants on order of 1 ppmv and not enough to distinguish from background levels.
    - The only contaminant that generated a substantial increase in CO was engine exhaust. Elevated CO was not observed with all exhaust ingestion.
    - Even though CO is not a useful indicator of bleed air contamination, there may be other causes of air contamination for which CO monitoring may be useful.
    - If elevated CO is detected in the cabin or if CO exposure is detected in individuals exposed during a cabin air quality event, sources other than bleed air contamination by engine oil, hydraulic fluid, or deicing fluid should be expected.

- Not all organic compound sensors responded reliably to contamination by oil, hydraulic fluid, or deicing fluid.
    - VOC concentrations appear to be very low to non-detectible by real time sensors during low level oil contamination. Chemical analysis shows that chemical sensors need to be able to detect at the ppbv level.
    - The Honeywell high temperature TVOC sensor responded well to oil and hydraulic fluid at the 5 ppmm level during the ground-based, on-wing aircraft tests, but was not extensively tested in this project.
    - The AirSense Aerotracer was able to detect and identify engine oil and hydraulic fluid at the 2 ppmm level. The incorporation of an ion mobility spectrometer appears to be a major factor contributing to the capability of this instrument as it is trained for specific base stocks of oils and hydraulic fluids. If oil base stocks change, the sensor will need to be retrained for the different base stock.
    - Limitations of electro-chemical cells include a high minimum detection limit, and calibration that is performed with pure gases, and not with a representative mixture of the test gas. Electro-chemical cells have many positive and negative cross-sensitivities.
    - Some photo ionization detectors (PID) were responsive to contamination but were unstable while others were unresponsive.
    - Some metal oxide sensors (MOS) responded to contamination, but most did not respond reliably or were noisy. MOS instruments need to be calibrated with representative gas mixtures and have suitable temperature profile programming.
    - Off-the-shelf electro-chemical cells and MOS base instruments marketed for single gas applications are in fact sensitive to a large number of gases.
    - Due to their high cost and complexity, real time instruments that can accurately measure the concentration of individual compounds, such as cavity ring down spectrometry (CRDS), were not extensively evaluated. In one case, a sensor manufacturer did not want to allow an untrained operator who did not know the sensor limitations (e.g., the effect of high moisture), to operate the sensor and potentially generate less than desirable results.
- The sensing principle utilized in radioisotope ionizing smoke detectors was shown to be responsive to the UFP associated with engine oil contamination and could potentially

serve as the basis for a low-cost sensor. However, the lower detection limit and sensitivity are not likely to be as good as with the corona discharge instruments. Products currently on the market utilizing this sensing technique are intended for a different application (i.e., smoke alarms), and new product development likely would be required to use this measurement technique for bleed air contamination detection.

- Evaluation of odor from bleed air contamination was not included in the objectives of this research. Trained odor panels and formal odor evaluation procedures were not included in the experiment design. Some informal evaluation of odor was conducted by researchers involved in the experiments. It appears the detection limits of the more sensitive instruments evaluated are near or above the odor detection limits for the researchers involved in these experiments. It is unlikely that any of the sensors and instruments evaluated could reliably detect engine oil contamination at concentrations lower than at which at least some crew or passengers would detect the resulting odor. However, these instruments do not become acclimatized to odors as does the human nose and they may be able to detect gradually worsening contamination during a flight before crew and passengers.
- All sensors and instruments that were identified as having good potential for detecting bleed air contaminants must be regularly maintained, routinely checked, and periodically calibrated in order to be reliable.

Aircraft bleed air contamination detection is best sensed in the bleed air stream as opposed to the in the airplane cabin as there an many potential confounding sources of contaminants that could be generated in the cabin.

- The best location for sensing along the bleed air path depends upon the sensing technology being deployed.
- Bleed air temperature has been used as the parameter of focus when setting and reporting test conditions. However, bleed air temperature and bleed air pressure are inextricably linked through the compression process that generates bleed air and the relationship is similar for most turbine engines. Thus, examination of the effect of bleed air temperature is inherently an examination of the effect of the corresponding bleed air pressure.
- We now have documentation of the effect of accumulation and release of contaminants (specifically oil) from the heat exchanger surfaces in response to bleed air temperature changes.

- Temperature transients in the bleed air system can generate temporary responses with UFP and VOC measurements that are similar to those generated by engine oil contamination.
- Presumably, this phenomenon is due to oil contamination in the bleed air that deposits on the heat exchanger or duct surfaces with VOCs being driven off with temperature increases.
- These transient effects can extend for periods of time up to 30 minutes but typically start to dissipate after about 10 minutes.
- These transient effects have the potential to cause misleading indications as to the cause of transient contamination events.
- It appears hydraulic fluid does not generate a similar deposition behavior.

4.1 Recommendations to address specific needs

- UFP has been shown to be an effective indicator of engine oil contamination of aircraft engine bleed air for a variety of engines and engine oils; however, available data with used engine oil from "in-use" aircraft engines is very limited. These limited experiments indicate that UFP also respond well when used engine oil contamination is present but are not sufficient to establish general applicability. A series of tests are needed to show whether or not the extensive database generated for new engine oils can be extended to used and aged engine oils.

- The experiments conducted show that oil contamination in the bleed air deposits on bleed air system surfaces (e.g., heat exchangers, duct walls, etc.). The experiments also show that elevating the temperatures in the bleed system can result in these contaminants being released back into the bleed air. Methods of post-contamination cleaning methods, such as elevated bleed temperatures, surfaces washing, and component replacement, should be evaluated for effectiveness, and standard cleaning methods that are documented to be effective should be developed.

- There are some limited data which indicate that elevated O_3 concentrations in the cabin air can generate elevated UFP concentrations. This effect should be investigated to determine if maximum ozone concentrations that can be encountered in ambient air during flight can generate elevated UFP concentrations in bleed air that might be confused with engine oil contamination. If so, then means of measuring O_3 that can be incorporated into an onboard instrument package for detecting bleed air contamination should be investigated. The measurement of O_3 is not as simple as adding an O_3 detector as some data show that ozone sensors give a false indication in response to engine oil contamination in the bleed air.

- Since bleed air contamination detection is a new application for sensors, there is need for a standard for instruments and sensors intended to be used for this application, as well as test methods for instruments to demonstrate compliance with this developed standard. This standard and test method(s) could be Society of Automotive Engineers (SAE) or American Society of Heating Refrigerating Air-Conditioning Engineers (ASHRAE) standards for example.

4.2 Recommendations for continuing the research program

(This work could proceed in parallel or independently of the above recommendations)

- The next major step is to design one or more prototype instrument packages for aircraft engine bleed air contamination detection and test them on routine revenue flights.
    - The specific instruments and sensors used, and how they are connected to and powered by aircraft systems, need to be determined.
    - As a minimum, this package would include UFP concentration measurements to detect engine oil and CO_2 measurements to detect engine exhaust. It might also include appropriate sensing of VOCs to supplement the UFP measurements and to detect hydraulic fluid. Given the low cost of FP concentration measurements, such sensors might also be included.
    - Importantly, the package should include data storage and appropriate communication capability to provide routine data downloading.
    - Appropriate maintenance, instrument checks, and instrument calibration guidelines should be developed for the sensors and instruments included.
    - The effect of shock and vibration and aircraft motion on instrument performance and measurement should be studied.
    - Instrument recovery from cold soaks or hot temperatures, as experienced in various regions, should be studied.
    - The instrument package should be designed so that it can be readily moved from aircraft to aircraft. If feasible, operate the prototype package on multiple aircraft.

    - It would be desirable, but not necessarily feasible, to install the prototype on an aircraft for which controlled contamination events could be generated.
    - Since contamination events occur on only a tiny fraction of flights, this prototype installation is unlikely to observe a contamination event if such an event is not artificially generated. The main purpose is to do the aircraft integration and develop instrument operation and data assessment procedures.
- Once a prototype package is developed and successfully deployed, the next step is to deploy multiple packages that could be moved from aircraft to aircraft so that large numbers of flights and substantial numbers of aircraft could be monitored.
    - The goal would be to have enough instrument packages deployed on a continuous basis on enough different aircraft to capture multiple bleed air contamination events and non-bleed air contamination cabin air quality events over a year of operation. Perhaps initially utilize 10 or more sensor packages that change aircraft at least monthly.
    - Consider giving priority to aircraft that have had multiple unresolved air quality events, to increase the probability of observing bleed air contamination events.
    - In addition to capturing actual bleed air contamination events and documenting how the instrument package performs, a major goal would be to develop data management procedures to download, store, retrieve, and assess the large volume of data generated.
    - Establish feasibility of widespread deployment of bleed air contamination detection.
    - Establish the usefulness of the instrumentation in detecting and assessing aircraft engine bleed air contamination events and to distinguish bleed air contamination events from other cabin air quality events.
    - A rough order of magnitude cost estimate to complete the described research program is $3,900,000.

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A Form letter soliciting participation from aircraft owners

July xx, 2022

Company Address

Dear xxxxxxxxxxx

Kansas State University (KSU) is currently under contract from the Federal Aviation Administration (FAA) for a research project titled Cabin Air Quality and Bleed Air Contamination Detection, Phase 2. The purpose of this letter is to inquire about the availability of an aircraft for conducting ground-based engine bleed air tests associated with this project.

This project is in response to the mandates Congress set in the FAA Reauthorization Act of 2018, Section 326, Subpart c and is focused on experimental measurements of contaminants and markers that result in engine bleed air with controlled ingestion of engine lubricating oil and hydraulic fluid into an engine compressor. Experiments were conducted on a small turbine engine on a test stand in May of this year. The next step is to conduct full-scale tests on a commercial airliner. We are inquiring as to the availability of a suitable aircraft for this purpose. The attached document describes the desired nature of the tests and aircraft characteristics.

Very importantly, it is fully understood that compromises may be necessary between what is desired and what is feasible. The primary purpose of this letter is to identify aircraft owners who are interested in participating in the on-aircraft tests. The more detailed description that follows is provided so that you can better judge the nature to the tests anticipated. Even if some of the desires are not feasible, we would still like to discuss possible aircraft availability. The absolute minimum requirement is an aircraft with an operational auxiliary power unit (APU) or propulsion engine and a fully functional environmental control system. We look forward to discussion of possible options you may have available.

Sincerely,

Byron W. Jones
Project Principal Investigator
Kansas State University

Richard Fox
Project Technical Lead
Aircraft Environment Solutions

CC: Traci Stadtmueller
Contract Officer Representative
Federal Aviation Administration

Cabin Air Quality and Bleed Air Contamination Detection, Phase 2 Aircraft Experiments Description

(Note that Details of the Experiment were modified during later discussions after the letter was sent out.)

Target Dates for Aircraft Tests:

The exact dates for the tests are flexible at this point in time. The project schedule has the aircraft tests being conducted in the time frame of January – February 2023. The test date was moved from January-February 2023 to May 2023, and the draft test plan was modified during discussions with the test stakeholders and the FAA.

Duration of Tests:

Four days of conducting tests with the aircraft are desired. An additional day for set up and ½ day for tear down likely will be needed.

Aircraft Type:

A specific make and model of aircraft is not required. The aircraft needs to be representative of a modern commercial airliner. Some of the desired capabilities may not be achievable with smaller aircraft engines (e.g. A 320 or B737). However, we do not wish to exclude any opportunities at this point.

Systems Requirements:

All tests are to be conducted on the ground. A flight-worthy aircraft is not required.

The majority of the test can be completed with the aircraft auxiliary power unit (APU) to save on operating costs. It is desired to conduct some tests with a propulsion engine. It is desired to include a limited number of tests with operating conditions that will yield bleed air temperatures of 300°C or higher. See additional discussion on this desired capability at the end of this document.

The environmental control system needs to be fully functional. In particular, the aircraft needs to have fully functional air-conditioning packs.

It is desired that the aircraft be equipped with ozone converters or able to be retrofitted with ozone converters. It is anticipated that KSU will provide the ozone converter(s) to be used during the tests. The ozone converter(s) will be provided to KSU by one of the suppliers to the industry.

Responsibility for Test Expenses:

The aircraft owner will be responsible for all expenses associated with operating the aircraft during the tests and for any cleanup of the aircraft that may be necessary after the tests.

KSU will be responsible for all bleed air measurement instrumentation required for the tests and the operation of that instrumentation. KSU and the FAA will be responsible for collection of bleed air samples, the equipment required for air sampling, the operation of that equipment, and the analysis of the collected samples. KSU will be responsible for providing a means of controlled injection of engine lubricating oil and hydraulic fluid. For the propulsion engine, the aircraft owner will be responsible for providing an appropriate connection for the injected contaminant. See further discussion of this connection at the end of this document. For the APU, it is anticipated that the contaminant can be injected directly into the inlet air.

Contaminants and Contamination Levels:

The contaminants will be commonly used turbine engine lubricating oil and aviation hydraulic fluid. The specific brands and fluids are not yet specified. Maximum contaminant concentrations will be 5 ppm mass of contaminant per mass of compressor airflow.

Air Sample Locations:

It is desired to extract air upstream and downstream of the ozone converter, upstream of the air-conditioning pack (could be same as downstream of the ozone converter), downstream of the air-conditioning pack, from the mix manifold (depending upon ECS configuration, may be collected from a gasper), from the cabin, and from the ambient air. Sample lines typically are small diameter stainless steel or copper tubes run from the sampling location to the cabin where the instrumentation and sampling equipment is located. It is anticipated that a modified ozone converter can be provided with upstream and downstream sample line connections. It is anticipated that KSU can provide an adapter that can be attached to the high-pressure ground airport to connect a sample line at that location. It is anticipated that KSU can provide an adapter that can be attached to the low-pressure ground airport to connect a sample line at that location. Thus, it is anticipated that required sample line connections can be made without modification to the aircraft.

Individual Test Duration

For some test conditions, it is desired to be on-point for one hour or longer. Thus, operating conditions for these tests, and likely all tests, are limited to operating parameters for the aircraft that can be sustained for extended periods of time.

Review of Test Plans and Procedures:

The test plan and procedures to be followed are subject to review and approval by the aircraft owner and the FAA.

Bleed Air Temperature

Maximum bleed air temperatures are typically achieved at power levels just prior to switching over from the high-pressure bleed port to the low-pressure bleed port on the propulsion engine and then again at maximum (take off) power. Clearly the latter case in not feasible for ground tests. It is anticipated that the high bleed temperature tests would be conducted at a power setting slightly below the switch over point. Thus, it is desired to have an aircraft engine that achieves a 300^{o}C or higher bleed temperature at this point and an aircraft that can be operated at this power setting on the ground. Other tests with the propulsion engine could be operated at lower power settings. It is understood that aircraft owners may not have readily available information on bleed temperatures, switch over power settings, etc. We are working closely with Boeing and Airbus in this project and, if specific aircraft and engine models are identified, we can obtain the necessary information from the manufacturer.

Contaminant Injection

Based on prior experience both with test stand APUs and on-aircraft APUs, the contaminant can be injected into the APU intake air stream and, thus, no special connection is required for tests conducted with an APU. The injection method for the propulsion engine will depend on the aircraft and engine selected. In the NASA VIPR project with an Air Force C-17 aircraft, contaminant injection was achieved through a modified plug on the AP1 compressor inspection port. It is anticipated that the method used will be developed collaboratively between the aircraft owner and the research team in consultation with the aircraft manufacturer and engine manufacturer. However, we would like for any part placed on the engine, such as a modified inspection port plug, to be provided by the aircraft owner.

B Test plan

Appendix B contains the FAA approved test plan. A contingency day was planned but was not utilized.

Table B-1. Test plan for Monday, May 15, 2023

Monday, 05/15/2023							Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	EPA TO-17 Thermal Desorption Tube	EPA TO-17 Thermal Desorption Tube	EPA TO-17 Thermal Desorption Tube	EPA TO-17 Thermal Desorption Tube	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter
		Pack Exit Temp. Pack #1 1.7° C - 74° C (35° F - 165° F)	Injected Fluid Contaminant	Fluid Injection Rate XX ml / hr. (ppmm)	Bleed Air Exit Temperature / Pressure	O3 Converter Exit Temperature / pressure	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")
Verify that all instrumentation is set to Eastern Daylight Time																						
Monday, 05/15/2023		APU ONLY -- SIMULATE MAX APU LEAK- from all locations in the APU (0.1 lbm/hour = 12 ml/hr= 0.31 ppmm) (5 ppmm = 16.2 x Max allowable leakage rate) w. MOBIL JET OIL II																				
		Mobil Jet Oil II 5 cSt Standard Oil																				
** Start time to crank APU 12:18 PM	Start APU, turn on Pack 1 to establish nominal conditions	356 F Bleed Upstream of O3, 33.94 PSIG; Post conv. 355.5 F @ 27.68 psig																				

8:00 - 10:30	Verify system stable using Ultrafine Particulate (UPF) sensor(s)	Pack 1 22° C (72° F) Pack 1 nominal	Monitor UFP for stability	0.0 ml/hr (0 ppmm)	APU																	
8:00 - 10:30 (likely less time)	Port-by-Port Flow Meter Checks for Chemical Sampling and Real Time Instrumentation						Flow Check 1				Flow Check 1				Flow Check 1				Flow Check 1			
10:30 - 11:00 (use real-time sensors to determine if return to steady state condition; if 30 minutes not long enough, run for an hour)	Operate Pack	Pack 1 Full Cold		0.0 ml/hr (0 ppmm)	APU	200° C																
11:30 - 12:00 (use real-time sensors to determine if return to steady state condition; if 30	Operate Pack	Pack 1 Full Hot		0.0 ml/hr (0 ppmm)	APU	200° C																

minutes not long enough, run for an hour)																						
12:00 - 13:00	**Baseline Condition**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**		**0.0 ml/hr (0 ppm m)**	**APU**	**200° C**																
	Label and store SHIPPING BLANK									**Shipping Blank 2**				**Shipping Blank 2**				**Shipping Blank 2**				**Shipping Blank 2**
Start at 15:14	**Collect BASELINE / SYSTEM BLANKS**				**356 F, 33.94 PSIG**	**355.5 F @ 27.68 psig**	**No KSU carbonyls chemical sampling**				**No KSU TO-17 chemical sampling**				**3**	**4**	**5**	**6**	**3**	**4**	**5**	**6**
	Collect FIELD BLANKS (handled in the same way as a sample tube, BUT NO SAMPLE TAKEN [i.e., sorbent tube opened, connected to sample port, but no engine bleed air sample / no sample run through the tube, close sorbent tube]). A FIELD BLANK is a "procedural" control						**No KSU carbonyls chemical sampling**				**Field Blank**	**Field Blank**	**Field Blank**	**Field Blank**	**Field Blank**	**Field Blank**	**Field Blank**	**Field Blank**	**Field Blank**	**Field Blank**	**Field Blank**	**Field Blank**
INJECT MOBIL JET OIL II (5 ppm) -- SIMULATE MAX APU LEAK																						
13:00 - 14:00 Start time 16:14	**Start and Stabilize Injection Perform APU System Injection Timing Run with Mobil Jet Oil II (use Navy HCDs)**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**	**Mobil Jet Oil II**	**200 g/hr (5 ppm m)**	**APU**	**200° C**																
14:00 - 15:00	**Collect captured samples and Engine Inlet ENVIRONMENTAL CONTROL Start @ 17:00 Hrs.; Stop @ 18:00 hrs**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**	**Mobil Jet Oil II**	**200 g/hr (5 ppm m)**	**APU**	**200° C**	**No KSU chemical sampling @ lower leakage rate**															

15:00 - 15:30	**Start and Stabilize Injection (use Navy HCDs)**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**	**Mobil Jet Oil II**	**10 ppmm (400 g/hr)**	**APU**	**200° C**																
15:30 - 16:30	**Increase Oil Flow Rat to 10 ppmm; collect captured samples and Engine Inlet ENVIRONMENTAL CONTROL**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**	**Mobil Jet Oil II**	**10 ppmm (400 g/hr)**	**APU**	**200° C**									**7**	**8**	**9**	**10**	**7**	**8**	**9**	**10**

Table B-2. Test plan for Tuesday, May 16, 2023

Tuesday, 05/16/2023		**#3 ENGINE -- MOBIL JET OIL II**																				
							Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	**Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber**	**Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber**	**Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber**	**EPA TO-17 Thermal Desorption Tube**	**EPA TO-17 Thermal Desorption Tube**	**EPA TO-17 Thermal Desorption Tube**	**EPA TO-17 Thermal Desorption Tube**	**PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter**	**PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter**	**PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter**	**PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter**	**Speciated Phosphate Isomers, Dual 102 mm Quartz Filter**	**Speciated Phosphate Isomers, Dual 102 mm Quartz Filter**	**Speciated Phosphate Isomers, Dual 102 mm Quartz Filter**	**Speciated Phosphate Isomers, Dual 102 mm Quartz Filter**
		Pack Exit Temp. Pack #1 1.7° C -	**Injected Fluid Contaminant**	**Fluid Injection Rate XX ml / hr. (ppmm)**	**Bleed Air Exit Temperature / Pressure**	**O3 Converter Exit Temperature / pressure**	**Ambient Air**	**O3 Converter Inlet**	**O3 Converter Exit**	**Pack 1 Inlet Hose to Distribution Box (i.e., "mix**	**Ambient Air**	**O3 Converter Inlet**	**O3 Converter Exit**	**Pack 1 Inlet Hose to Distribution Box (i.e., "mix**	**Ambient Air**	**O3 Converter Inlet**	**O3 Converter Exit**	**Pack 1 Inlet Hose to Distribution Box (i.e., "mix**	**Ambient Air**	**O3 Converter Inlet**	**O3 Converter Exit**	**Pack 1 Inlet Hose to Distribution Box (i.e., "mix**

		74° C (35° F - 165° F)								manifold")				manifold")				manifold")				manifold")
		Mobil Jet Oil II 5 cSt Standard Oil																				
** Start time to crank APU -- Start APU at 9:50	Start APU, turn on Pack 1 to establish nominal conditions																					
8:00 - 8:30 (use real-time sensors to determine if return to steady state condition; if 30 minutes not long enough, run for an hour)	Operate Pack	Pack 1 Full Cold		0.0 ml/hr (0 ppmm)	Engine #3	275° C																
8:00 - 10:30 (likely less time)	Port-by-Port Flow Meter Checks for Chemical Sampling and Real Time Instrumentation																					

8:30 - 9:00 (use real-time sensors to determine if return to steady state condition; if 30 minutes not long enough, run for an hour)	**Operate Pack**	**Pack 1 Full Hot**		**0.0 ml/hr (0 ppm)**	**Engine #3 260 C**																	
10:50 - 12:00	**Baseline Condition for 200° C**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**		**0.0 ml/hr (0 ppm)**	**Engine #3 260 C**																	
	Collect BASELINE / SYSTEM BLANKS																					
	Collect FIELD BLANKS							**Field Blank**	**Field Blank**	**Field Blank**		**Field Blank**	**Field Blank**	**Field Blank**		**Field Blank**	**Field Blank**	**Field Blank**		**Field Blank**	**Field Blank**	**Field Blank**
10:00 - 11:00	**Start and Stabilize Injection Perform APU System Injection Timing Run with Mobil Jet Oil II (use Navy HCDs)**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**	**Mobil Jet Oil II**	**35 ml/hr (5 ppm)**	**Engine #3 225° C**	**151.8 C in, 151.2 C out**	**Real-time sensors measurements -- how long to reach a system steady state value**															

11:00 - 12:00	**Collect captured samples, Engine Inlet ENVIRONMENTAL CONTROL, and real time instrument samples**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**	**Mobil Jet Oil II**	**35 ml/hr (5 ppmm)**	**Engine #3 225° C**	**151.8 C in, 151.2 C out**	**No KSU chemical sampling due at lower engine temps. (i.e., 200º C)**															
14:20 - 15:12		**Pack 1 Nominal**		**0.0 ml/hr (0 ppmm)**	**Engine #3**	**330° C (631F)**																
15:12 - 15:35	**Baseline Condition for 300º C**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**		**0.0 ml/hr (0 ppmm)**	**Engine #3**	**315° C (600F)**																
15:35- 16:35	**Collect BASELINE / SYSTEM BLANKS**						**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**11**	**12**	**13**	**14**
16:35 - 17:36	**Start and Stabilize injection**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**	**Mobil Jet Oil II**	**22.7 ml/hr (5 ppmm)**	**Engine #3**	**315° C**																
17:36 - 18:36	**Collect captured samples and Engine Inlet ENVIRONMENTAL CONTROL**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**	**Mobil Jet Oil II**	**22.7 ml/hr (5 ppmm)**	**Engine #3**	**315° C (600F)**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**15**	**16**	**17**	**18**

18:36-18:41	OPC Samples	Pack 1 Full Cold	Mobil Jet Oil II	0.0 ml/hr (0 ppmm)	Engine #3	Reduced speed 315° C (600F) to 278 C(533F) for 30 minutes																
18:41 PM	Download data for the day and keep instruments on, store chemical sample media in freezer	Pack Off	Mobil Jet Oil II	0.0 ml/hr (0 ppmm)	Engine #3 Off																	

Table B-3. Test plan for Wednesday, May 17, 2023

Wednesday, 05/17/2023		#3 ENGINE -- EASTMAN 2197 OIL																				
							Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	EPA TO-17 Thermal Desorption Tube	EPA TO-17 Thermal Desorption Tube	EPA TO-17 Thermal Desorption Tube	EPA TO-17 Thermal Desorption Tube	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter
		Pack Exit Temp. Pack #1 1.7° C - 74° C (35° F - 165° F)	Injected Fluid Contaminant	Fluid Injection Rate XX ml / hr. (ppmm)	Bleed Air Exit Temperature / Pressure	O3 Converter Exit Temperature / pressure	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")

		Eastman 2197 Oil			5 cSt High Thermal Stability Oil																	
APU on 09:20 Engine on 09:30	Start APU, turn on Pack 1 to establish nominal conditions																					
9:38-10:28	Cleanout	Pack 1 Nominal		0.0 ml/hr (0 ppm)	Engine #3	315° C (600F)																
	Collect FIELD BLANKS					503F (312 C)		Field Blank				Field Blank				Field Blank				Field Blank		
10:28-11:28	Baseline Condition for 315° C	Pack 1 22° C (72° F) Pack Nominal		0.0 ml/hr (0 ppm)	Engine #3	315° C (600F)																
	Collect BASELINE / SYSTEM BLANKS					503F (312 C)		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
11:28 - 12:00??	Start and Stabilize injection	Pack 1 22° C (72° F) Pack Nominal	Eastman 2197	35 ml/hr (5 ppm)	Engine #3	315° C	Real-time sensors measurements -- how long to reach a system steady state value															
12:00 - 13:00	Collect captured samples and Engine Inlet ENVIRONMENTAL CONTROL	Pack 1 22° C (72° F) Pack Nominal	Eastman 2197	35 ml/hr (5 ppm)	Engine #3	315° C (600F)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
13:00 - 13:30	System Cleanup	Pack 1 Nominal	Eastman 2197	0.0 ml/hr (0 ppm)	Engine #3	315° C (600F)																
13:30-14:30	Reduce Engine Speed and Stabilize																					
14:30 - 15:32	Baseline Condition for 220° C	Pack 1 22° C (72° F) Pack	Eastman 2197	0.0 ml/hr (0 ppm)	Engine #3	220° C																

		Nominal																				
	Collect BASELINE / SYSTEM BLANKS										**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**19**	**20**	**21**	**22**
15:32 - 16:40	**Start and Stabilize injection**	**Pack 1 22° C (72° F) Pack Nominal**	**Eastman 2197**	**22.7 ml/hr (5 ppm)**	**Engine #3**	**220° C**																
16:40 - 17:40	**Collect captured samples and Engine Inlet ENVIRONMENTAL CONTROL**	**Pack 1 22° C (72° F) Pack Nominal**	**Eastman 2197**	**22.7 ml/hr (5 ppm)**	**Engine #3**	**220° C**					**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**23**	**24**	**25**	**26**
17:40 - 18:10	**System Cleanup**	**Pack 1 22° C (72° F) Pack Nominal**	**Eastman 2197**	**0.0 ml/hr (0 ppm)**	**Engine #3**	**315° C (600F)**																
18:10:00 PM	**Download data for the day and keep instruments on, store chemical sample media in freezer**	**Pack Off**		**0.0 ml/hr (0 ppm)**	**Engine #3 Off**																	

Table B-4. Test plan for Thursday, May 18, 2023

Thursday, 05/18/2023		APU ONLY -- Mobil Jet Oil II (@10 ppmm simulate max APU oil leakage) and HYDRAULIC FLUID (SKYDROL PE-5)																				
							Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	Carbonyls by EPA TO-11A, DNPH Cartridge w Ozone Scrubber	EPA TO-17 Thermal Desorption Tube	EPA TO-17 Thermal Desorption Tube	EPA TO-17 Thermal Desorption Tube	EPA TO-17 Thermal Desorption Tube	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	PAHs by method TO-13A Mod. Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter	Speciated Phosphate Isomers, Dual 102 mm Quartz Filter
		Pack Exit Temp. Pack #1 1.7° C - 74° C (35° F - 165° F)	Injected Fluid Contaminant	Fluid Injection Rate XX ml / hr. (ppmm)	Bleed Air Exit Temperature / Pressure	O3 Converter Exit Temperature / pressure	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")	Ambient Air	O3 Converter Inlet	O3 Converter Exit	Pack 1 Inlet Hose to Distribution Box (i.e., "mix manifold")
Packs 2 and 3 must be turned OFF																						
8:55	08:55 APU Start / 09:01 Pack ON																					
9:01 - :20	Verify system stable using Ultrafine Particulate (UPF) sensor(s)	Pack 1 22° C (72° F) Pack 1 nominal	Monitor UFP for stability	0.0 ml/hr (0 ppmm)	APU ONLY																	
10:20 - 11:20	Baseline Condition	Pack 1 22° C (72° F) APU ON, Pack		0.0 ml/hr (0 ppmm)	APU ONLY	220° C																

		Nominal																				
	Collect BASELINE / SYSTEM BLANKS						**No KSU carbonyls chemical sampling**															
	Collect FIELD BLANKS						**No KSU carbonyls chemical sampling**															
11:20 - 12:00	**Start and Stabilize injection**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**	**Mobil Jet Oil II**	**400 ml/hr (10 ppmm)**	**APU ONLY**	**220° C**	**Real-time sensors measurements -- how long to reach a system steady state value**															
12:00 - 13:05	**Collect captured samples and Engine Inlet ENVIRONMENTAL CONTROL**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**	**Mobil Jet Oil II**	**400 ml/hr (10 ppmm)**	**APU ONLY**	**220° C**	**No KSU carbonyls chemical sampling**															
SYSTEM CLEAN OUT																						
13:05 - 15:00	**System Cleanup**			**0.0 ml/hr (0 ppmm)**	**Engine #3**	**315° C (600F)**																
15:00 - 15:xx	**Baseline Condition**	**Pack 1 22° C (72° F) APU ON, Pack Nominal**		**0.0 ml/hr (0 ppmm)**	**APU ONLY**	**220° C**																
	Collect BASELINE / SYSTEM BLANKS						**No KSU carbonyls chemical sampling**				**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**27**	**28**	**29**	**30**
	Collect FIELD BLANKS						**No KSU carbonyls chemical sampling**					**Field Blank**				**Field Blank**				**Field Blank**		

14:30 - 15:00	Start and Stabilize injection	Pack 1 22° C (72° F) APU ON, Pack Nominal	Skydrol PE-5	200 ml/hr (5 ppmm)	APU ONLY	220° C	Real-time sensors measurements -- how long to reach a system steady state value															
17:01 - 18:04	Collect captured samples and Engine Inlet ENVIRONMENTAL CONTROL	Pack 1 22° C (72° F) APU ON, Pack Nominal	Skydrol PE-5	200 ml/hr (5 ppmm)	APU ONLY	220° C	No KSU carbonyls chemical sampling				27	28	29	30	31	32	33	34	31	32	33	34
18:01 - 18:30	**Download data for the day and keep instruments on, store chemical sample media in freezer**	**Pack Off**		**0.0 ml/hr (0 ppmm)**	**APU Off**	**315° C (600F)**																
After system clean out, APU needs additional time to spool down (i.e., follow normal shut down procedure)																						

C Auxiliary power unit (APU) and engine test log

The Test Logs and sample logs contain the actual times and conditions that test events occurred.

Table C-1. Engine and APU test log

Only condition changes are shown each day. Indicated conditions stay the same unless a change is noted

							Nominal		Nominal			
Date	**Time**	**#3 Engine**	**APU**	**Pack**	**Injection**	**Fluid**	**Injection Rate**	**Injection Rate**	**Bleed Air**	**Baseline**	**Injection**	**Comment**
							(ppmm)	**(mL/hr)**	**Temp (C)**	**Sampling**	**Sampling**	
5/15/2023	14:00	Off	On	Off	No	NA	0	0	NA	No	No	Engine start time not recorded, estimated time
	14:41			On					180			
	15:14									Start		
	16:14				Start	MJOII	5	200		Stop		
	17:00										Start	
	18:00				Stop	NA	0	0			Stop	
	18:34			Off					NA			
	18:35	Off										Engine stop time not recorded, estimated time
5/16/2023	9:50	On	On	Off	No	NA	0	0	325	No	No	
	10:15			On								
	10:50								220			
	11:00									Start		
	12:00				Start	MJOII	5	35		Stop		
	13:00										Start	
	14:00				Stop						Stop	
	14:20								333			
	15:00								316			
	15:35									Start		
	16:35				Start	MJOII	5	35		Stop		
	17:36										Start	
	18:36				Stop		0	0	277		Stop	
	19:04		Off	Off								
							Nominal		**Nominal**			
Date	**Time**	**Engine #3**	**APU**	**Pack**	**Injection**	**Contaminant Fluid**	**Rate**	**Rate**	**Bleed**	**Baseline**	**Injection**	**Comment**
							(ppm)	**(mL/hr)**	**Temp (C)**	**Sampling**	**Sampling**	
5/17/2023	9:20	Off	On	Off	No	NA	0	0	NA	No	No	
	9:30	On							315			

	9:35			On								Pack start time not recorded, guess
	10:28									Start		
	11:28				Start	EO 2197	5	35		Stop		
	12:00								315		Start	
	13:00				Stop						Stop	
	13:51								225			
	14:30									Start		
	15:32				Start	EO 2197	5	35		Stop		
	16:40										Start	
	17:40				Stop				315		Stop	
	18:03			Off								
	18:08	Off	Off									
5/18/2023	8:55	Off	On	Off	No	NA	0	0	0	No	No	
	9:01			On								
	10:20									Start		
	11:20				Start	MJOII	10	400		Stop		
	12:00										Start	
	13:05				Stop	NA	0	0			Stop	
	15:00									Start		
	16:30				Start	Skydrol PE-5	5	200		Stop		
	17:01										Start	
	18:01				Stop	NA	0	0			Stop	
	18:03		Off	Off								

MJOII = Mobil Jet Oil II
EO 2197 = Eastman Oil 2197

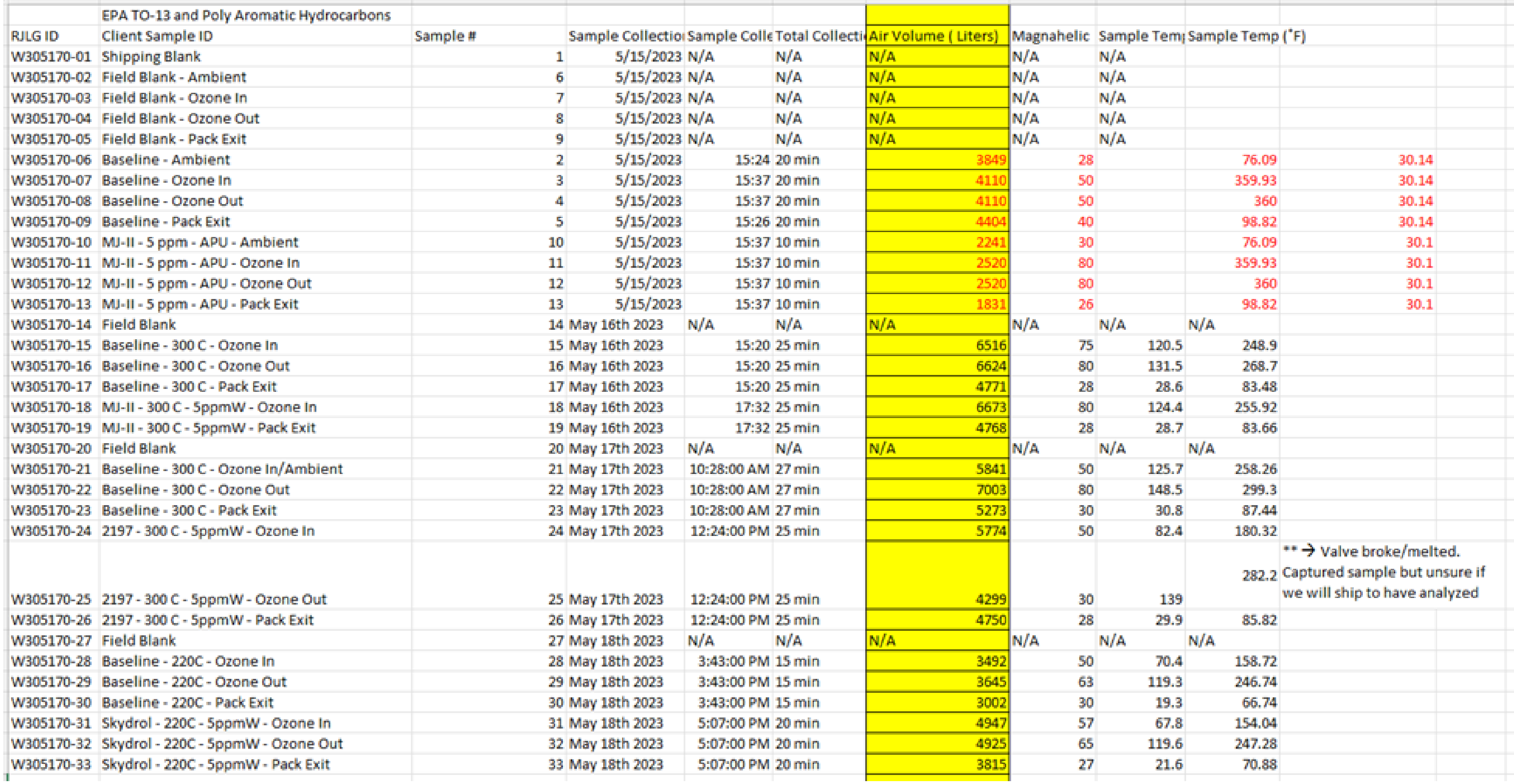
Table C-2. Carbonyls (DNPH) EPA TO-11A sample volume log; Atmospheric Analysis Consulting (AAC) Laboratory

Sample Location	Test Condition	Sample Time	Sample Number	Sample Duration (min)	Sample Volume-L	Actual Sample Flow Rate-L
Tuesday May 16th	**#3Engine**					
Pack Exit	200°C Baseline	11:12	3	15	21.75	1.45
VOC/Ozone Converter Inlet	200°C Baseline	11:12	4	15	29.85	1.99
VOC/Ozone Converter Outlet	200°C Baseline	11:12	5	15	29.7	1.98
Ambient	200°C Baseline	11:12	6	15	29.25	1.95
Pack Exit	300°C Baseline	15:21	3B	15	21.75	1.45
VOC/Ozone Converter Inlet	300°C Baseline	15:21	4B	15	29.85	1.99
VOC/Ozone Converter Outlet	300°C Baseline	15:21	5B	15	29.7	1.98
Ambient	300°C Baseline	15:21	6B	15	29.25	1.95
Pack Exit	315°C 5ppm MJII	17:30	7	15	21.75	1.45
VOC/Ozone Converter Inlet	315°C 5ppm MJII		8	15	30	2
VOC/Ozone Converter Outlet	315°C 5ppm MJII		9	15	30	2
Ambient	315°C 5ppm MJII		10	15	29.1	1.94
Wednesday May 17th	**#3Engine**					
Pack Exit	----------------	---------------	------	------	------	------
VOC/Ozone Converter Inlet	300°C Baseline	10:35	12	15	29.85	1.99
VOC/Ozone Converter Outlet	300°C Baseline		13	15	30.3	2.02
Ambient	300°C Baseline		14	15	29.55	1.97
Pack Exit	----------------	---------------	------	------	------	------
VOC/Ozone Converter Inlet	312°C ETO2197 5ppm	12:30	15	15	29.85	1.99
VOC/Ozone Converter Outlet	312°C ETO2197 5ppm		16	15	30	2
Ambient	312°C ETO2197 5ppm		17	15	29.4	1.96
Thursday May 18th	**APU**					
VOC/Ozone Converter Inlet	220°C Skydrol 5ppm	17:05	18	15	29.85	1.99

MJII = Mobil Jet Oil II

ETO2197 = Eastman Oil 2197; Skydrol = Skydrol PE-5 Hydraulic Fluid

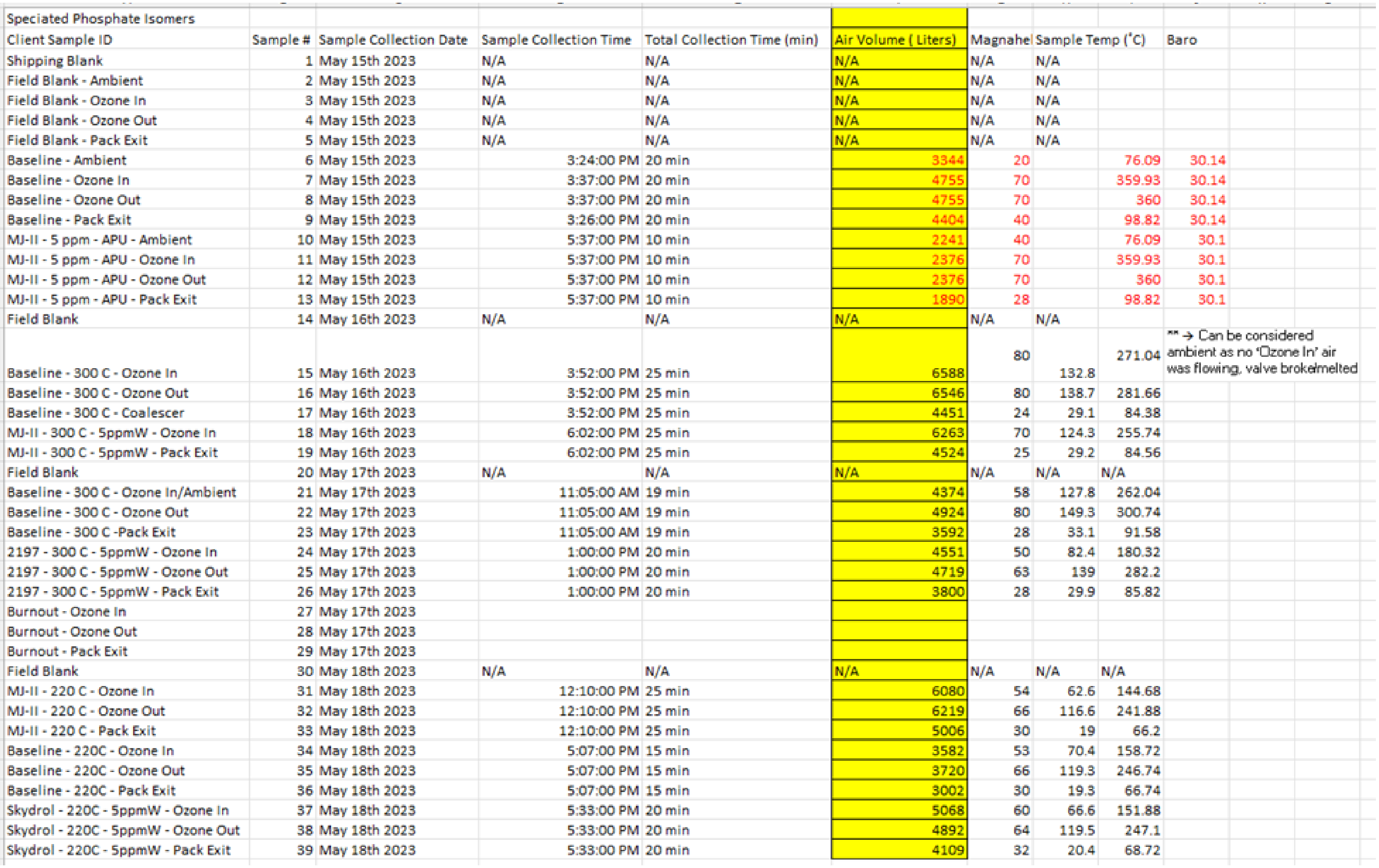
Table C-3. High volume sample calculations for EPA TO-13A and polyaromatic hydrocarbons—quartz filters (RJLG)



	EPA TO-13 and Poly Aromatic Hydrocarbons									
RJLG ID	Client Sample ID	Sample #	Sample Collectio	Sample Colle	Total Collecti	Air Volume (Liters)	Magnahelic	Sample Tem	Sample Temp (°F)	
W305170-01	Shipping Blank	1	5/15/2023	N/A	N/A	N/A	N/A	N/A		
W305170-02	Field Blank - Ambient	6	5/15/2023	N/A	N/A	N/A	N/A	N/A		
W305170-03	Field Blank - Ozone In	7	5/15/2023	N/A	N/A	N/A	N/A	N/A		
W305170-04	Field Blank - Ozone Out	8	5/15/2023	N/A	N/A	N/A	N/A	N/A		
W305170-05	Field Blank - Pack Exit	9	5/15/2023	N/A	N/A	N/A	N/A	N/A		
W305170-06	Baseline - Ambient	2	5/15/2023	15:24	20 min	3849	28		76.09	30.14
W305170-07	Baseline - Ozone In	3	5/15/2023	15:37	20 min	4110	50		359.93	30.14
W305170-08	Baseline - Ozone Out	4	5/15/2023	15:37	20 min	4110	50		360	30.14
W305170-09	Baseline - Pack Exit	5	5/15/2023	15:26	20 min	4404	40		98.82	30.14
W305170-10	MJ-II - 5 ppm - APU - Ambient	10	5/15/2023	15:37	10 min	2241	30		76.09	30.1
W305170-11	MJ-II - 5 ppm - APU - Ozone In	11	5/15/2023	15:37	10 min	2520	80		359.93	30.1
W305170-12	MJ-II - 5 ppm - APU - Ozone Out	12	5/15/2023	15:37	10 min	2520	80		360	30.1
W305170-13	MJ-II - 5 ppm - APU - Pack Exit	13	5/15/2023	15:37	10 min	1831	26		98.82	30.1
W305170-14	Field Blank	14	May 16th 2023	N/A	N/A	N/A	N/A	N/A	N/A	
W305170-15	Baseline - 300 C - Ozone In	15	May 16th 2023	15:20	25 min	6516	75	120.5	248.9	
W305170-16	Baseline - 300 C - Ozone Out	16	May 16th 2023	15:20	25 min	6624	80	131.5	268.7	
W305170-17	Baseline - 300 C - Pack Exit	17	May 16th 2023	15:20	25 min	4771	28	28.6	83.48	
W305170-18	MJ-II - 300 C - 5ppmW - Ozone In	18	May 16th 2023	17:32	25 min	6673	80	124.4	255.92	
W305170-19	MJ-II - 300 C - 5ppmW - Pack Exit	19	May 16th 2023	17:32	25 min	4768	28	28.7	83.66	
W305170-20	Field Blank	20	May 17th 2023	N/A	N/A	N/A	N/A	N/A	N/A	
W305170-21	Baseline - 300 C - Ozone In/Ambient	21	May 17th 2023	10:28:00 AM	27 min	5841	50	125.7	258.26	
W305170-22	Baseline - 300 C - Ozone Out	22	May 17th 2023	10:28:00 AM	27 min	7003	80	148.5	299.3	
W305170-23	Baseline - 300 C - Pack Exit	23	May 17th 2023	10:28:00 AM	27 min	5273	30	30.8	87.44	
W305170-24	2197 - 300 C - 5ppmW - Ozone In	24	May 17th 2023	12:24:00 PM	25 min	5774	50	82.4	180.32	
W305170-25	2197 - 300 C - 5ppmW - Ozone Out	25	May 17th 2023	12:24:00 PM	25 min	4299	30	139	282.2	** → Valve broke/melted. Captured sample but unsure if we will ship to have analyzed
W305170-26	2197 - 300 C - 5ppmW - Pack Exit	26	May 17th 2023	12:24:00 PM	25 min	4750	28	29.9	85.82	
W305170-27	Field Blank	27	May 18th 2023	N/A	N/A	N/A	N/A	N/A	N/A	
W305170-28	Baseline - 220C - Ozone In	28	May 18th 2023	3:43:00 PM	15 min	3492	50	70.4	158.72	
W305170-29	Baseline - 220C - Ozone Out	29	May 18th 2023	3:43:00 PM	15 min	3645	63	119.3	246.74	
W305170-30	Baseline - 220C - Pack Exit	30	May 18th 2023	3:43:00 PM	15 min	3002	30	19.3	66.74	
W305170-31	Skydrol - 220C - 5ppmW - Ozone In	31	May 18th 2023	5:07:00 PM	20 min	4947	57	67.8	154.04	
W305170-32	Skydrol - 220C - 5ppmW - Ozone Out	32	May 18th 2023	5:07:00 PM	20 min	4925	65	119.6	247.28	
W305170-33	Skydrol - 220C - 5ppmW - Pack Exit	33	May 18th 2023	5:07:00 PM	20 min	3815	27	21.6	70.88	

MJ- II = Mobil Jet Oil II; 2197 = Eastman Oil 2197; Skydrol = Skydrol PE-5 Hydraulic Fluid

Table C-4. High volume sample calculations for speciated phosphate isomers, quartz filters, EPA Method TO-13A (RJLG)



Speciated Phosphate Isomers									
Client Sample ID	Sample #	Sample Collection Date	Sample Collection Time	Total Collection Time (min)	Air Volume (Liters)	Magnahel	Sample Temp (˚C)		Baro
Shipping Blank	1	May 15th 2023	N/A	N/A	N/A	N/A	N/A		
Field Blank - Ambient	2	May 15th 2023	N/A	N/A	N/A	N/A	N/A		
Field Blank - Ozone In	3	May 15th 2023	N/A	N/A	N/A	N/A	N/A		
Field Blank - Ozone Out	4	May 15th 2023	N/A	N/A	N/A	N/A	N/A		
Field Blank - Pack Exit	5	May 15th 2023	N/A	N/A	N/A	N/A	N/A		
Baseline - Ambient	6	May 15th 2023	3:24:00 PM	20 min	3344	20		76.09	30.14
Baseline - Ozone In	7	May 15th 2023	3:37:00 PM	20 min	4755	70		359.93	30.14
Baseline - Ozone Out	8	May 15th 2023	3:37:00 PM	20 min	4755	70		360	30.14
Baseline - Pack Exit	9	May 15th 2023	3:26:00 PM	20 min	4404	40		98.82	30.14
MJ-II - 5 ppm - APU - Ambient	10	May 15th 2023	5:37:00 PM	10 min	2241	40		76.09	30.1
MJ-II - 5 ppm - APU - Ozone In	11	May 15th 2023	5:37:00 PM	10 min	2376	70		359.93	30.1
MJ-II - 5 ppm - APU - Ozone Out	12	May 15th 2023	5:37:00 PM	10 min	2376	70		360	30.1
MJ-II - 5 ppm - APU - Pack Exit	13	May 15th 2023	5:37:00 PM	10 min	1890	28		98.82	30.1
Field Blank	14	May 16th 2023	N/A	N/A	N/A	N/A	N/A		
Baseline - 300 C - Ozone In	15	May 16th 2023	3:52:00 PM	25 min	6588	80	132.8	271.04	** → Can be considered ambient as no 'Ozone In' air was flowing, valve broke/melted
Baseline - 300 C - Ozone Out	16	May 16th 2023	3:52:00 PM	25 min	6546	80	138.7	281.66	
Baseline - 300 C - Coalescer	17	May 16th 2023	3:52:00 PM	25 min	4451	24	29.1	84.38	
MJ-II - 300 C - 5ppmW - Ozone In	18	May 16th 2023	6:02:00 PM	25 min	6263	70	124.3	255.74	
MJ-II - 300 C - 5ppmW - Pack Exit	19	May 16th 2023	6:02:00 PM	25 min	4524	25	29.2	84.56	
Field Blank	20	May 17th 2023	N/A	N/A	N/A	N/A	N/A	N/A	
Baseline - 300 C - Ozone In/Ambient	21	May 17th 2023	11:05:00 AM	19 min	4374	58	127.8	262.04	
Baseline - 300 C - Ozone Out	22	May 17th 2023	11:05:00 AM	19 min	4924	80	149.3	300.74	
Baseline - 300 C -Pack Exit	23	May 17th 2023	11:05:00 AM	19 min	3592	28	33.1	91.58	
2197 - 300 C - 5ppmW - Ozone In	24	May 17th 2023	1:00:00 PM	20 min	4551	50	82.4	180.32	
2197 - 300 C - 5ppmW - Ozone Out	25	May 17th 2023	1:00:00 PM	20 min	4719	63	139	282.2	
2197 - 300 C - 5ppmW - Pack Exit	26	May 17th 2023	1:00:00 PM	20 min	3800	28	29.9	85.82	
Burnout - Ozone In	27	May 17th 2023							
Burnout - Ozone Out	28	May 17th 2023							
Burnout - Pack Exit	29	May 17th 2023							
Field Blank	30	May 18th 2023	N/A	N/A	N/A	N/A	N/A	N/A	
MJ-II - 220 C - Ozone In	31	May 18th 2023	12:10:00 PM	25 min	6080	54	62.6	144.68	
MJ-II - 220 C - Ozone Out	32	May 18th 2023	12:10:00 PM	25 min	6219	66	116.6	241.88	
MJ-II - 220 C - Pack Exit	33	May 18th 2023	12:10:00 PM	25 min	5006	30	19	66.2	
Baseline - 220C - Ozone In	34	May 18th 2023	5:07:00 PM	15 min	3582	53	70.4	158.72	
Baseline - 220C - Ozone Out	35	May 18th 2023	5:07:00 PM	15 min	3720	66	119.3	246.74	
Baseline - 220C - Pack Exit	36	May 18th 2023	5:07:00 PM	15 min	3002	30	19.3	66.74	
Skydrol - 220C - 5ppmW - Ozone In	37	May 18th 2023	5:33:00 PM	20 min	5068	60	66.6	151.88	
Skydrol - 220C - 5ppmW - Ozone Out	38	May 18th 2023	5:33:00 PM	20 min	4892	64	119.5	247.1	
Skydrol - 220C - 5ppmW - Pack Exit	39	May 18th 2023	5:33:00 PM	20 min	4109	32	20.4	68.72	

MJ- II = Mobil Jet Oil II; 2197 = Eastman Oil 2197; Skydrol = Skydrol PE-5 Hydraulic Fluid

Table C-5. Organophosphates, Fraunhofer laboratory log

Sample Location	Test Condition	Sample Time	Sample Number	Sample Duration (min)	Sample Volume-L	Actual Sample Flow Rate-L	Remarks
Tuesday May 16th	**#3Engine**						
Pack Exit	-------------------	--------------	------------	-----------	--------	-------	
VOC/ozone Converter Inlet	315°C MJII 5ppm	18:25	OP1	30	60	2	throttled back only 280°C for most of the time
VOC/ozone Converter Exit	315°C MJII 5ppm	18:25	OP2			departed	throttled back only 280°C for most of the time
Ambient	315°C MJII 5ppm	18:25	OP3			departed	throttled back only 280°C for most of the time
Wednesday May 17th	**#3 Engine**						
Pack Exit	-------------------	--------------	------------	-----------	--------	-------	
VOC/ozone Converter Inlet	312°C ETO2197 5ppm	12:18	OP4	30	59.4	1.98	
VOC/ozone Converter Exit	312°C ETO2197 5ppm		OP5	30	59.7	1.99	
Ambient	312°C ETO2197 5ppm		OP6	30	58.5	1.95	Shortly dropped 30-60 seconds sampled 1 minute longer
Pack Exit	-------------------	--------------	------------	-----------	--------	-------	
VOC/ozone Converter Inlet	220°C ETO2197 5ppm	16:45	OP7	30	59.4	1.98	
VOC/ozone Converter Exit	220°C ETO2197 5ppm		OP8	30	60.3	2.01	
Ambient	--------	---------	-----------	-------	-----	----	
Thursday May 18th	**APU**						
Pack Exit	-------------------	--------------	------------	-----------	--------	-------	
VOC/ozone Converter Inlet	220°C MJII 10ppm	12:32	OP10	30		2	
VOC/ozone Converter Exit	220°C MJII 10ppm		OP11	30		2.01	
Ambient	220°C MJII 10ppm		OP12	30		1.97	The sample carrier briefly detached itself from the supply air twice

MJII = Mobil Jet Oil II; ETO2197 = Eastman Oil 2197

Table C-6. Volatile organic compounds (VOCs) EPA TO-17; RJ Lee Laboratory sample volume log

Sample Location	Test Condition	Sample Time	Sample Number	Sample Duration (min)	Sample Volume-L	Actual Sample Flow Rate-L
Tuesday May 16th	**#3Engine**					
Pack Exit	300°C Baseline	15:21	3 / 673924	15	1.95	0.13
VOC/Ozone Converter Inlet	300°C Baseline	15:21	4 / 673916	15	2.7	0.18
VOC/Ozone Converter Outlet	300°C Baseline	15:21	5 / 463626	15	1.8	0.12
Ambient	300°C Baseline	15:21	6 / 473917	15	1.95	0.13
Pack Exit	315°C 5ppm MJII	17:30	7 / 673912	15	3.15	0.21
VOC/Ozone Converter Inlet	315°C 5ppm MJII		8 / 163623	15	2.85	0.19
VOC/Ozone Converter Outlet	315°C 5ppm MJII		9 / 673925	15	3	0.2
Ambient	315°C 5ppm MJII		10 / 673915	15	2.85	0.19
Wednesday May17th	**#3Engine**					
Pack Exit	300°C Baseline	10:35	12 / 673921	15	3	0.2
VOC/Ozone Converter Inlet	300°C Baseline		13 / 463636	15	3	0.2
VOC/Ozone Converter Outlet	300°C Baseline		14 / 673930	15	2.7	0.18
Ambient	300°C Baseline		15 / 463638	15	3	0.2
Pack Exit	312°C ETO2197 5ppm	12:30	16 / 463648	15	2.85	0.19
VOC/Ozone Converter Inlet	312°C ETO2197 5ppm		17 / 673922	15	3	0.2
VOC/Ozone Converter Outlet	312°C ETO2197 5ppm		18 / 673914	15	2.85	0.19
Ambient	312°C ETO2197 5ppm		19 / 463635	15	2.85	0.19
Pack Exit	220°C ETO2197 5ppm	16:45	20 / 673918	15	3	0.2
VOC/Ozone Converter Inlet	220°C ETO2197 5ppm		21 / 673933	15	3	0.2

Sample Location	Test Condition	Sample Time	Sample Number	Sample Duration (min)	Sample Volume-L	Actual Sample Flow Rate-L
VOC/Ozone Converter Outlet	220°C ETO2197 5ppm		22 / 463625	15	3	0.2
Ambient	220°C ETO2197 5ppm		23 / 673927	15	3	0.2
Thursday May 18th	**APU**					
Pack Exit	220°C MJII 10ppm	11:58	24 / 463634	15	3	0.2
VOC/Ozone Converter Inlet	220°C MJII 10ppm		25 / 673940	15	2.85	0.19
VOC/Ozone Converter Outlet	220°C MJII 10ppm		26 / 463642	15	3	0.2
Ambient	220°C MJII 10ppm		27 / 673937	15	3.15	0.21
Pack Exit	----------------	----------------	----------------	----------------	-----------	---------------
VOC/Ozone Converter Inlet	220°C Baseline Skydrol	15:40	28 / 643650	15	3.15	0.21
VOC/Ozone Converter Outlet	220°C Baseline Skydrol		29 / 673928	15	3	0.2
Ambient	220°C Baseline Skydrol		30 / 673936	15	3.15	0.21
Pack Exit	220°C Skydrol 5ppm	17:05	31 / 673932	15	3.15	0.21
Pack Exit	----------------	----------------	----------------	----------------	-----------	---------------
VOC/Ozone Converter Inlet	220°C Skydrol 5ppm		32 / 463624	15	3	0.2
VOC/Ozone Converter Outlet	220°C Skydrol 5ppm		33 / 463647	15	3.15	0.21
Ambient	220°C Skydrol 5ppm		34 / 463644	15	3.15	0.21

MJII = Mobil Jet Oil II
ETO2197 – Eastman Oil 2197
Skydrol = Skydrol PE-5 Hydraulic Fluid

Table C-7. Supelco Tenax thermal desorption cartridges for VOC, Fraunhofer laboratory log

Sample Location	Test Condition	Sample Time	Sample Number	Sample Duration (min)	Sample Volume-L	Actual Sample Flow Rate-L	Remarks
Tuesday May 16th	**#3Engine**						
Ambient	200°C Baseline	11:12	T1	15		not sure about volume, most should have rather a bit less than 2 L, one approx. 2,7 L	
VOC/ozone converter inlet	200°C Baseline	11:12	T2	15			
VOC/ozone converter outlet	200°C Baseline	11:12	T3	15			potentially touched tube outlet
Pack Exit	200°C Baseline	11:12	T4	15			
Ambient	315°C 5ppm MJII	17:50	T5	15	3.15	0.21	
VOC/ozone converter inlet	315°C 5ppm MJII	17:50	T6	15	2.85	0.19	
VOC/ozone converter outlet	315°C 5ppm MJII	17:50	T7	15	3	0.2	
Pack Exit	315°C 5ppm MJII	17:50	T8	15	2.85	0.19	
Wednesday May17th	**#3Engine**						
VOC/ozone converter inlet	312°C ETO2197	12:50	T9	15	3	0.2	
VOC/ozone converter outlet	312°C ETO2198		T10	15	2.85	0.19	
Pack Exit	312°C ETO2199		T11	15	2.85	0.19	
Thursday May 18th	**APU**						
VOC/ozone converter inlet	220°C Skydrol 5ppm	17:25	T12	15	3	0.2	

MJII = Mobil Jet Oil II
ETO2197 = Eastman Oil 2197
Skydrol = Skydrol PE-5 Hydraulic Fluid

Table C-8. Supelco Orbo-53 cartridges for carboxylic acids, Fraunhofer laboratory log

Sample Location	Test Condition	Sample Time	Sample Number	Sample Duration (min)	Sample Volume-L	Actual Sample Flow Rate-L	Remarks
Tuesday May 16th	**#3Engine**						
Pack Exit	200°C Baseline	11:33	C1	30	43.5	1.45	
VOC/ozone Converter Inlet	200°C Baseline	11:33	C2	30	59.7	1.99	
VOC/ozone Converter Exit	200°C Baseline	11:33	C3	30	59.4	1.98	
Ambient	200°C Baseline	11:33	C4	30	58.5	1.95	
Pack Exit	315°C 5ppm MJII					1.48	
VOC/ozone Converter Inlet	315°C 5ppm MJII	17:50	C5	30	60	2	
VOC/ozone Converter Exit	315°C 5ppm MJII	17:50	C6	19	38	2	13 minutes on ambient stop 2 minutes later
Ambient	315°C 5ppm MJII	17:50	C7	30	58.2	1.94	
Wednesday May 17th	**#3Engine**						
Pack Exit	-----	------	------	------	------	------	
VOC/ozone Converter Inlet	312°C ETO2197 5ppm	12:50	C8	30	59.7	1.99	
VOC/ozone Converter Exit	312°C ETO2197 5ppm		C9	30	60	2	
Ambient	312°C ETO2197 5ppm		C10	30	58.8	1.96	
Thursday May 18th	**APU**						
Pack Exit	-----	------	------	------	------	------	
VOC/ozone Converter Inlet	220°C MJII 10ppm APU	11:58	C11	30	59.7	1.99	
VOC/ozone Converter Exit	220°C MJII 10ppm APU		C12	30	60	2	
Ambient	------	------	------	------	------	------	

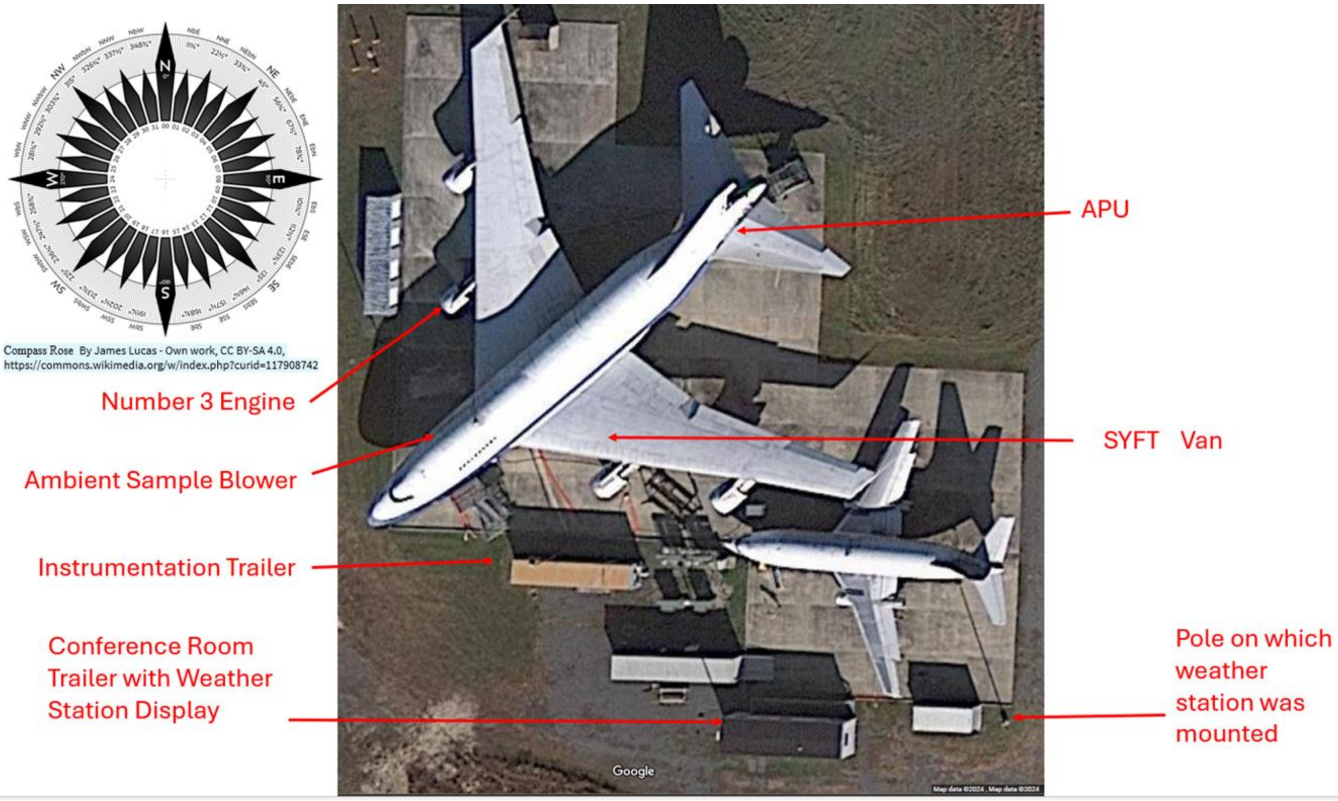
MJII = Mobil Jet Oil II
ETO2197 = Eastman Oil 2197

Table C-9. Flow controller and flow meter information for laboratory chemical sampling

Sample Location	Flow Setpoint	Manufacturer	Part Number	Serial Number	Owner	Max Flow Range	
VOC/ozone Converter Inlet	2 Liters	Alicat	MC-10SLPM-D/10M	130722	USA Navy	10 SLPM	used for DNPH by US EPA TO-11, carboxylic acids and organophosphates
Ambient	2 Liters	APEX	AX-MC-5SLPM-D/5M	399965	USA FAA	5 SLPM	
VOC/ozone Converter Exit	2 Liters	ALICAT	MC-20SLPM-D/5M	149477	USA FAA	20 SLPM	
Pack Exit	2 Liters	APEX	AX-MC-2SLPM-D/5M	399961	USA FAA	2 SLPM	
VOC/ozone Converter Inlet	0.2 Liters	ALICAT	MC-2SLPM-D/5M	113095	Honeywell	2 SLPM	Used for Tenax Tubes for Speciated VOC by US EPA Method TO-17
Ambient	0.2 Liters	APEX	AX-MC-2SLPM-D/5M	399960	USA FAA	2 SLPM	
VOC/ozone Converter Exit	0.2 Liters	APEX	AX-MC-2SLPM-D/5M	399959	USA FAA	2 SLPM	
Pack Exit	0.2 Liters	ALICAT	MC-2SLPM-D-24V/5M	17665	Honeywell	2 SLPM	
Secondary Transfer Standard		TSI	4043 H	4043 1231 007	KSU		used to verify flow through sample media

D Test setup

Test setups included plumbing and instrumentation externally and internally to the aircraft.



Compass Rose By James Lucas - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=117908742

Figure D-1. Test topography


Figure D-2. Weather station located on light pole

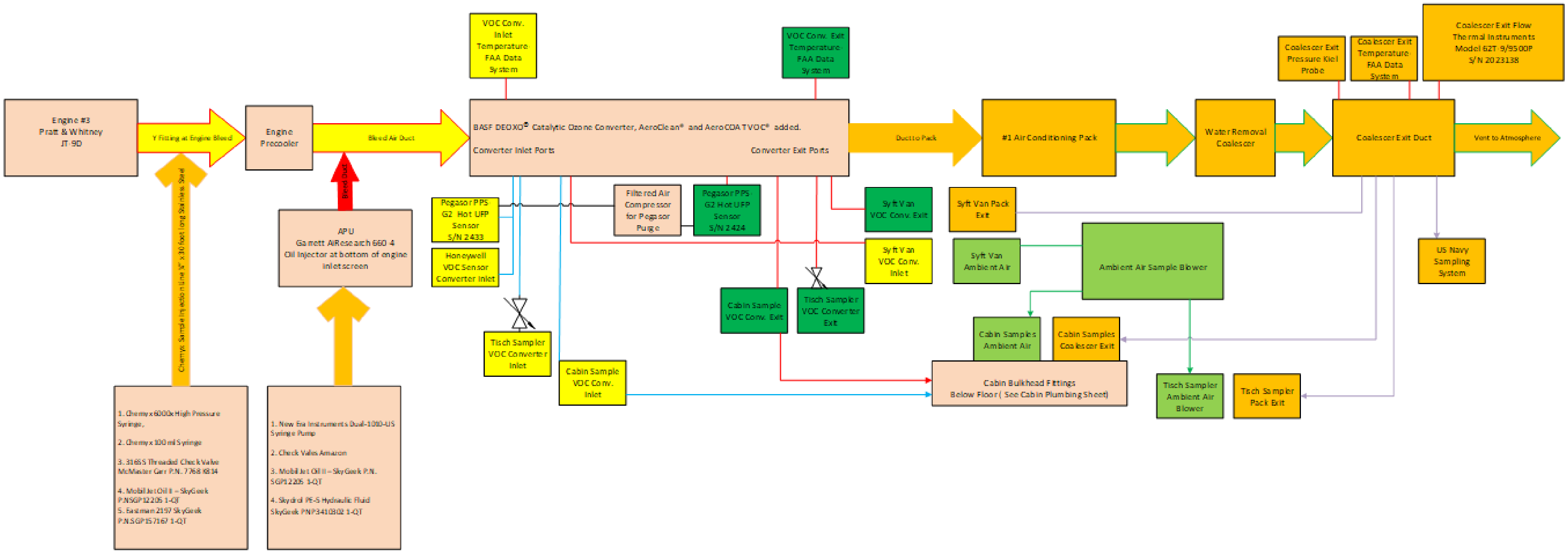


Figure D-3. Outside cabin plumbing layout

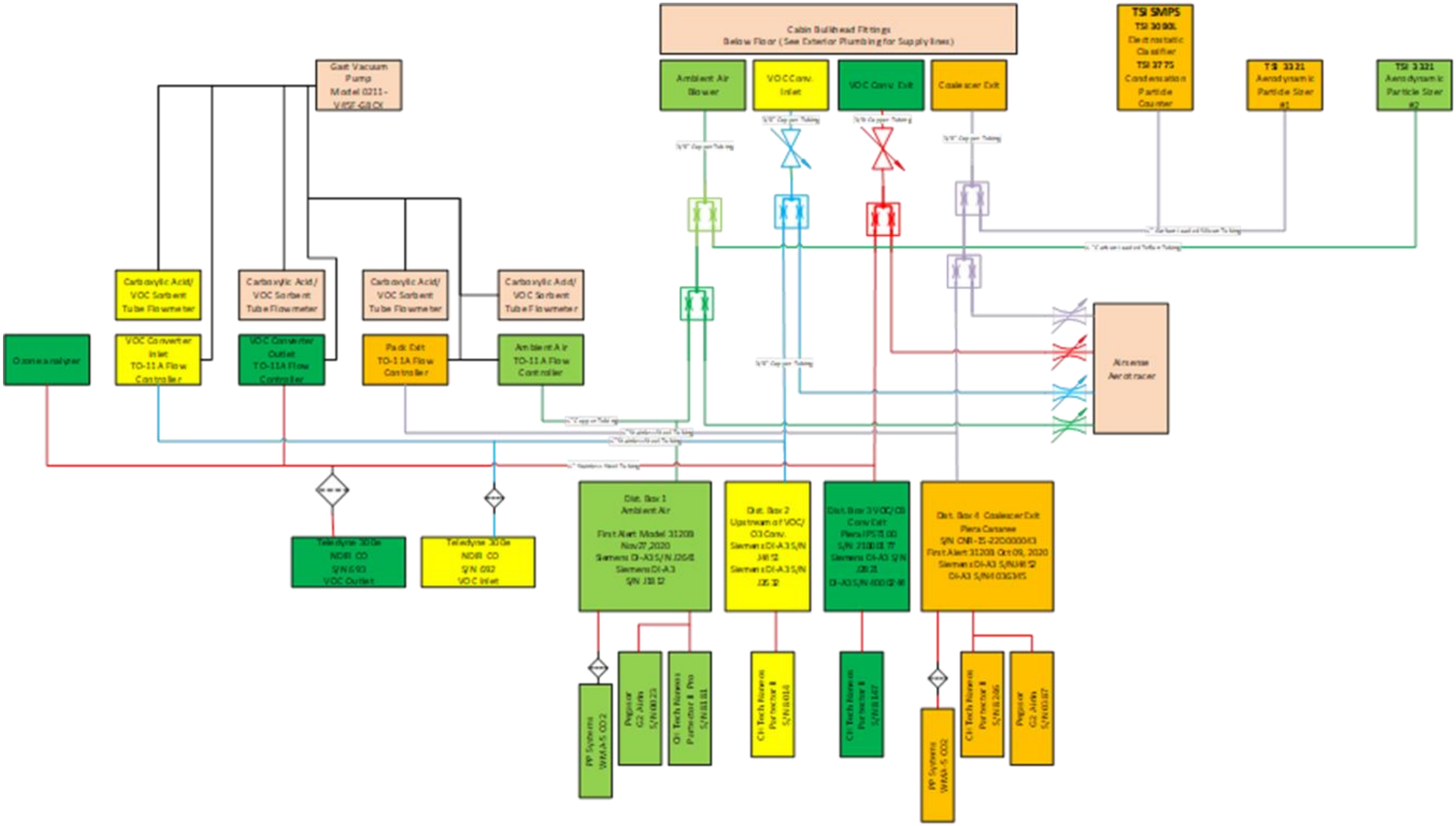


Figure D-4. Inside cabin plumbing layout

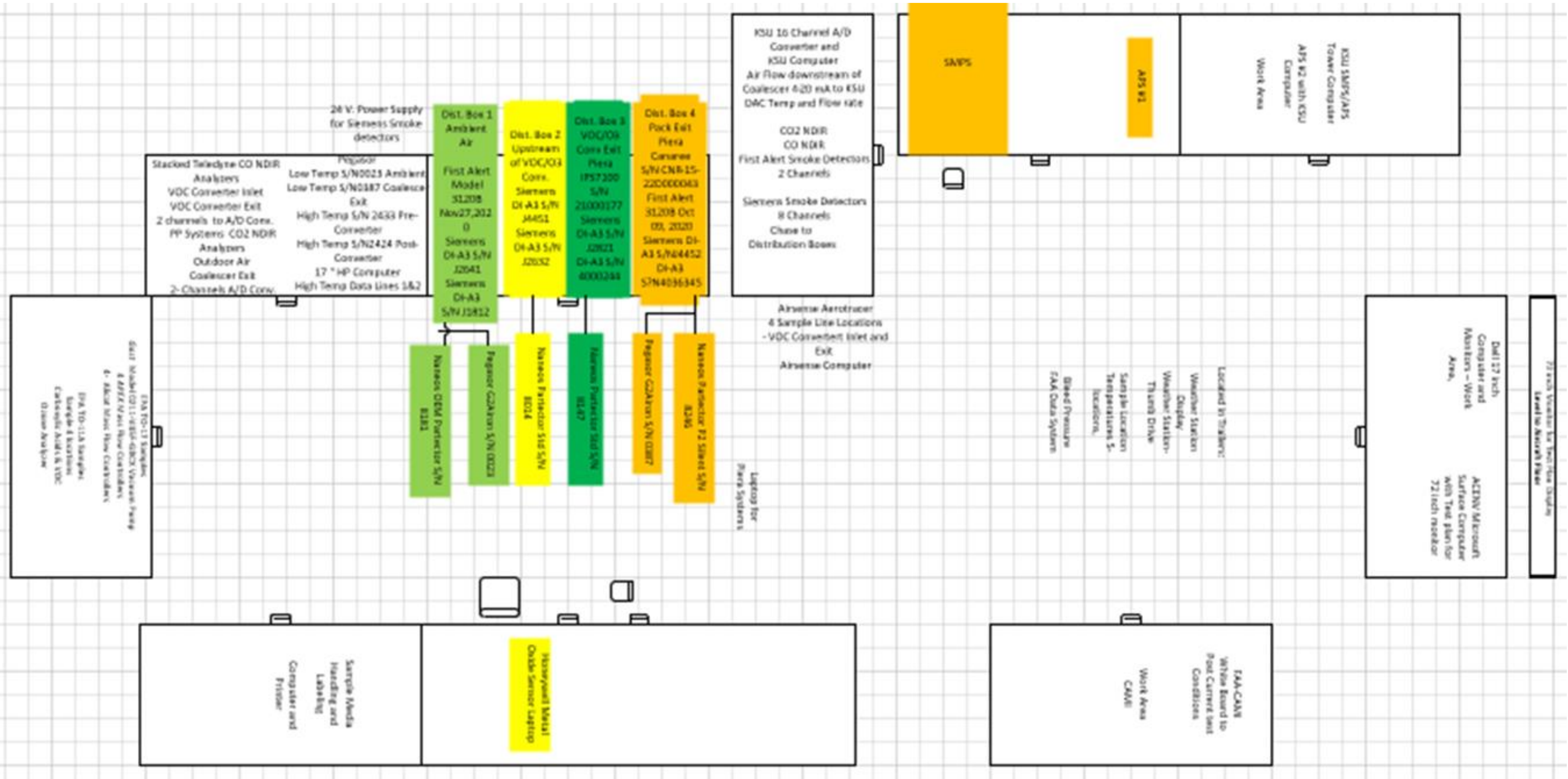


Figure D-5. Inside cabin instrument layout

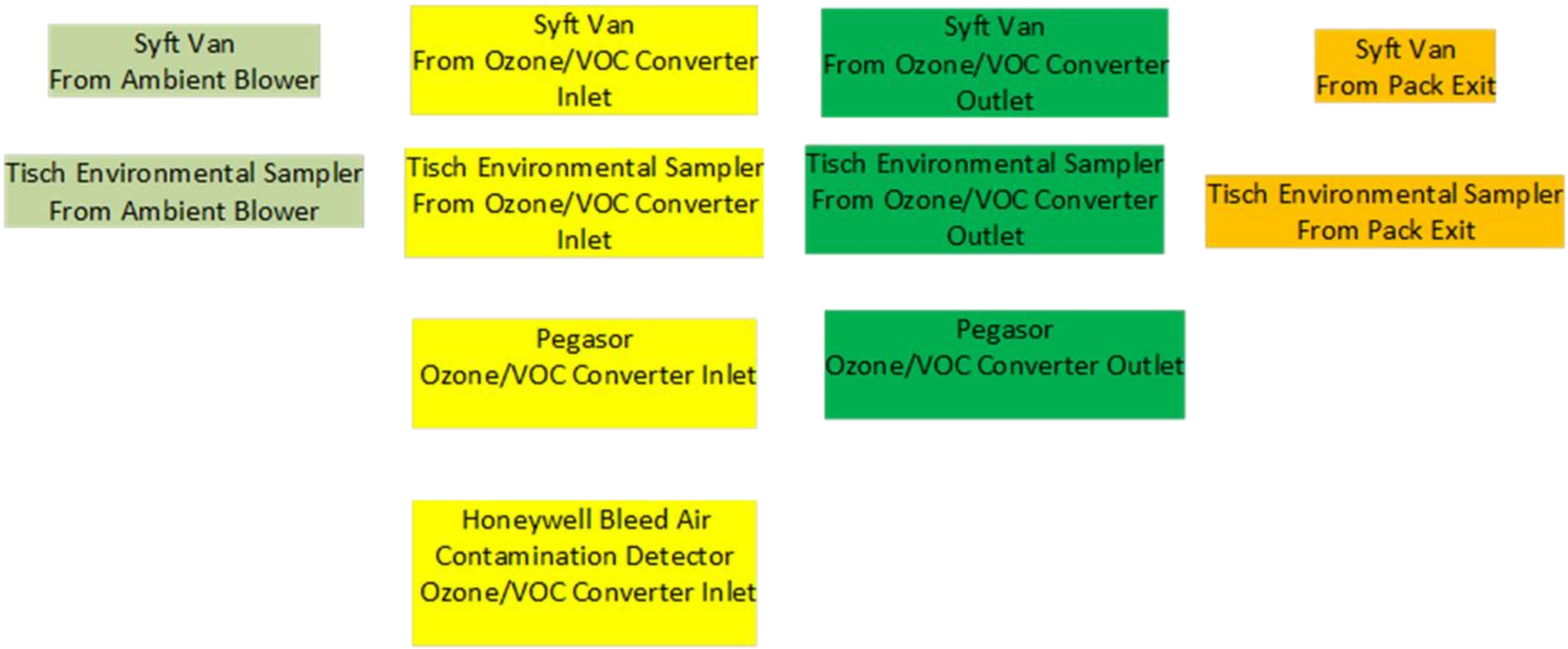
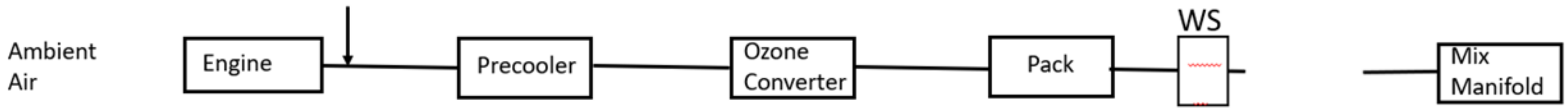


Figure D-6. Outside cabin sampler layout

Sensors and Sampling for Propulsion Engines



Ambient Air

Temperature
Barometer
Sample Line 1 (3" duct with blower)
- TSI APS (Fine Particles)
- Piera Systems (Fine Particles)
- Partector (Ultrafine Particles)
- Honeywell NDIR (CO
- PP Systems NDIR (CO_2)
- Pegasor Low Temp? (Ultrafine Particles)
- MOCON (TVOC)
- Modified Smoke Detector

- EPA TO 11a (Lab Analysis)
- EPA TO 17 (Lab Analysis)

High Vol Sampler EPA TO13a (Lab analysis)

Sample Line 2
- Navy Mod TO 17
- (What does the Navy need for ambient air?)

Engine / Contaminant Injection

Temperature (inline sensor upstream of injection)

Precooler

Temperature (inline sensor)
Sample Line 1
- Piera Systems (Fine Particles)
- Partector? (Ultrafine Particle)
- Pegasor High Temp? (Ultrafine Particles)
- MOCON (TVOC)
- Honeywell Metal Oxide

- EPA TO 11a (Lab Analysis)
- EPA TO 17

Sample Line 2
- High Vol Sampler EPA TO13a (Lab Analysis)

Sample Line 3
- Navy Mod TO17

Sample Line 4
- Spare

Ozone Converter

Temperature (inline sensor)
Sample Line 1
- Piera Systems (Fine Particles)
- Partector? (Ultrafine Particles)
- Pegasor High Temp?)Ultrafine Particles)
- MOCON (TVOC)
- Honeywell Metal Oxide

- EPA TO 11a (Lab Analysis)
- EPA TO 17 (Lab Analysis)

Sample Line 2
- High Vol Sampler EPA TO13a (Lab Analysis)

Sample Line 3
- Navy Mod TO 17

Sample Line 4
Spare

Mix Manifold

Flow Meter (inline, could go further upstream)
Temperature (inline sensor)
Sample Line 1
- TSI SMPS (Ultrafine Particles)
- TSI APS (Fine Particles)
- Piera Systems (Fine Particles)
- Partector (Ultrafine Particles)
- Pegasor Low Temp? (Ultrafine Particles)
- MOCON (TVOC)
- Honeywell NDIR (CO)
- PP Systems NDIR (CO_2)
- Aerometrix AEAIR 2
- Aero Tracer (Multiple sensor)
- CRDS (CH_2O, CH_4, H_2O, NH_3?)
- Shift MS? (composition)
- PTRMS? (composition)
- Modified Smoke Detector

- EPA TO 11a
- EPA TO 17

Sample Line 2
- High Vol Sampler EPA TO13a (Lab Analysis)

Sample Line 3
- Navy 1 Mod TO 17

Sample Line 4
- Spare

If we have a second Aerotracer, where do we put it?

Figure D-7. Detailed list of sensors and sampling location

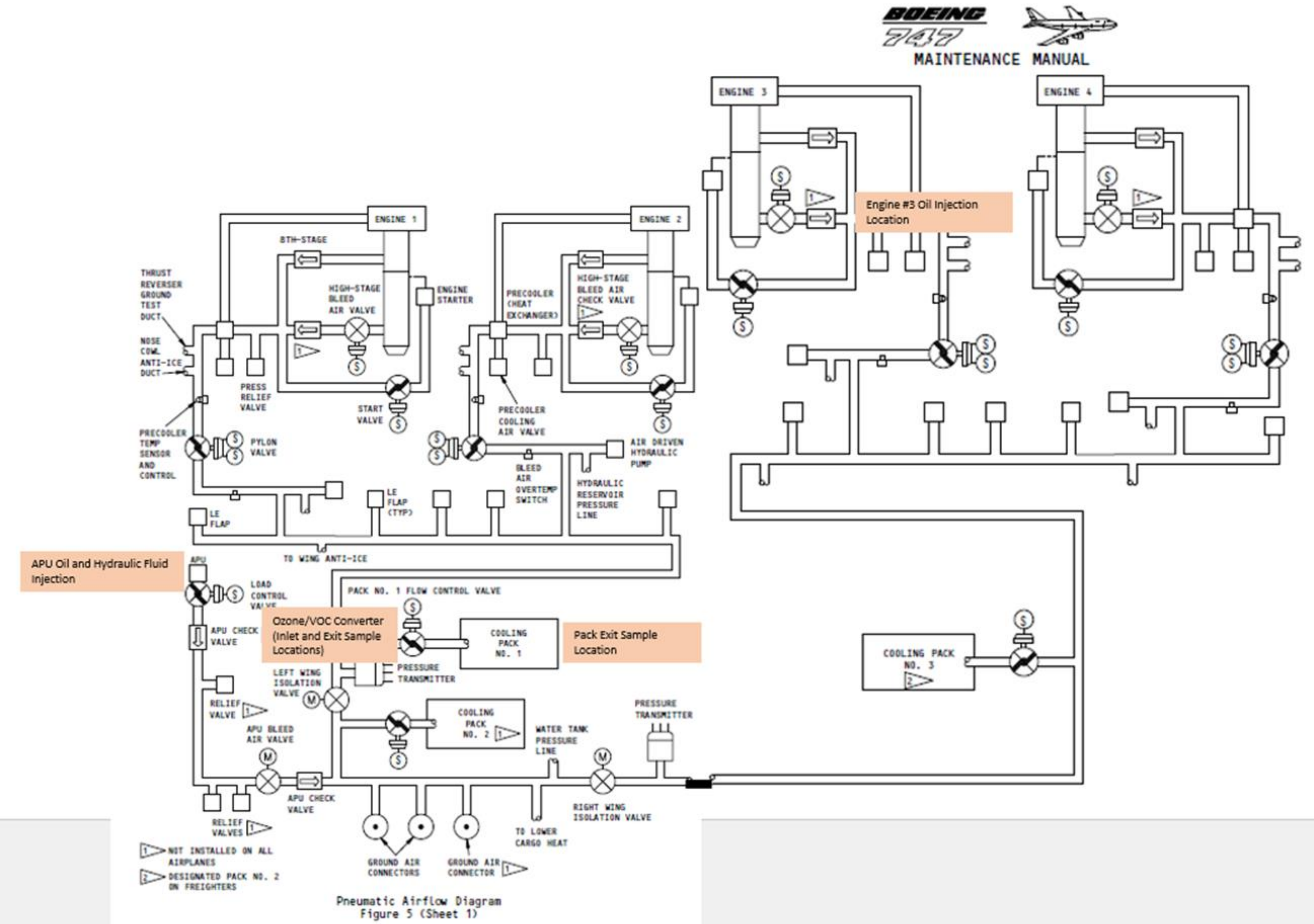
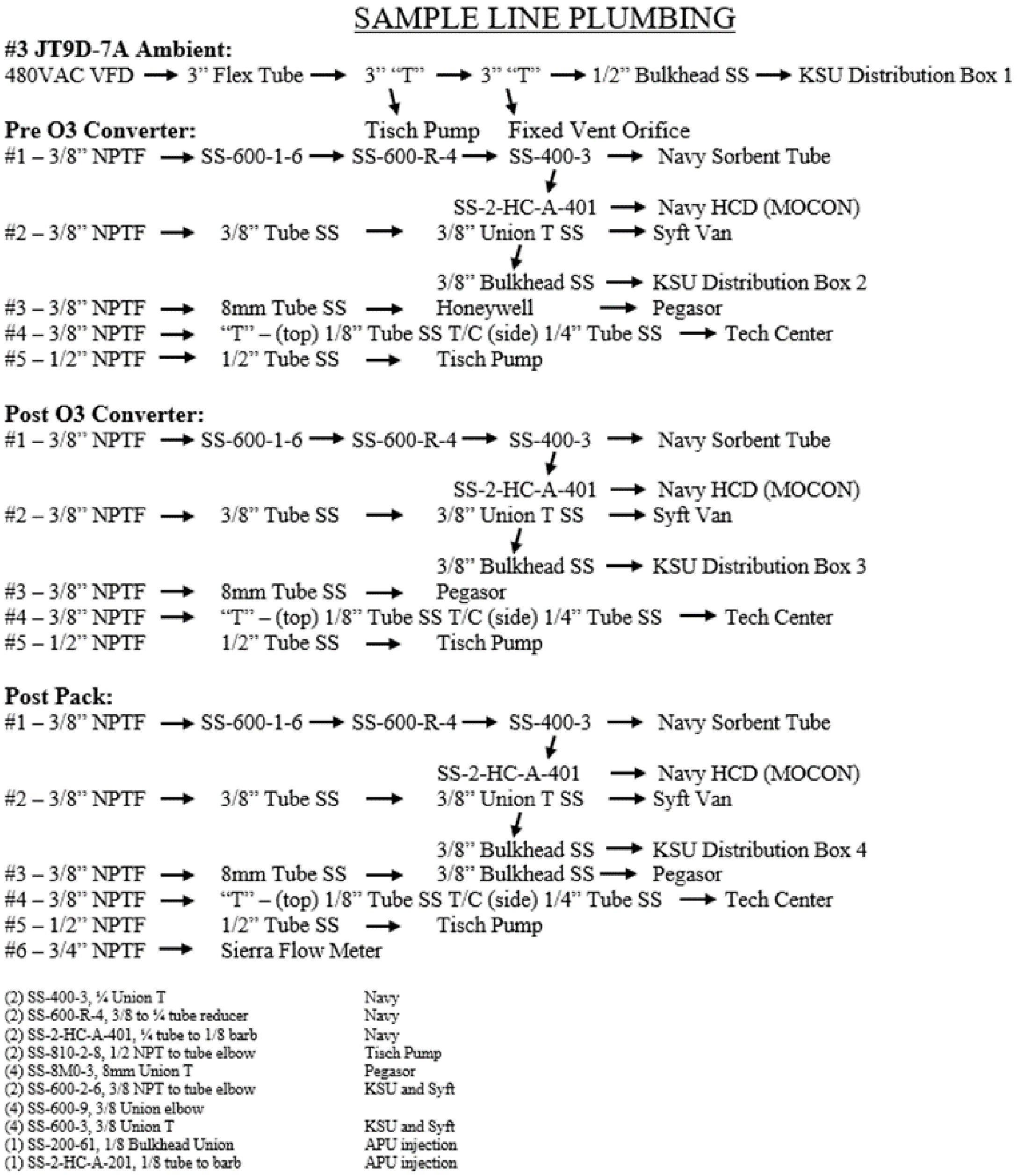


Figure D-8. Boeing 747 aircraft environmental control system schematic



SAMPLE LINE PLUMBING

#3 JT9D-7A Ambient:

480VAC VFD → 3" Flex Tube → 3" "T" → 3" "T" → 1/2" Bulkhead SS → KSU Distribution Box 1
↓ Tisch Pump (from first 3" "T")
↓ Fixed Vent Orifice (from second 3" "T")

Pre O3 Converter:

#1 – 3/8" NPTF → SS-600-1-6 → SS-600-R-4 → SS-400-3 → Navy Sorbent Tube
↓
SS-2-HC-A-401 → Navy HCD (MOCON)
#2 – 3/8" NPTF → 3/8" Tube SS → 3/8" Union T SS → Syft Van
↓
3/8" Bulkhead SS → KSU Distribution Box 2
#3 – 3/8" NPTF → 8mm Tube SS → Honeywell → Pegasor
#4 – 3/8" NPTF → "T" – (top) 1/8" Tube SS T/C (side) 1/4" Tube SS → Tech Center
#5 – 1/2" NPTF → 1/2" Tube SS → Tisch Pump

Post O3 Converter:

#1 – 3/8" NPTF → SS-600-1-6 → SS-600-R-4 → SS-400-3 → Navy Sorbent Tube
↓
SS-2-HC-A-401 → Navy HCD (MOCON)
#2 – 3/8" NPTF → 3/8" Tube SS → 3/8" Union T SS → Syft Van
↓
3/8" Bulkhead SS → KSU Distribution Box 3
#3 – 3/8" NPTF → 8mm Tube SS → Pegasor
#4 – 3/8" NPTF → "T" – (top) 1/8" Tube SS T/C (side) 1/4" Tube SS → Tech Center
#5 – 1/2" NPTF 1/2" Tube SS → Tisch Pump

Post Pack:

#1 – 3/8" NPTF → SS-600-1-6 → SS-600-R-4 → SS-400-3 → Navy Sorbent Tube
↓
SS-2-HC-A-401 → Navy HCD (MOCON)
#2 – 3/8" NPTF → 3/8" Tube SS → 3/8" Union T SS → Syft Van
↓
3/8" Bulkhead SS → KSU Distribution Box 4
#3 – 3/8" NPTF → 8mm Tube SS → 3/8" Bulkhead SS → Pegasor
#4 – 3/8" NPTF → "T" – (top) 1/8" Tube SS T/C (side) 1/4" Tube SS → Tech Center
#5 – 1/2" NPTF 1/2" Tube SS → Tisch Pump
#6 – 3/4" NPTF → Sierra Flow Meter

(2) SS-400-3, ¼ Union T	Navy
(2) SS-600-R-4, 3/8 to ¼ tube reducer	Navy
(2) SS-2-HC-A-401, ¼ tube to 1/8 barb	Navy
(2) SS-810-2-8, 1/2 NPT to tube elbow	Tisch Pump
(4) SS-8M0-3, 8mm Union T	Pegasor
(2) SS-600-2-6, 3/8 NPT to tube elbow	KSU and Syft
(4) SS-600-9, 3/8 Union elbow	
(4) SS-600-3, 3/8 Union T	KSU and Syft
(1) SS-200-61, 1/8 Bulkhead Union	APU injection
(1) SS-2-HC-A-201, 1/8 tube to barb	APU injection

Figure D-9. Sample line plumbing

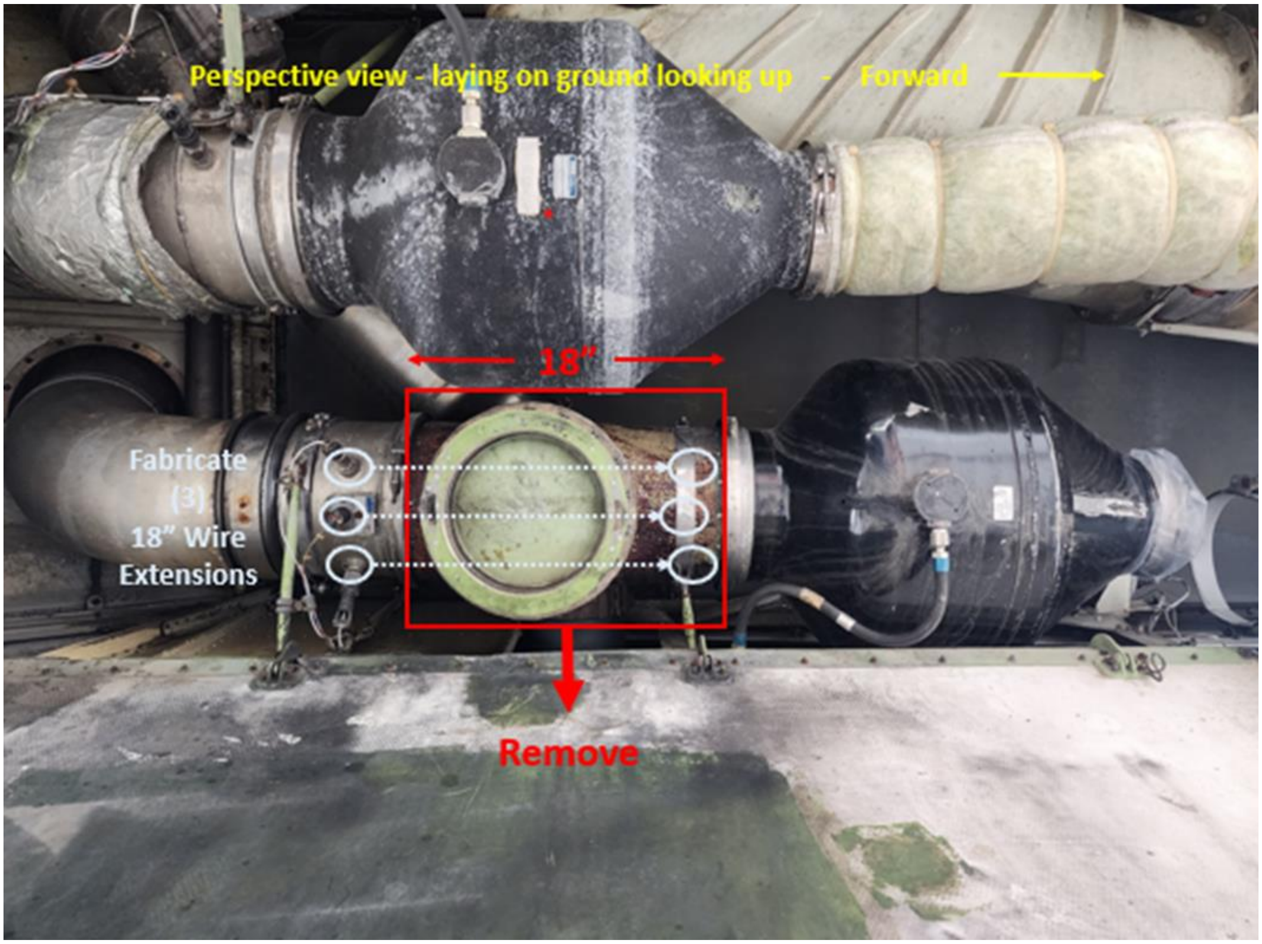


Figure D-10. Aircraft environmental control system duct modification
Removal of ground air port

Figure D-11. Aircraft environmental control system duct modification
Ground air conditioning port and coalescer housing removed

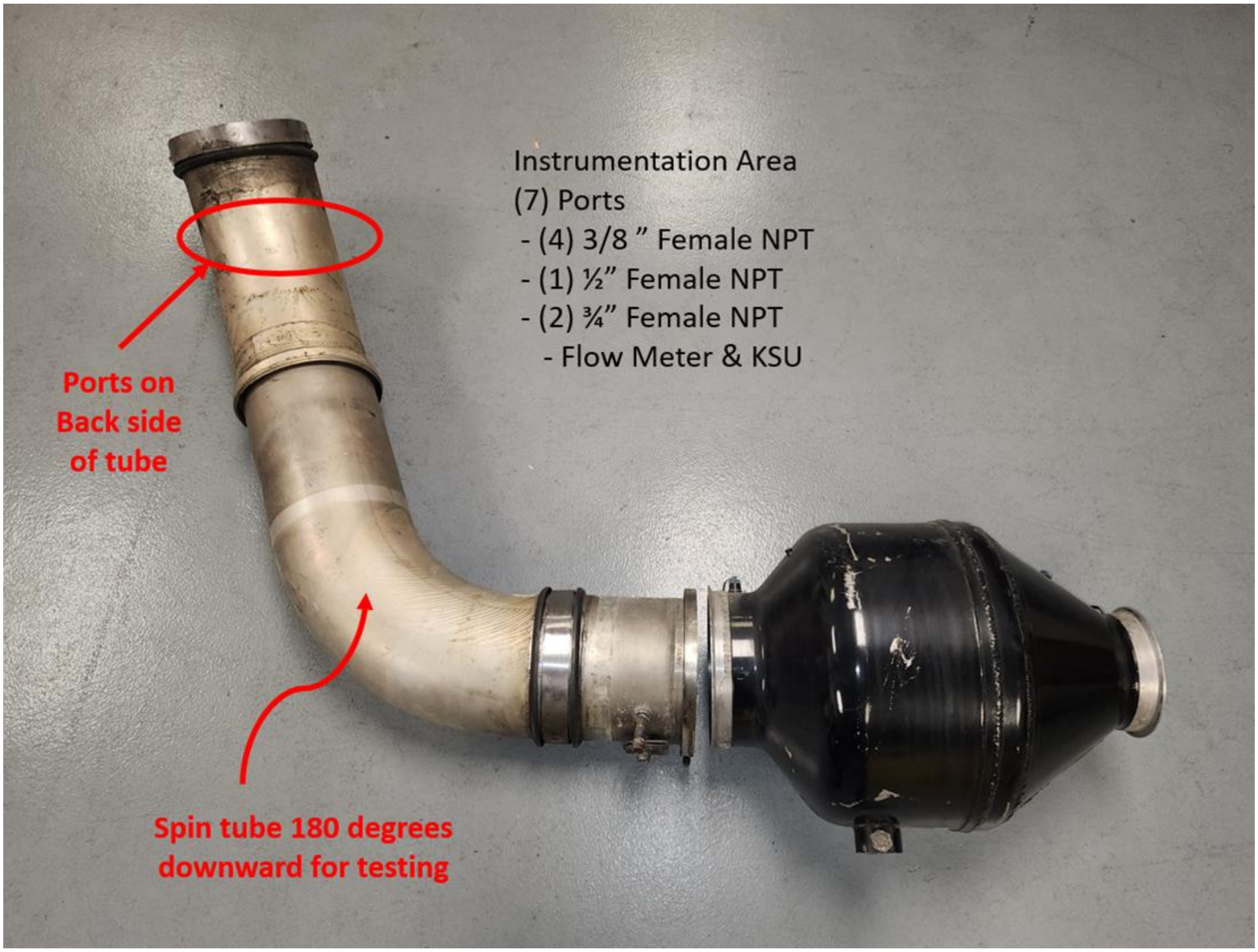
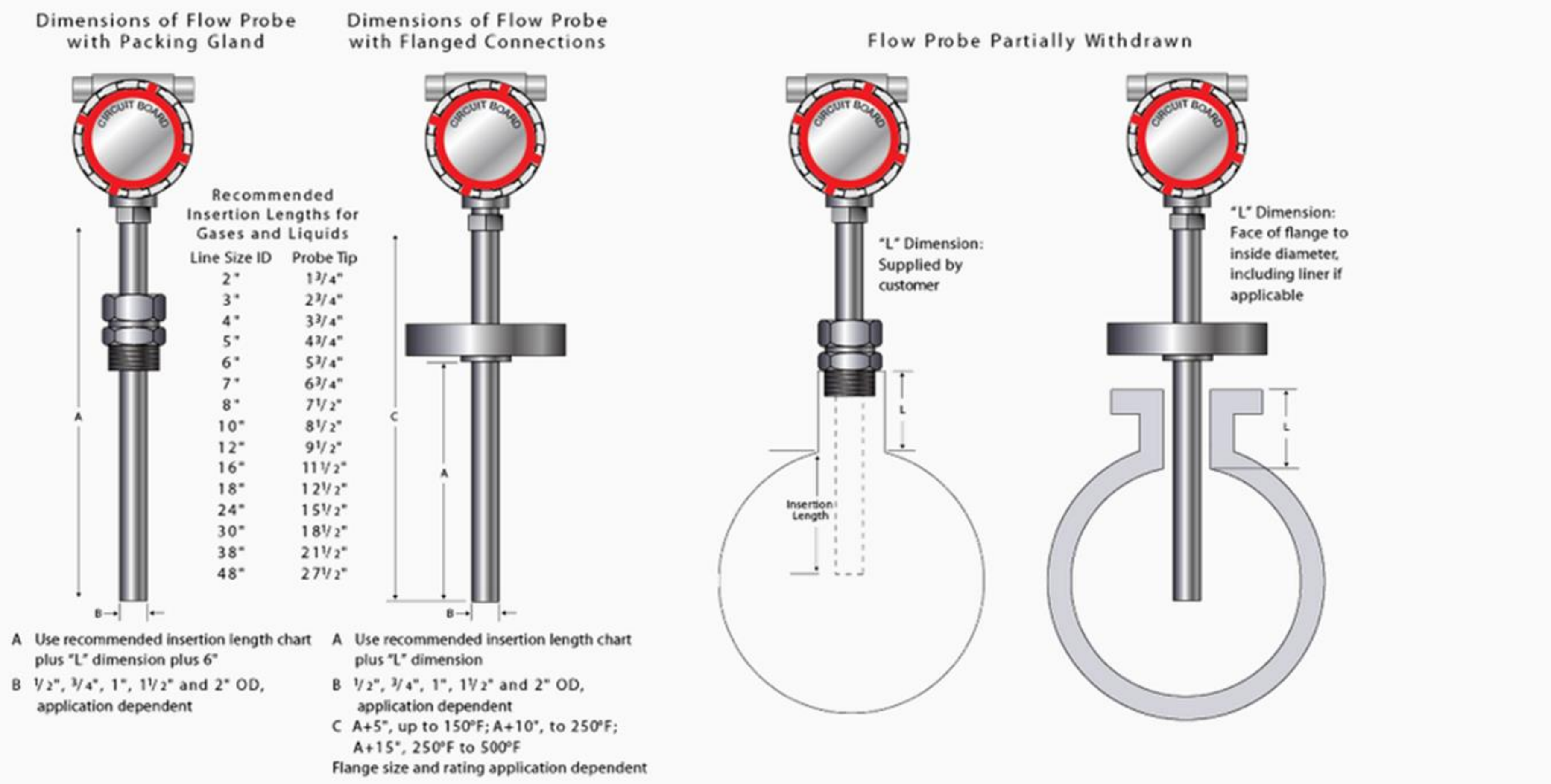


Figure D-12. Aircraft environment control system duct modification

Figure D-13. Pack exit duct rotated down and reinstalled to coalescer without ground port - upward view

Figure D-14. Pack exit duct rotated down and reinstalled to coalescer without ground port - side view

Figure D-15. Duct rotated down and reinstalled to coalescer without ground port
Looking forward towards aircraft nose from aft wheel well



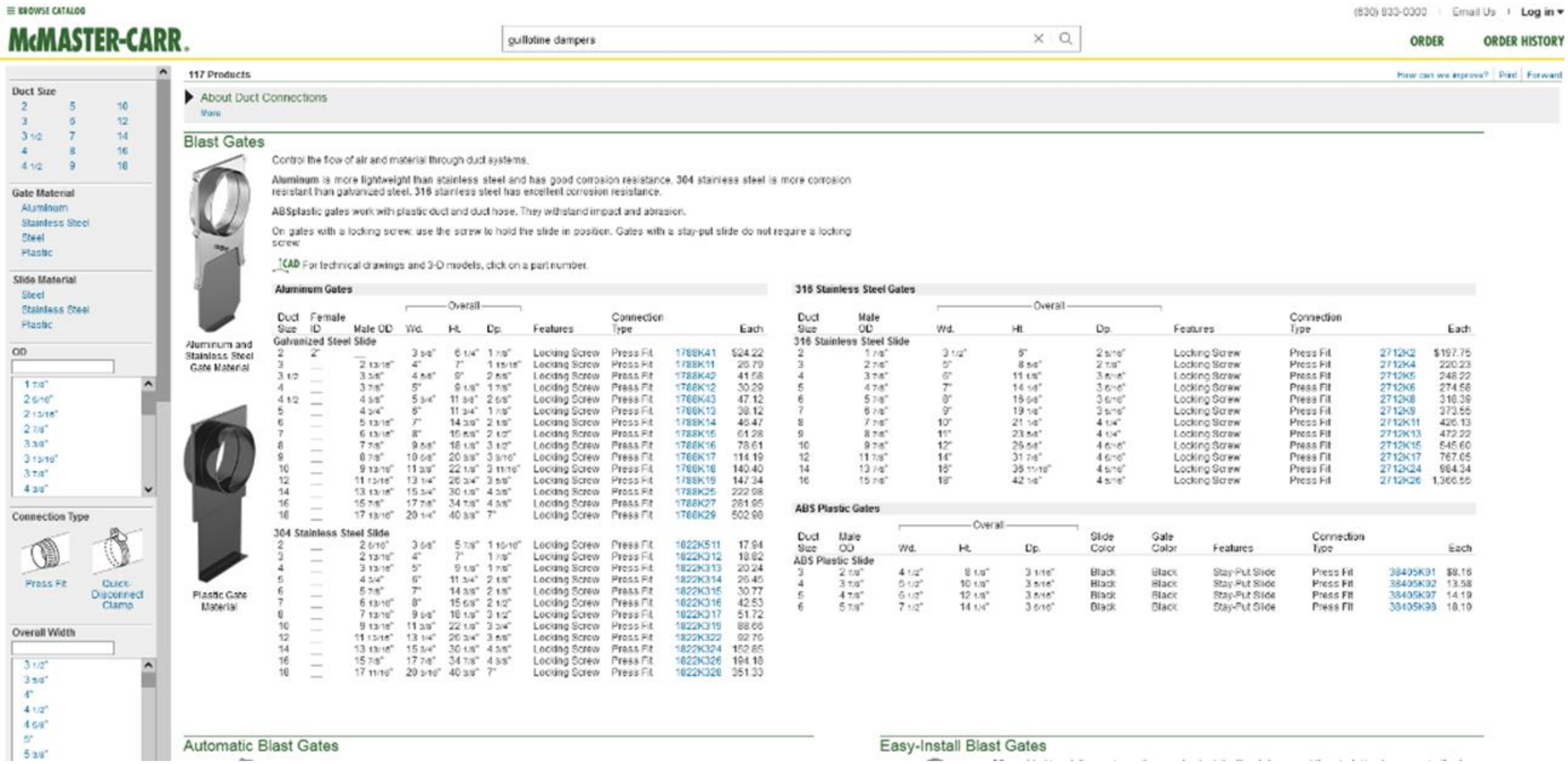
Recommended Insertion Lengths for Gases and Liquids

Line Size ID	Probe Tip
2"	1¾"
3"	2¾"
4"	3¾"
5"	4¾"
6"	5¾"
7"	6¾"
8"	7½"
10"	8½"
12"	9½"
16"	11½"
18"	12½"
24"	15½"
30"	18½"
38"	21½"
48"	27½"

A Use recommended insertion length chart plus "L" dimension plus 6"
B ½", ¾", 1", 1½" and 2" OD, application dependent

A Use recommended insertion length chart plus "L" dimension
B ½", ¾", 1", 1½" and 2" OD, application dependent
C A+5", up to 150°F; A+10", to 250°F; A+15", 250°F to 500°F
Flange size and rating application dependent

Figure D-16. Air mass-flow probe installation for air duct



117 Products

About Duct Connections

More

Blast Gates

Control the flow of air and material through duct systems.

Aluminum is more lightweight than stainless steel and has good corrosion resistance. **304** stainless steel is more corrosion resistant than galvanized steel. **316** stainless steel has excellent corrosion resistance.

ABS plastic gates work with plastic duct and duct hose. They withstand impact and abrasion.

On gates with a locking screw, use the screw to hold the slide in position. Gates with a stay-put slide do not require a locking screw.

CAD For technical drawings and 3-D models, click on a part number.

Aluminum Gates

Duct Size	Female ID	Male OD	Overall Wd.	Overall Ht.	Overall Dp.	Features	Connection Type		Each
Galvanized Steel Slide									
2	2"	—	3 5/8"	6 1/4"	1 7/8"	Locking Screw	Press Fit	1788K41	$24.22
3	—	2 13/16"	4"	7"	1 15/16"	Locking Screw	Press Fit	1788K11	26.79
3 1/2	—	3 3/8"	4 5/8"	9"	2 5/8"	Locking Screw	Press Fit	1788K42	41.58
4	—	3 7/8"	5"	9 1/8"	1 7/8"	Locking Screw	Press Fit	1788K12	30.29
4 1/2	—	4 3/8"	5 3/4"	11 3/8"	2 5/8"	Locking Screw	Press Fit	1788K43	47.12
5	—	4 3/4"	6"	11 3/4"	1 7/8"	Locking Screw	Press Fit	1788K13	38.12
6	—	5 13/16"	7"	14 3/8"	2 1/8"	Locking Screw	Press Fit	1788K14	46.47
7	—	6 13/16"	8"	15 5/8"	2 1/2"	Locking Screw	Press Fit	1788K15	61.28
8	—	7 7/8"	9 5/8"	18 1/8"	3 1/2"	Locking Screw	Press Fit	1788K16	78.61
9	—	8 7/8"	10 5/8"	20 3/8"	3 5/16"	Locking Screw	Press Fit	1788K17	114.19
10	—	9 13/16"	11 3/8"	22 1/8"	3 11/16"	Locking Screw	Press Fit	1788K18	140.40
12	—	11 13/16"	13 1/4"	26 3/4"	3 5/8"	Locking Screw	Press Fit	1788K19	147.34
14	—	13 13/16"	15 3/4"	30 1/8"	4 3/8"	Locking Screw	Press Fit	1788K25	222.98
16	—	15 7/8"	17 7/8"	34 7/8"	4 3/8"	Locking Screw	Press Fit	1788K27	281.95
18	—	17 13/16"	20 1/4"	40 3/8"	7"	Locking Screw	Press Fit	1788K29	502.98
304 Stainless Steel Slide									
2	—	2 5/16"	3 5/8"	5 7/8"	1 15/16"	Locking Screw	Press Fit	1822K511	17.94
3	—	2 13/16"	4"	7"	1 7/8"	Locking Screw	Press Fit	1822K312	18.82
4	—	3 13/16"	5"	9 1/8"	1 7/8"	Locking Screw	Press Fit	1822K313	20.24
5	—	4 3/4"	6"	11 3/4"	2 1/8"	Locking Screw	Press Fit	1822K314	26.45
6	—	5 7/8"	7"	14 3/8"	2 1/8"	Locking Screw	Press Fit	1822K315	30.77
7	—	6 13/16"	8"	15 5/8"	2 1/2"	Locking Screw	Press Fit	1822K316	42.53
8	—	7 13/16"	9 5/8"	18 1/8"	3 1/2"	Locking Screw	Press Fit	1822K317	51.72
10	—	9 13/16"	11 3/8"	22 1/8"	3 3/4"	Locking Screw	Press Fit	1822K319	88.66
12	—	11 13/16"	13 1/4"	26 3/4"	3 5/8"	Locking Screw	Press Fit	1822K322	92.76
14	—	13 13/16"	15 3/4"	30 1/8"	4 3/8"	Locking Screw	Press Fit	1822K324	152.85
16	—	15 7/8"	17 7/8"	34 7/8"	4 3/8"	Locking Screw	Press Fit	1822K326	194.18
18	—	17 11/16"	20 3/16"	40 3/8"	7"	Locking Screw	Press Fit	1822K328	351.33

316 Stainless Steel Gates

Duct Size	Male OD	Overall Wd.	Overall Ht.	Overall Dp.	Features	Connection Type		Each
316 Stainless Steel Slide								
2	1 7/8"	3 1/2"	6"	2 5/16"	Locking Screw	Press Fit	2712K2	$197.75
3	2 7/8"	5"	8 5/8"	2 7/8"	Locking Screw	Press Fit	2712K4	220.23
4	3 7/8"	6"	11 1/8"	3 5/16"	Locking Screw	Press Fit	2712K5	248.22
5	4 7/8"	7"	14 1/8"	3 5/16"	Locking Screw	Press Fit	2712K6	274.56
6	5 7/8"	8"	16 5/8"	3 5/16"	Locking Screw	Press Fit	2712K8	318.39
7	6 7/8"	9"	19 1/4"	3 5/16"	Locking Screw	Press Fit	2712K9	373.55
8	7 7/8"	10"	21 1/8"	4 1/4"	Locking Screw	Press Fit	2712K11	426.13
9	8 7/8"	11"	23 5/8"	4 1/4"	Locking Screw	Press Fit	2712K13	472.22
10	9 7/8"	12"	25 5/8"	4 5/16"	Locking Screw	Press Fit	2712K15	545.60
12	11 7/8"	14"	31 7/8"	4 5/16"	Locking Screw	Press Fit	2712K17	767.05
14	13 7/8"	16"	35 11/16"	4 5/16"	Locking Screw	Press Fit	2712K24	984.34
16	15 7/8"	18"	42 1/4"	4 5/16"	Locking Screw	Press Fit	2712K26	1,366.55

ABS Plastic Gates

Duct Size	Male OD	Overall Wd.	Overall Ht.	Overall Dp.	Slide Color	Gate Color	Features	Connection Type		Each
ABS Plastic Slide										
3	2 7/8"	4 1/2"	8 1/8"	3 1/16"	Black	Black	Stay-Put Slide	Press Fit	38405K91	$8.16
4	3 7/8"	5 1/2"	10 1/8"	3 5/16"	Black	Black	Stay-Put Slide	Press Fit	38405K92	13.58
5	4 7/8"	6 1/2"	12 1/8"	3 5/16"	Black	Black	Stay-Put Slide	Press Fit	38405K97	14.19
6	5 7/8"	7 1/2"	14 1/4"	3 5/16"	Black	Black	Stay-Put Slide	Press Fit	38405K98	18.10

Automatic Blast Gates

Easy-Install Blast Gates

Figure D-17. 8-inch guillotine valve to provide back-pressure for air duct

Figure D-18. Guillotine valve attached to duct adapter