

Evaluation of potential markers of bleed air contamination

by

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Abstract

Gas turbine engine oil and other fluids can contaminate the bleed air of an aircraft and, consequently, infiltrate cabin air. This thesis examines potential markers of bleed air contamination that can be used to detect the presence of these fluids in bleed air. Additionally, common instrumentation devices and techniques that are used to measure and identify background levels, contamination rates, particles, and chemicals in bleed air and cabin air quality on an aircraft are briefly discussed. Next, the thesis discusses the current ASHRAE 1830-RP project, which focuses on engine oil, hydraulic fluid, and deicing fluid contamination of bleed air and the resulting particulates that result as markers of this contamination. Furthermore, two major studies known as VIPR and Cranfield are addressed in this thesis and specifically deal with bleed air and cabin air on aircraft for comparison purposes. The VIPR project provides detailed information on substances, chemicals, and particulates found in bleed air from engine oil, but it is somewhat limited in scope. While a sizeable number of substances in the bleed air were evaluated the results apply to a limited range of operating conditions and a single contaminant (Mobil Jet Oil II). The Cranfield project was identified as a relevant study. It was somewhat narrow in measurement scope, but it was extensive in that it conducted measurements on 100 flights. Thus, it adds useful information and is included in this thesis. Both VIPR and Cranfield have relatively useful particulate data, and therefore will be compared to the ASHRAE 1830-RP project data. Based on the results from VIPR and ASHRAE 1830-RP, it can be inferred that there indeed can be uses of particulates as a marker for bleed air contamination, where markers are able to be measured and reliably associated with the contaminant. The results indicate that ultrafine particles ($<100\text{nm}$) tend to show large responses for engine oils. While ultrafine particles remain a prime candidate for detection of oil contamination, sensing needs to be upstream of the cabin in the supply air stream to ensure particles are detected from bleed air and not from other sources for future studies. Fine particles ($0.3\text{-}2\mu\text{m}$) show clear response for engine oils. Additionally, formaldehyde and acetaldehyde may be promising markers for bleed air contamination and their location in the cabin has not been ruled out. Also, carbon monoxide (CO) is likely not a good marker for bleed air contamination, but total volatile organic compounds (TVOCs) are still possible indicators of oil contamination and both markers probably cannot be used to detect oil contamination by measurements of the cabin air. Carbon dioxide (CO₂) appears to be a poor marker for bleed air contamination but is a useful discriminator on determining whether particles arise from bleed air contamination or exhaust ingestion. Fine particles appear to be a good marker for hydraulic fluid. Ultrafine particles are however probably not a reliable marker for hydraulic fluid. Lastly, particles of any size are very poor markers for deicing fluid based on the results from ASHRAE 1830- RP.

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Disclaimer

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1. Introduction

The main purpose of this thesis is to examine the suitability of potential markers for bleed air contaminants that are generated during “fume events” inside pressurized aircraft. This is possible by examining particulate data and other pertinent data. Most commercial aircraft utilize bleed air from the propulsion engine compressors for pressurization and ventilation during flight. Sometimes they also utilize an auxiliary power unit for proper pressurization and ventilation. Contamination from lubricating oil or other fluids that are ingested into the engine air intake or through bearing seal leakage will cause the air supplied to the aircraft to become contaminated (Roth, 2015). Furthermore, thermal decomposition is also a possibility if the temperatures in the engine compressor at the bleed air extraction location are high enough under certain operating conditions (NRC, 2002). There is also potential for chronic, unidentified exposure if lower levels of bleed air contamination are present. On the other hand, greater levels of contamination create a fume event where there is an obvious odor or occasionally visible smoke or mist inside the aircraft. It is imperative that the flight crew make critical decisions in the case of visible smoke. A clear emergency would arise in the case of an onboard fire, requiring immediate landing perhaps at a less than ideal runway (Jones et al., 2017). Smoke from oil in the bleed air from a compressor seal leak could be managed by source isolation and the flight can proceed normally without the need to seek a safe landing point. Aircraft are however, not usually equipped with instrumentation that can detect bleed air contamination. As a result, flight crew could potentially waste valuable time trying to isolate a bleed air source when there actually is an onboard fire (Jones et al., 2017). Unnecessary emergency landings are also possible when the source could have been isolated with little to no disruption of the flight. For more serious cases, bleed air contamination from oil may cause unscheduled landings or turn backs with their inherent costs and disruptions (Shehadi et al 2015a, Lebbin 2013). The chance of a bleed air fume occurrence on any random flight is extremely remote; Shehadi et al (2015b) estimated the frequency to be approximately one in 5000 flights and lubricating oil is just one of many causes. Still, having the ability to detect bleed air contamination and to know the source engine of this contamination is an asset that is valuable in mitigating the risk of occupant exposure to contamination and assisting in critical decision making in the case of a serious smoke in the cabin event. This vital need is recognized in ASHRAE Standard 161 (ASHRAE, 2013) which calls for sensors to detect contamination of bleed air. Unfortunately, sensors that can reliably detect bleed air contamination on aircraft are not standard yet. However, one of the objectives of the ASHRAE 1830-RP bleed air contamination research is to find adequate sensing technology to properly assess the chemicals associated with bleed air contamination from oil, deicing fluid, hydraulic fluid, etc.

2. Bleed Air Review

It is important to understand the fundamentals of bleed air and how it operates on aircraft before discussing the specifics of bleed air contamination and the chemicals and particles associated with it. Bleed air is the air that is extracted from the engine compressor (Roth, 2015). In some instances, small amounts of lubricating oil may leak through the compressor seals and enter the bleed air stream. As a result, these particles get heated by the hot compressed bleed air and travel with the bleed air to the cabin for ventilation and pressurization. Typically, the bleed air has a temperature in the range of 200-250°C and is at a medium-high pressure so that its energy can effectively be utilized to power several systems, such as air conditioning. Furthermore, the temperature will depend upon the phase of flight and engine operation. Typical values of temperature and pressure are shown in Table 1 (NRC, 2002). During certain phases of flight, the temperature will be higher and can exceed 300°C. The bleed air system utilized on an aircraft extracts the air from the engine compressor section. Bleed air, as previously mentioned, can be over 250°C so when it leaves the engine it must be cooled via an air-to-air heat exchanger before it is distributed to other locations on the aircraft. The auxiliary power unit (APU) is a commonly used on the ground as external air is not always available. Located at the rear of the aircraft, the APU is a small turbine engine used to supply compressed air to the aircraft. This is the source of air conditioning if the propulsion engines are not operating, and no external air source is connected. It is important to note that not every bleed air system is the same and they vary between engine models. However, modern engines such as the Whitney PW2000 have over 20 stages of compression and compression ratios up to 30, and require multiple bleed air ports (Roth, 2015). Smaller aircraft may have engines that consist of less stages and will only have one available bleed air extraction stage and the pressure ratio will be in the range of 5 to 10. Generally, jet engines have compressors that are axial on a large aircraft but consist of a single centrifugal stage on smaller engines that are used on small helicopters and smaller turboprop aircraft. The low pressure (LP) stage bleed air port is used during high power operations such as cruising power, whereas the high pressure (HP) stage is used for extraction during lower power operations. During take-off, the LP stage is used when the engine is operating at high power, while the HP stage is used during landing when the engine is operating at low power. The LP stage however, can provide the necessary bleed air flow (Roth, 2015). The air is then passed through a precooler, pressure regulating valve, ozone converter, air condition pack system and a mixing air plenum before coming inside the aircraft (Roth, 2015). In the case of an oil leak in the compressor, lubricating fluid would be present at a high temperature environment via the heated compressed air. Thermal decomposition of oil is also another possibility with the temperature of bleed air reaching up to 320°C. At these high temperatures, the oil may release CO and other toxic compounds (Roth, 2015).

Table 1-Typical Bleed Air Temperatures and Pressures

Data from (NRC, 2002)

Mode of Operation	Temperature, °C (°F)	Absolute Pressure, kPa (psi)	Extraction Stage
Takeoff — Maximal power	350 (660)	1170 (170)	Low pressure
Top of climb	310 (590)	690 (100)	Low pressure
Cruise	250 (480)	340 (100)	Low pressure
Initial descent	185 (365)	200 (29)	High pressure
End of descent (ground level)	230 (445)	460 (67)	High pressure
Switchover from high to low pressure	280 (535)	480 (70)	High pressure
Ground operations	170 (340)	—	Auxiliary power unit

3. Methods to Assess Particles in Bleed Air and Cabin Air

As stated previously, the objective of this research was to evaluate potential markers for various types of bleed air contamination. The key part of this research was to have the appropriate instrumentation to measure particles to see if they can be used as markers for bleed air contamination. The objective was not to evaluate the contamination itself from controlled contamination rates. Previous research from the VIPR study indicated that particles were promising markers for bleed air contamination. Therefore, it is important to look at potential ways to measure particles.

It is a common practice to utilize particle counters to properly measure particles in terms of size and concentration. Measurement of bleed air is possible by using various types of devices. These devices include aerosol sensing systems (particle counters), pumps and ab-/adsorption materials, various types of absorbent tubes for detecting different chemicals, photoionization detectors, ultrafine particle counters, and other devices used for bleed air and cabin air applications. These instruments are often quite fragile and costly. Detecting the particle is important, but determining the size is crucial as well. The practice of obtaining accurate measurements for particles is quite challenging. Additionally, there is the issue of classifying particles in a manner that is both clearly understood and interpreted (Roth, 2015). Most instruments that measure particles will ‘bin’ the particles that are counted into discrete size ranges, like that of a histogram. Due to the resolution and accuracy of the equipment, not all the measured particles will be binned properly, but statistics can effectively characterize the error probability and corrections may then be applied accordingly (Roth, 2015). The following equipment was used for the VIPR data and ASHRAE 1830-RP data reported in this thesis.

3.1 Aerodynamic Particle Sizer (APS Model 3321)

The Model 3321 APSTM spectrometer, is a general-purpose, high-performance particle spectrometer that can measure both aerodynamic diameter and light-scattering intensity, as shown in Figure 1 (TSI, 2014). The model 3321 can provide accurate count size distributions for particles with aerodynamic diameters ranging from 0.5-20 μ m. It also detects light-scattering intensity for particles from 0.3-20 μ m (TSI, 2014). The Model 3321 can operate without a computer for setup and initial sampling. However, to save, interpret, or print data, requires a computer or some other data collection system to be connected.



Figure 1- Model Aerodynamic Particle Sizer Spectrometer

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3.2 Model 3775 Condensation Particle Counter (CPC)

The Model 3375 Condensation Particle Counter (CPC) is a device that can detect airborne particles down to 4nm in diameter. It can provide extremely accurate measurements for a wide concentration range from 0 to 10⁷ particles per cubic centimeter (TSI, 2014). Because of this, the CPC is well known for its versatility and suitability for various applications. These applications include but are not limited to basic aerosol research, filter and air-cleaning testing, combustion and engine exhaust research, health effect studies, inhalation and exposure studies, atmospheric and climate studies, and nanotechnology research. In addition, it can be utilized as part of a TSI Scanning Mobility Particle Sizer (SMPS) spectrometer to measure particle size distribution (TSI, 2014).



Figure 2-Model Condensation Particle Counter

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3.3 Electrostatic Classifier (TSI Model 3080L)

The Model 3080 Electrostatic Classifier has a Kr-85 bipolar charger to neutralize the charges on particles, a controller to control high-voltage and flows, and a Differential Mobility Analyzer (DMA) which separates particles based on their electrical mobility (TSI, 2014). The DMA is the main component for generating or sizing aerosols (TSI, 2014). Given a polydisperse input aerosol, the instrument output can be a stream of monodisperse aerosol of known particle size. The Model 3080 Electrostatic Classifier can also be used in an aerosol generation system to produce highly monodisperse particles by selecting aerosol particles of uniform size from a polydisperse source, and when used in a TSI SMPS spectrometer particle sizing system can offer high-resolution sizing of sub-micrometer particles (TSI, 2014).



Figure 3-Model 3030 Electrostatic Classifier with Model 3081 Long DMA and Model 3085 Nano DMA

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3.4 SMPS

The Electrostatic Classifier and CPC make up what is referred to as the scanning mobility particle sizer (SMPS) that can detect ultrafine particles. Thus, the SMPS consists of the Electrostatic Classifier and CPC. A wide range of particle sizes ranging from 10nm to 20 μ m can be covered by both the APS and SMPS system (Roth, 2015). The SMPS also has a feature in which the Electrostatic Classifier separates the particles by size by creating a continually change particle size window by applying an exponential ramped charge to the voltage rod shown in the figure above on the electrostatic classifier (Roth, 2015).

4. Contamination Events

Since the ASHRAE 1830-RP project from the FAA deals extensively with bleed air contamination, it is imperative to understand how it arises. Contamination of bleed air systems can be caused by worn or leaky oil seals. Oil may also be a factor when the compressor fails to maintain a vacuum pressure on the lubricating oil reservoir. Sometimes APUs may also cause a bleed air contamination event while aircraft are on the ramp. Data made available from the FAA indicate that 33% of incidents were due to fuel leaks, 23% were due to engine oil leaks, 18% were due to APU oil leaks and 13% were due to hydraulic fluid leaks, with the rest being attributed to air cycle machine oil leaks (Overfelt, Jones, Loo, Haney, & Neer, 2012; Shehadi et al., n.d.).

5. Thermal Degradation

An important factor in bleed air contamination events that is worth mentioning would be the thermal degradation of oil in the bleed air. The process of thermal degradation involves the decomposition of oil. There is no open flame during thermal decomposition. During this process, carbon dioxide and carbon monoxide are released as a result along with other gaseous chemicals and smoke particles. Thermal degradation is therefore of interest as it may generate substances that can be used as markers of contamination (e.g., certain volatile organic compounds). Furthermore, an ACER report gives a breakdown of the potential bleed air contaminants reproduced here as Table 2 (Overfelt et al., 2012).

Table 2-Summary of Potential Bleed Air Contaminants

Reproduced from (Overfelt et al., 2012)

<i>Potential Bleed Air Contamination Event</i>	<i>Probable Contaminant</i>
Engine oil leak producing aerosolized droplets of oil in the engine compressor	• Very fine mist of engine oil aerosols • Small amounts of carbon monoxide (CO) and carbon dioxide (CO₂)
Partially pyrolyzed jet engine oil	• Very fine mist of engine oil aerosols • Carbon monoxide (CO) • Carbon dioxide (CO₂) • Misc. unburned hydrocarbons • Ultrafine smoke particles
Fully pyrolyzed jet engine oil	• Carbon monoxide (CO) • Carbon dioxide (CO₂) • Ultrafine smoke particles

6. VOCs

Volatile organic Compounds (VOCs) are compounds that have a high vapor pressure and low water solubility (EPA, 2021). Most VOCs are human-made chemicals that are used and produced in the manufacture of paints, pharmaceuticals, and refrigerants. VOCs are usually industrial solvents, such as trichloroethylene; fuel oxygenates, such as methyl tert-butyl ether (MTBE); or by-products produced by chlorination in water treatment, such as chloroform. VOCs are typically components of petroleum fuels, hydraulic fluids, paint thinners, and dry-cleaning agents (EPA, 2021). VOCs are emitted as gases from certain solids or liquids. They include a variety of chemicals, some of which may have short- and long-term adverse health effects. Additionally, concentrations of a lot of VOCs are always higher indoors than outdoors (EPA, 2021). Health effects of VOCs may include eye, nose and throat irritation, headaches, loss of coordination and nausea, and damage to the liver, kidney, and central nervous system. Key symptoms or signs or symptoms associated with exposure to VOCs include conjunctival irritation, allergic skin reaction, dyspnea, declines in serum cholinesterase levels, emesis, epistaxis, and fatigue (EPA, 2021). Studies such as VIPR have identified VOCs in bleed air contamination experiments. VOCs can also arise from volatilization from the oils from worn seals and or/hydraulic fluids in the engine compartment, producing vapors that are subsequently released into the cockpit/cabin via bleed ports. VOCs are of interest as thermal decomposition of oil may generate a range of VOCs that can be detected. More specifically, VOCs undergo volatilization when they are converted from a liquid state to a vapor state by the application of heat, reduction of pressure, or a combination of the two processes. Deicing fluids and exhaust from jet engines may also enter the bleed air supply during ground operations. The next sections will discuss studies that identify particulates such as ultrafine particles, fine particles, and previously mentioned chemicals such as VOCs, CO, formaldehyde, acetaldehyde CO₂ etc., and whether or not they are good potential markers for bleed air contamination.

7. ASHRAE 1830-RP

A series of experiments was conducted with an aircraft auxiliary power unit (APU) and with a test stand turbine engine. These experiments were funded by the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) through ASHRAE research project 1830-RP. This project was conducted in collaboration with a second research project, “Aircraft Air Quality and Bleed Air Contamination Detection,” funded by the Federal Aviation Administration (FAA). The objective of the 1830 project was to evaluate the potential for using particulates in the bleed air as markers for bleed air contamination. The objective of the bleed air contamination detection project was to evaluate sensors that potentially can detect markers of this same bleed air contamination. The intent of both projects is to address the response of markers of contamination and not necessarily to characterize the contamination itself.

Since the project focuses on the ability to detect the contaminants and not necessarily attempting to characterize the contaminants, the focus is therefore on how different sensors respond to contaminants. More specifically, the response of different sensors are being evaluated relative to background levels. Therefore, there isn’t much concern regarding the actual value of the response itself or the accuracy of these sensors. Thus, the purpose of this project is not to evaluate the accuracy of the measurements, but to closely examine the relative response compared to background levels.

The project tested engine oil, hydraulic fluid, and deicing fluid as target contaminants for bleed air. For engine oil, Mobil Jet II, Eastman 2197, and Eastman 2389 were tested. For hydraulic fluid, Skydrol LD4 and Skydrol PE5 were tested. For deicing fluid, Type 1 and Type 4 were tested. Multiple contamination levels focused on low to medium values down to 1 ppm by mass. Key factors are mass of the injected contaminant and the mass of air flow through the compressor. The test stand engine that was used for this project was the Allison 250 C28B turbine engine and the auxiliary power unit (APU) that was used was the Honeywell (Garrett) GTCP85-98DHF APU. Multiple devices such as analyzers and canisters were used to detect aldehydes, VOCs, CO₂, and other compounds. Contamination was introduced by being injected into inlet air and was accurately being controlled by a syringe pump. The particle measuring instrumentation included the SMPS utilized for ultrafine particles along with the APS utilized for fine particles as mentioned previously and results from both instruments are shown in the figures below from November, March, and June. Allison 250 data is from March and June and the APU data is from November. Operation temperature of the bleed air was approximately 230°C for the Allison 250 March experiments with the exception of Figures 27 and 28 where it was approximately 270°C. Bleed air temperatures were approximately 200°C for the APU experiments in November and got as high as 285°C for the Allison 250 experiments in June. Furthermore, Table 3 below shows the instrumentation used. Figure 4 shows the two engines for the bleed air experiments with the APU and Allison 250. Figures 5-22 show APU data with both the SMPS and APS that show the responses of various contaminants that were injected at different contamination rates. The same story is presented from Figures 23-28, which present similar results for the Allison 250 data. Lastly, Figures 29-36 present QTRAK data that

measured CO, particles, formaldehyde, and VOCs from March and June with the Allison 250 engine and also CO₂ data.



Figure 4-Allison 250 location/Testing Site and APU For ASHRAE 1830-RP

Table 3-Bleed air contamination instrumentation used for ASHRAE 1830-RP project

Instrument	Measurements
TSI 3080 Classifier with TSI 3775 CPC	Concentration and size distribution of particles (15-700 nm)
TSI 3321 APS	Concentration and size distribution of particles (0.5 -20 µm)
Naneos Partector 2	Fine and ultrafine particle concentrations
TSI 3007 CPC	Fine and ultrafine particle concentrations
TSI 7585 QTRAK XP Air Quality Monitor	Fine particles and sixgasses, temperature, pressure, and relative humidity
Teledyne ACES Aircraft Air Quality Monitor (two units)	Fine particles and eight gasses, temperature, pressure, relative humidity
Pall Mark 1 Cabin Air Quality Sensor (two units)	Detection and identification f specific bleed air contaminants
IPVideo Halo (two units)	Detection of a range of environmental variables, CO, CO ₂ equivalent, VOC, noise, temperature, pressure, relative humidity
Air Sense Aerotracer	Detection and identification of specific bleed air contaminants
Astronics cabin environment sensor	Gaseous Chemicals
Honeywell ppbRae 3000 (two units)	Total Volatile Organic Compounds
Interscan Gas Sensor model 8160-2000b	Formaldehyde concentration
PP Systems WMA-5 CO ₂ Analyzer (two units)	CO ₂ Concentrations
SUMMA Canister	Post experiment chemical analysis
PUF-XAD cartridge	Post experiment chemical analysis
DNPH cartridge	Post experiment chemical analysis
Tenax cartridge	Post experiment chemical analysis

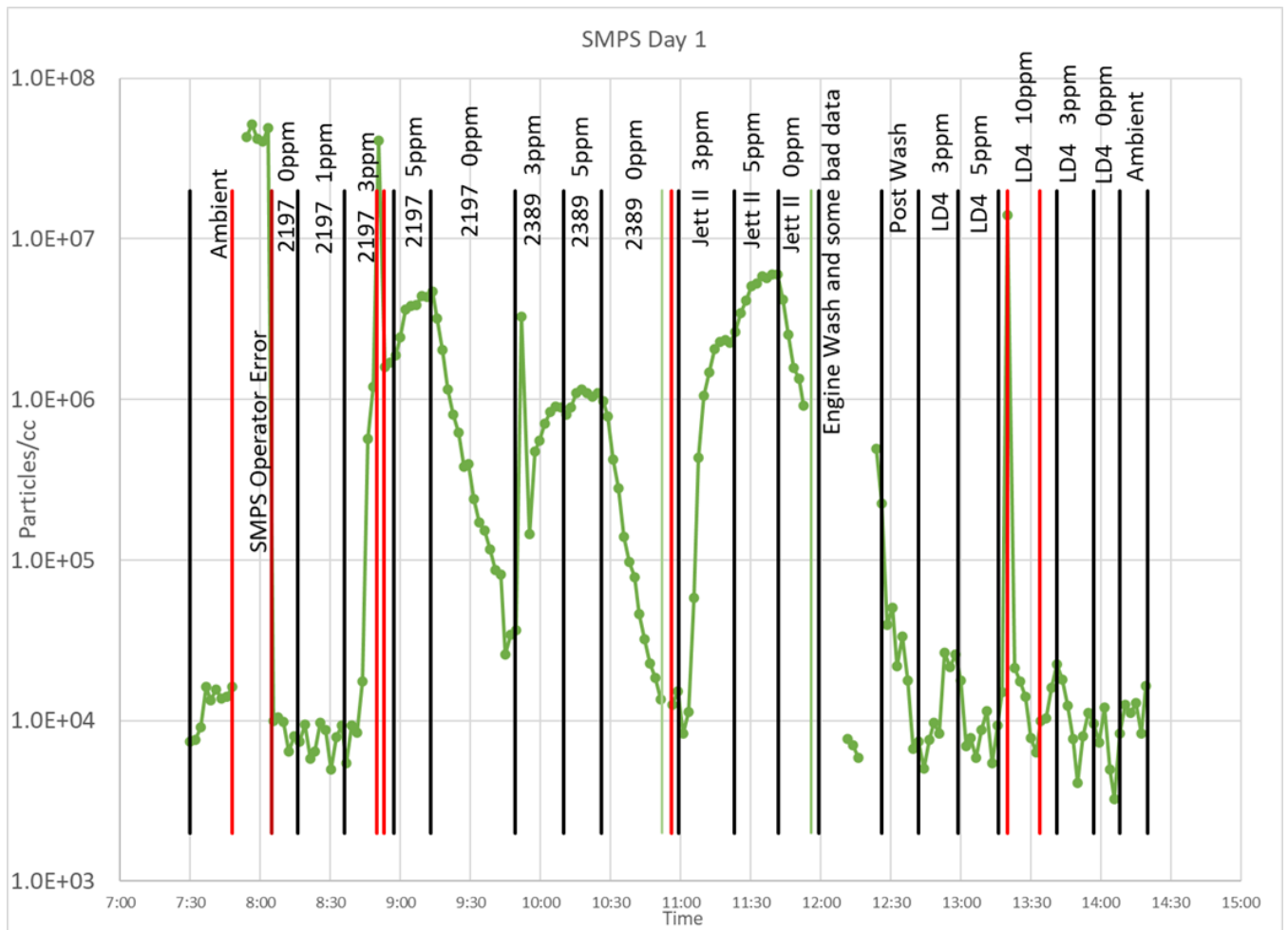


Figure 5-APU SMPS Day 1 Data

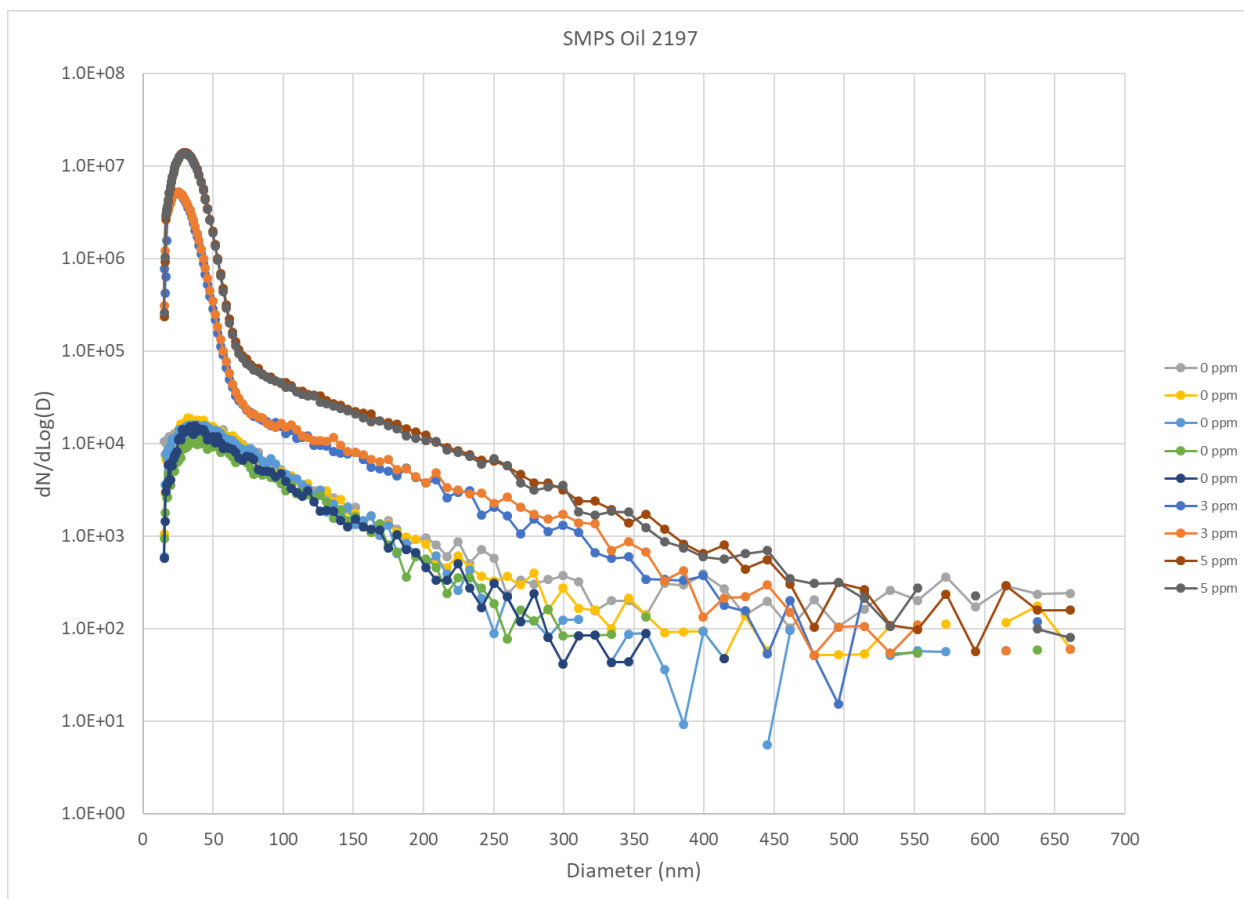


Figure 6-APU SMPS Oil 2197 Data

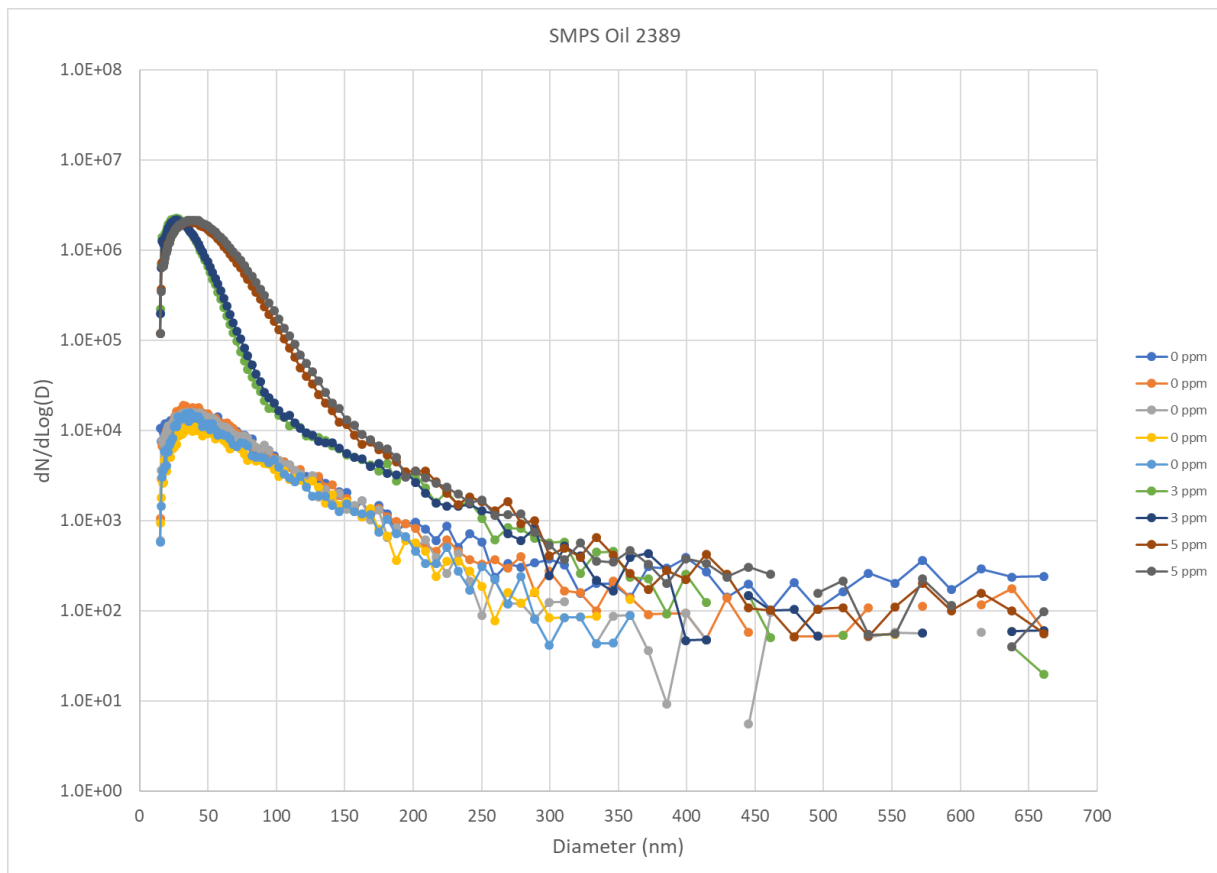


Figure 7-APU SMPS Oil 2389 Data

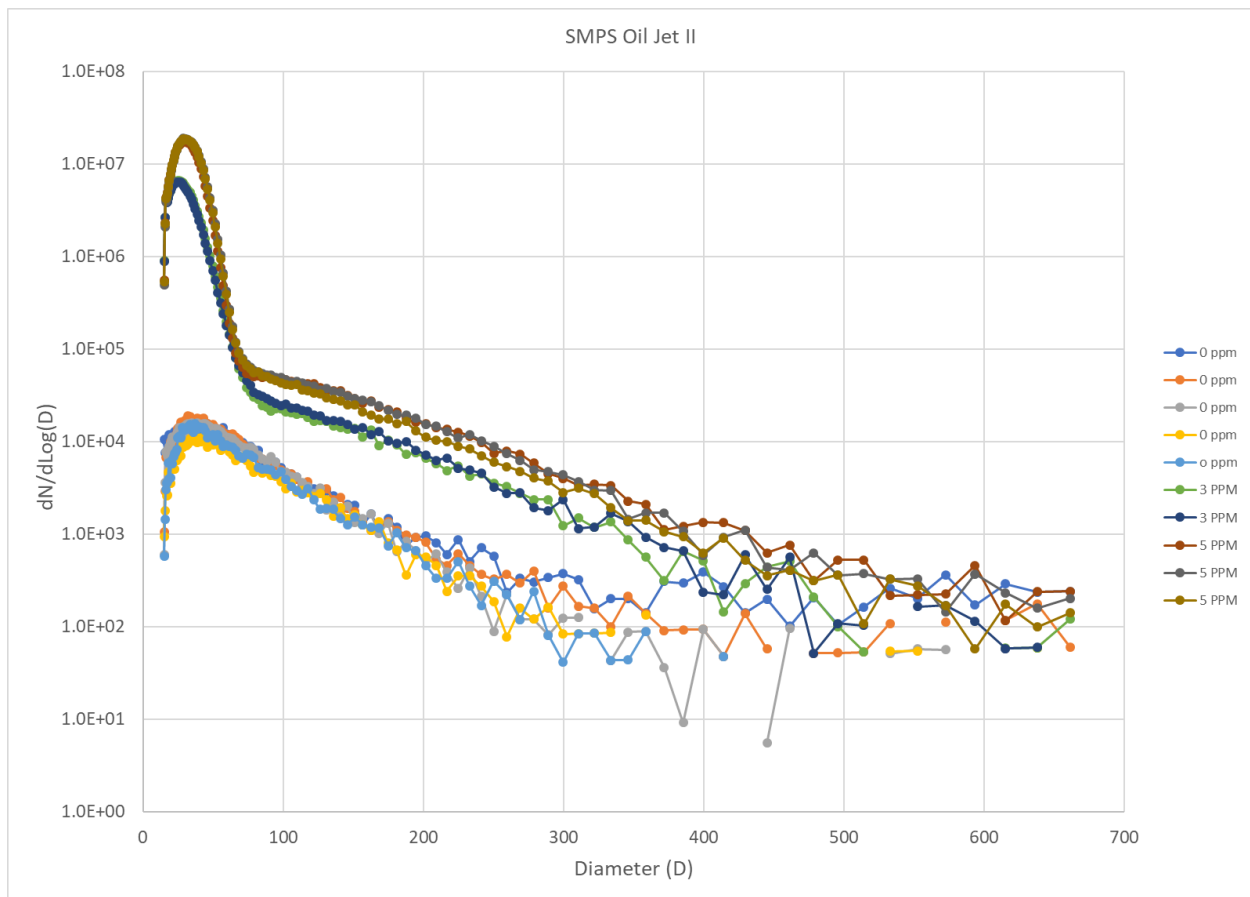


Figure 8-APU SMPS Oil Jet II Data

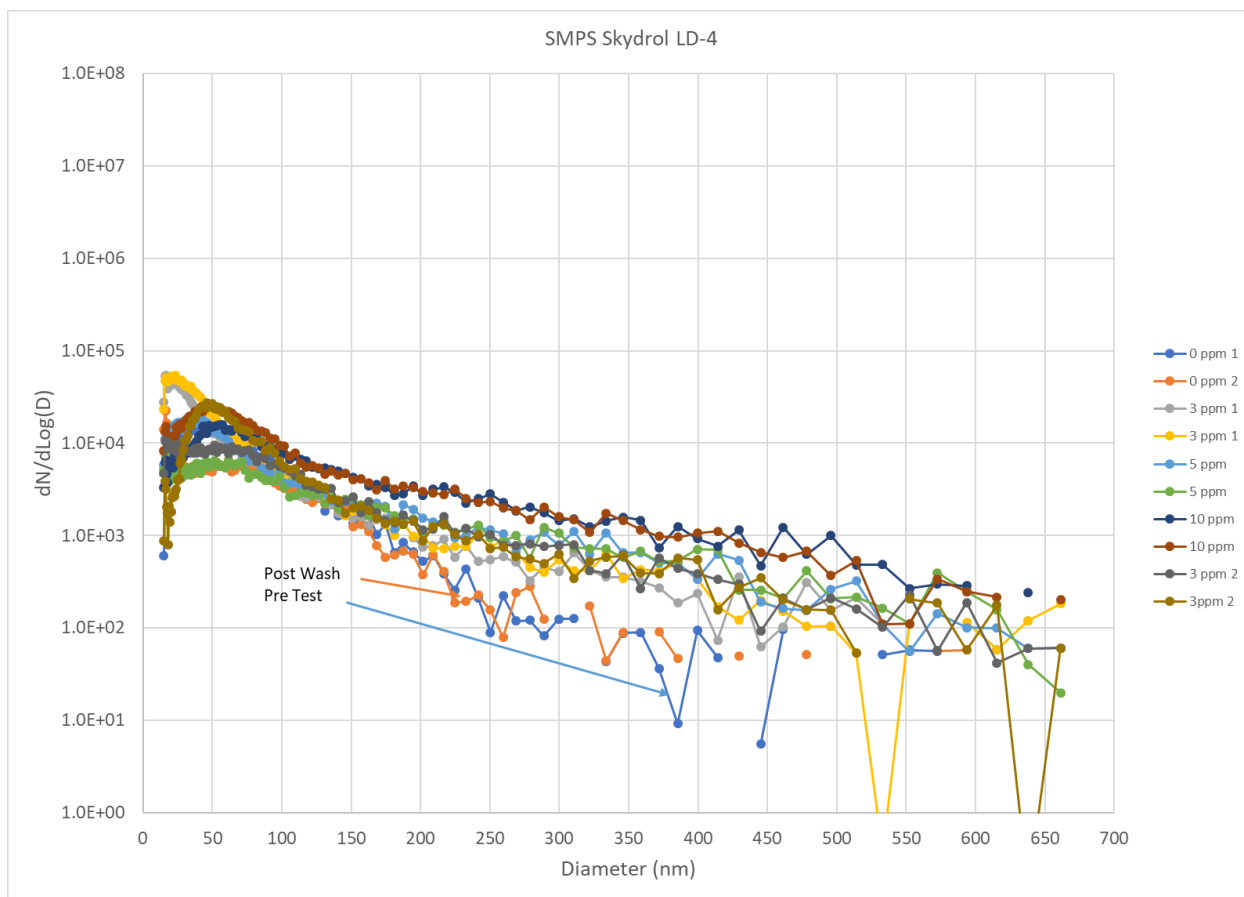


Figure 9-APU SMPS Skydrol LD-4 Data

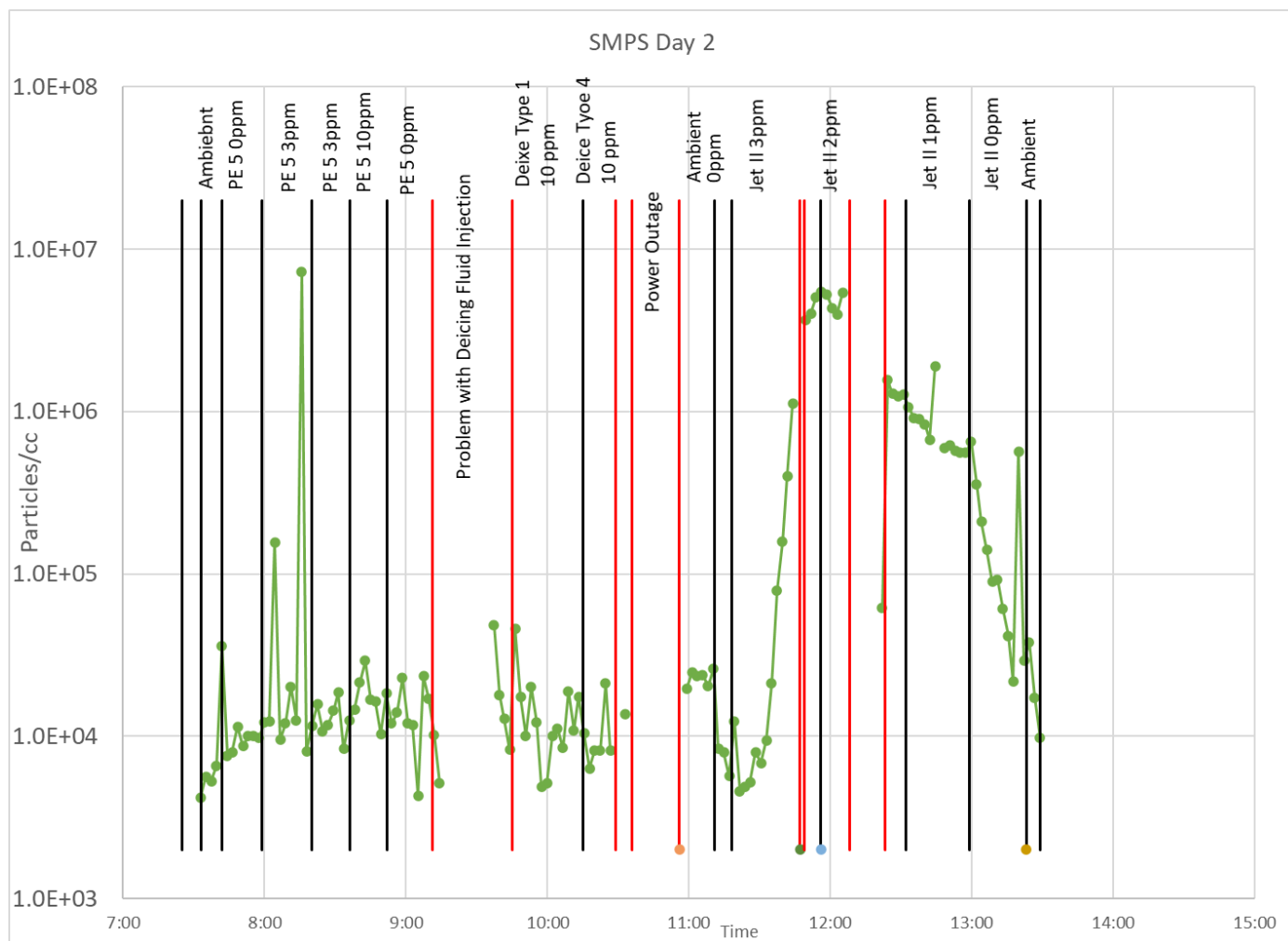


Figure 10-APU SMPS Day 2 Data

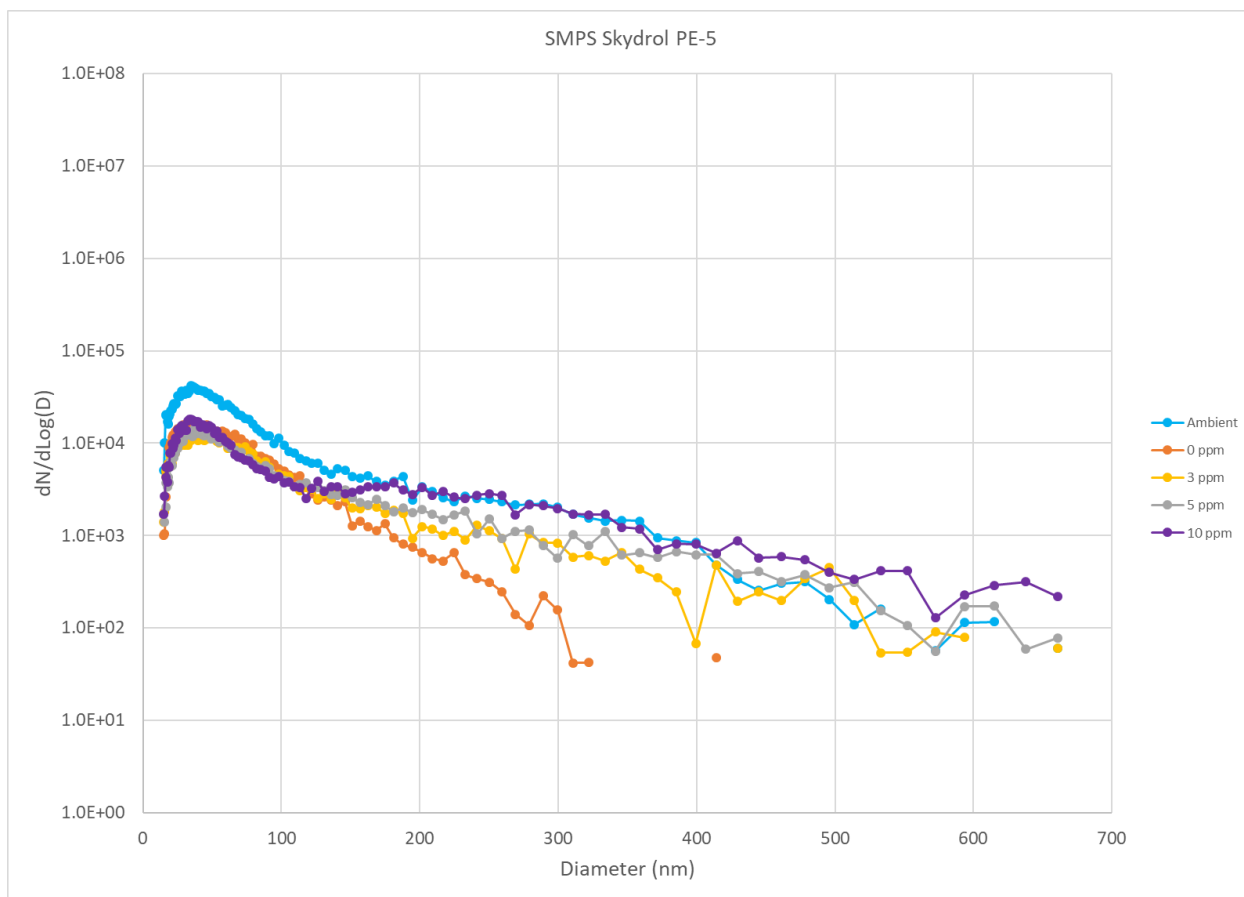


Figure 11-APU SMPS Skydrol PE-5 Data

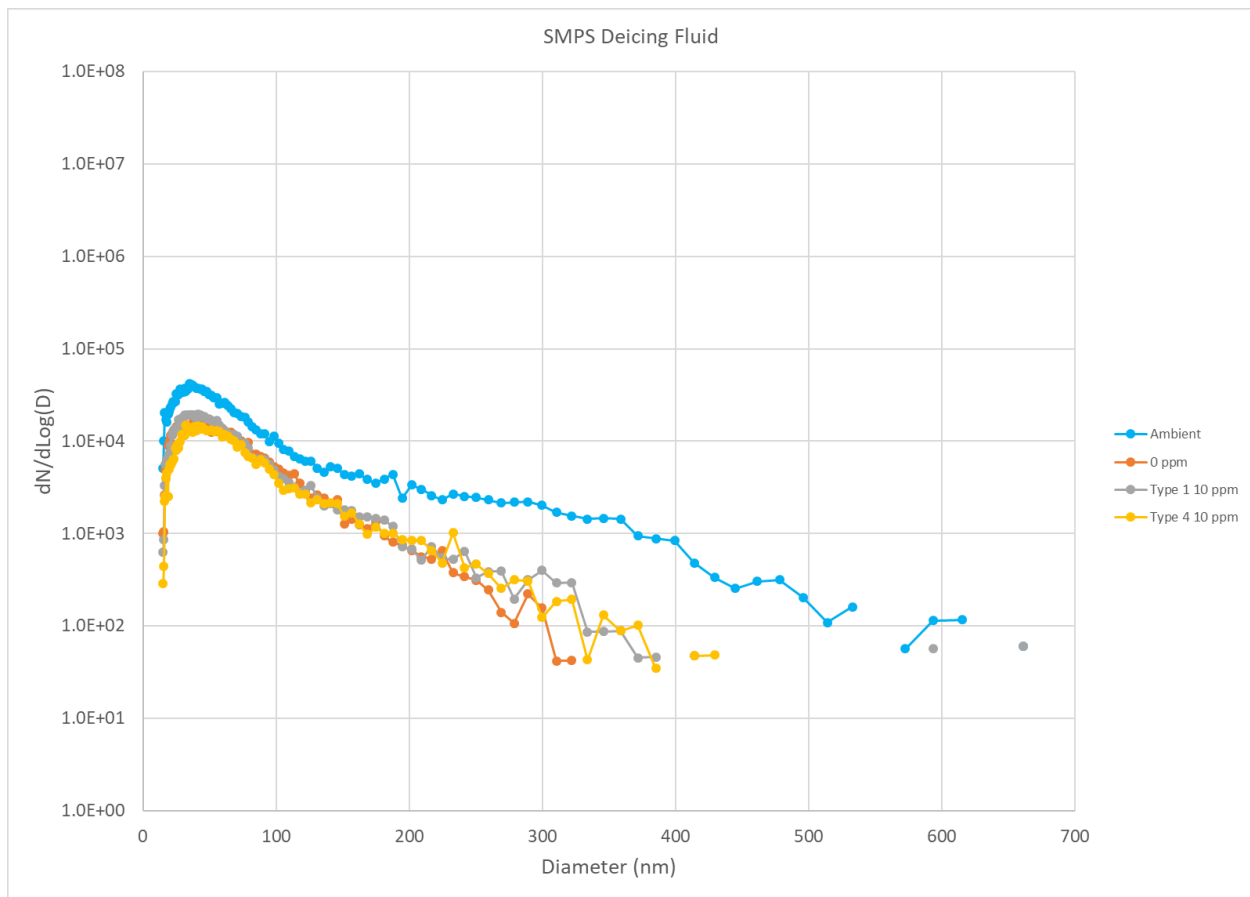


Figure 12-APU SMPS Deicing Fluid Data

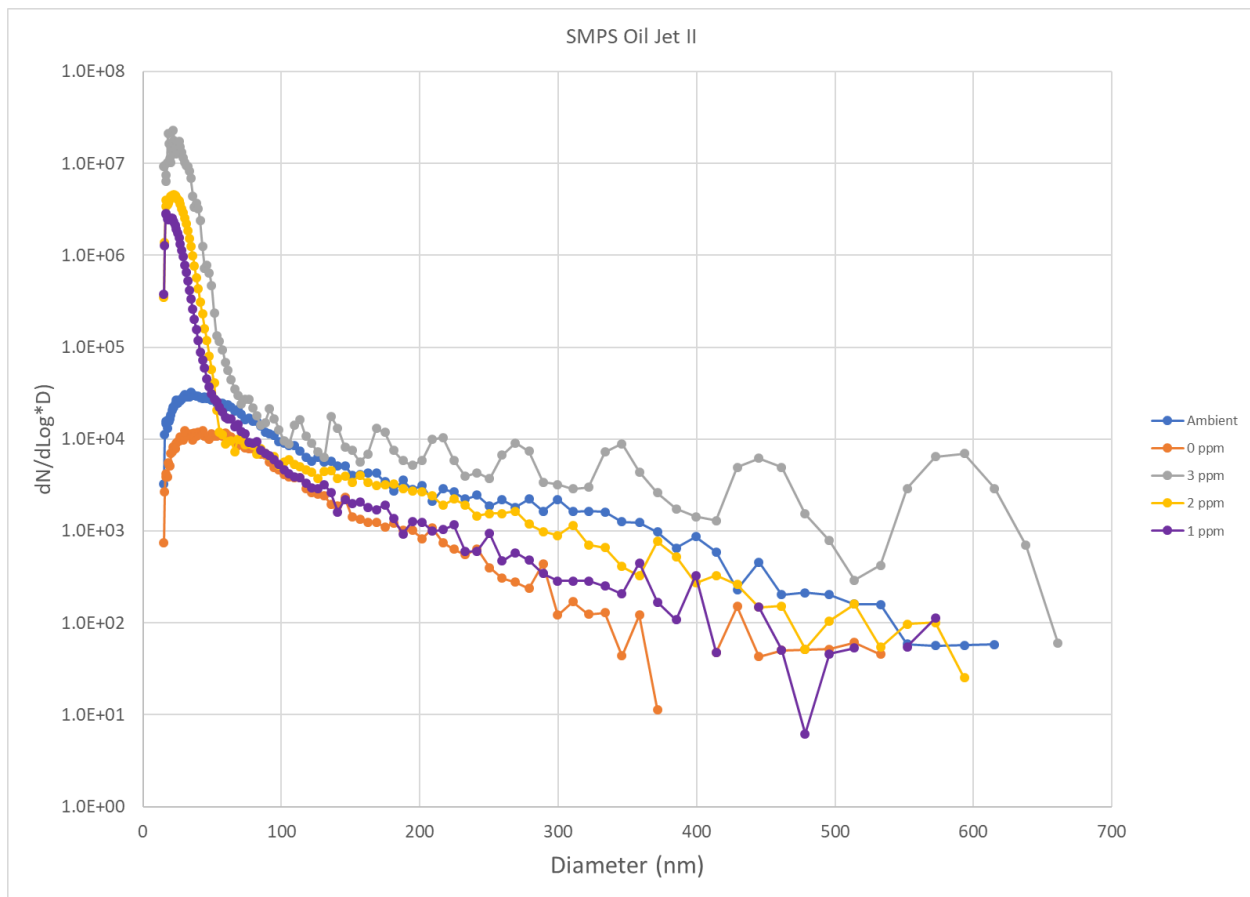


Figure 13-APU SMPS Oil Jet II Data

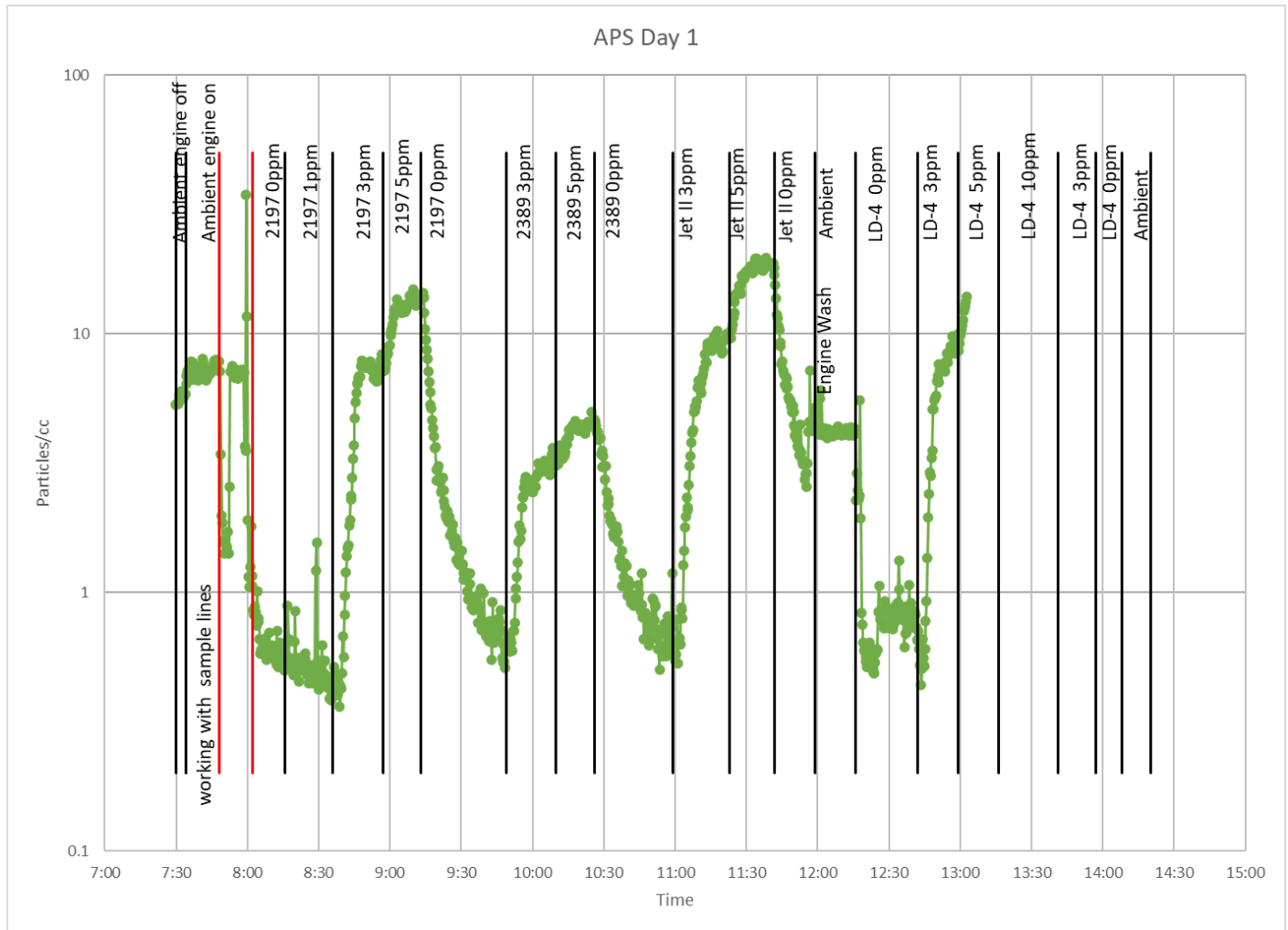


Figure 14-APU APS Day 1 Data

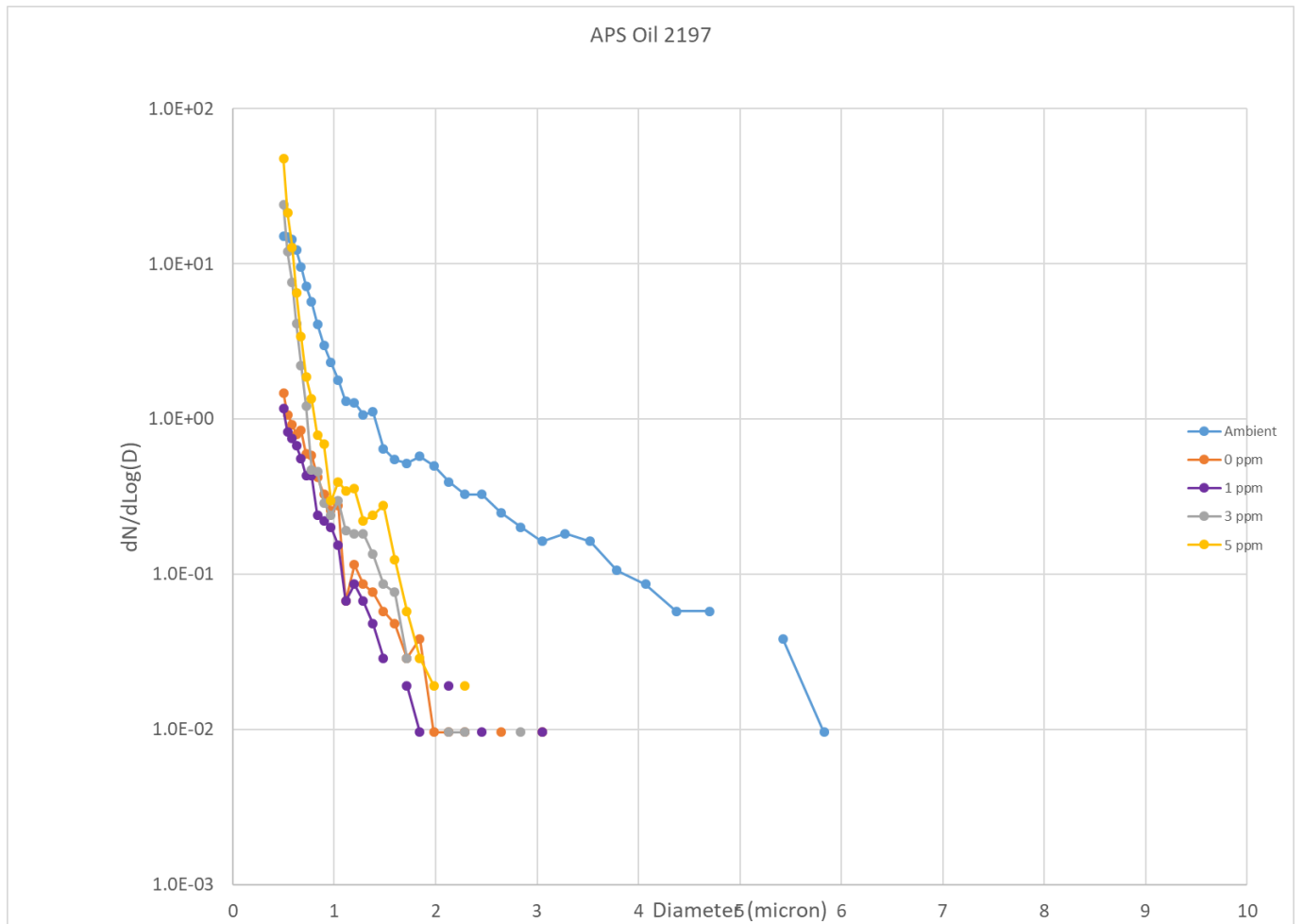


Figure 15-APU APS Oil 2197 Data

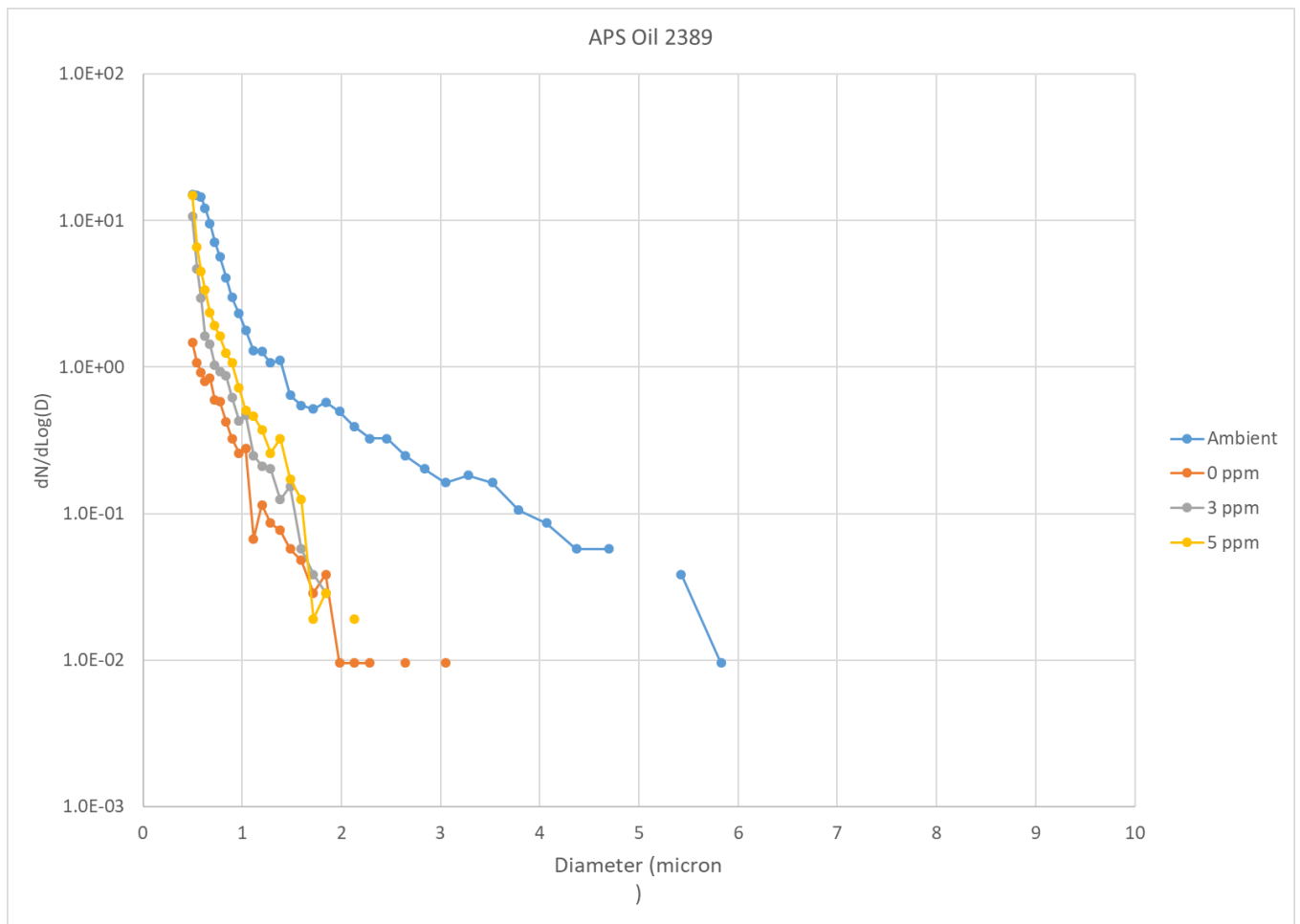


Figure 16-APU APS Oil 2389 Data

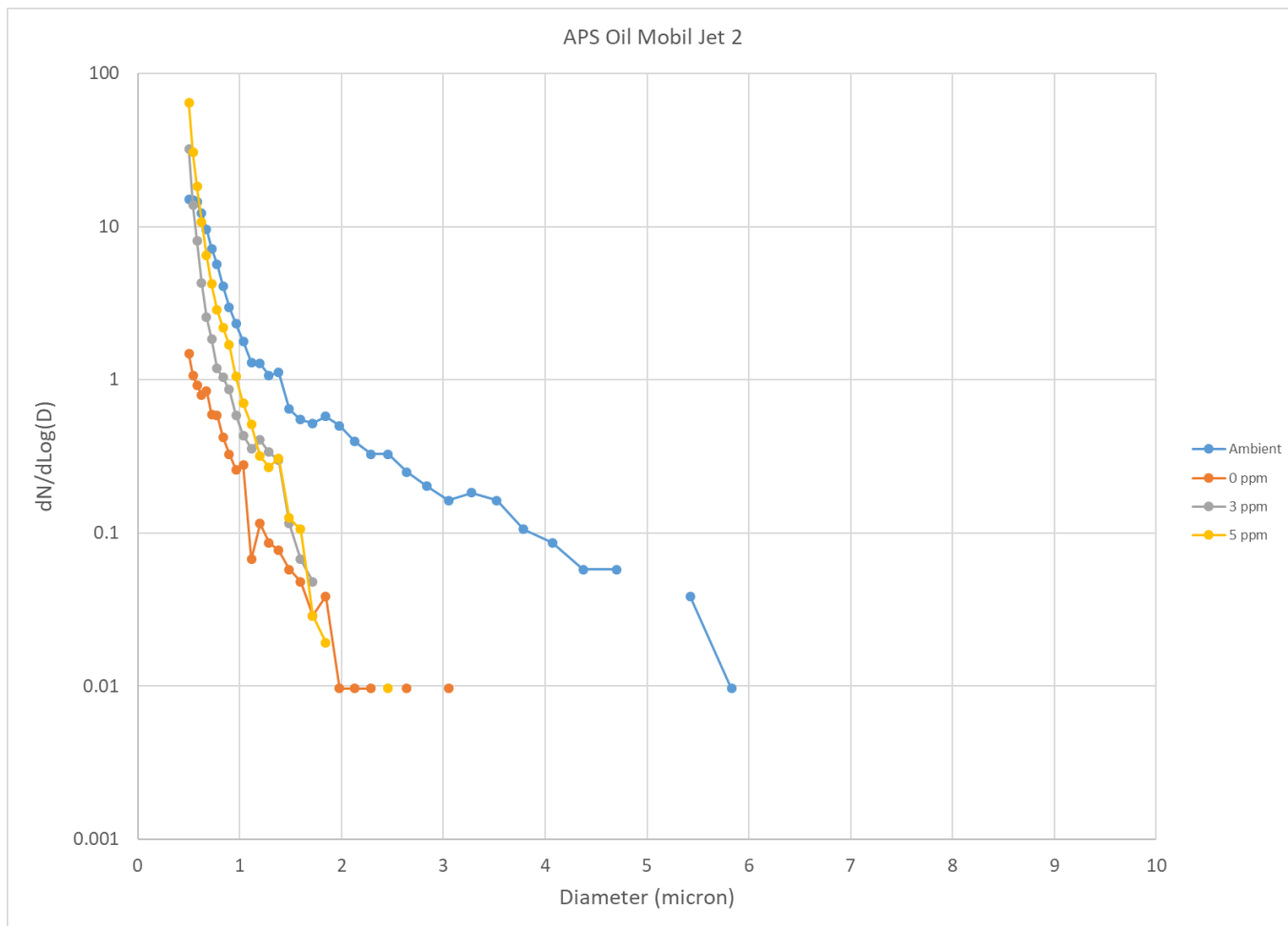


Figure 17-APU APS Oil Mobil Jet 2 Data

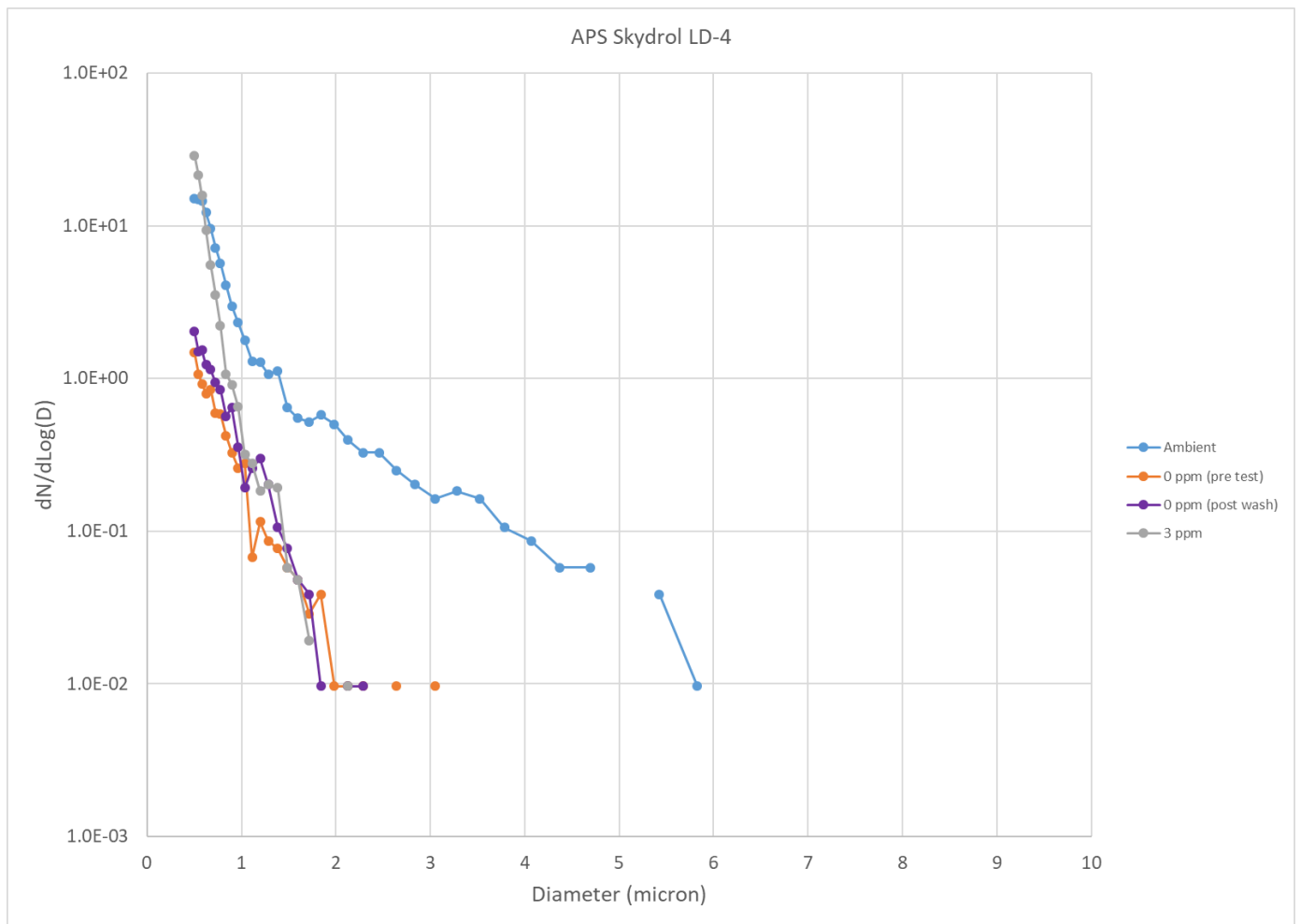


Figure 18-APU APS Skydrol LD-4 Data

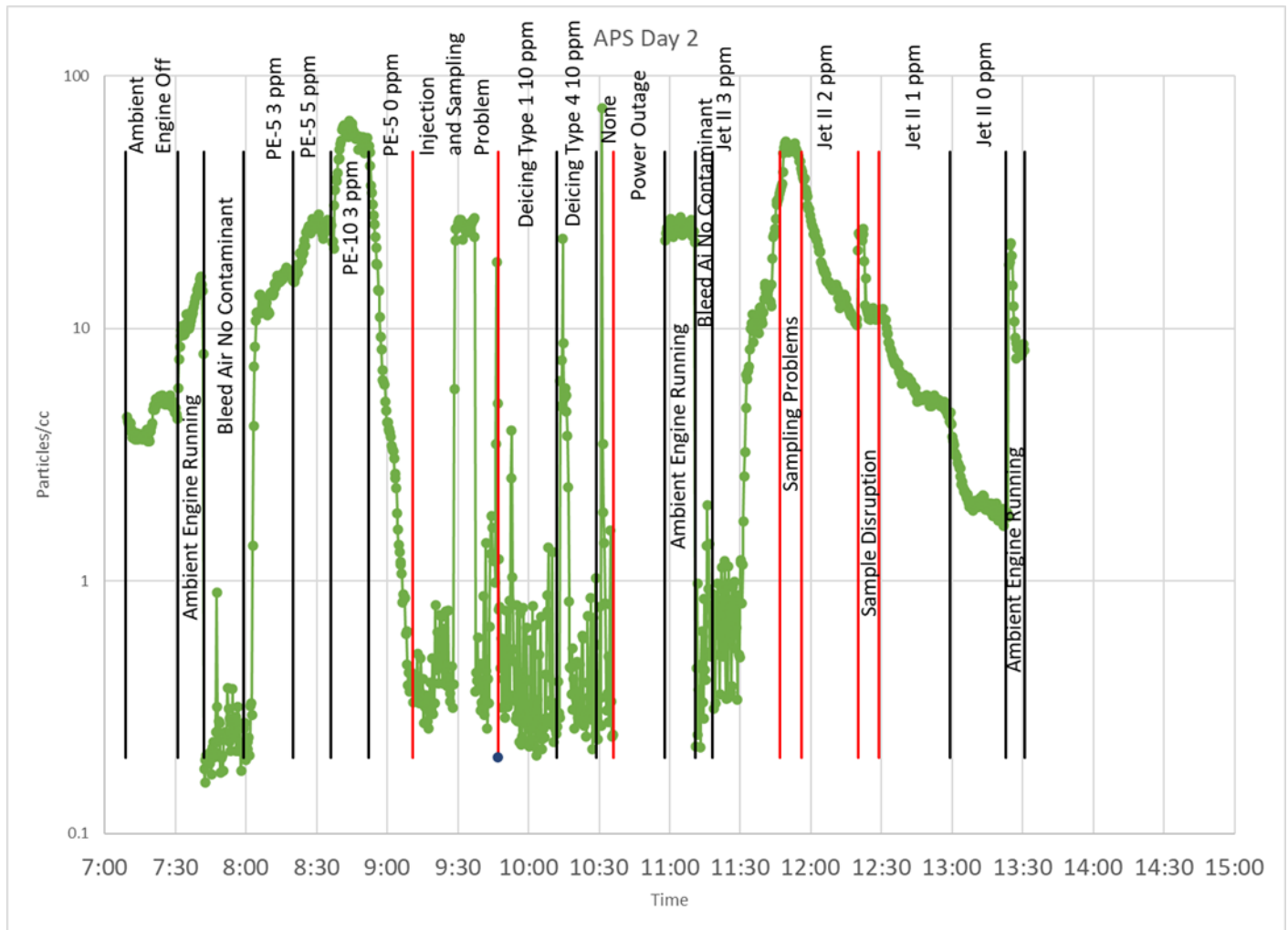


Figure 19-APU APS Day 2 Data

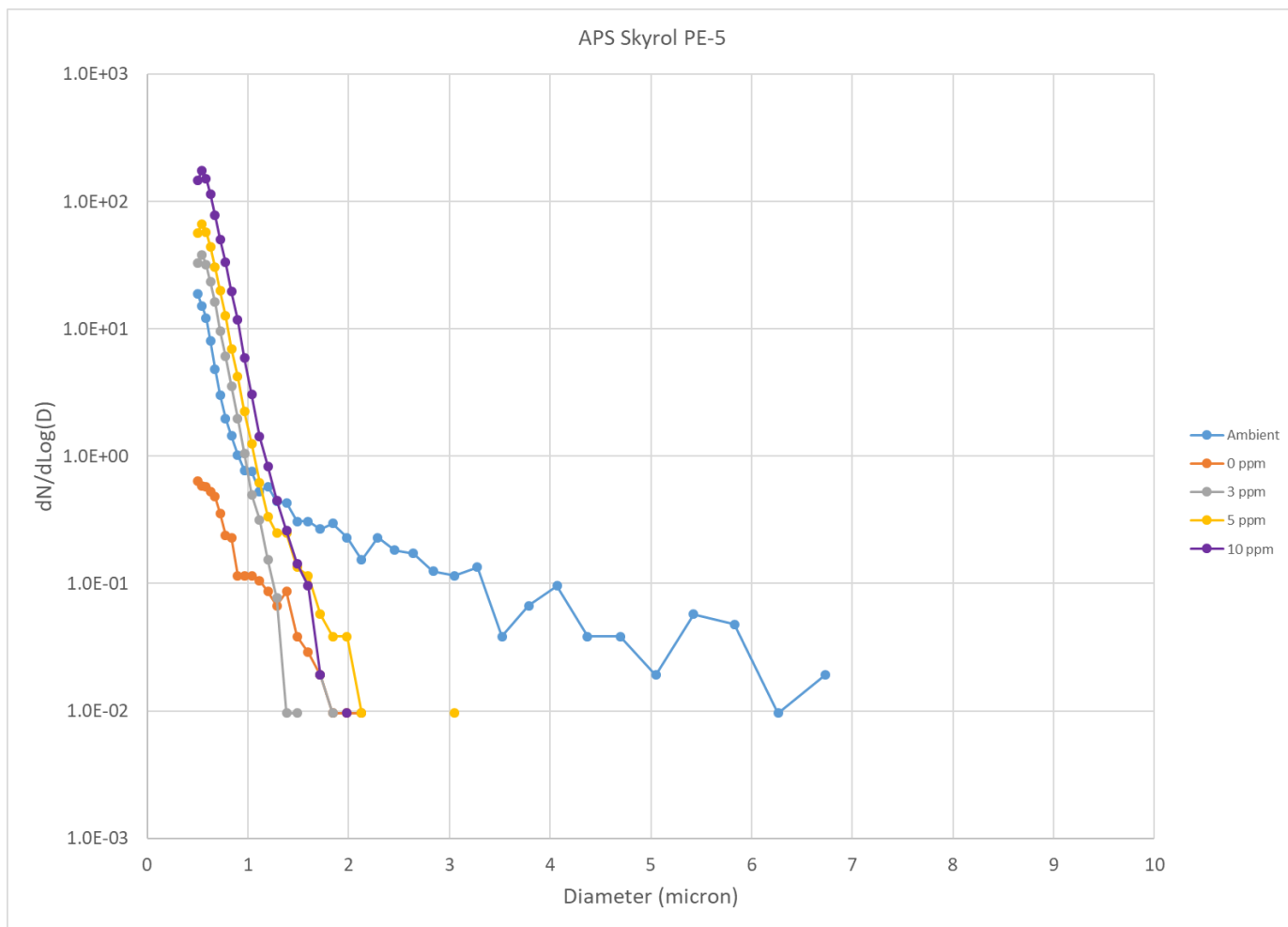


Figure 20-APU APS Skydrol PE-5 Data

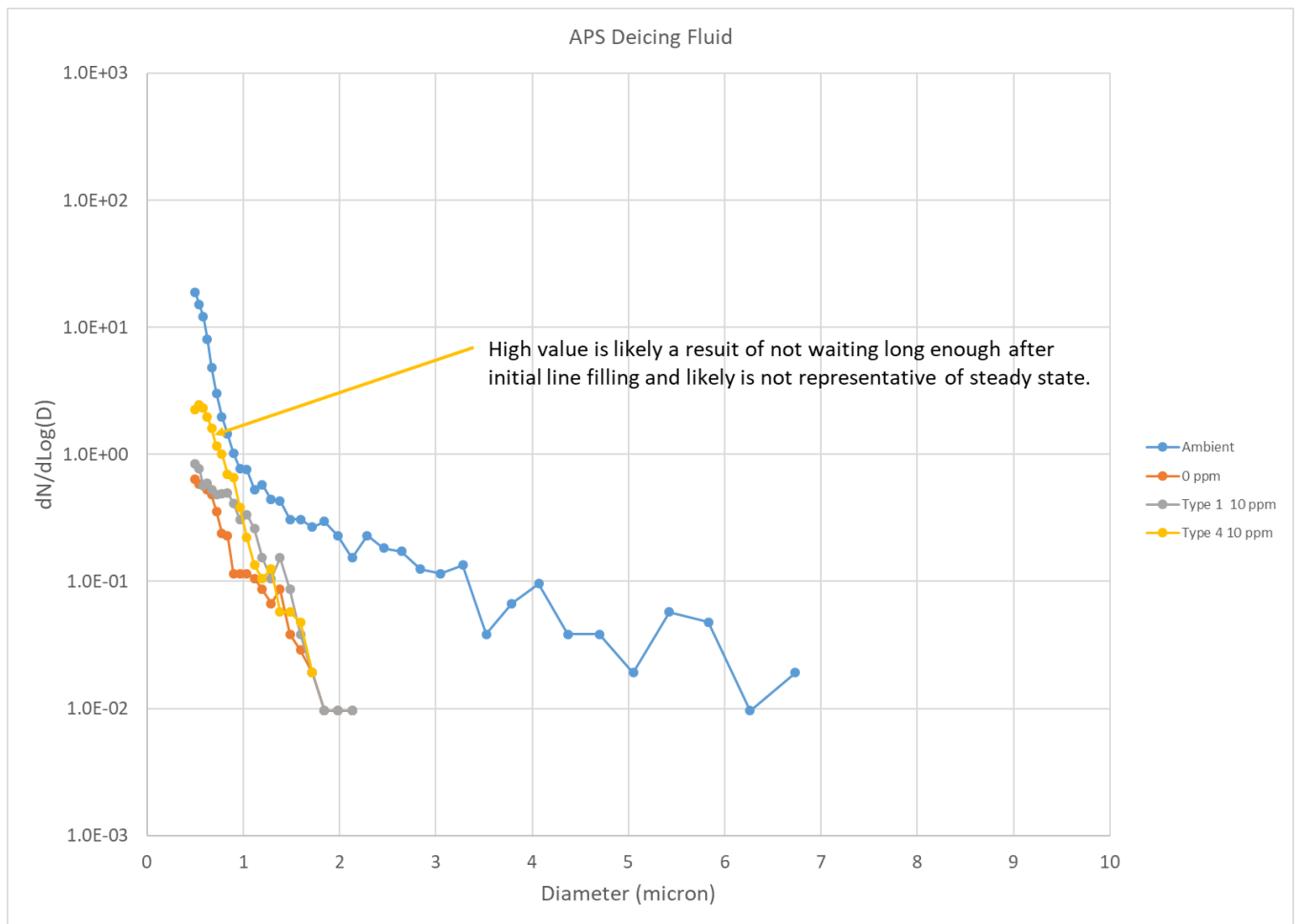


Figure 21-APU APS Deicing Fluid Data

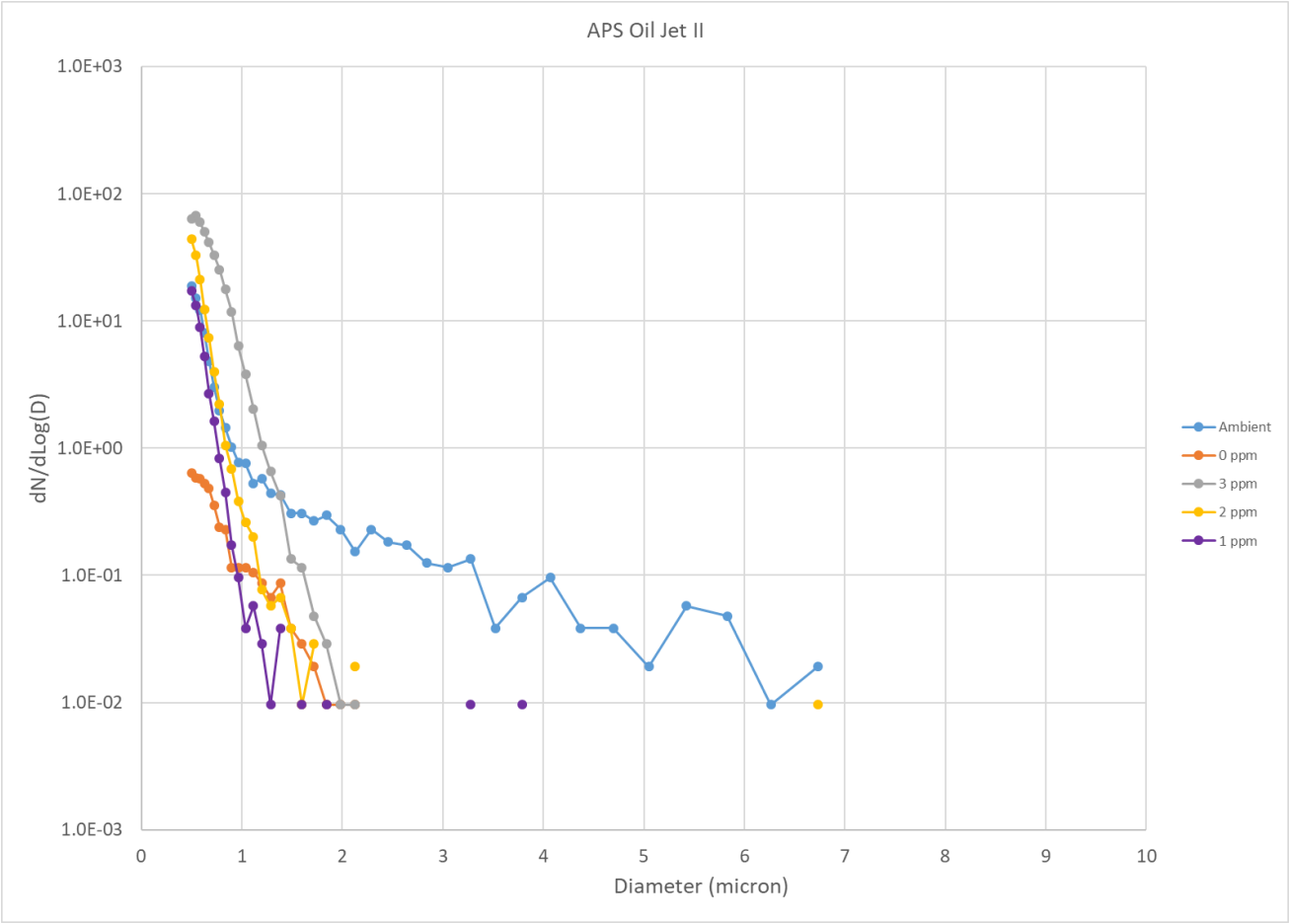


Figure 22-APU APS Oil Jet II Data

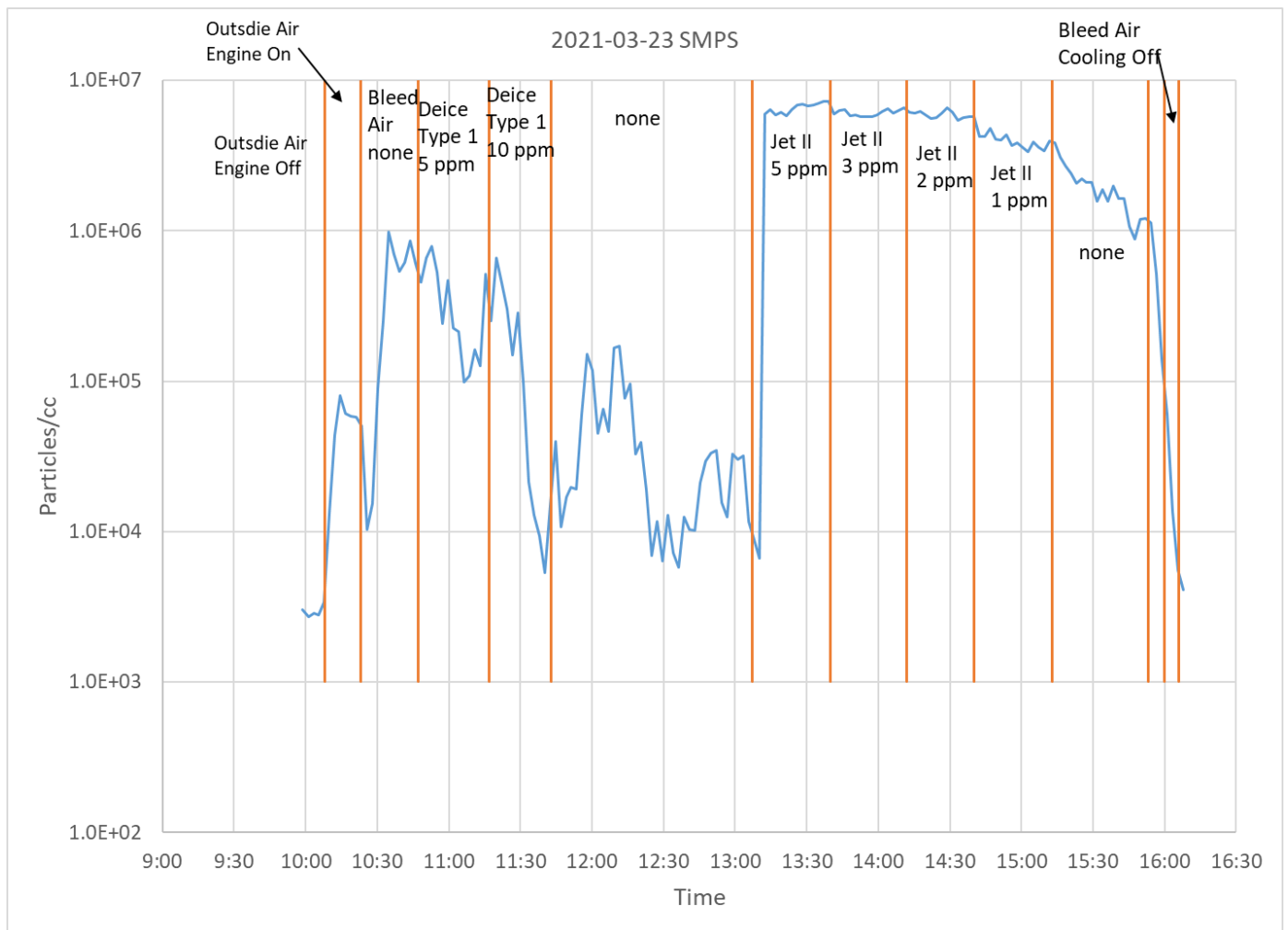


Figure 23-Allison 250 SMPS Total Concentration Data

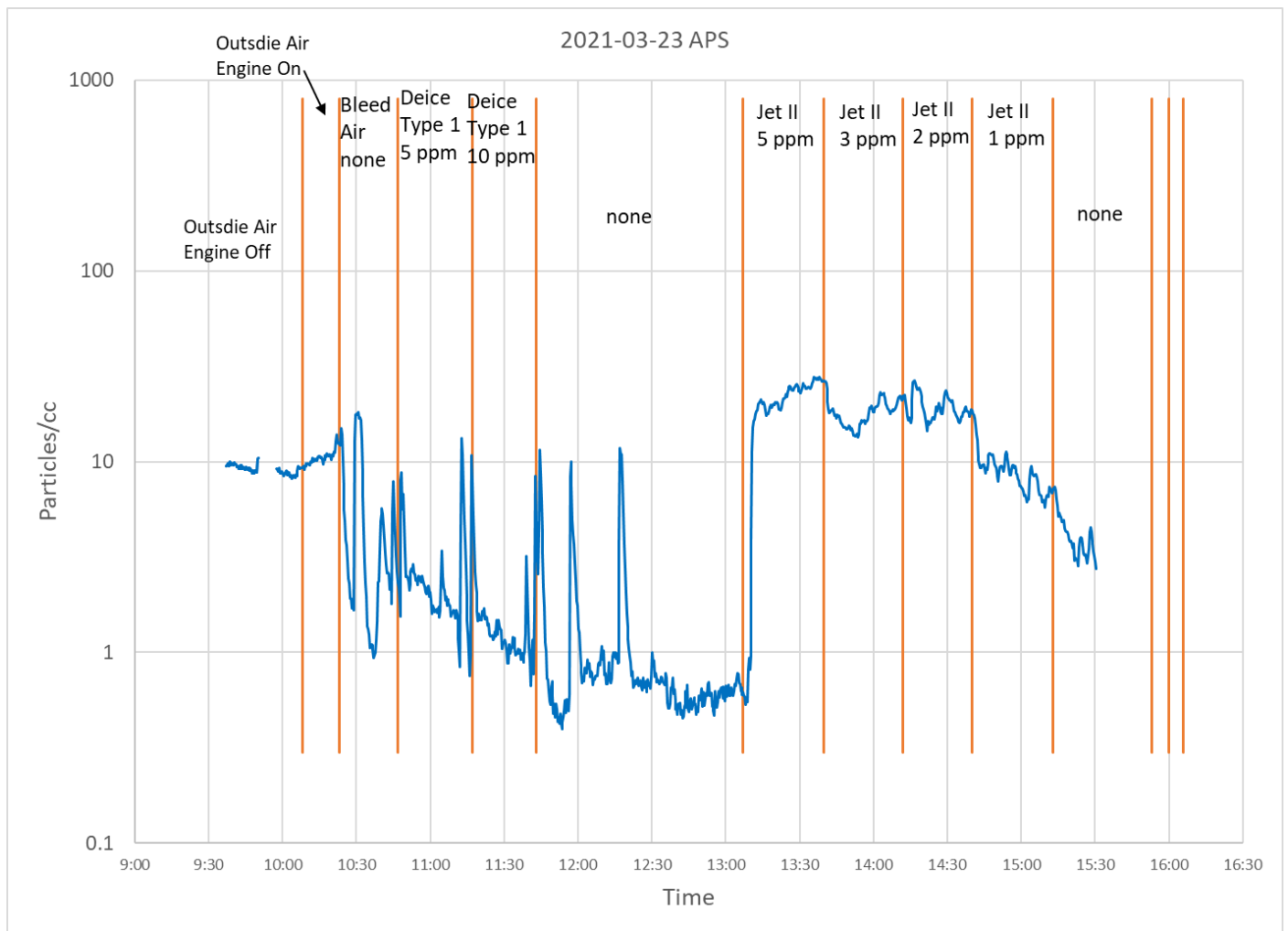


Figure 24-Allison 250 APS Total Concentration Data

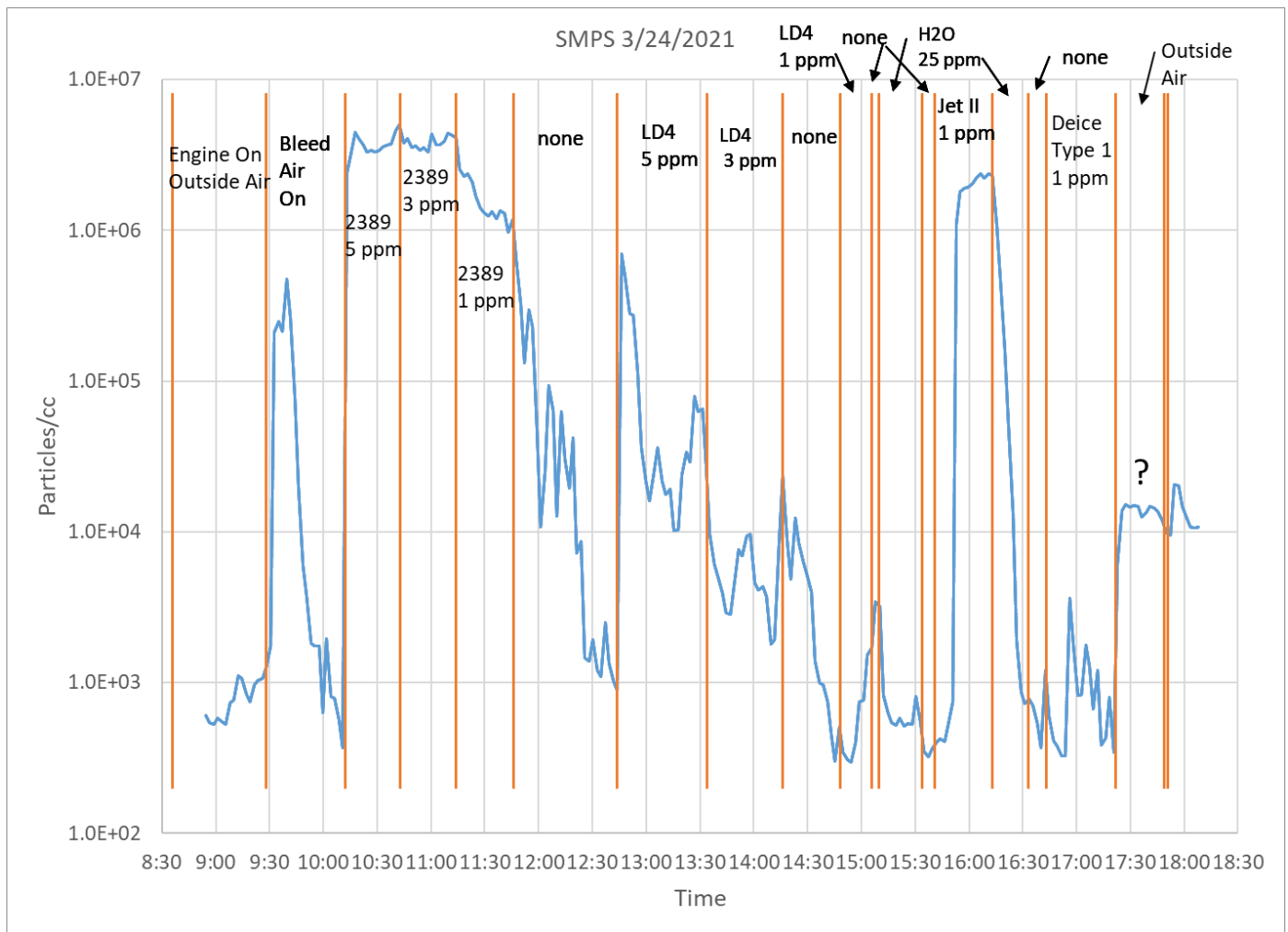


Figure 25-Allison 250 SMPS Total Concentration Data 3-24

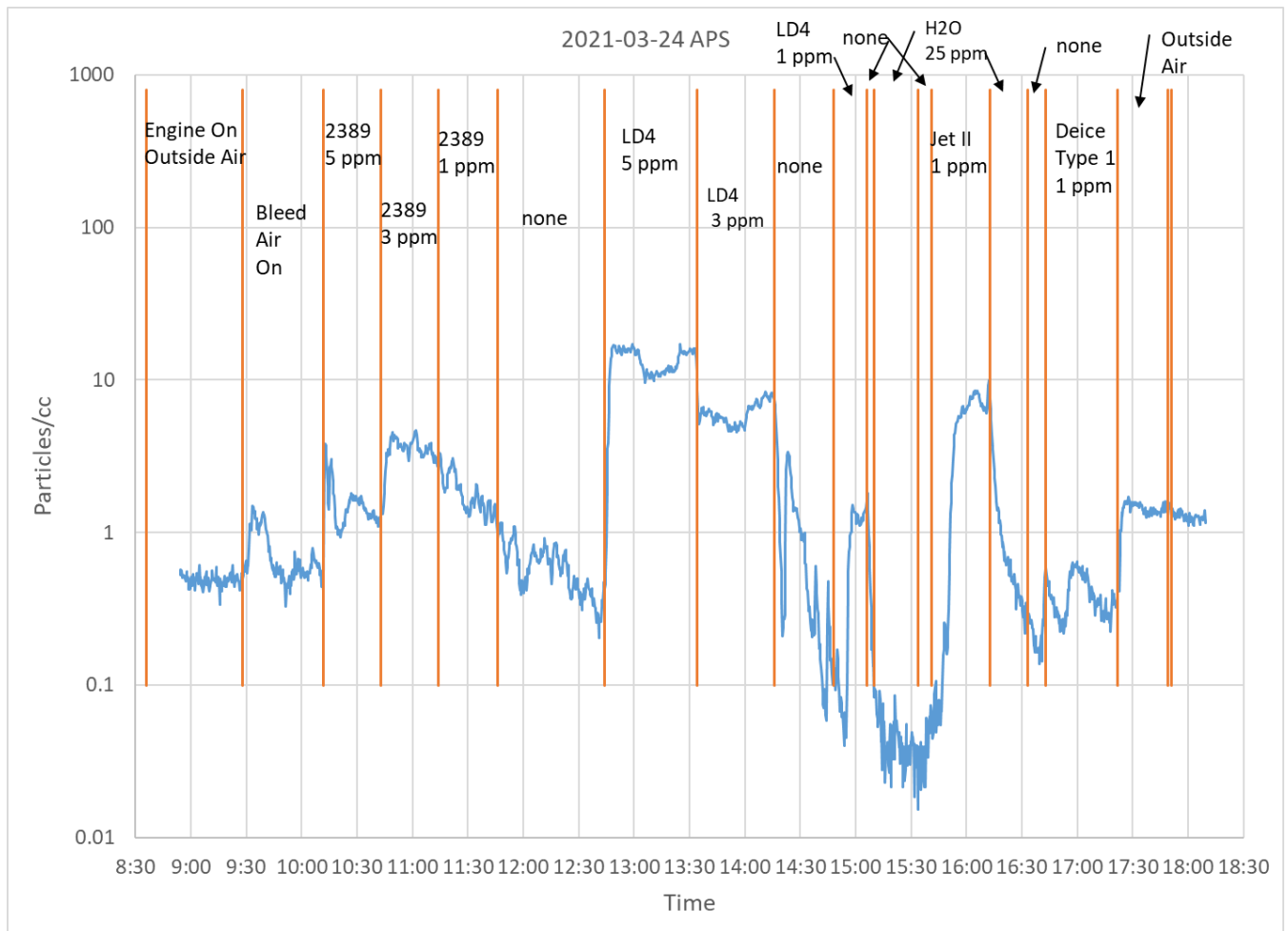


Figure 26-Allison 250 APS Total Concentration Data 3-24

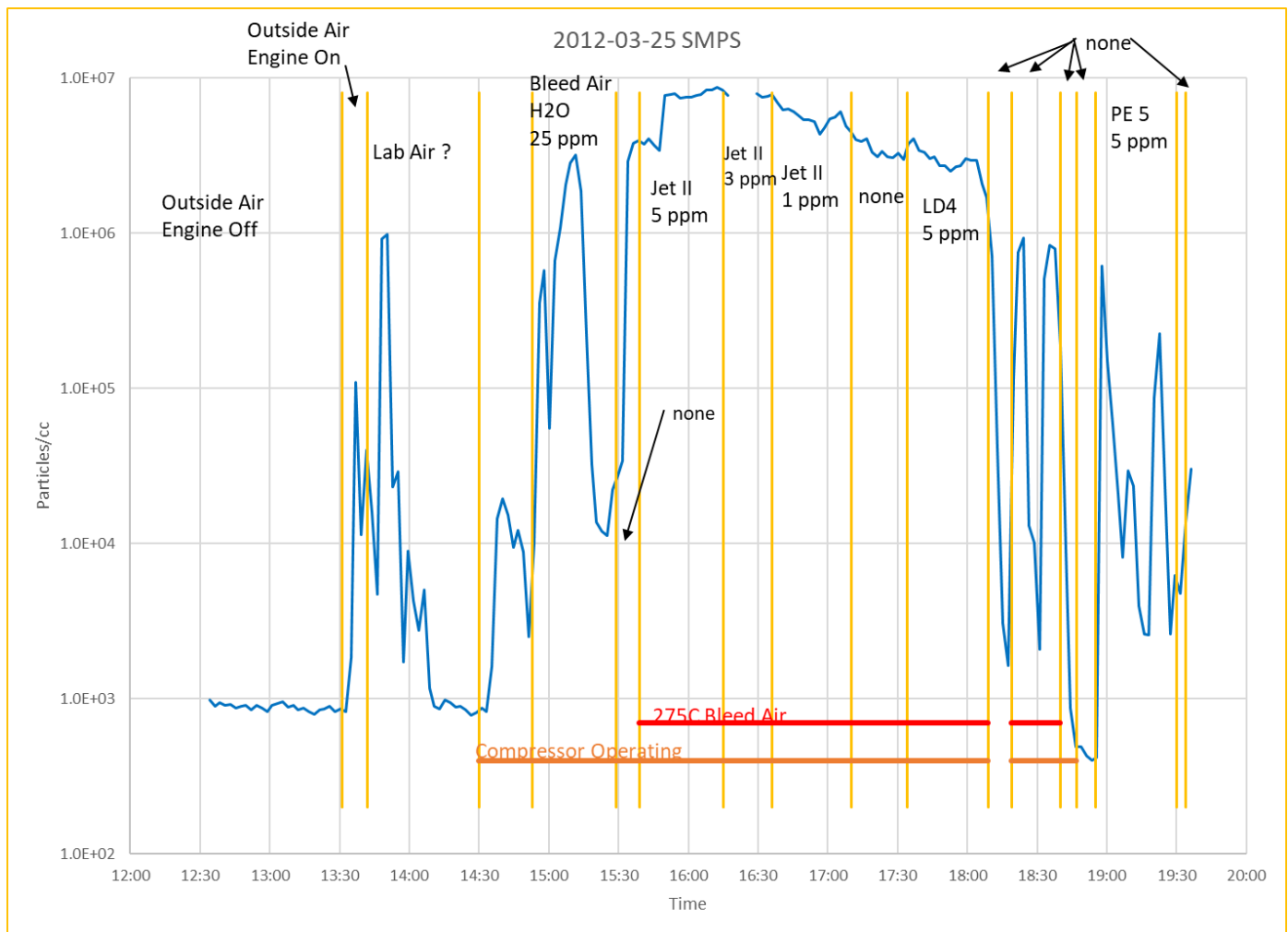


Figure 27-Allison 250 SMPS Total Concentration Data 3-25

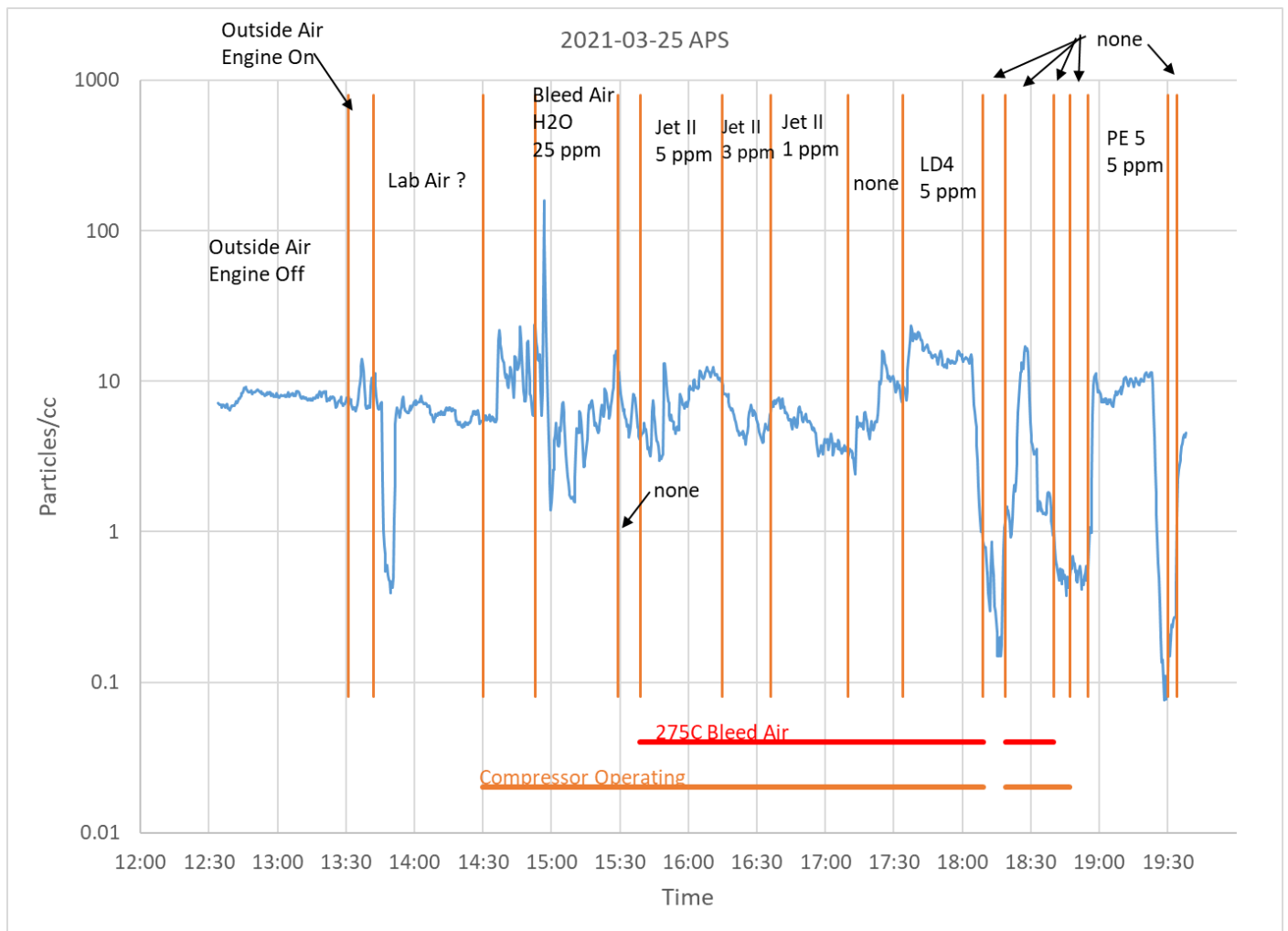


Figure 28-Allison 250 APS Total Concentration Data 3-25

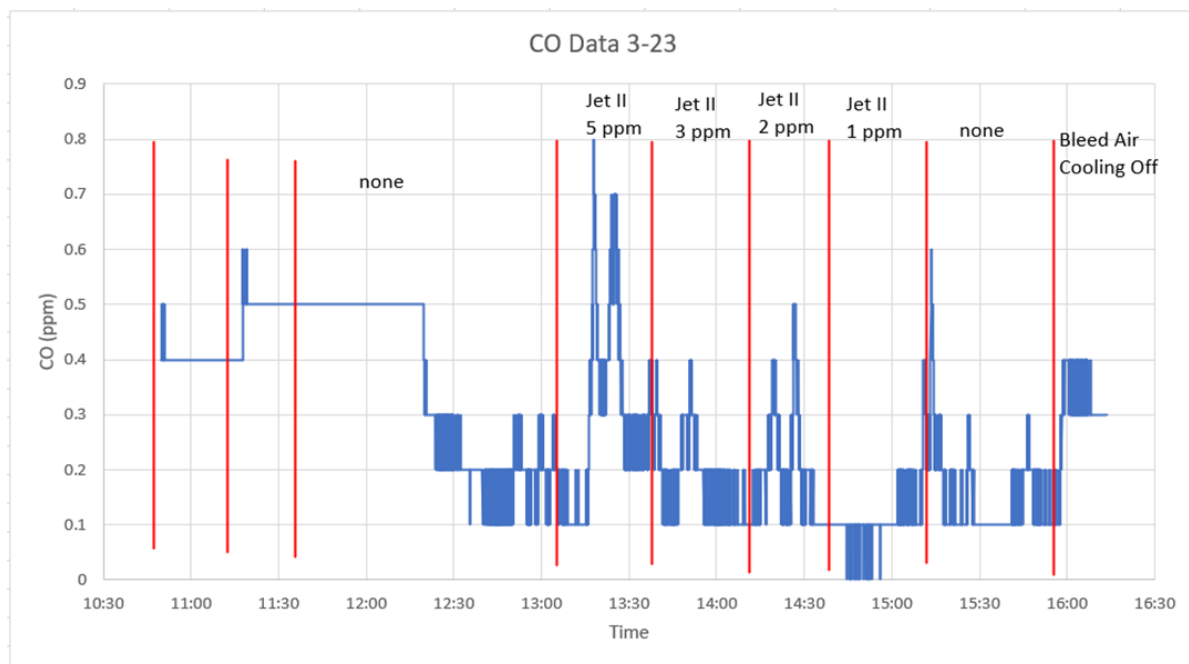


Figure 29-QTRAK CO Data for March 23rd

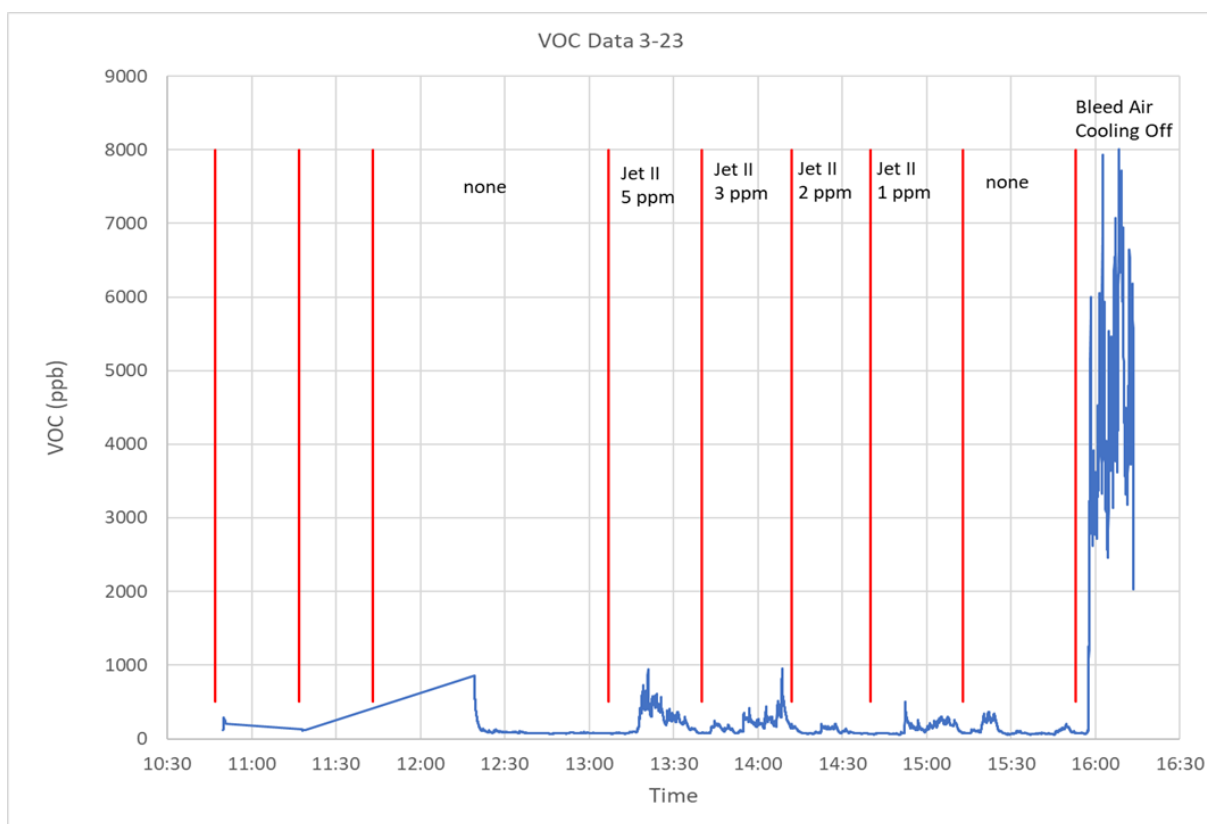


Figure 30-QTRAK VOC Data for March 23rd

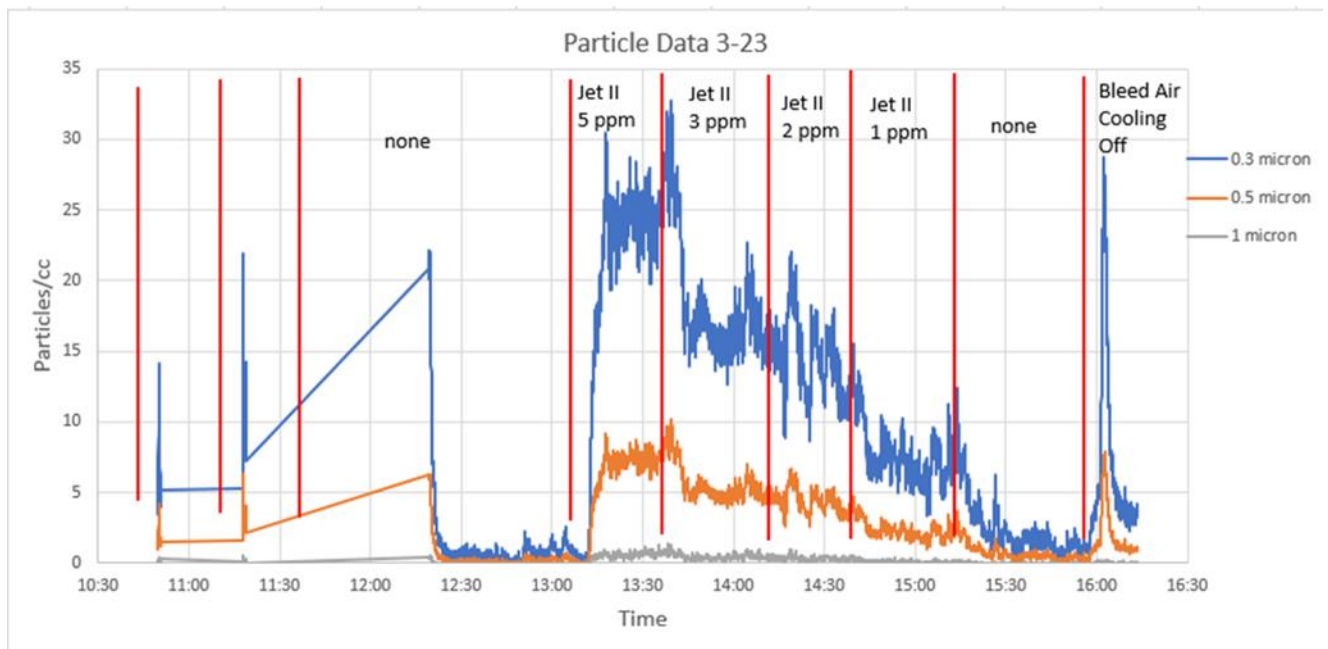


Figure 31-QTRAK Particle Data for March 23rd

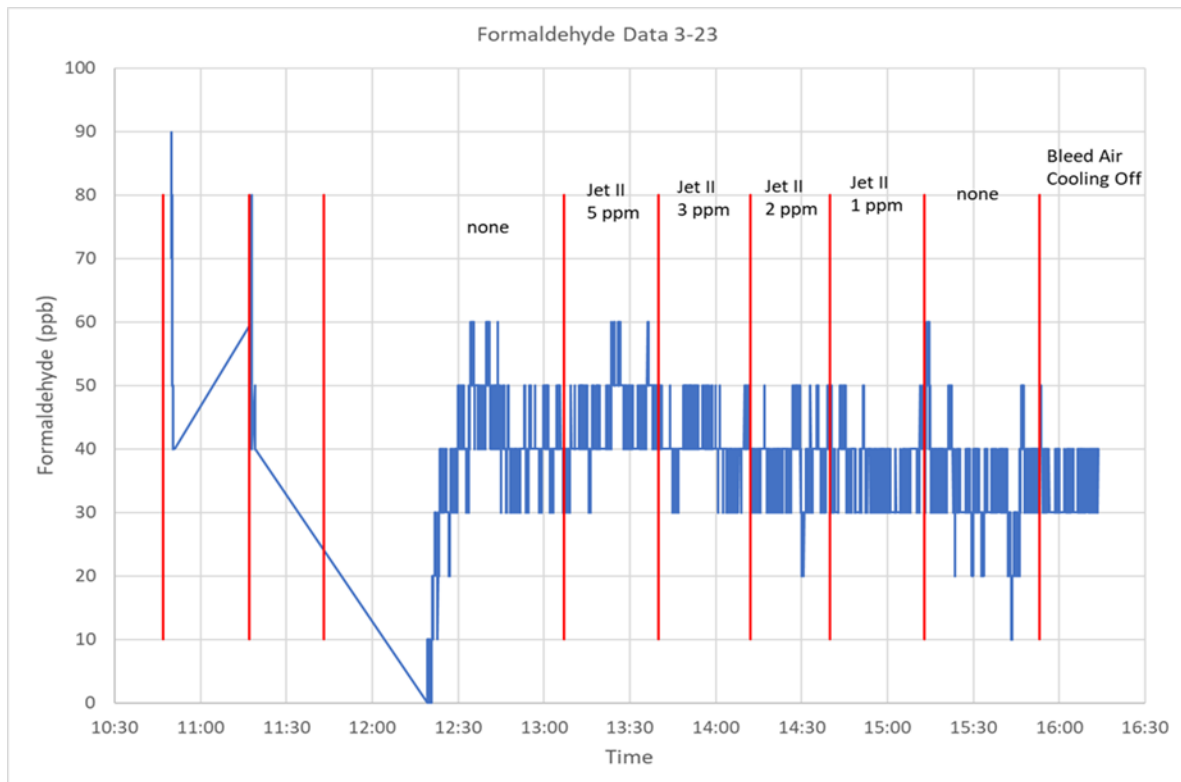


Figure 32-QTRAK Formaldehyde Data for March 23rd

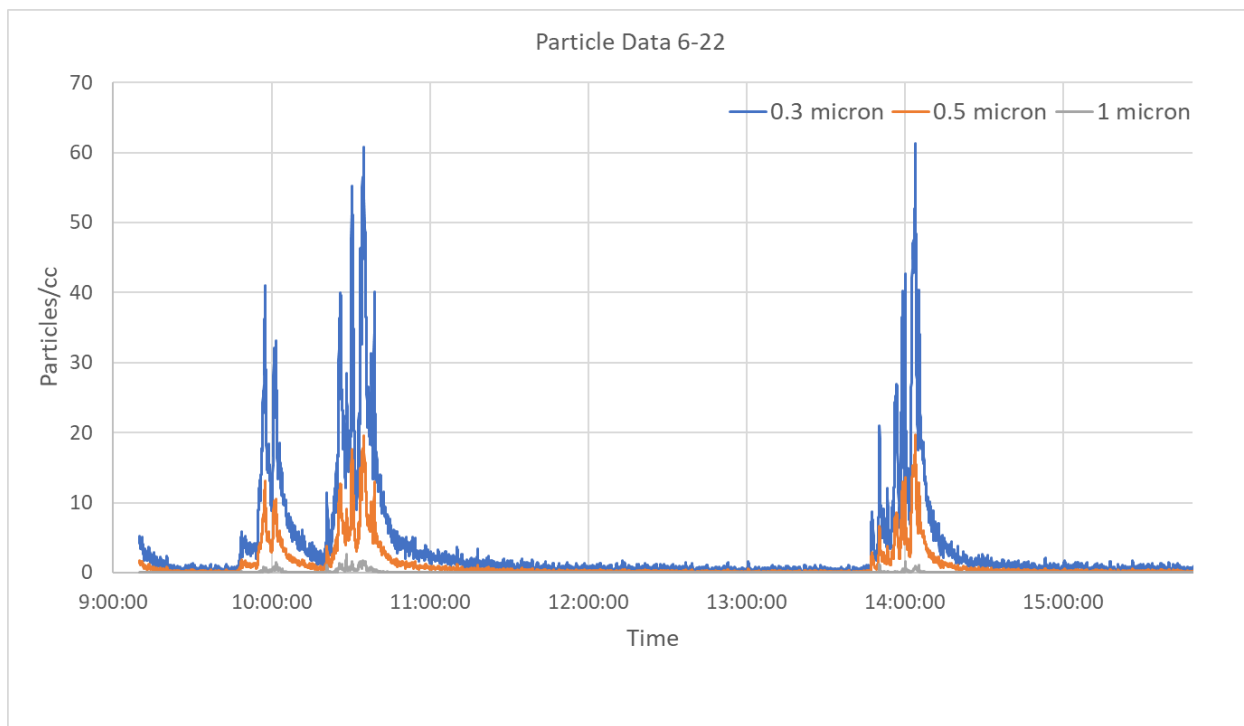


Figure 33-QTRAK Particle Data for June 22nd

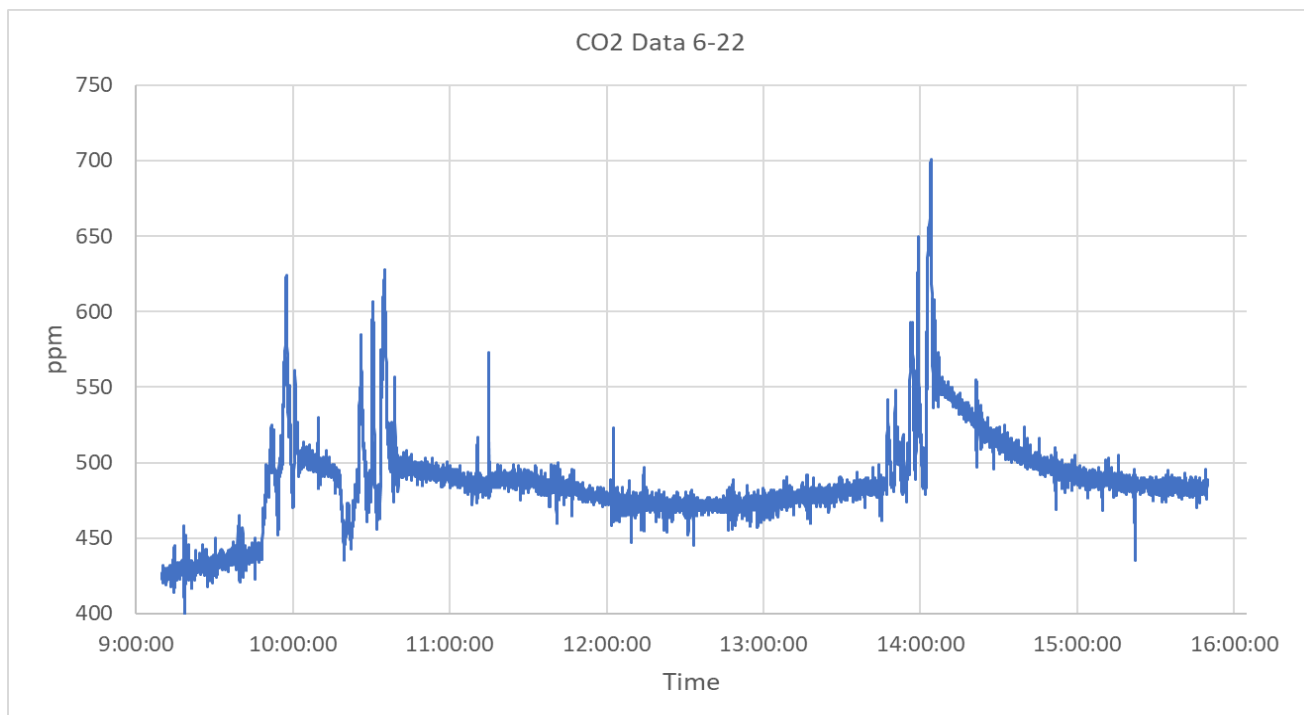


Figure 34-QTRAK CO2 Data for June 22nd

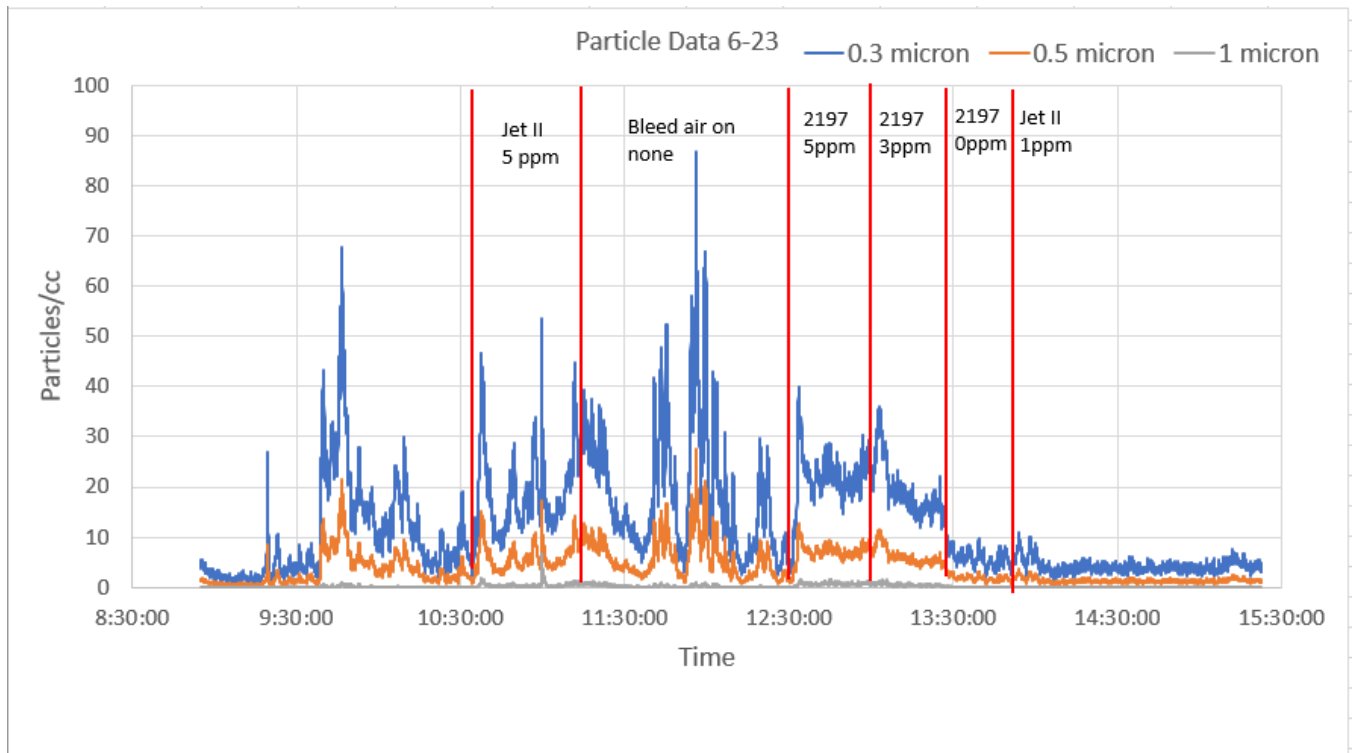


Figure 35-QTRAK Particle Data for June 23rd

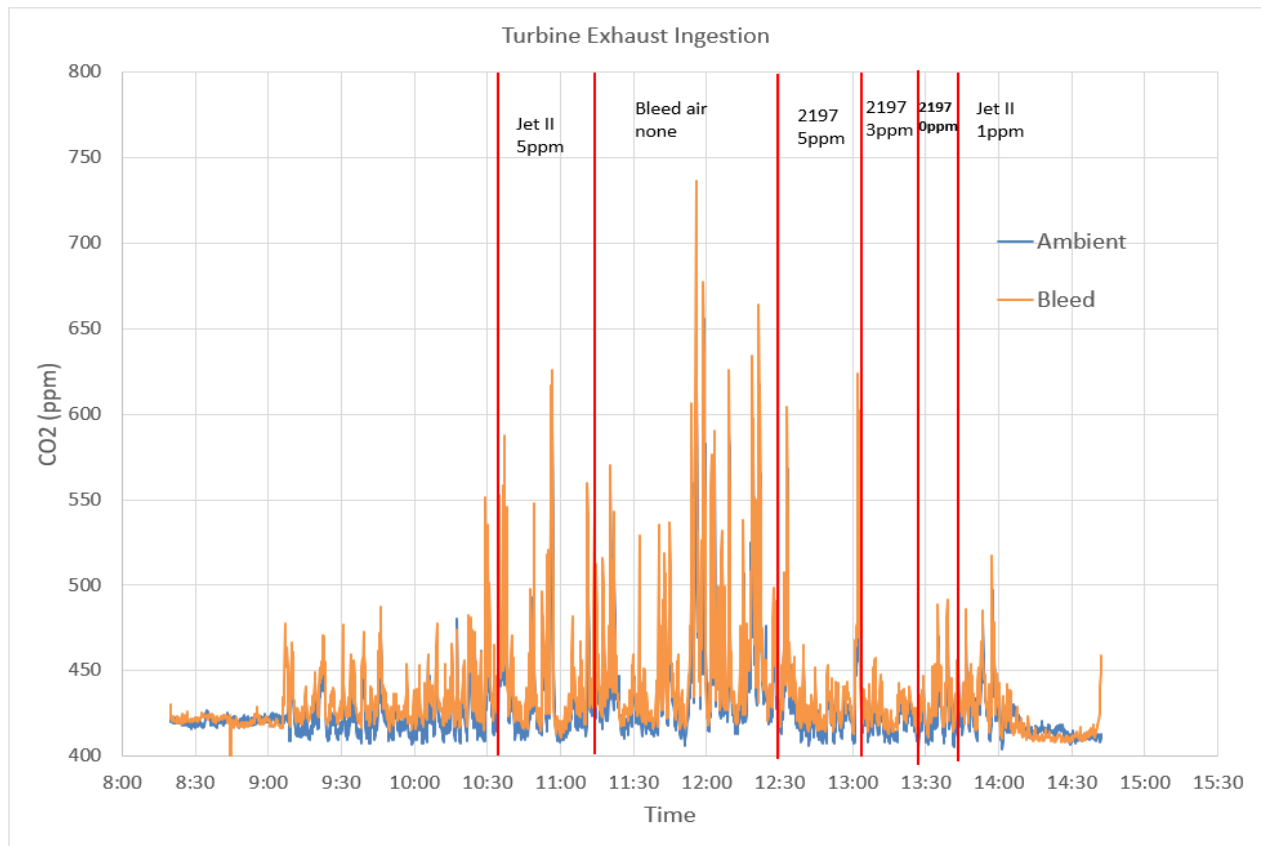


Figure 36-CO2 Data for June 23rd

8. ASHRAE 1830-RP Results/Conclusions

Note that the size distribution graphs use a logarithmic scale for concentrations and each gridline represents an order of magnitude. Similarly, the total concentration graphs also use a logarithmic scale for concentration and each gridline represents an order of magnitude. SMPS data with the APU starts with Figure 5, which seems to show that there is a noticeable response with Eastman 2197 oil, Eastman 2389 oil, and Jet II oil, especially at higher contamination rates later in the graph. In the beginning of the graph however, it is observed that there isn't much of a response for 2197 even for 1 ppm and 3 ppm nominal contamination rates. This is because the APU was recently refurbished and had not operated much since then. Particularly, it took a while for the films to build up on the surfaces as injection took place. Coating on the surface of the compressor took place, making the film bigger. This issue would've been combatted if more time was allotted, so that more contaminants could be injected so that the compressor could shear off particles from its surface but waiting was not a viable option as limited time was available for the November APU experiments.

The LD-4 Skydrol hydraulic fluid had a considerably lower response of particles even with higher contamination rates, which may suggest that ultrafine particles are not a good marker for hydraulic fluid. The engine oil APU data with the SMPS appears to indicate that there is a strong response with ultrafine particles even with 1 ppm contamination rates. Figures 6, 7, and 8 illustrate this finding. This furthermore reinforces the idea that ultrafine particles are indeed a viable marker for engine oil in bleed air contamination. It was also observed that 2389 oil and Jet II were very similar in response. It is important to note that 2389 oil is specifically made for APUs, whereas Jet II and 2197 are propulsion engine oils, which makes the similarity between 2389 and Jet II interesting. Furthermore, APUs do not get nearly as hot as propulsion engines. LD-4 Skydrol fluid and PE-5 Skydrol fluid still showed a response, but it was not nearly as significant as the APU SMPS engine oil data, especially when higher contamination rates and ambient test runs were not significantly different for the APU SMPS hydraulic fluid data, as indicated by Figures 9 and 11. As shown in Figure 9, LD-4 responded well compared to the no contamination case. Figure 10 for the second day of testing with the APU using the SMPS showed some spikes with PE-5 on the graph. The spikes can likely be attributed to exhaust ingestion from gases or other noise factors such as particles induced from nearby traffic. Still, PE-5 did not generate much of a response. On the other hand, Jet II showed a significant response at low contamination rates between 1 and 3 ppm, while both deicing fluids type 1 and type 4 exhibited a fairly low response for a high contamination rate of 10 ppm. Figure 11 is interesting in that the ambient response was initially greater in concentration of particles than all the nominal contamination rates as shown. This is because engine compressors will remove particles from the air. Particles in the air impact surfaces in the compressor and can stick to those surfaces. Therefore, it is crucial to use the 0 ppm condition as a baseline. It is clear from the graph that there are good responses relative to the 0 ppm condition but not ambient. Figure 12 presents the same story as Figure 11 when it comes to compressor fouling. It is evident that type 1 and type 4 deicing fluid respond the same. Furthermore, there is a low response of ultrafine particles for deicing fluid even at high contamination rates, which shows that particles are not a good marker for deicing fluid. Lastly, Figure 13 shows a significant response of

ultrafine particles for contamination rates between 1 and 5 ppm for Jet II oil. The periodic variation in concentration with respect to diameter likely is not real but is unexplained.

The APS data with the APU starts with Figure 14. It is important to note that the APS deals with larger particles, so numbers will appear much smaller on the graphs compared to the SMPS, which would show larger numbers on the graphs since it deals with ultrafine particles. Furthermore, Figure 14 shows that 2197 exhibits a noticeable response at contamination rates of 1 ppm, 3 ppm, and 5 ppm. 2389 shows similar behavior but not as significant of a response as 2197. Jet II also showed similar behavior as the other two oils and had a greater response than 2197 and 2389 as well. LD-4 surprisingly showed a significant response at 3 ppm and 5 ppm but was very brief since the APS malfunctioned and didn't measure for the remainder of the testing period. Figures 15-17 show very similar behavior to the SMPS APU engine oil data, where higher contamination rates tend to yield higher concentration of particles. Interestingly, Figures 18 and 20 with LD-4 and PE-5 seem to exhibit similar behavior to Figures 15-17, which suggests that fine particles are viable markers for hydraulic fluid when dealing with bleed air contamination. Looking closely at Figures 15 and 16, 2389 is similar but better in response than 2197. Very good responses are visible for diameters less than 1 micron but beyond 1 micron isn't very useful as noise becomes an issue in that range. Figure 20 is very similar in response to Figure 18 and shows that PE-5 and LD-4 are very similar in characteristics. They both also showed a good response. Figure 19 shows APU APS data all compiled during day 2 of testing. Note that the sampling problems and sample disruption presented on the graph was due to the SMPS having issues for that test day, which was likely attributed to the way air was supplied to the SMPS. Furthermore, the graph showed PE-5 having a noticeable response for contamination rates of 3 ppm and 5 ppm. Both type 1 and type 4 deicing fluid showed a very low response for contamination rates of 10 ppm. Jet II also showed a significant response for contamination rates of 3 ppm, 2 ppm, and 1 ppm. Figure 21 shows a noticeable but not significant response for deicing fluid for the APS, therefore reinforcing the idea that ultrafine particles are not viable markers for deicing fluid when dealing with bleed air on engines. On the other hand, Figure 22 still shows a strong response with a high concentration of fine particles with Jet II, showing higher concentrations as the contamination rate increases.

Allison 250 SMPS data is shown in Figure 23, which appears to show a significant response for deicing fluid but, is not significant because the deicing fluid was possibly cleaning the engine as a solvent and there was also exhaust ingestion issues with exhaust gas and other sources of background noise. Furthermore, Jet II showed a strong response for contamination rates of 5, 3, 2, and 1 ppm. Figure 24 with the APS shows similar behavior with Jet II having a decent response with contamination rates of 5, 3, 2, and 1 ppm. Note that the peaks from deicing fluid are again from exhaust ingestion and may not be from the deicing fluid. Figure 25 with the SMPS shows a very strong response for 2389 with 5, 3, and 1 ppm. LD4 shows a questionable response for 5 ppm and 3 ppm contamination rates as the data was fairly noisy. Furthermore, Jet II shows a very good response for a 1 ppm contamination rate. Deicing fluid was unsurprisingly very low for a 10 ppm contamination rate. The data was again noisy due to exhaust ingestion. Allison 250 APS data is shown in Figure 26, which shows a low response for 2389 at 5, 3, and 1 ppm, likely from exhaust ingestion and other noise factors. Interestingly, LD4 showed a greater

response than oil at 5 ppm and 3 ppm. Still, Jet II showed a decent response at 1 ppm, while deicing fluid didn't respond well even at 10 ppm. Note that LD4 and Jet II are close in response due to both oil and hydraulic fluid being well suited for fine particles. Total concentration data is presented in Figure 27 with the SMPS, which unsurprisingly shows a very strong response for Jet II at 5, 3, and 1 ppm. Even LD4 showed a strong response at 5 ppm, but the response for PE 5 is questionable as that section of the graph is noisy. Figure 28 with the APS unsurprisingly shows a lower response with Jet II at 5, 3, and 1 ppm, due to a noisy environment. LD4 and PE 5 showed similar responses to Jet II at 5 ppm, which reinforces the idea that hydraulic fluid and oil behave similarly in response when it comes to fine particles.

It's important to note that the QTRAK was not very precise at measuring the changes in CO and formaldehyde levels. However, this was not a limiting factor since the changes in these levels were very small anyway. The changes in these levels would have to be considerably greater than what was seen in the QTRAK to deem either CO or formaldehyde as a viable marker given the background levels observed in these instruments.

The QTRAK data for particles and VOCs showed a good response to engine oil and hydraulic fluid but had minimal response for formaldehyde and CO. Figure 29 as an example, shows a poor response from CO from Jet II oil contamination. The graph peaked at 5 ppm and the resolution of the QTRAK instrument was clearly not sufficient for measuring CO. Furthermore, the response from CO was underwhelming, suggesting it most likely is not a suitable marker for bleed air contamination. Figure 30 showed an interesting response for VOCs. Most of the graph had somewhat of a response from Jet II contamination, but it's difficult to say whether or not the response was from Jet II contamination or from exhaust ingestion. However, towards the end of the graph, there was a huge increase in VOC concentration as shown. This increase occurred when the cooling fan from the heat exchanger to the bleed air was turned off, allowing the bleed air cooling heat exchanger to get hot, thus resulting in more VOCs. Figure 31 showed a great response for particles from Jet II engine oil contamination. The figure also shows that the QTRAK clearly responds to smaller particles. As shown, 0.3-micron particles responded significantly more than 0.5 micron and 1-micron particles. 0.5-micron particles also responded noticeably more than 1-micron particles, with 1-micron particles hardly responding at all. Based on the CO response on the same day, it's reasonable to assume that much of the response was from bleed air engine oil contamination and not from exhaust ingestion. This Figure again reinforces that idea that particles are good markers for engine oil. Figure 32 shows formaldehyde data. In this Figure, it is clear that the response of the formaldehyde sensor is not sufficient to detect the contaminants. Furthermore, the data showed little variation in formaldehyde on the order of 10-15 ppb, which was rather surprising considering the VIPR formaldehyde data were more promising. Figure 33 shows particle data with the three large spikes clearly being attributed to exhaust ingestion. This assessment is valid given that Figure 34 shows a large response from CO₂, which happened during the day exhaust ingestion was present.

Figure 35 shows another case of exhaust ingestion with contaminant injection from Jet II oil and Eastman 2197 oil. Figure 36 again confirms this assessment given the similarity of the CO₂ response with the particle response, with CO₂ responding quite significantly on that test day. In

conclusion, it can be said that ultrafine particles are a very good marker for engine oil. Fine particles are good markers for both engine oil and hydraulic fluid. Finally, particles in general are a very poor marker for deicing fluid. Furthermore, VOCs may be potential markers of engine oil contamination in the right applications if proper sensors are utilized. The same goes with formaldehyde. Carbon monoxide, on the other hand, is likely a poor marker for bleed air oil contamination. Carbon dioxide is also a useful discriminator for determining whether or not a response of particles is due to exhaust ingestion or bleed air contamination.

9. Cranfield

This study was funded by the UK Department of Transportation and was conducted by researchers at Cranfield University in collaboration with the UK Building Research Establishment National Laboratory. This study is officially known as the “Cabin Air Sampling Study” but is commonly referred to as the “Cranfield Study”. The purpose of this study being established was to respond to concerns regarding impacts on the health of crew from exposure to substances in the cabin air. This project is unique in that it focused significantly on fume events with both the researchers and crew members identifying the occurrence of fume events. Numerous flights are designated as having fume events. The project is also unique since it included the Bae 146 aircraft, which is known to have fume events. Since this project focused on health and fume events, the air sampling was directed at specific compounds that may be indicative of the health impacts and not necessarily those that are useful for contamination detection. This study was still chosen for this thesis mainly to show that background marker concentrations in cabin air can be far greater than those observed in bleed air with significant oil contamination. The study is also included in this thesis to indicate that concentrations of particulates are low compared to those measured in bleed air with significant contamination levels in the VIPR project. Still, many isolated cases of highly elevated levels during the boarding phase with no apparent association with bleed air contamination were observed, which means that using particulate measurements in the cabin to identify bleed air contamination events may not be a viable option. Finally, sampling was conducted throughout all flight phases from boarding to deplaning. As shown in the Table 4, data were collected on five aircraft types and on 20 flights for each type for a total 100 flights. Data are associated with 10 different flight phases starting with boarding and ending with deplaning as indicated by Table 5. A separate category is designated for an air quality event which could be linked with any of the flight phases. Continuous measurements collected TVOC, carbon monoxide, and particulates. Air samples were collected for later analysis in the laboratory. The instrumentation used is shown in Table 6. The particulate data were collected with a condensation particle counter that counted particles in the 0.020 to 1.0 μ m range. This range includes part of what is normally considered ultrafine particles, <0.10 μ m, and part of what is normally considered fine particles, 0.10 μ m to 2.5 μ m as mentioned previously. The air samples were analyzed for a limited number of targeted compounds as described in Table 7. Fume events were identified in real time by the onboard

researcher and, if identified, immediate air sampling was conducted. It appears this detection of an event was mainly subjective on the part of the researcher based primarily on smells. However, an “abnormal” increase in TVOC or particulates also could be indicative of an air quality event. Furthermore, the objective criteria for designating an event were not clear.

Table 9 summarizes the number of flights with different levels of particulate concentration. Table 9 presents particle counts for aircraft with air quality events and Table 10 shows TVOC maximums for a given number of flights. Table 11 shows carbon monoxide peak values for a given number of flights. Tables 12 and 13 summarize chemical data for all flights, based on all 981 samples collected. Table 14 summarizes statistics for toluene by phase of flight. Tables 15 shows the number of air quality events identified by researchers, whereas Table 16 shows air quality events identified by crew members. Lastly, Figures 29-33 show particulate, carbon monoxide, and TVOC data.

Table 4-Aircraft Included in the Study and the Number of Flights

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B757 cargo	B757 pax	A319	A320/321	Bae146	Total
20	20	20	20	20	100

Table 5-Summary of Specific Flights Phases Identified for Data Collection

Reproduced from (Walton et al., 2011) with permission

Sample No.	Flight phase	Cues	Comments
1	Immediate	As soon as kit is set up	
2	First engine start	Pilot says “Starting right/left engine”	Usually during push-back
3	Taxi	As aircraft begins to move under own power	
4	Take off	Throttle up	
5	Climb	As aircraft climbs above 20,000 ft	In some cases (e.g. short sectors) the altitude for this sampling cue was reduced to 13,000 ft after consultation with the flight crew
6	Top of climb	Throttle back	
7	Cruise	10 minutes after top of climb	
8	Start of descent	Throttle back, aircraft pitches down	
9	Pre-landing	2,500 feet (“Radio altimeter” heard -757 only)	Will include landing and into Taxi
10	Taxi-back	End of previous sample	
F	Air quality event	Smell reported or warning from PID or ultrafine particle monitoring instruments	Second pump started immediately

Table 6-Summary of Instrumentation Use in the Aircraft for Measurements

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Variable	Method	Instrument	Range	Accuracy
TVOC	PID	Ion Science First Check+5000	1ppb-10,000 ppm	± 5%
CO	Electrochemical Cell	Not specified	0.1 -1000 ppm	Not specified 1 ppm resolution
Particulates	CPC	TSI Model 8525 P-Trak	0.02 to 1 µm	Not specified
Air Sample	stainless steel sorbent tubes	packed with quartz wool and Tenax TA	Flow of 500 mL/min for five minutes typical	NA

Table 7-Targeted Chemical Compounds for Laboratory Analysis

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Targeted Compounds	Comments
Tri-ortho cresyl phosphate (TOCP)	A particularly toxic isomer of TCP
Other tri-cresyl phosphate (TCP) isomers	applications include as a minor component of engine oil
Tri-butyl phosphate (TBP)	applications include a component of hydraulic fluid
Toluene	widely occurring VOC e.g. in inks, adhesives, component of solvent cleaners and petroleum based fuels
Limonene	present in natural products such as wood and citrus fruits and widely applied as fragrance in a range of cosmetic and cleaning products
Tetrachloroethylene (TCE)	a solvent used in cleaning products
Undecane	present in petroleum mixtures such as fuels and solvents e.g. white spirits used in construction products and cleaning liquids

Table 8-Summary of the Number of Flights with Different Levels of Particulate Concentration

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Number of Particles cm^{-3}	0-100	101-1,000	1,001-10,000	10,001-50,000	50,001-100,000	100,001- >500,000
Minimum	95	5	0	0	0	0
Mean (for duration of flight)	0	0	63	34	3	0
maximum	0	0	0	13	22	65*

*5 of the 65 were >500,000 particles cm^{-3}

Table 9-Particle Counts for Aircraft with Air Quality Events

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Number of Particles cm^{-3}	0-100	101-1,000	1,001-10,000	10,001-50,000	50,001-100,000	100,001- >500,000
minimum	24	1	0	0	0	0
mean	0	0	12	12	1	0
maximum	0	0	0	1	5	19

Table 10-TVOC Maximums (the term “sectors” is equivalent to “flights”)

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Total VOC ppm	0-2	2-4	4-6	6-10	>10
Number of sectors (n)	34	27	5	5	19

Table 11-Carbon Monoxide Peak Values (the term “sectors” is equivalent to “flights”)

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CO ppm	<1	1	2	3-5	>5
Number of sectors (n)	6	45	23	6	1*

Table 12-Summary of Chemical Data for All Flights, Based on All Samples Collected (981 total)

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Compound	Concentration $\mu\text{g m}^{-3}$							
(n)	10%	50%	75%	95%	AM**	SD	min	max
TOCP (981)	ND*	ND	ND	ND	0.07	0.88	ND	22.8
Other TCPs (981)	ND	ND	ND	ND	0.14	1.36	ND	28.5
Sum of TOCP and other TCPs	ND	ND	ND	ND	0.22	2.08	ND	37.7
TBP (981)	ND	0.4	1.3	5.0	1.07	1.96	ND	21.8
Toluene (981)	ND	6.3	16.6	50.1	13.93	21.23	ND	170.2
m+p xylene (981)	ND	0.4	1.8	9.1	1.78	3.63	ND	52.3
Limonene (981)	ND	1.4	6.5	37.8	11.85	45.77	ND	540.3
TCE (981)	ND	ND	0.6	1.8	0.43	1.04	ND	20.1
C ₁₁ (981)	ND	ND	2.0	13.8	2.74	7.60	ND	87.3

Table 13-Summary of Chemical Database on Flight Mean Values

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Compound (n=100)	Concentration $\mu\text{g m}^{-3}$							
	10%	50%	75%	95%	AM	SD	min	max
TOCP	ND	ND	ND	0.29	0.08	0.38	ND	2.5
Other TCPs	ND	ND	ND	0.44	0.15	0.74	ND	6.6
All TCPs	ND	ND	0.005	0.73	0.23	1.06	ND	8.0
TBP	ND	0.7	1.2	5.7	1.11	1.72	ND	8.2
Toluene	1.7	8.4	21.2	39.8	13.95	14.28	ND	70.1
m+p xylene	0.3	0.8	1.3	8.5	1.75	2.55	ND	11.3
Limonene	ND	2.2	6.1	37.0	11.68	42.88	ND	342.7
TCE	ND	0.1	0.6	1.5	0.43	0.67	ND	3.7
C ₁₁	ND	0.9	2.2	11.7	2.68	6.35	ND	47.1

Table 14-Summary Statistics for Toluene by Phase of Flight

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Phase of flight	Toluene concentration $\mu\text{g m}^{-3}$							
	10%	50%	75%	95%	AM	SD	min	max
Immediate	2.6	7.1	13.8	31.1	11.62	15.03	ND	127.5
First engine start	4.2	15.2	35.0	82.9	26.00	29.47	ND	152.2
Taxi	ND	9.6	38.1	78.7	22.95	29.94	ND	159.0
Take off	ND	6.2	24.7	53.7	16.76	26.34	ND	170.2
Climb	ND	4.3	14.9	41.1	10.10	12.62	ND	57.6
Top of climb	ND	3.1	10.3	36.5	7.57	10.74	ND	45.7
Cruise	ND	3.4	11.5	40.9	8.00	11.74	ND	49.8
Start of descent	ND	3.6	12.4	41.2	9.38	14.89	ND	94.0
Pre-landing	ND	4.0	11.8	49.6	12.12	22.92	ND	150.8
Taxi-back	ND	7.1	16.5	59.4	13.80	17.32	ND	73.3
AQ event	0.4	10.1	19.1	82.4	17.69	25.03	ND	107.6

Table 15-Number of Air Quality Events Identified by Researchers

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Part	Phase of flight										
	Immediate	Engine start	Taxi	Take off	Climb	Top of climb	Cruise	Start descent	Pre-landing	Taxi back	Total
1						1		1	1	1	4
2		3		2							5
3		2		1				2			5
4	1	1		2	2		2		2	1	11
5			2							3	5
Total	1	6	2	5	2	1	2	3	3	5	30

Table 16-Air Quality Events Identified by Crew Members

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Part	Phase of flight										
	Immediate	Engine start	Taxi out	Take off	Climb	Top of climb	Cruise	Start descent	Pre-landing	Taxi in	Total
1	0	0	0	2	1	0	0	2	2	2	9
2	0	6	8	7	3	0	0	0	0	0	24*
3	0	5	6	0	1	0	1	1	2	0	16*
4	0	0	1	0	0	0	0	2	1	0	4
5	0	0	1	1	0	0	0	0	0	2	4
Total	0	11	16	10	5	0	1	5	5	4	57

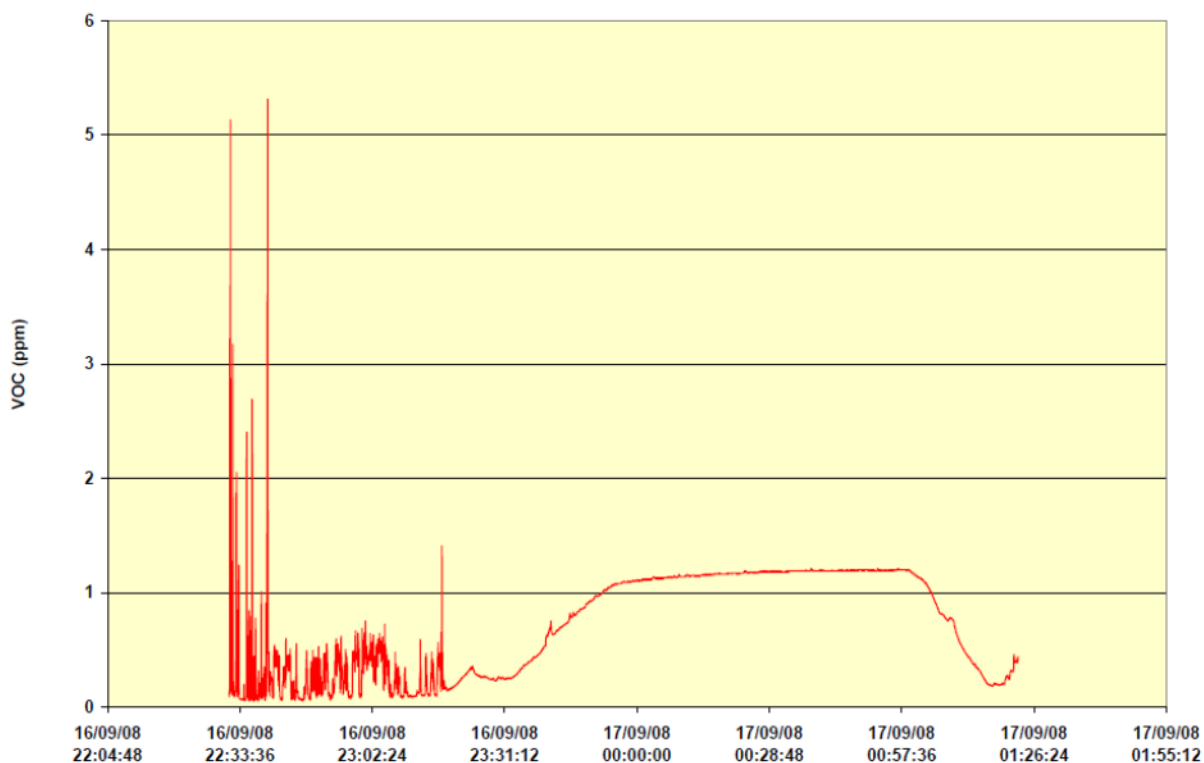


Figure 37-Example of TVOC Data Recorded for One Flight

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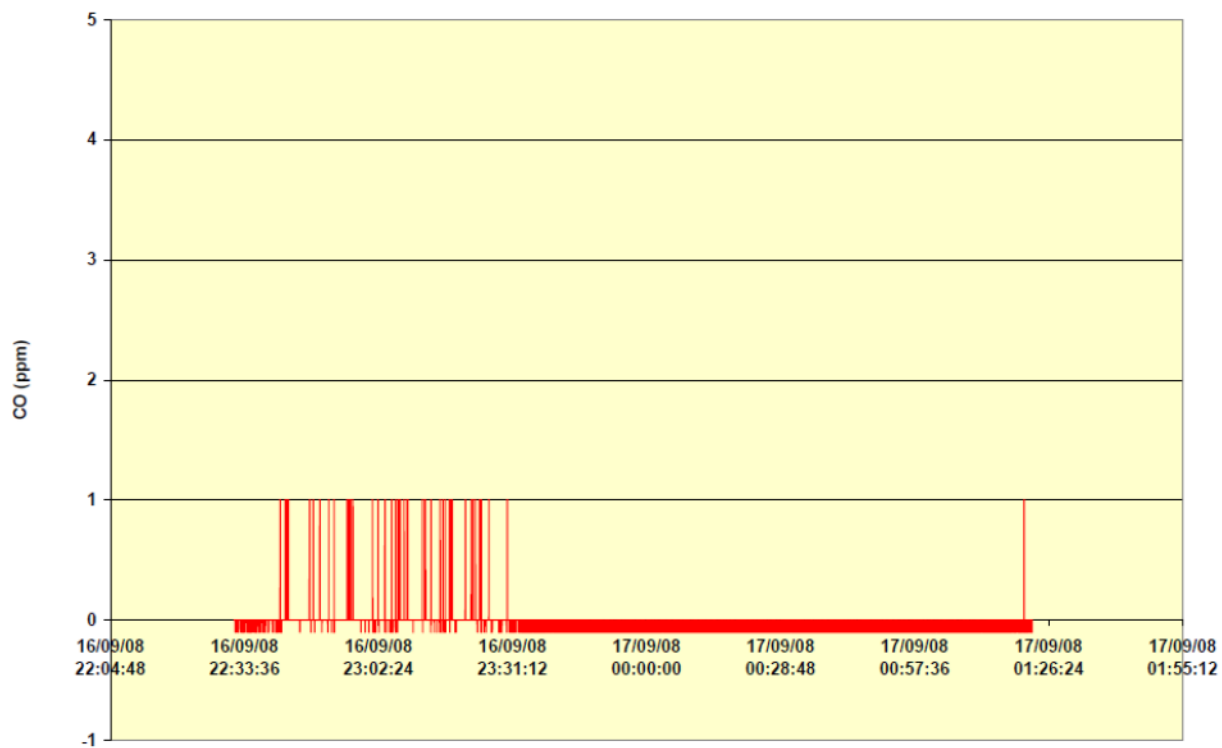


Figure 38-Example of CO Data recorded for One Flight

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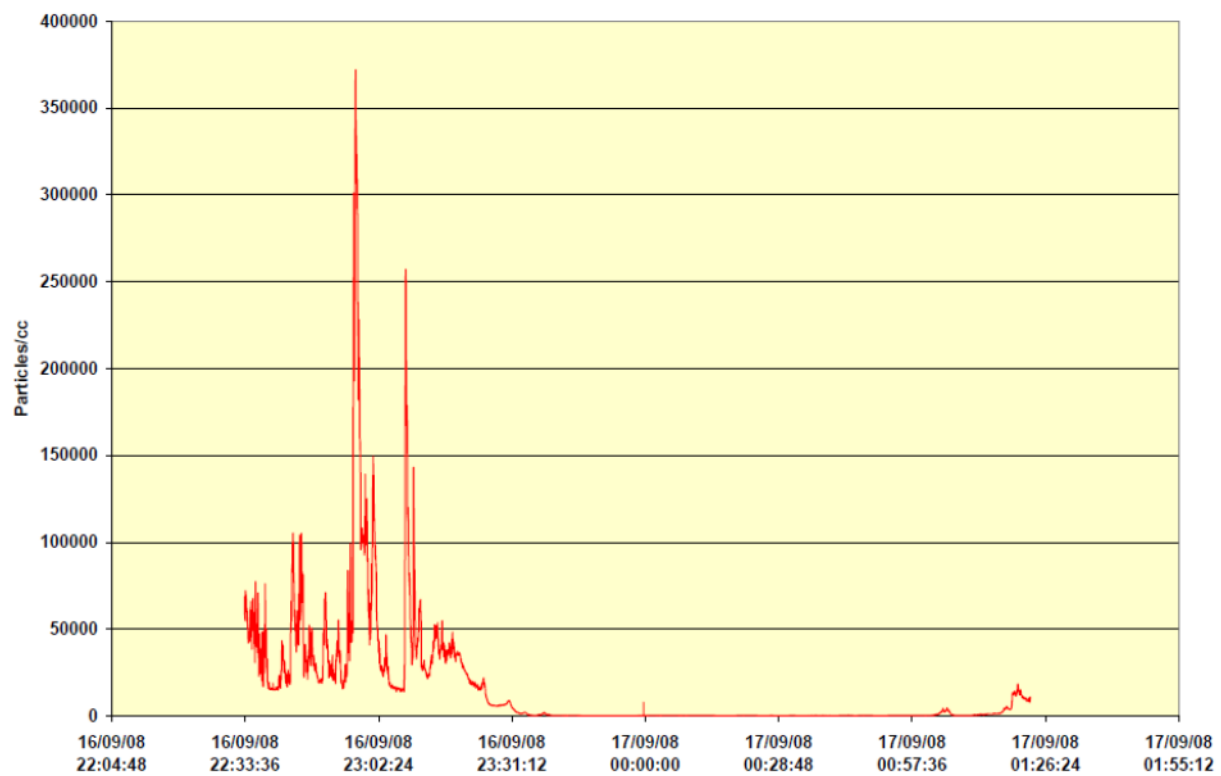


Figure 39-Example of Particulate Data Collected for One Flight

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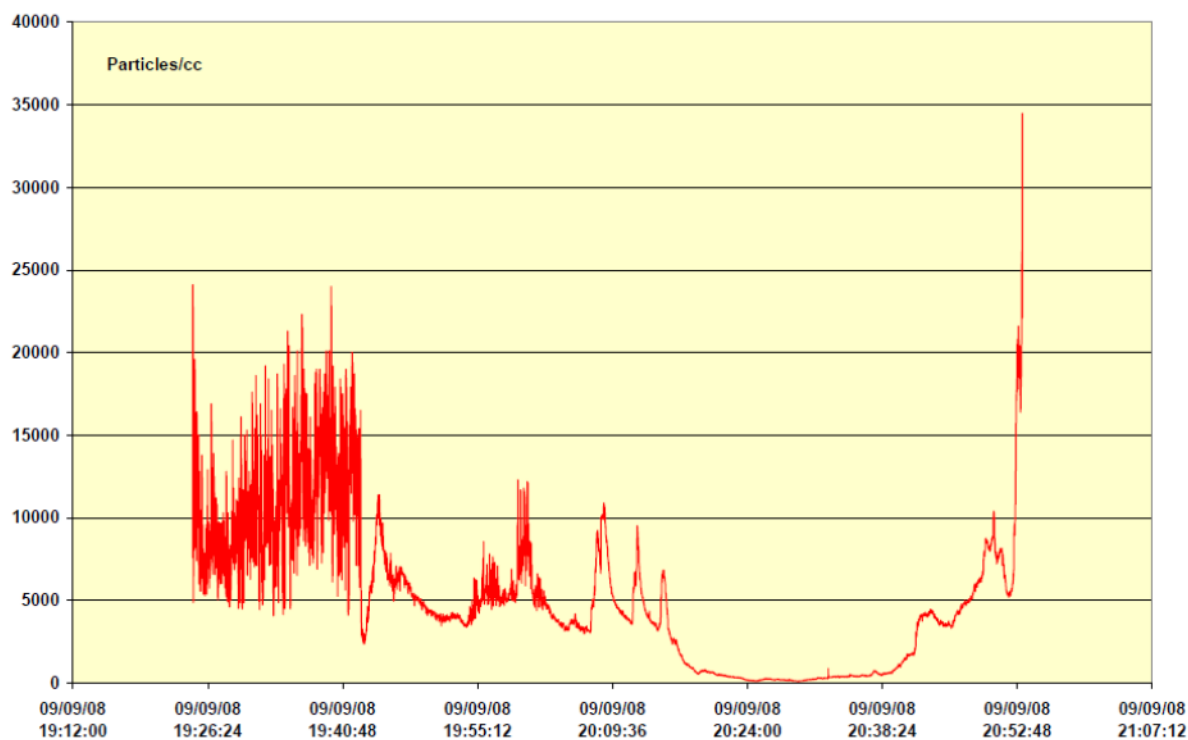


Figure 40-Example of Flight with Lower Peak Particulate Levels

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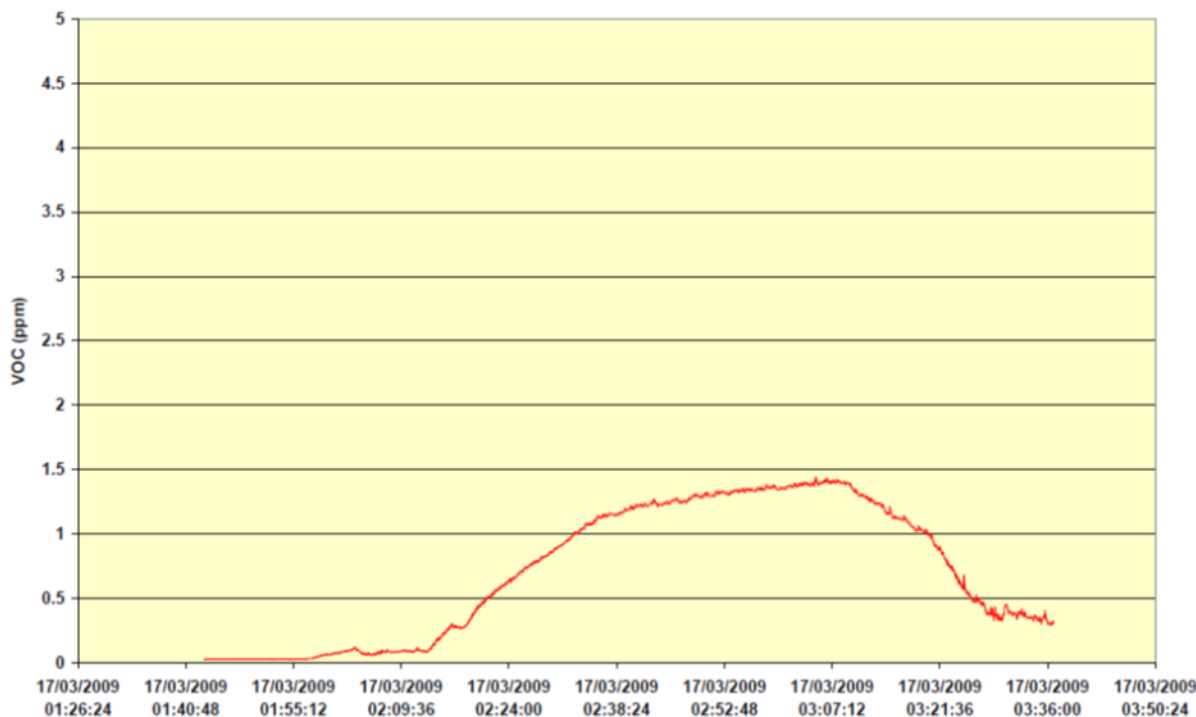


Figure 41-Example of Low Initial Value of TVOC

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10. Summary of Cranfield Results/Conclusions

The reports for the continuous measurements document the results in graphical form for every single flight. Examples for the three continuously recorded variables, TVOC, CO, and particulates for the same flight are shown in Figures 37-39. However, the flight phases are not shown on the graphs, so it is crucial to use judgement when viewing the data. Additionally, the scales alter from flight to flight so direct comparisons between plots, particularly for particulates which range over several orders of magnitude, must be done carefully. For instance, Figure 40 has a peak particle concentration approximately an order of magnitude lower than for the flight shown in Figure 39. Therefore, the particulate variation during the in-air portion of the latter flight can be seen more easily. Generally, the highest particulate concentrations are seen during the boarding phase, and, to a lesser degree, the deplaning phase as seen in both Figures 39 and 40. Generally, during the in-air portion of the flight, the values are low with occasional peaks as seen in Figure 40, likely due to activity surrounding the instrument. However, a true “typical” flight does not exist as particle concentrations and time characteristics varied considerably from flight-to-flight and the concentration varied considerably during most flights as well. Table 8 summarizes the levels that were measured for all flights and Table 9 contains the same information for those flights identified as event flights. There is no noticeable difference in the patterns between the two tables. Like particulates, the highest levels of TVOC were often observed at the beginning of a flight, likely during boarding. Figure 37 represents such instances. Unlike particles which almost always had higher values at the beginning and sometimes at the

end than the rest of the flight, TVOC was not consistent in this manner and numerous flights had low initial values as shown in Figure 41. The levels during what appears to be the in-air portion of the flights were more consistent from flight to flight. The project report does not provide much summary data for TVOC measurements. Peak values are characterized in Table 10. The 1 ppm resolution of the CO data makes the CO information not very useful. Figure 38 is typical of most of the flights with readings of either 0 or 1 ppm for most of the flight. Reviewing the individual flight graphs shows that there are occasionally short-term peaks of a few ppm at most. Table 11 summarizes the number of such peak values. The resolution of the sensor makes it difficult to discern if values of 2 ppm represent a true peak. Values greater than 2 most likely indicate an elevated CO level. All such excursions were brief, on the order of minutes. None of the chemicals included have been identified as potential markers for detection so only an overview is provided here. Table 12 provides summary statistics for all samples collected on all flights, 981 total. Table 13 provides summary statistics for all flights based on mean values for each flight. Summary statistics by aircraft and by phase of flight are presented in the project report. Table 14 presents the toluene results as an example. Researchers identified a total of 30 events of 25 different flights over the course of the project. The results are summarized by flight phase in Table 15.

It is observed that the events were spread throughout all phases of flights but were most common during engine start, takeoff, and taxi back. Crew members identified 57 air quality events. Table 16 presents the same information for events identified by crew members. The events identified by the crew members tend to be clustered in the earlier phases of the flights, engine start, taxi, and takeoff. The events identified by crew members were based on post flight surveys. The reports do not indicate if there is any correlation between when researchers identified events and when crew members identified events. While some of the events were associated with increased levels of TVOC, particularly those that were identified by such an increase, the consensus of the study is that there was no association between concentrations of chemicals or other variables and the identification of an event. Also, none of the events raised to the level of requiring follow up reporting or actions by the airline. The particulate data reported in this project, however, are useful for the current ASHRAE 1830-RP project. Even though concentrations are typically low compared to those measured in the bleed air with significant oil contamination levels in the VIPR project, there are still numerous cases of highly elevated levels particularly during the boarding phase with no apparent association with bleed air contamination that are comparable to concentrations with contamination measured in the VIPR project. These results make a case for not attempting to use particulate measurements in the cabin to identify bleed air contamination events. The continuous recordings for every flight are particularly informative but cumbersome to use. The TVOC data is also informative. In this case, the data show that the background levels in the cabin are normally well above the levels seen in bleed air the VIPR project with contamination. Therefore, attempting to utilize TVOC measurements in the cabin to identify bleed air contamination will not work. The low resolution of the carbon monoxide measurements results in limited quantification of the actual CO levels on the aircraft other than that they typically appear to be 1 ppm or less. However, those measurements are sufficient for documenting the lack of health risk. Given that the occasional short peaks above 2 ppm are not, in general, associated with air quality events, CO measurements in the cabin are

also shown to be of little use for detecting bleed air event based on the levels measured with significant contamination in the VIPR project. Furthermore, none of the compounds evaluated have been identified as a likely candidate as a marker for bleed air contamination. The number of air quality events identified in this project is surprising and indicates a very low threshold for defining an event. Given that none of the events raise to a level that would require any kind of follow up action by the airline confirms the observation that the threshold was very low. Similarly, the lack of association with any physical measurements further confirms this observation. It also points to the challenge associated with identifying physical variables that can be used to detect low level air quality events whether they originate from the bleed air or elsewhere.

11. VIPR

The NASA Vehicle Integrated Propulsion Research (VIPR) program was a large, multi-agency program that involved NASA, the U.S. Air Force, Pratt & Whitney, Boeing, and other agencies and industry collaborators. The scope of the project revolved around sensors and measurements for engine health monitoring. The VIPR Bleed Air Project was just one part of a much larger program. The VIPR Bleed Air Project was led by Boeing and the FAA participated through RITE-ACER. RITE-ACER universities Auburn, Kansas State, and Boise State prepared instrumentation and other equipment for the experiments. Auburn University and Kansas State University had personnel on site and assisted in the preparation and conduct of the experiments at Edwards Air Force Base. The actual measurements were conducted on June 8 and June 9, 2015. The experiments were conducted on a USAF C-17 Globemaster III aircraft with F117/PW2000 Turbofan engines. The Boeing 757 aircraft utilizes the same engine model. A modified bleed air manifold was placed on the engine which allowed the bleed air to be directed to an instrumentation platform located beneath the engine, as shown in Figure 42, where it was cooled, measured, and sampled. All experiments were conducted on the ground. The AP1 inspection port on the engine was modified so that an oil injection line could be connected to it for controlled oil injection into the engine compressor. This port is located after the fan and near the front of the compressor.

As part of the FAA sponsored work for VIPR, additional experiments were conducted at Kansas State University using Allison 250 C-18 and 250 C28B engines; see Figure 43. For these experiments, oil was aerosolized and injected into the engine inlet air stream. The bleed air was cooled using an aircraft bleed air pre-cooler and then directed to a manifold where it could be sampled. The primary purpose of these experiments was to test out measurement methods prior to the C-17 experiments and it was utilized by KSU and Boeing.

For the C-17 experiments, there were two sets of experiments conducted. On the first day, the plan was to step through injection rates starting at 200 gram/hour with increasing steps to 1200 gr/hr. The short duration of each step limited the measurements only to real-time sensors. There were two limitations for this first day of experiments. First, there was an unexpected transport lag in filling the injection line and, as a result, oil did not reach the engine before the 600 gram/hr injection rate. Therefore, the lower injection rates were not evaluated.

Second, the injection nozzle plugged after the 800 gram/hr injection rate. Only two conditions were evaluated as a result. The main purpose of the experiments for the first day were to collect data to determine the appropriate rate for the second day of experiments. Adequate data were collected for this purpose. On the second day, all experiments were conducted either with no injection or with 1200 gram/hr injection. Part of the test plan was to test air cleaning technology and experiments were repeated with different air cleaning technology. The results of the air cleaning are not addressed in this thesis. The test conditions with the 1200 gram/hr injection were maintained for 30 minutes each with a clean out run between tests. The 30-minute test period allowed a variety of samples to be collected for later laboratory analysis as well as for real time measurements. While the injection rate in gram/hr was used for experiment documentation, the more important parameter is the concentration of the oil in the air going through the compressor. This airflow was not measured but was estimated from engine models. All experiments were conducted at the same engine setting. The following information was provided by Boeing indicating that the engine core airflow was about 100 lb/sec. Mobil Jet Oil II was the injected fluid for all experiments. Mobil Jet Oil II has a specific gravity of 1.003. Using this information, the concentration of the oil in the compressor air is as shown in Table 17 (Jones, 2020). While the data are all reported according to injection rate, they are identified here by the approximate concentration numbers as those numbers have more relevance for the current project and allow data from different engines to be compared. For simplicity, the corresponding nominal contamination rates are 4, 5, and 8 ppm (Jones, 2020). A variety of measurement methods were employed for the C-17 experiments. Table 18 summarizes the real time instrumentation that provided measurable responses to the oil injection. Real time sensors for carbon dioxide and methane were also included but did not provide measurable responses. A variety of techniques were used to collect samples for later laboratory analysis. These measurement techniques are summarized in Table 19.

The primary measurements made on the KSU engines were the particulates in the bleed air using the same instrumentation used for the C-17 experiments. As with the C-17 engine, the airflow through the engines was not measured and, in this case, were only roughly estimated to be in the 1.0 -1.5kg/s range for the experiments. Three levels of oil injection were used with nominal levels of 20, 40, and 60 grams/hour. Consequently, roughly, the nominal oil concentrations were 4, 8, and 12 ppm by mass (Jones, 2020).

Table 20 below shows the response of real time sensors for the C-17 experiments. Figure 42 shows the experimental setup for the C-17 and Figure 43 shows the Allison 250 C28B engine test facility. Figures 44-48 show VIPR bleed air data with various contamination rates and ambient air with the C-17 engine. Figure 49 shows the Allison 250 C28B engine particle data for various temperatures. Figure 50 presents the same thing as the previous figure only using the Allison 250 C18 engine. Figure 52 shows the Allison 250 C28B engine particle data showing the effect of different contamination rates. Figure 51 shows the distribution number of particles with respect to particle diameter for C18 engine. Finally, Figures 53 and 54 show VOC concentrations and tri-cresyl phosphate data for 0 and 8 ppm nominal contamination rates.

Table 17-Oil Concentrations in Compressor Air at Different Injection Rates for VIPR Data

Reproduced from (Jones, 2020)

Injection Rate (gram/hr)	Oil Concentration (ppm by mass)	Nominal Contamination Rate (ppm)
600	3.9	4
800	5.1	5
1200	7.7	8

Table 18-Real Time Sensing for C-17 Experiments

Reproduced from (Jones, 2020)

Parameter	Instrument	Additional Information
Carbon Monoxide	Alphasense CO-B4	Lower detection limit 20 ppb
TVOC	Honeywell ppbRAE 3000	
Particulate	TSI 3321 Aerodynamic Particle Sizer	Size and concentration over 0.5-20 μm range
Particulate	TSI Scanning mobility particle sizer: 3936L75-M classifier, 3087 X-ray neutralizer, 3081 differential mobility analyzer, 3775 condensation particle counter	Size and concentration over 12 – 1000nm range
Oil Odor	Aerotracers	In addition to odor indication, the response of individual sensors was recorded

Table 19-Sampling Techniques Used in C-17 Experiments

Reproduced from (Jones, 2020)

Sampling Technique	Application
DNPH Tubes	aldehydes
PUF/CAD Cartridges	Compounds associated with engine oil
Markes Tubes	Low to mid range-semi-VOC
Summa Canisters	VOCs and thermal breakdown products

Table 20-Response of Real Time Sensors in C-17 Experiments

Reproduced from (Jones, 2020)

Parameter	Nominal Contamination Level (ppm)	Response
Carbon Monoxide	0	0.35 – 0.68 ppm
	4	0.70 – 0.85 ppm
	6	1.05 – 1.10 ppm
	8	1.10 – 1.15 ppm
TVOC	0	0.1 ppm-0.3 ppm
	4	0.58 ppm
	6	0.74 ppm
	8	0.82 ppm
Particle Number	0	$0.9 \times 10^3 - 1.5 \times 10^3 \text{ \#/cm}^3$
	4	$0.9 \times 10^5 \text{ \#/cm}^3$
	6	$2.2 \times 10^6 \text{ \#/cm}^3$
	8	$1.8 \times 10^7 \text{ \#/cm}^3$
Particle Mass	0	$0.17\text{-}0.40 \text{ \mu g/m}^3$
	4	$2.4 \text{ \mu g/m}^3$
	6	$7.4 \text{ \mu g/m}^3$
	8	$2600 \text{ \mu g/m}^3$
Odor	0	1.0 – 1.8
	4	3.7-7.0
	6	5.8 – 7.0
	8	5.9 – 7.0



Figure 42-(a) CAD model representation of integrated C-17 and BAESS test platform (b) C-17 and BAESS test platform at EAFB prior to connection to aircraft, and (c) C-17 and platform during prior VIPR experiments

Reproduced from (Space et al., 2015), NASA 2015



Figure 43-Allison 250 C28B engine test facility

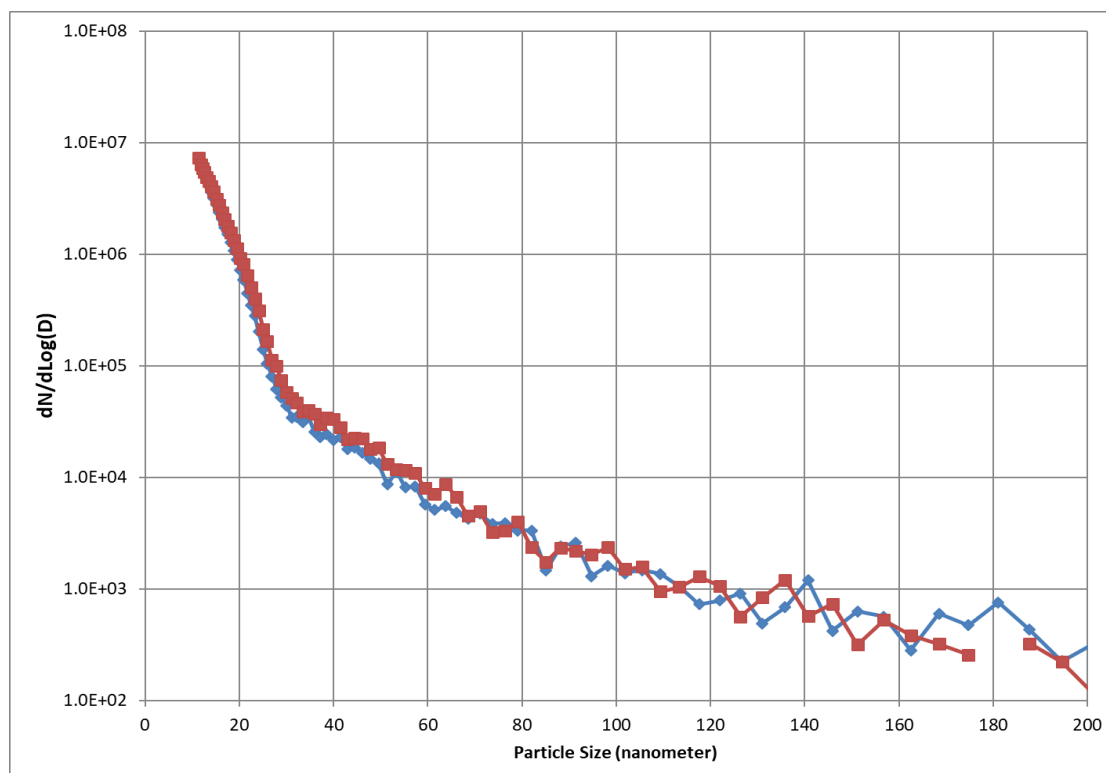


Figure 44-VIPR Bleed Air Data for Nominal Contamination Rate of 4 ppm

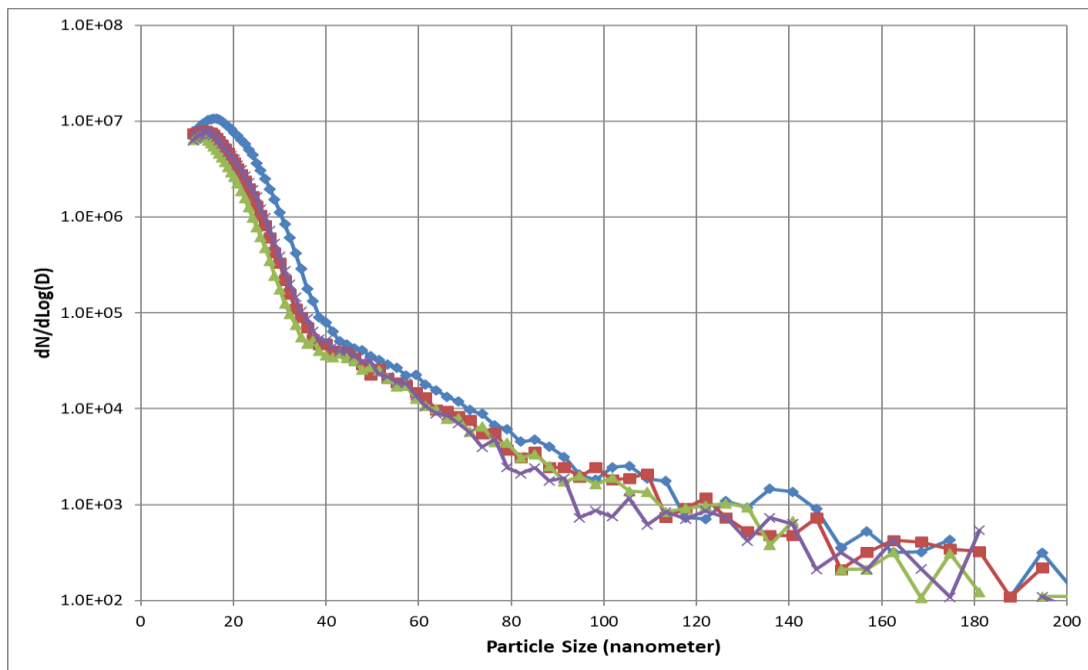


Figure 45-VIPR Bleed Air Data for Nominal Contamination Rate of 5 ppm

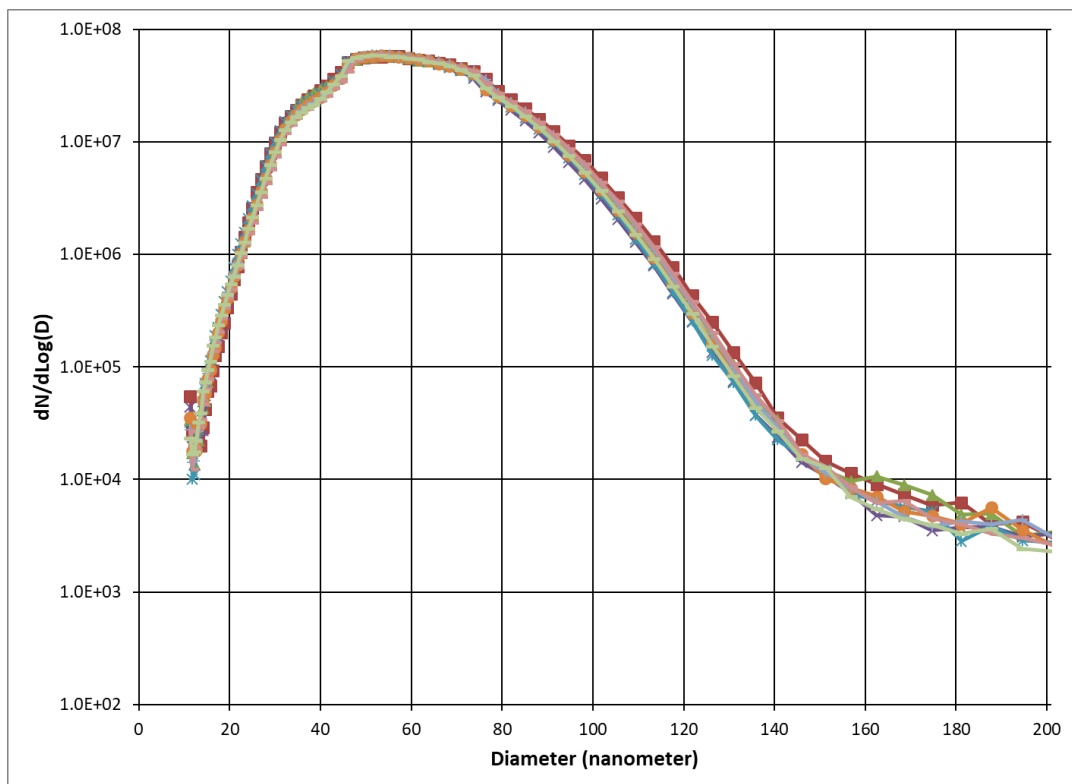


Figure 46-VIPR Bleed Air Data for Nominal Contamination Rate of 8 ppm

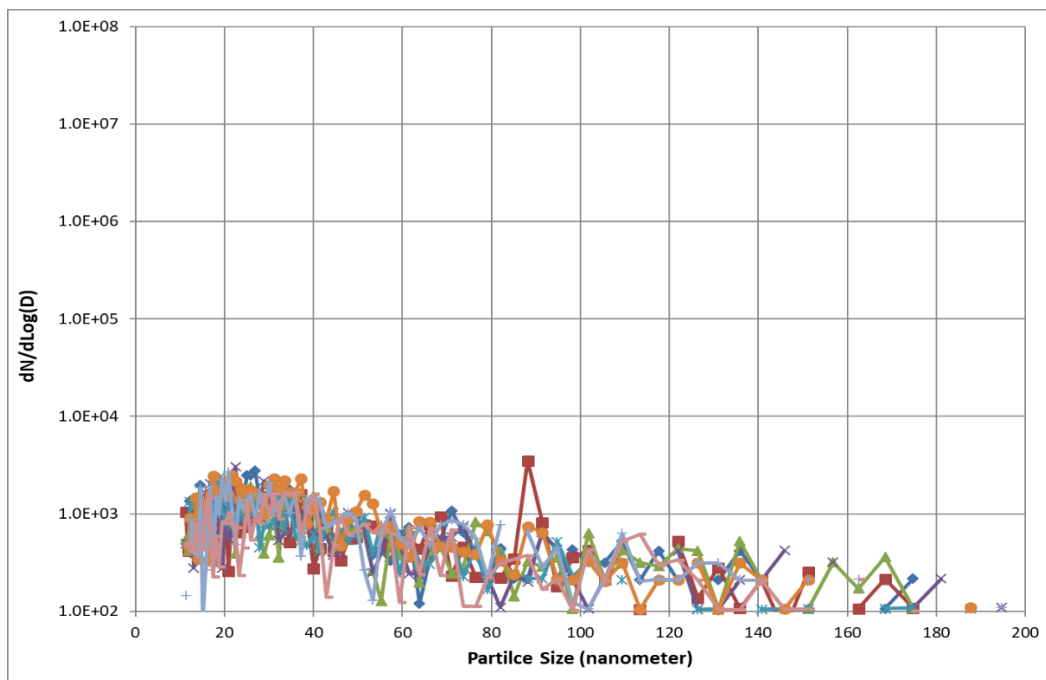


Figure 47-VIPR Bleed Air Data for Contamination Rate of 0 ppm

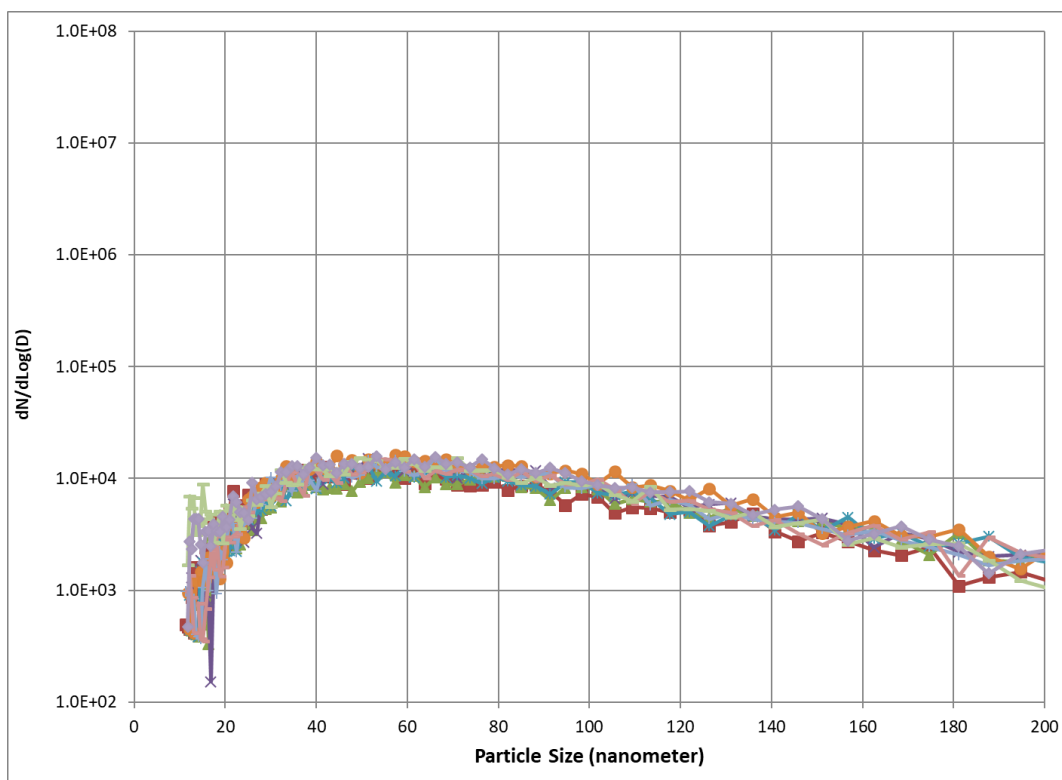


Figure 48-VIPR Ambient Air Data

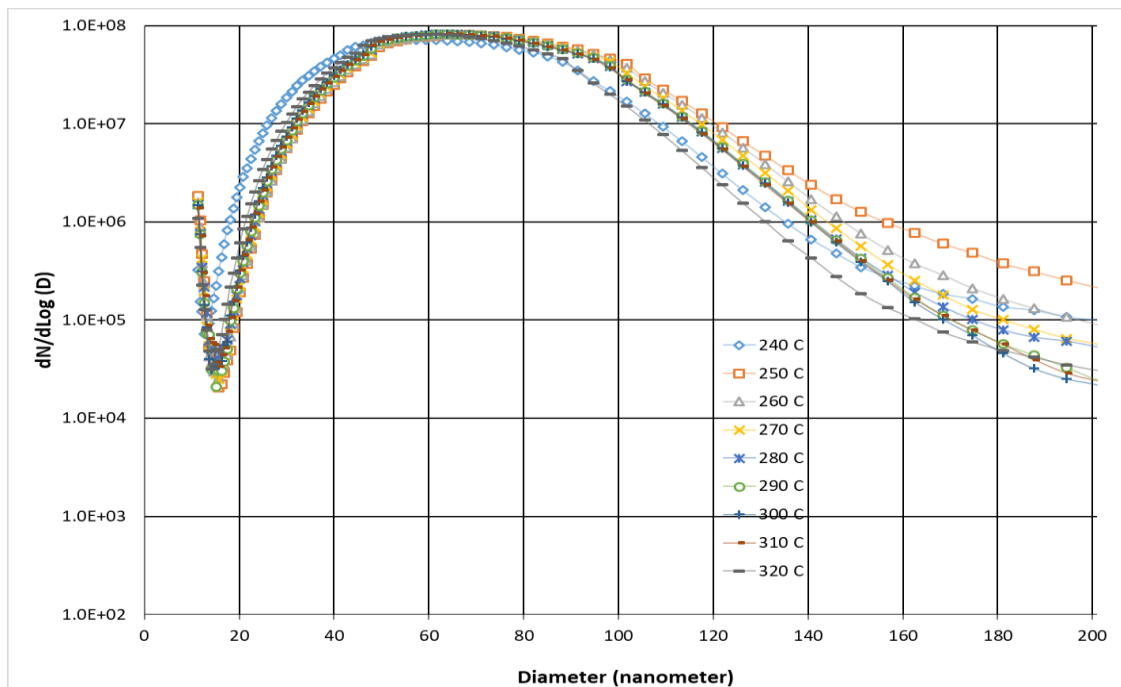


Figure 49-Allison 250 C28B Engine Data at Nominal Contamination Rate of 12 ppm

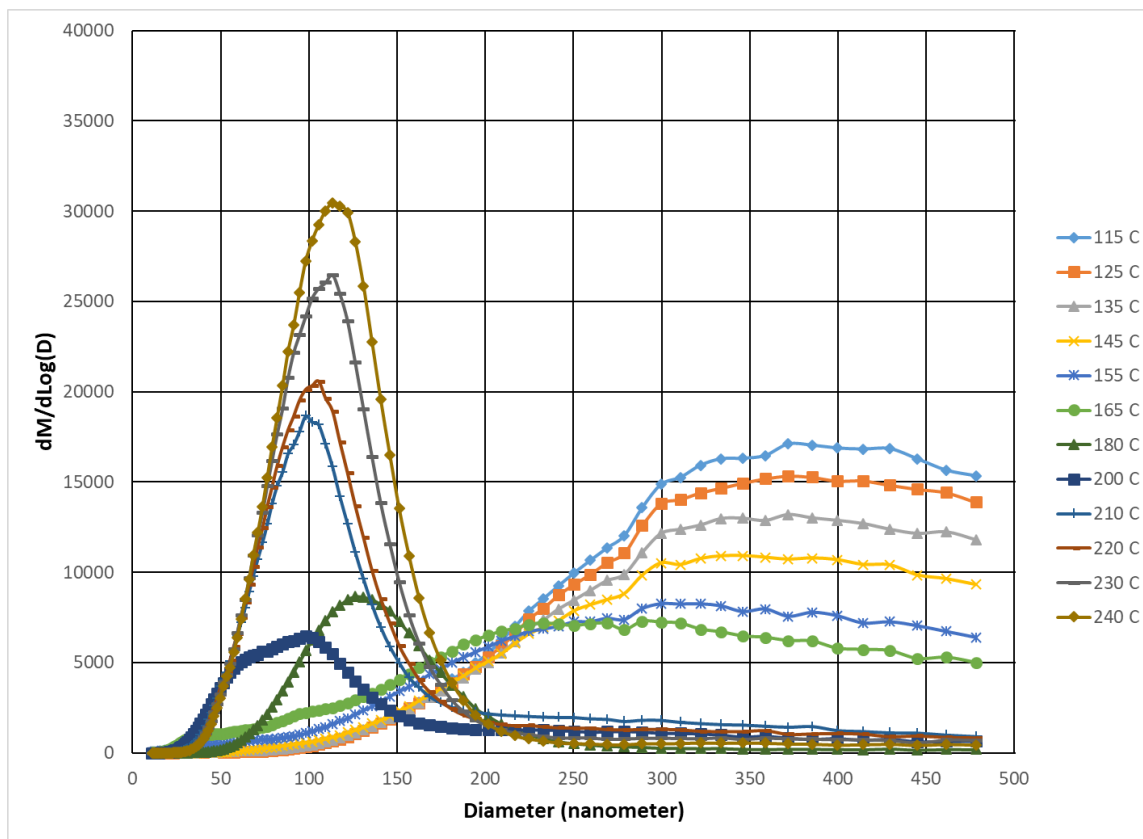


Figure 50-Allison 250 C18 Engine Data at Nominal Contamination Rate of 12 ppm

Reproduced from (Amiri, 2018) with permission

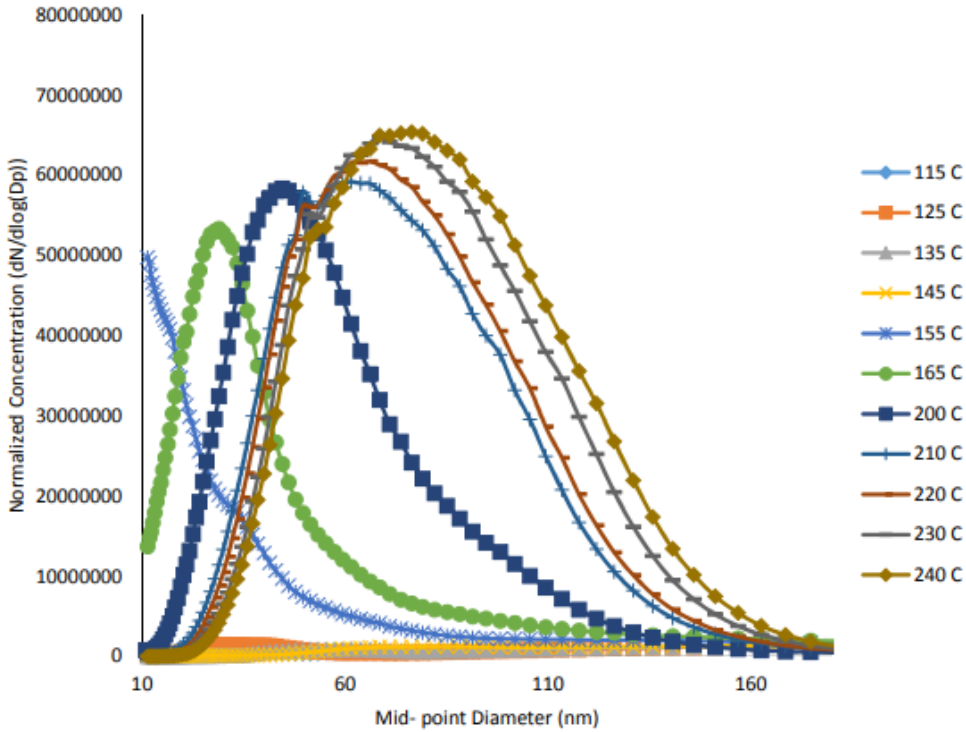


Figure 51-Distribution number of particles with respect to particle diameter for C18 engine

Reproduced from (Amiri, 2018) with permission

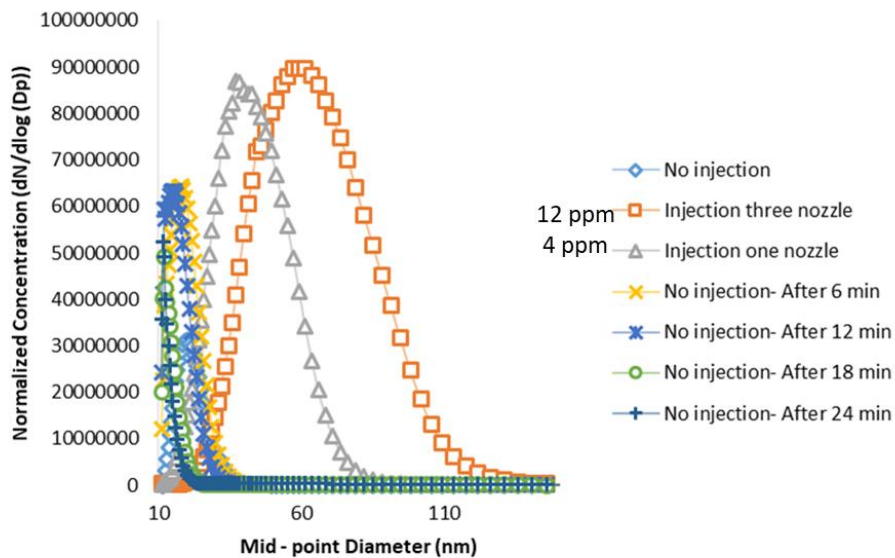


Figure 52-Allison 250 C28B Engine Data Showing Effect of Contamination Rate

Reproduced from (Amiri, 2018) with permission

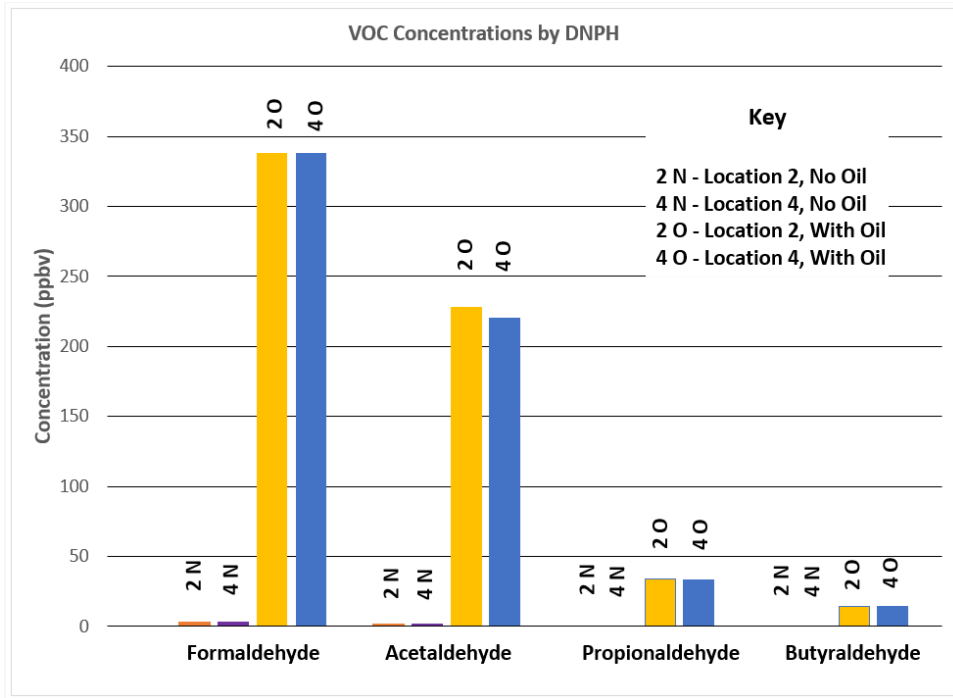


Figure 53-VIPR VOC Data at 0 and 8ppm Nominal Contamination Rates

Data from (Space et al., 2015)

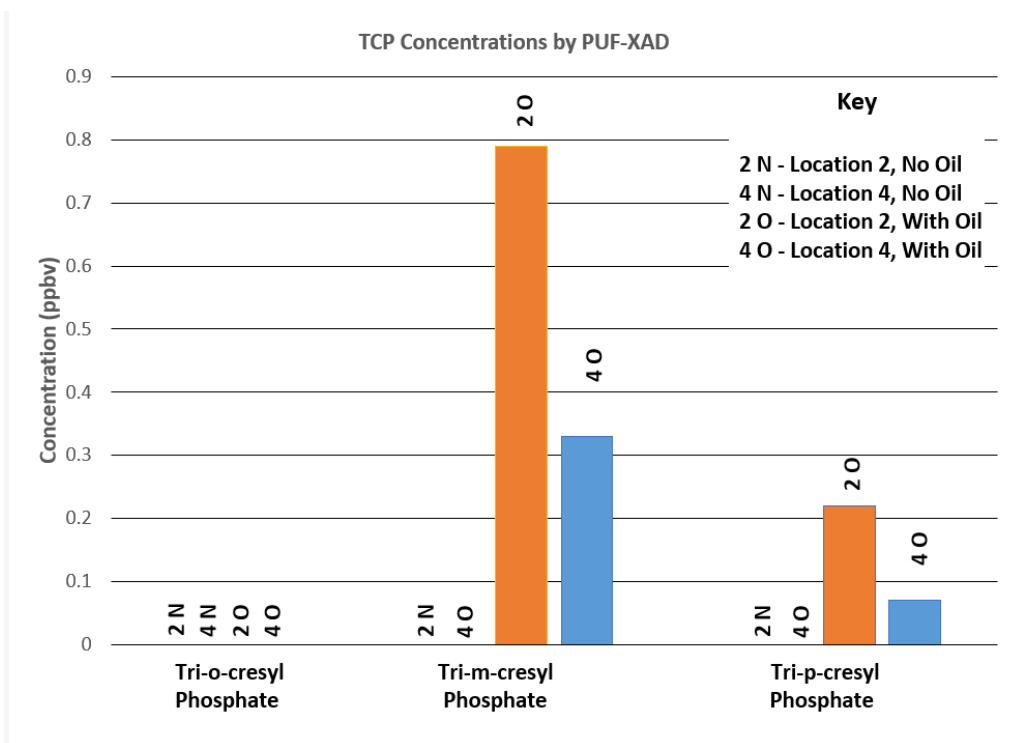


Figure 54-VIPR Tri-Cresyl Phosphate Data at 0 and 8ppm Nominal Contamination Rates

Data from (Space et al., 2015)

12. VIPR Results/Conclusions

Table 20 summarizes the results for the real time sensors for the C-17 VIPR experiments. All numbers except the particle data were obtained by reading from graphs so accuracy may not be as optimal as the numbers would suggest otherwise. The particle data are two dimensional in that both number and size distribution are measured. Figures 44-46 show size distributions for each of the contamination levels. For comparison, Figure 47 presents bleed air data with no oil contamination and Figure 48 presents an example of ambient air data. Note that all graphs are plotted on the same scale and the vertical axis is logarithmic; each gridline represents an increase by an order of magnitude. Numerous experiments were conducted on the KSU Allison 250 engines. While these engines, as compared to the VIPR C-17 aircraft engine, are quite different in both size and configuration, these data may provide some useful insights into the particle generation phenomena that will be useful for large aircraft engines. Several relevant graphs are shown. It should be mentioned that the Allison engine facility was constructed prior to the VIPR C17 data being collected and the contamination injection rates for VIPR were not known. Luckily, the contamination rates ended up being similar. Figure 49 shows bleed air data for a range of bleed air temperatures. Bleed air temperature is controlled on this engine by adjusting speed, so this figure is also presenting the effect of engine speed which is miniscule. It also shows concentrations and sizes are similar to those measured on the C17 engine. Figure 50 presents the rest of the story. This figure shows mass concentration, not number concentration. It shows that below a certain bleed air temperature (engine speed) there is a huge shift in particle size and the size observed in the bleed air is similar to the size that is injected into the inlet air stream. Finally, Figure 52 shows the effect of contamination injection rate in this engine, and it is considerably different than the results seen for the C17 engine. Figure 5 further shows that increasing temperature increases particle concentration and particle size.

The VOC data and the tricresyl phosphate data were collected both for baseline conditions and for the 8 ppm nominal contamination rate. These data are presented in Figures 53 and 54. At the 8 ppm nominal contamination rate, the total concentration is over 10,000 times greater than the no contamination case. On a mass basis the ratio is slightly less but still nearly 10,000 times greater. At the minimum nominal contaminant rate evaluated, 4 ppm, the ratio to the no contamination case is 100 for particle numbers and 10 for particle mass. This huge signal to background ratio shows that particle measurement is a promising marker if appropriate sensors are available. The sophisticated, laboratory grade instruments used in this project are not suitable for routine aircraft applications. Additionally, there are some questions regarding the particulate data. The highly non-linear response regarding contamination rate is not explained. The Allison 250 data do not have similar characteristics. While the size gets smaller at lower contamination rates in both cases, the shift is not nearly as large for the Allison engine as for the C-17 engine. More specifically, the number concentration did not decrease markedly for the Allison data, the size just got smaller, and the mass decreased relatively in proportion to the change in contamination rate. It's a possibility that the size shift is merely much larger with the C-17 engine and the bulk of the particles are below the measurement range. It is challenging to explain the big decrease in mass nonetheless. These data, thereby leave some question as to the lower detection limit with particulate measurements and the nature of the particles that will be present.

Also, the Allison 250 data show that the particle generating phenomena are dependent on engine speed which may have some implications for detection at engine idle conditions. At low speed, the particle size distribution reflected the distribution of the injected aerosol. The nature of the aerosol generated by an actual engine leak or ingestion event is not known, and therefore brings some questions regarding the nature of the aerosol that would need to be detected at low engine speeds. Finally, the VIPR C-17 data and the Allison 250 data collected in that study only included Mobil Jet Oil II contamination. There is no valid reason for applying these results to other fluids, especially to hydraulic fluid and deicing fluid which have very different composition and physical characteristics.

The other real time chemical measurements for the VIPR C-17 aircraft engine, CO and TVOC, both responded to the nominal contamination rates shown in Table 20. CO responded noticeably more than TVOC. Both clearly responded to the 4 ppm nominal contamination rate but their suitability as primary markers was questionable, but ASHRAE 1830-RP revealed CO to likely be a poor marker. The assessment is relevant given the possibility of considerably higher background levels, especially on the ground, in many locations. Compared to many urban airport environments, the Edwards Air Force Base in the high Mojave Desert is pristine. Also, the potential background levels of these parameters in the cabin would prevent their use at any locations not upstream of the mix manifold. The data collected by sampling and laboratory analysis show specific VOCs may have good potential for oil detection if suitable real time sensors are available. As shown in Figure 53, both formaldehyde and acetaldehyde have essentially zero background and significant concentrations with the 8 ppm contamination rate. Also, comparison of the concentrations measured to the TVOC levels show they are the major component of the TVOC increase seen. While the background levels seen in this experiment are very low, some assessment of the background in the aircraft operational environments needs to be conducted. Also, if cabin or mix manifold measurement locations are to be considered, the background levels in the cabin would need to be examined. The Aerotracer also responded to the oil contamination and gave a real time odor indication as shown in Table 20. Even though the odor indication was recorded continuously and there was considerable variation at any given contaminant level, it still responded with a clear major increase in the odor indication even at the lowest contamination rate tested and the indication increased with increasing contamination rate practically reaching the upper end of the odor scale at the highest contamination rate. The individual sensors within the Aerotracer were also monitored in real time. These individual sensors had a response that, qualitatively appeared to have a temporal response similar to the CO and TVOC sensors. It is unknown what each individual sensor was detecting or how that information is combined to obtain an odor rating. To the extent that the odor rating is accurate, the Aerotracer results show that, even with a nominal contamination rate of 4 ppm, the resulting “air quality event” would yield a strong and noticeable odor. The 8 ppm nominal contamination rate would yield a very strong odor and would certainly be a significant event.

13. Assessment of particles as potential markers for bleed air contamination

The VIPR Study and ASHRAE 1830-RP project clearly showed particles to be good markers for hydraulic fluid and engine oil but not for deicing fluid. Different parties were involved for these studies, but the main objective of KSU for these studies in particular was to characterize the number and size distribution of particulates in the bleed air with different contamination rates of oil, hydraulic fluid, and deicing fluid to further assess the ability to use particulate measurements as a means of detecting contamination by each contaminant. It is also important to understand particulate behavior based on bleed air temperature and engine configuration for engine oil. Based on Figure 51, the number of particles increases with temperature (engine speed). Furthermore, from 145°C to 155°C, there was a huge increase in the number of particles. However, after 155°C, the increase in the number of particles is small. This may be due to the fact that the maximum bleed air temperature of the C18 engine is lower than the charring point of the engine oil (Mobil Jet II) temperature (Amiri, 2018). Clearly, both temperature and pressure in a turbine engine compressor increase together with engine speed and engine power. An important thing to note is the phenomenon observed in Figure 50 that was mentioned earlier from Figure 11 in ASHRAE 1830-RP. Figure 50 shows that at lower temperatures (engine speeds) (from 115°C to 165°C), the mass is located in bigger particles and then, as the temperature (engine speed) increases, the larger particles appear to be sheared into smaller pieces (Amiri, 2018).

The VIPR experiment also included the Allison 250 C28B engine as mentioned previously. This was useful not only in that it could effectively be compared to the C18 engine, but that it could generate bleed air pressures and corresponding temperatures in the range that is typical of large aircraft engines, like the C-17 aircraft. (Amiri, 2018) found that the C28B data show that additional increases in temperature (engine speed) beyond 240°C have only a minimal effect on the size particles generated. Figure 51 for the C18 engine on the other hand, shows that particle size and concentration distribution markedly increase as temperature increases from 115°C to 240°C. Therefore, moderately high contamination rates at elevated power levels (high bleed air temperature) will result in little variation in concentration distribution and particle size. Based on the particulate data results of VIPR and ASHRAE 1830-RP, concentration and particle size generally depends on the rate of contamination of engine oil. Moreover, at elevated power levels, the peak particle concentration tends to be considerably less than 100 nanometers for the particulate data and the bulk of particles form at less than 100 nanometers as well. Ultrafine particles can also be generated in the size of 10 nanometers or less for low contamination rates. This was also observed in ASHRAE 1830-RP and VIPR when closely examining the engine oil particulate data. Therefore, detection may be required for a range of sizes ranging from roughly 100 nanometers to 10 nanometers. It is imperative to utilize particle measuring technology that is optimal for very small particles typically in the range of 10-100 nanometers and likely lower for low contamination rates. Traditional optical counters do not work well in this size range. Condensation particle counters work well in this size range but may not be ideal for routine aircraft applications as they require a reservoir of fluid for the saturation process that needs regular servicing. A technology that may be worth considering would be ionization particle sensing devices. Despite the potential limitations in technology, particles are still a very good marker for

engine oil. This can certainly be seen from Figure 32 from the QTRAK for 0.5 micron and 0.3-micron particles from Jet II oil contamination. Ultrafine particles are also especially good markers for engine oil as seen from the SMPS engine oil data.

ASHRAE 1830-RP is more extensive than VIPR in that it evaluated deicing fluid and hydraulic fluid contaminants in addition to engine oil. Eastman 2197 oil and 2389 oil was also tested in addition to Mobil jet II oil. Hydraulic fluid particle data was fairly promising for the APU and C28B engines. While the bulk of particles was less than 150 nanometers for the SMPS APU hydraulic fluid data, the SMPS data for the APU and Allison 250 showed the concentration of ultrafine particles to be somewhat low. However, the opposite was seen for the APS APU and Allison 250 data for fine particles. Furthermore, PE-5 and LD-4 responded similarly to each other. Overall, the suitability of ultrafine particles as potential markers for hydraulic fluid bleed air contamination is not very promising, but fine particles are certainly suitable markers for hydraulic fluid contamination based on the particle data presented. Furthermore, particle size may be a useful discriminator between engine oil and hydraulic fluid.

Particles were shown to be very poor markers for deicing fluid. Both fine and ultrafine particles proved to be not very promising in their suitability as potential markers for bleed air contamination. Figure 12 as an example shows the bulk of particles from type 1 and type 4 deicing fluid to be less than 150 nanometers, but both contaminants did not respond very well to even 10 ppm contamination rates. Figure 21 presents roughly the same story. Total concentration data from Figures 10, 19, 24, 25, and 26 showed low responses for deicing fluid. Figure 23 deicing fluid data on the other hand was noisy, so no meaningful data could be gathered from that particular figure.

As mentioned previously, Cranfield data were included for comparison purposes to show how data in cabin air compares to bleed air. As seen from the particle data in Cranfield, assessment of particles as potential markers is quite challenging given the background levels observed in cabin air. Passengers on the plane, boarding, deplaning, and food service contribute to the significant background levels observed in cabin air. Figures 39 and 40 illustrate this by the variation shown on both graphs, which makes it difficult use these data to identify bleed air contamination. These activities surrounding the instruments in the cabin can therefore make the characterization of any anomalous elevations in particle concentrations during any ‘fume events’ or ‘air quality events’ in normal operations during all phases of flight (e.g., climb, cruise, descent) difficult.

The results from Cranfield indicated that mean ultrafine particles on all flight sectors were always in the range 1,000-100,000 particles/cc. On five flight sectors peak concentrations exceeded the maximum range of the P-Trak ultrafine particle counter (500,000). The peak concentrations can again likely be attributed to the boarding phase and deplaning phase. The in-air portion of the flights were usually low in particulate concentration with occasional peaks, likely due to activity surrounding the instrument. Based on these observations, attempting to use particulate measurements in the cabin to identify bleed air contaminations events is probably not a viable option. Perhaps sensing upstream of the cabin in the supply air stream would yield more useful results.

14. Assessment of other potential markers of bleed air contamination

As previously stated, it is important to assess the suitability of specific VOCs, TVOCs, and formaldehyde as potential markers for bleed air contamination as there may be a range of chemicals that can be detected that may prove to be useful for detecting a bleed air contamination event. VIPR has relatively useful data for VOCs, TVOC, and formaldehyde. Figure 53 as an example presents relatively useful data for VOCs. The VIPR project showed that formaldehyde and acetaldehyde both had low levels in the bleed air without oil contamination and had clearly elevated levels with oil contamination. During day 2 of testing the BAESS, several aldehydes were detected, with formaldehyde and acetaldehyde yielding the highest concentrations as seen in Figure 53 (Space et al., 2015). Formaldehyde and acetaldehyde were present in much larger concentrations (around 325 and 225 ppb, respectively) compared to others such as butyraldehyde and propionaldehyde (Space et al., 2015). Although formaldehyde and acetaldehyde concentrations were detected at around 300 ppb, the observed levels are well below OSHA PEL and short-term limit (STEL) requirements (750 ppb and 2000 ppb, respectively for formaldehyde and 250000 ppb PEL for acetaldehyde) (OSHA 1970). Still, these concentrations of formaldehyde and acetaldehyde are still good enough to use as potential markers to foresee a potential bleed air contamination event, provided appropriate sensing technology is available. (Space et al., 2015) also found that Silonite® canisters used during BAESS day 2 of testing captured chemical compound data through the various test conditions. Acrolein and acetone were detected by the canisters at 18 and 26 ppb, respectively; these conditions are well below the OSHA PEL limits of 100 ppb and 500ppm. (Space et al., 2015). Various other compounds were detected by the Silonite® canisters, but the concentrations were in the low to sub ppb level. Again, while the concentration of acrolein and acetone may be below the limit, their concentration may be suitable to use as potential markers provided appropriate sensing technology is available. As seen in Table 20, TVOC responded to engine oil contamination but not well above background to confirm its suitability as a viable marker. Based on these observations, formaldehyde and acetaldehyde are certainly promising markers, at least for Jet II engine oil. Acrolein and acetone on the other hand, are questionable markers given their low concentration levels, but appropriate sensing technology may shed light on their suitability as markers for bleed air contamination in the future.

Toluene and limonene are also potential markers for bleed air contamination. These particular VOCs were generally observed to be the most abundant target VOC/SVOCs for the Cranfield study. The highest levels of limonene occurred during first engine start, whereas the highest levels of toluene occurred during climb, pre-landing and take-off respectively. While these levels did not exceed safety, health or comfort limits described in the European standard ‘Aircraft internal air quality standards, criteria and determination methods’, the levels can still again be used as potential markers if appropriate sensing is available. Furthermore, the Cranfield study showed that mean total VOC concentrations measured by the PID were mostly below 2 ppm. Many short duration peak concentrations above 10 ppm were probably due to exposure to isopropyl alcohol vapor generated by the p-Trak instrument (Walton et al., 2011). However, there was evidence for a rise in total VOC concentration coincident with some reported air quality events (Walton et al., 2011). This may have been from the effect of cabin conditions

(mainly pressure change) on the instrument and not from any real change in VOC levels. This assertion is further validated by the lack of any corresponding change in VOCs analyzed by TD/GC/MS. This shows that although there is difficulty analyzing data due to background noise and other factors, some events may help discern whether the data is useful or not. Proper placement of sensors in the cabin can also potentially yield more useful data. Overall, specific VOCs from sampling may prove to be useful markers for bleed air contamination, and TVOCs in general remain questionable in their suitability as markers since their response is not well above background, which would suggest that appropriate sensing technology may be needed. Although the suitability of VOCs as markers is somewhat promising for engine oil, its viability as a marker for deicing fluid and hydraulic fluid remains unknown. The same goes for formaldehyde.

CO is probably not a very reliable marker for bleed air contamination. This can certainly be observed in Cranfield and VIPR. Cranfield showed that maximum CO concentrations were mostly below 2 ppm. Peak concentrations of >3ppm were recorded on 7 flights but were not associated with reported air quality events. Table 20 from VIPR also showed CO to not respond well enough above background at all nominal contamination rates, deeming its suitability as a marker not very promising. Furthermore, CO concentrations aboard pressurized aircraft have been measured to range between <0.2 and 2.9 ppm (Waters et al., 2002). This range is certainly not ideal to utilize CO as a marker for bleed air contamination, especially given the background levels present in cabin air. Spengler et al. (2012) also collected measurements from 83 flights and determined that CO concentrations were below 1 ppm. Figure 38 from Cranfield further confirms the idea of CO not being useful as a means to detect bleed air contamination as there is hardly any response at all. Figure 29 from the QTRAK also show low responses from CO, even from engine oil contamination at high contamination rates. Overall, CO isn't a good marker for engine oil contamination, and its suitability as a marker for deicing fluid and hydraulic fluid remain unknown. Carbon dioxide is also likely a poor marker for bleed air contamination but is a useful discriminator for knowing whether particle response is from exhaust ingestion or bleed air contamination.

15. Conclusions and future work recommendations

Overall, the information presented in this thesis gives the reader insight into the fundamentals of bleed air contamination and cabin air quality. This is possible by properly identifying and measuring the representative constituents of bleed air during contaminate air events. The ASHRAE 1830-RP test results from March, November, and June indicate that ultrafine particles show a very strong response for engine oil. Furthermore, fine particles show significant responses for hydraulic fluid and engine oil. Ultrafine particles show a minimal response for hydraulic fluid. Particles of any size on the other hand, are a very poor marker for deicing fluid. ASHRAE 1830-RP also showed that CO is likely not a good marker for bleed air contamination and CO₂ is a good discriminator in determining whether a high response in particles is attributed to bleed air contamination or exhaust ingestion but probably not a reliable marker. The VIPR study showed a significant amount of contaminants that resulted from a bleed air simulator that replicates a real-life contamination event. Ultrafine particles showed a significant response, with larger responses as the contamination injection rates increased, deeming particles as a reliable marker for bleed air contamination with engine oil. VIPR data also showed that formaldehyde and acetaldehyde are potential oil contamination markers as both had low levels in the bleed air without oil contamination but had clearly elevated levels with oil contamination. The Cranfield study indicated that the TVOC data along with the numerous cases of highly elevated levels particularly during the boarding phase were informative but cumbersome since there were no apparent association with bleed air contamination that is comparable to concentrations with contamination measured in the VIPR project. The low resolution of the carbon monoxide measurements was also a limiting factor. Carbon monoxide is likely a poor marker for bleed air contamination and TVOCs still remains to be questionable indicators of oil contamination and both CO and TVOCs certainly cannot be used to detect oil contamination by measurements of the cabin air. Based on the Cranfield cabin air study, it can be concluded that ultrafine particles in the cabin are usually very low in comparison to the levels observed in contaminated bleed air. However, there are many cases of highly elevated particle concentrations in the cabin that appear to be unrelated to bleed air.

Future work should mainly focus on the investigation of testing certain sensing technologies on aerosols. A low-cost sensor that can detect air quality incidents can potentially be developed and deployed on commercial aircraft. Sensors that are well suited for submicron particles are useful, especially if they are practical for routine monitoring on aircraft. A technology that may be worth considering is the ionization sensor technology used in many common smoke detectors. These devices use a tiny radioactive source to ionize the particles in the air in an electric field. The ionized particles move in the presence of the electrical field and the more particles present, the greater the resulting current. Particles in the 10-300 nanometer respond well in these sensors and thus the technology may be practical for this application. This technology was also tested on the KSU turbine engine and proved to be a reliable indicator of oil contamination without false alarms. Furthermore, this technology is well established, is low cost, and is simple and rugged and shows great potential for bleed air contamination sensing on aircraft. Another recommendation to make would be to further examine the viability of VOCs and other chemicals as potential markers for deicing fluid. Particles have clearly been shown not

to be good markers for deicing fluid. There are insufficient data to determine whether or not VOCs or other chemicals are good markers for deicing fluid. Therefore, if determining useful markers for deicing fluid is desired, additional experimentation is needed to evaluate the response of VOCs and other real time chemical sensors to deicing fluid contamination. Lastly, an important recommendation would be to examine other sources of elevated particles other than from bleed air contamination. Bleed air particulate data to date was collected either on a test stand engine or on a stationary aircraft. Those markers that seemed promising in this environment need to be evaluated in real flight operations environments. Exhaust ingestion, for example, was observed to have resulted in elevated ultrafine particulates in the bleed air. Thus, it needs to be determined if other, non-fume event sources, will result in false indications of bleed air contamination with the markers proposed in real operating environments.

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