DOT/FAA/TC-21/45

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Aircraft Air Quality and Bleed Air Contamination Detection

May 2022

Final Report

U.S. Department of Transportation
Federal Aviation Administration

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-21/45		

4. Title and Subtitle	5. Report Date
Aircraft Air Quality and Bleed Air Contamination Detection	May 2022
	6. Performing Organization Code: ANG-E271

7. Author(s)	8. Performing Organization Report No.
Byron W. Jones	

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Kansas State University Manhattan, KS 66506	11. Contract or Grant No.: 693KA9-20-P-00033

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Federal Aviation Administration, Attn: Robert McGuire FAA William J. Hughes Technical Center, ANG-E271 Bldg 300, 2nd floor Atlantic City International Airport, NJ 08405	Final Report
	14. Sponsoring Agency Code: AIR-600

15. Supplementary Notes

16. Abstract

The purpose of this project was to provide a data-driven process to identify sensing technology with good potential for detecting bleed air contamination from engine oil, hydraulic fluid, or deicing fluid. Reports from major aircraft cabin air studies were reviewed to identify the range of constituents that can be expected in cabin air, especially as they pertain to the aforementioned contaminants and their potential markers. One of the projects was the National Aeronautics and Space Administration Vehicle Integrated Propulsion Research (NASA-VIPR) project where controlled amounts of engine oil were injected into the engine compressor of a C-17 transport aircraft and the resulting contaminants in the bleed air measured. Three additional cabin air quality studies conducted on revenue flights were reviewed. These three studies provide data for a combined total of 249 flights on a variety of makes and models of aircraft. These studies provide adequate documentation of typical aircraft cabin air. Information from this review was used to identify potential markers of the bleed air contaminants. Additionally, collaboration was established with several technical committees from the Society of Automotive Engineers (SAE), American Society of Heating, Air-Conditioning and Refrigerating Engineers (ASHRAE), and American Society for Testing and Materials (ASTM) and with project personnel from the prior European Union Aviation Safety Administration (EASA)-funded cabin air study. Key objectives of the project were to identify sensors and sensing technology with potential for detection of one or more of the three aforementioned bleed air contaminants and to develop a plan for test stand engine experiments to evaluate the sensors with controlled amounts of the three contaminants. Sensors and instruments were identified and a test plan was developed. Additionally, through the collaboration with ASHRAE 1830 and the support of the industry working group, many of the experiments identified in the test plan were completed. The analysis of the data from these experiments is ongoing and will be reported in the ASHRAE 1830 project report. However, preliminary assessment of the sensing technology has been possible.

17. Key Words	18. Distribution Statement
Bleed Air, Contaminants, Cabin Air, Measurements	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	164	

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Acronyms

Acronym	Definition
ACER	Airliner Cabin Environment Research
ACES	Aircraft Cabin Environment Sensor
APU	Auxiliary Power Unit
APS	Aerodynamic Particle Sizer
ASHRAE	American Society of Heating, Air-Conditioning and Refrigerating Engineers
ASHRAE 1830-RP	An ASHRAE-funded research project entitled "Experiment Characterization of Aircraft Bleed Air Particulate Contamination"
ASTM	American Society for Testing and Materials
CAQM	Cabin Air Quality Monitor
CMOS	Ceramic Metal Oxide Sensor
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPC	Condensation Particle Counter
CRDS	Cavity Ring Down Spectroscopy
DMA	Differential Mobility Analysis
EASA	European Union Aviation Safety Administration
ECS	Environmental Control System
FAA	Federal Aviation Administration
FACTS	Aircraft Cabin Air Quality Projected Funded by EASA
HEPA	High Efficiency Particulate Air, with regard to air filters
HOT	Hold Over Time, time for which protection exists after deicing
IMS	Ion Mobility Spectroscopy
KSU	Kansas State University
mb	millibar
MIRL	Mid-Infrared Laser
MOS	Metal Oxide Sensor
NASA	National Aeronautics and Space Administration
NDIR	Non-Dispersive Infrared
OPC	Organophosphate compound
PID	Photo-ionization Detector
$PM_{1.0}$	Fine particles with an aerodynamic diameter of 1.0 μm (1000nm) and smaller
$PM_{2.5}$	Fine particles with an aerodynamic diameter of 2.5 μm and smaller
PMS	Project Monitoring Subcommittee
ppb	parts per billion

ppm	parts per million
pt	particles
RITE	Research in the Intermodal Transport Environment
SAE	SAE International, formerly, Society of Automotive Engineers
SAE E31B	SAE International Bleed Air Committee which is developing standards for measurement of bleed air contaminants
SIFT-MS	Selected Ion Flow Tube - Mass Spectrometer
SMPS	Scanning Mobility Particle Sizer
SVOC	Semi-volatile organic compounds
TCP	Tri-cresyl Phosphate
TILDAS	Tunable Infrared Laser Direct Absorption Spectroscopy
TOF-PTR-MS	Time of Flight - Proton Transfer Reaction Mass Spectroscopy
TVOC	Total Volatile Organic Compounds
UFP	Ultrafine Particles
UK	United Kingdom
USAF	United States Air Force
UV	Ultraviolet
VIPR	Vehicle Integrated Propulsion Research
VIPR3	Phase 3 of the VIPR program which included bleed air contamination experiments
VOC	Volatile organic compound

Executive summary

The purpose of this project was to provide a data-driven process to identify sensing technology with good potential for detecting bleed air contamination from engine oil, hydraulic fluid, or deicing fluid. Reports from major aircraft cabin-air studies were reviewed to identify the range of constituents that can be expected in cabin air, especially as they pertain to the aforementioned contaminants and their potential markers. One of the projects was the National Aeronautics and Space Administration Vehicle Integrated Propulsion Research (NASA-VIPR) project where controlled amounts of engine oil were injected into the engine compressor of a C-17 transport aircraft and the resulting contaminants in the bleed air measured. Three additional cabin-air quality studies conducted on revenue flights were reviewed. These three studies provide data for 249 flights on a variety of makes and models of aircraft. These studies provide adequate documentation of typical aircraft cabin air. Information from this review was used to identify potential markers of the bleed air contaminants. Additionally, collaboration was established with several technical committees from the Society of Automotive Engineers (SAE), American Society of Heating, Air-Conditioning and Refrigerating Engineers (ASHRAE), and American Society for Testing and Materials (ASTM) and with project personnel from the prior European Union Aviation Safety Administration (EASA)-funded cabin air study. There was extensive interaction with SAE E31b and a formal collaboration agreement was established between ASHRAE research project 1830-RP and Kansas State University. Two industry webinars were held to obtain industry input and participation in the industry-working group that was formed. Key objectives of the project were to identify sensors and sensing technology with potential for detection of one or more of the three aforementioned bleed air contaminants and to develop a plan for test stand engine experiments to evaluate the sensors with controlled amounts of the three contaminants. Sensors and instruments were identified and a test plan was developed. The detailed plan describing contaminants, rates, and operating conditions is presented in Section 4.11 of this report and instruments recommended for testing are described in Section 5.2. Additionally, through the collaboration with ASHRAE 1830 and the support of the industry-working group, many of the experiments identified in the test plan were completed. The analysis of the data from these experiments is ongoing and will be reported in the ASHRAE 1830 project report. However, preliminary assessment of the sensing technology has been possible.

1 Assessment of the current state of knowledge

1.1 Introduction

The objective of this task was to review three major aircraft air-quality studies:

1. ASHRAE Research Project 1262-RP, Relate Air Quality and Other Factors to Comfort and Health Symptoms Reported by Passengers and Crew on Commercial Transport Aircraft (Jones, Roth, Madden, & Hosni, 2015) (Nagda, Rector, Li, & Hunt, 2001)
2. EASA_REP_RESHA_2014-4, CAQ, Preliminary Cabin Air Quality Measurement Campaign (National Research Council, 2002)
3. USAF/NASA/FAA VIPR, Aircraft Bleed Air Study ([Unpublished data files from the VIPR3 project]) ([Unpublished data ASHRAE 1262-RP Database]) (Amiri, 2018) (Amiri & Jones, in press)

These projects are referred to as the ASHRAE 1262 Project, the EASA Project, and the VIPR project respectively. Additionally, at least one other relevant project and other data sources were reviewed. All of these projects were large, complex projects and it was necessary to focus the review to those aspects relevant to the current project addressing Section 326 of the FAA Reauthorization Act of 2018. Specifically, the current project addresses bleed air contamination from engine oil, hydraulic fluid, and deicing fluid and the detection of this contamination. These studies can support the current FAA project in several important ways.

1. Provide data about the substances and their concentrations that can be expected to result from this contamination. These data are needed for both substances that may be harmful to aircraft occupants and substances that may be used as markers of specific contamination. It is important to determine not only what substances are present but also what concentrations will need to be measured so appropriate sensing methods can be identified.
2. Data are needed for background concentrations in the cabin during normal operation when no bleed air contamination is present. These data are needed for substances that would be used for detection so that the potential for in-cabin sensing can be evaluated. It should be noted that bleed air contamination detection could potentially take place anywhere from the bleed air manifold on the engine (or equivalent on an auxiliary power unit (APU)) to the cabin. However, locations in the cabin are the most convenient.

3. Bleed air contamination detection has two potential functions. The primary function is to detect the presence of contamination. If the presence of contamination can be detected, it can be addressed appropriately. The secondary function is to assure the lack of contamination. In the latter role, it is necessary to know the concentrations of a wide range of substances associated with contamination and the corresponding background levels in the cabin. If the levels of potentially harmful substances in the bleed air are low compared to background levels in the cabin, then the bleed air contamination is not a concern. Data on potentially harmful substances in bleed air and their background levels in aircraft cabins are needed to make this determination.

These projects were reviewed from this perspective. Other potential sources of data that should be included in the review were assessed from the same perspective.

Ongoing activities such as ASHRAE 1830-RP "Experiment Characterization of Aircraft Bleed Air Particulate Contamination" and SAE E31B "Aircraft Engine Gas and Particulate Emissions Measurement Bleed Air Subcommittee" are expected to provide useful information in this regard but are not included in this review given in this section. These activities are addressed in later sections of this report.

Similarly, sensors for detecting the substances are not addressed here as they are also addressed in later sections of this report.

Early on in the project, the UK Department of Transportation "Cabin Air Sampling Study" conducted by Cranfield University and referred to herein as the "Cranfield Project" was identified as an additional relevant study. It is somewhat narrower in measurement scope than the two above cabin air studies but was extensive in that it conducted measurements on 100 flights (Crump, Harrison, & Walton, 2011), (Crump, Harrison, & Walton, 2011). Thus, it adds useful breadth to the above studies and is therefore included in this review.

Between these three cabin air projects, ASHRAE 1262-RP, the EASA Project, and the Cranfield Project, it is believed that background cabin-air conditions are well documented in the literature.

The VIPR Project is the only one of the above studies that provides information on substances in bleed air and it was somewhat limited in scope. While a sizable number of substances resulting from the contamination were evaluated, the results apply to a limited range of operating conditions and a single contaminant (Mobil Jet Oil II) in the engine (Jones, Roth, Madden, & Hosni, 2015). Thus, additional sources of information that could give insights into what substances and their concentrations that are or could be present because of bleed air contamination are needed.

Additional sources of information about bleed air contamination for engine oil, hydraulic fluid, and deicing fluid will continue to be sought. To this end, an industry database of thermal decomposition products that result from heating a variety of engine oils as well as hydraulic fluid and deicing fluid was identified. The confidentiality restrictions associated with these data are not 100% clear and are still in the process of being resolved. Thus, only a broad overview of the data can be included in the current review, but it is considered an important source of information for the current FAA project.

The remainder of this review is divided into six sections, one for each of the major studies and sources of information described above and then a brief overarching summary and conclusions section. The review of the four major studies are all organized in the same format for ease of comparison: brief description of the project, description of the measurements taken, an overview of the results, and an assessment of what can be learned from the data with regard to the present Federal Aviation Administration (FAA) project.[1]

1.2 VIPR project

1.2.1 Overview of the VIPR project

The NASA-VIPR program was a large, multi-agency, multi-year program. (Overfelt, et al., 2015), (Jones, Roth, Madden, & Hosni, 2015), (Space, Salgar, Scheer, Jones, & Amiri, 2017), (Roth, 2015), (Amiri, 2018), (Amiri & Jones, in press), ([Unpublished data files from the VIPR3 project]). The overall project focused on sensors and measurements for engine health monitoring. The VIPR Bleed Air Project was just one component of the much larger program. The VIPR Bleed Air Project was just one component of the much larger program. Participants in the Bleed Air Project included NASA, the U.S. Air Force, the FAA, Pratt & Whitney, Boeing, and Makel Engineering with Boeing serving as the technical lead for the project. RITE-ACER universities participated through the FAA. RITE-ACER universities Auburn University, Kansas State University (KSU), and Boise State University developed instrumentation and other equipment for the experiments. The actual measurements were conducted on June 8 - 9, 2015. The experiments were conducted on a United States Air Force (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 1, where

[1] The term "present FAA project" used throughout this report refers to the Aircraft Air Quality and Bleed Air Contamination Detection project for which this report is prepared.

the bleed air 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.

(a) (b) (c)

Figure 1. (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

As part of the FAA sponsored work for VIPR, additional experiments were conducted at KSU using Allison 250 C-18 and Allison 250 C28B engines. Figure 2 displays the test facility. 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 evaluate measurement methods prior to the C-17 experiments. The Allison engines were utilized by KSU and Boeing.

Figure 2. Allison 250 C28B engine test facility

1.2.2 Data collected during the VIPR research

For the C-17 experiments, there were two sets of experiments conducted ([Unpublished data files from the VIPR3 project]), ([Unpublished data ASHRAE 1262-RP Database]). On the first day, the plan was to step through injection rates starting at 200 g/hour (7.1 oz_m/hr) with increasing steps to 1200 g/hr (42.3 oz_m/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 unanticipated transport lag in filling the injection line and, as a result, oil did not reach the engine prior to the 600 g/hr (21.2 oz_m/hr) injection rate. Thus, the lower injection rates were not evaluated. Second, the injection nozzle plugged after the 800 g/hr (28.2 oz_m/hr) injection rate. Thus, only two conditions were evaluated. The primary purpose of the experiments this first day were to collect data to determine the appropriate rate for the second day of experiments. Adequate data were collected for that purpose.

On the second day, all experiments were conducted either with no injection or with 1200 g/hr (42.3 oz_m/hr) injection. Part of the test plan was to test air-cleaning technology and experiments

were repeated with different air-cleaning technologies. The results of the air cleaning are not addressed in this report. The test conditions with the 1200 g/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 g/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 airflow was used to calculate mass flow of oil injected:

- Engine core airflow: estimated 100 lb/s (45.4 kg/s)

Mobil Jet Oil II was the injected fluid for all experiments. Mobil Jet Oil II has a specific gravity of 1.003 per the manufacturer's product literature. Using this information, the concentration of the oil in the compressor air is as shown in Table 1. 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.

Table 1. Oil concentrations in compressor air at different injection rates for VIPR data

Injection Rate g/hr (oz_m/hr)	**Oil Concentration ppm by mass**	**Nominal Contamination Rate ppm**
600 (21.2)	3.9	4
800 (28.2)	5.1	5
1200 (42.3)	7.7	8

A variety of measurement methods were employed for the C-17 experiments. Table 2 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.

Table 2. Real time sensing for C-17 experiments

Parameter	**Instrument**	**Additional Information**
Carbon Monoxide	Alphasense CO-B4 Makel CoMS-BMS	Alpha: Lower detection limit 20 ppb Makel: High temperature requirement

Parameter	Instrument	Additional Information
TVOC	Honeywell ppbRAE 3000 Makel CoMS-BMS	Makel: High temperature requirement
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	Aerotracer	In addition to odor indication, the response of individual sensors was recorded

Samples were collected using a variety of techniques for later laboratory analysis. These measurement techniques are summarized in Table 3.

Table 3. Sampling techniques used in C-17 experiments

Sampling Technique	Application
DNPH Tubes	aldehydes
PUF/XAD Cartridges	Compounds associated with engine oil, semi-volatile compounds
Markes Tubes (Tenax)	Low to mid-range-semi-VOC
Summa Canisters	VOCs and thermal breakdown products

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. Some samples were collected for laboratory analysis but the data were never put into a database and are not published. 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 -1.5 kg/s (2.2-3.3 lb/s) range for the experiments. he levels of oil injection used were nominal levels of 20, 40, and 60 g/hour (0.71, 1.41 and 2.12 oz_m/hr). As a result, roughly, the nominal oil concentrations were 4, 8, and 12 ppm by mass.

1.2.3 Results from the VIPR project

The data summarized here are based on the data that have been published in the open literature or that have been otherwise approved for release ([Unpublished data files from the VIPR3 project]). Much of the data resulting from the laboratory analyses has not been published.

Table 4 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 good as the numbers would imply. The particle data are two-dimensional in that both number and size distribution are measured. Figure 3-5 show size distributions for each of the contamination levels. For comparison, Figure 6 presents bleed air data with no oil contamination and Figure 7 presents an example result for 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 ([Unpublished data files from the VIPR3 project]).

Table 4. Response of real time sensors in C-17 experiments

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	$0.9x10^3 – 1.5x10^3$ #/cm^3
	4	$0.9x10^5$ #/cm^3
	6	$2.2x10^6$ #/cm^3
	8	$1.8x10^7$ #/cm^3
Particle Mass	0	0.17-0.40 μg/m^3
	4	2.4 μg/m^3
	6	7.4 μg/m^3
	8	2600 μg/m^3
Odor	0	1.0 – 1.8
	4	3.7-7.0
	6	5.8 – 7.0
	8	5.9 – 7.0

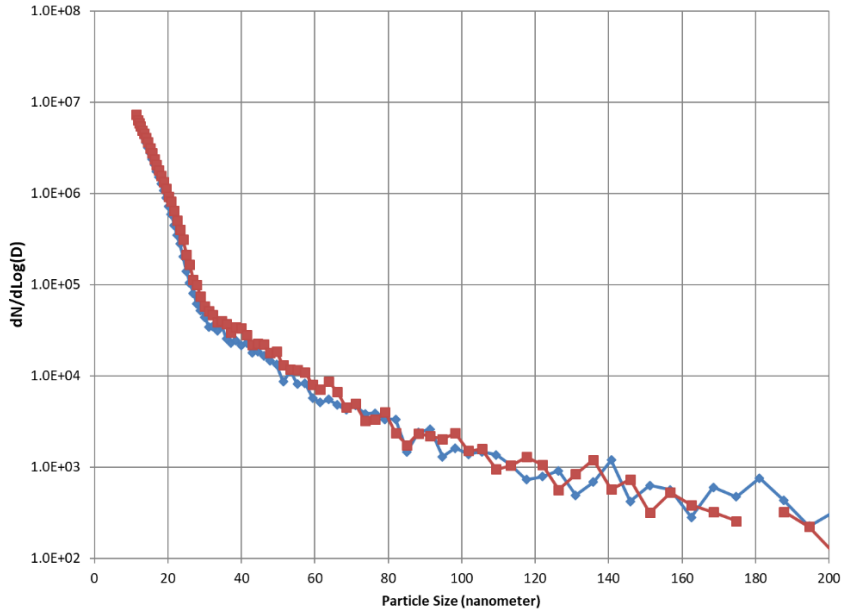

Figure 3. VIPR bleed air data for nominal contamination rate of 4 ppm

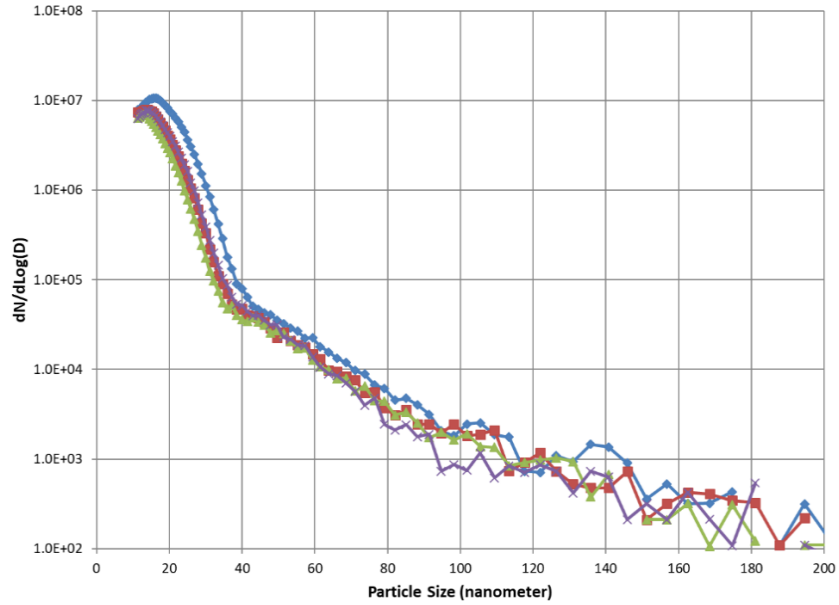

Figure 4. VIPR bleed air data for nominal contamination rate of 5 ppm

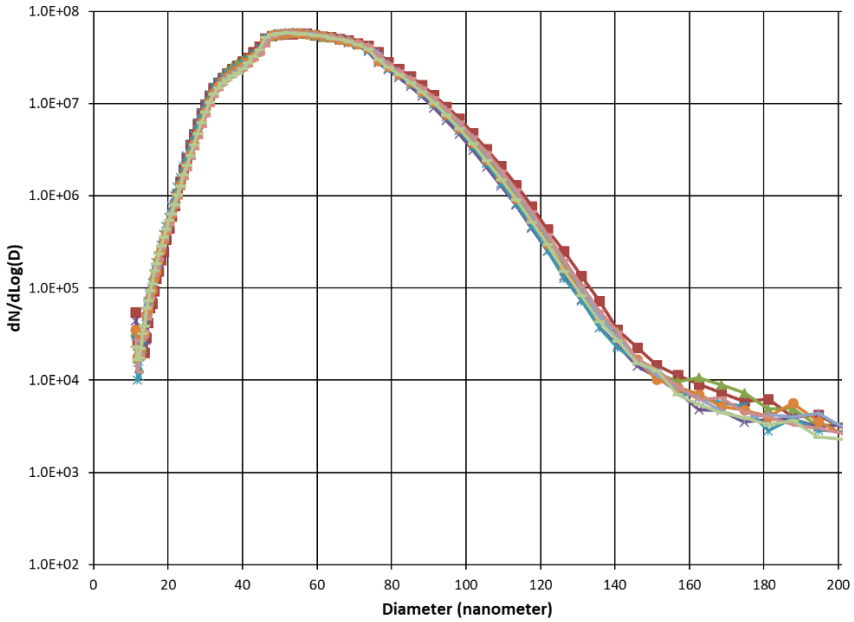

Figure 5. VIPR bleed air data for nominal contamination rate of 8 ppm

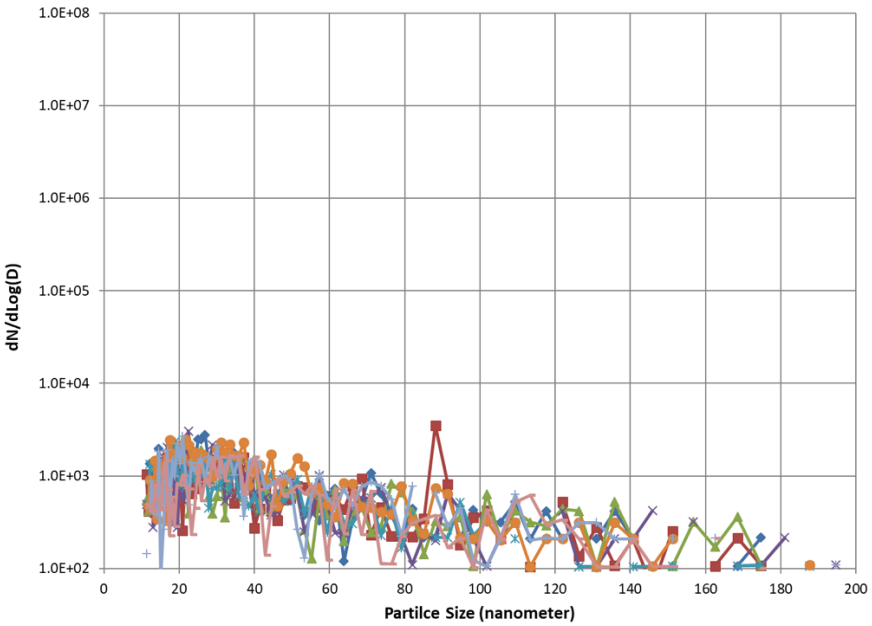

Figure 6. VIPR bleed air data for contamination rate of 0 ppm

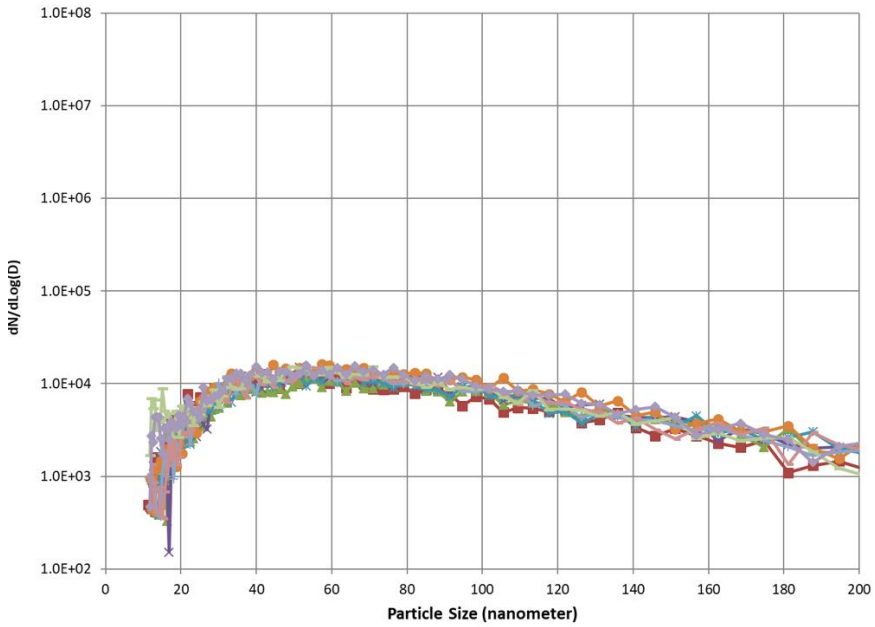

Figure 7. VIPR ambient air data

A large number of experiments were conducted on the KSU Allison 250 engines. While the 250 engines are considerably different in both size and configuration from the F117/PW2000 on the C-17 aircraft, these data may provide some useful insights into the particle generation phenomena that will be relevant for large aircraft engines. Several particularly relevant graphs are presented. It should be noted that the Allison engine facility was constructed before the VIPR

C17 data were collected and the contamination injection rates for VIPR were not known. It is a primarily good fortune that the contamination rates ended up being similar. Figure 7 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 also shows the effect of engine speed which is minimal. It also shows concentrations and sizes that are similar to those measured on the C17 engine. Figure 8 presents the rest of the story (Amiri, 2018). This figure shows mass concentration, not number concentration. It shows that below certain bleed air temperature (engine speed), there is a big shift in particle size, and the size seen in the bleed air is similar to the size that is injected into the inlet air stream. Figure 9 (Amiri, 2018) shows the effect of contamination injection rate in this engine and it is considerably different from the results seen for the C17 engine. Finally, Figure 10 (Amiri, 2018) shows the effect of contamination rate on the concentration and size distribution. There is a decrease in particle size with decreasing amount of oil contamination but minimal decrease in particle concentration. This figure also shows that there is a slow decay after cessation of contamination. It is speculated that these latter size distributions are representative of much lower levels of contamination.

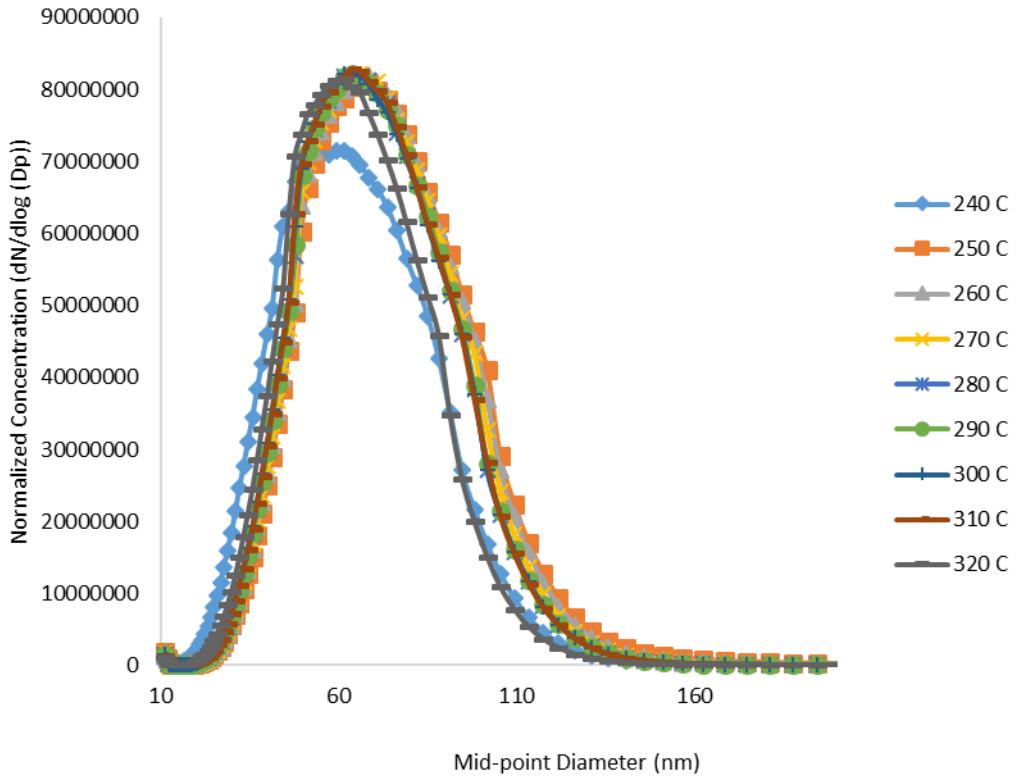

Figure 8. Allison 250 C28B engine data at nominal contamination rate of 12 ppm

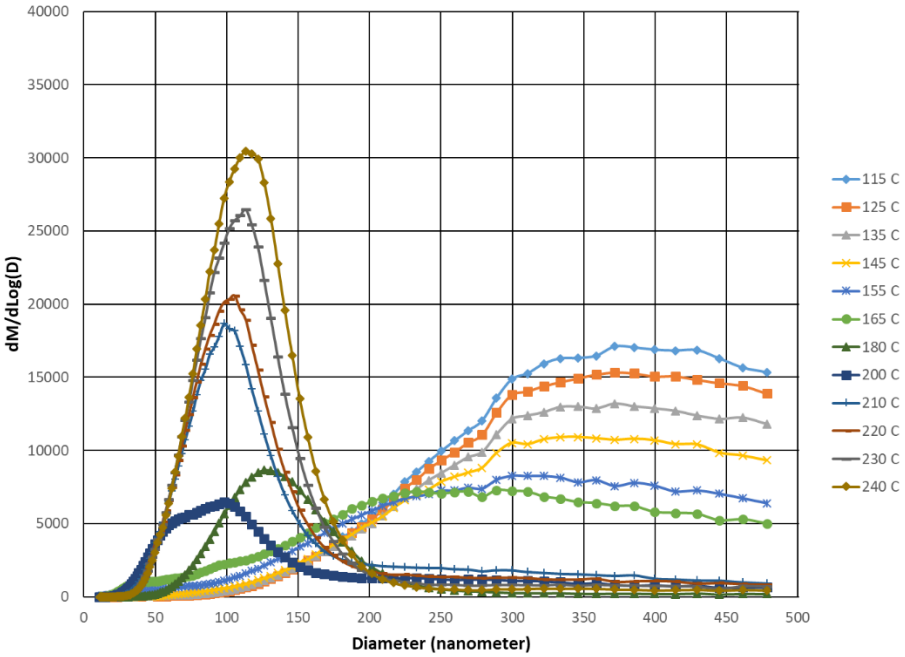

Figure 9. Allison 250 C18 engine data at nominal contamination rate of 12 ppm. Reproduced with permission. Copyright 2019, Shahin Nayyeri Amiri.

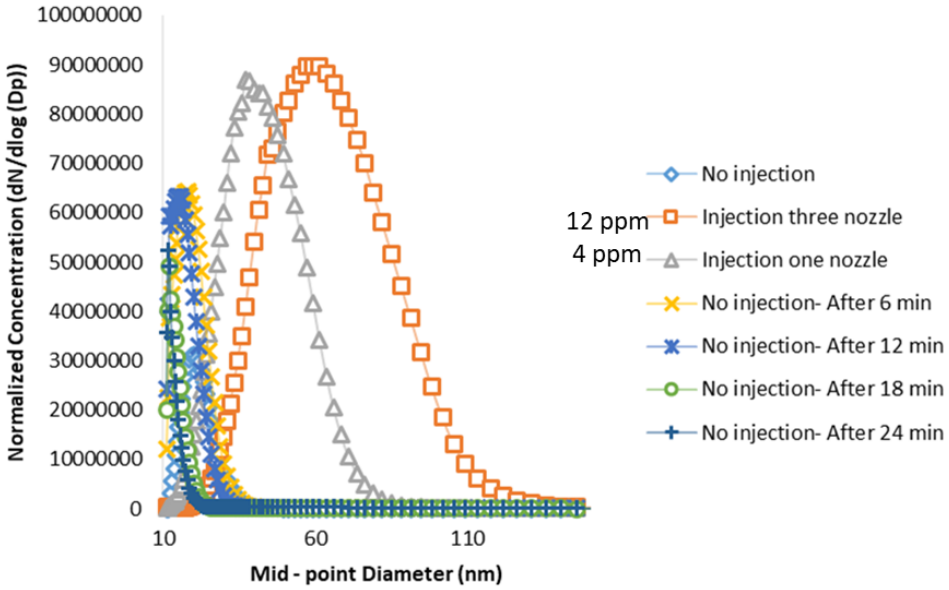

Figure 10. Allison 250 C28B engine data showing effect of contamination rate. Reproduced with permission. Copyright 2019, Shahin Nayyeri Amiri

For the data that were collected by sampling for laboratory analysis, only the volatile organic compound (VOC) data and the tri-cresyl phosphate (TCP) data have been published. The VOC data and the TCP data were collected both for baseline conditions and for the 8 ppm nominal contamination rate. These data are presented in Figure 11 and Figure 12 (Space, Salgar, Scheer, Jones, & Amiri, 2017). As shown in Table 2, a variety of samples was collected and thus there is additional data. A subset of data was presented to RITE-ACER researchers under a confidentiality agreement so it is not included in this report.

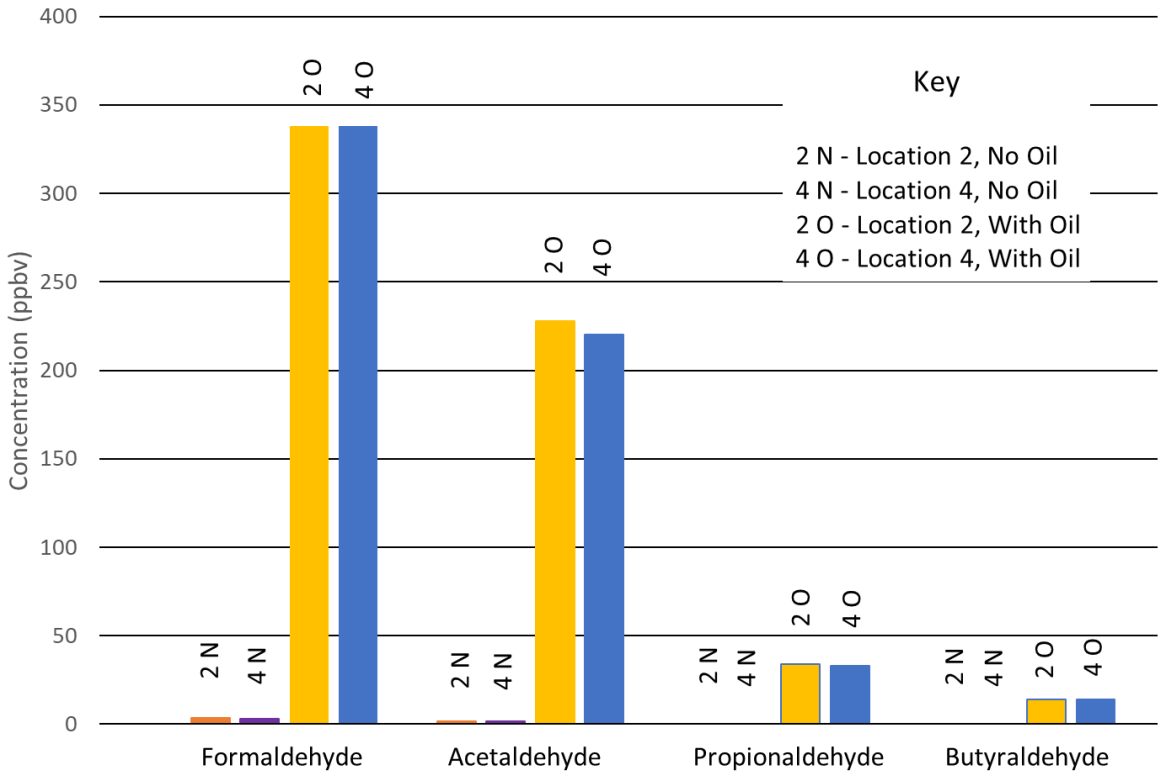

Figure 11. VIPR VOC data at 0 and 8ppm nominal contamination rates

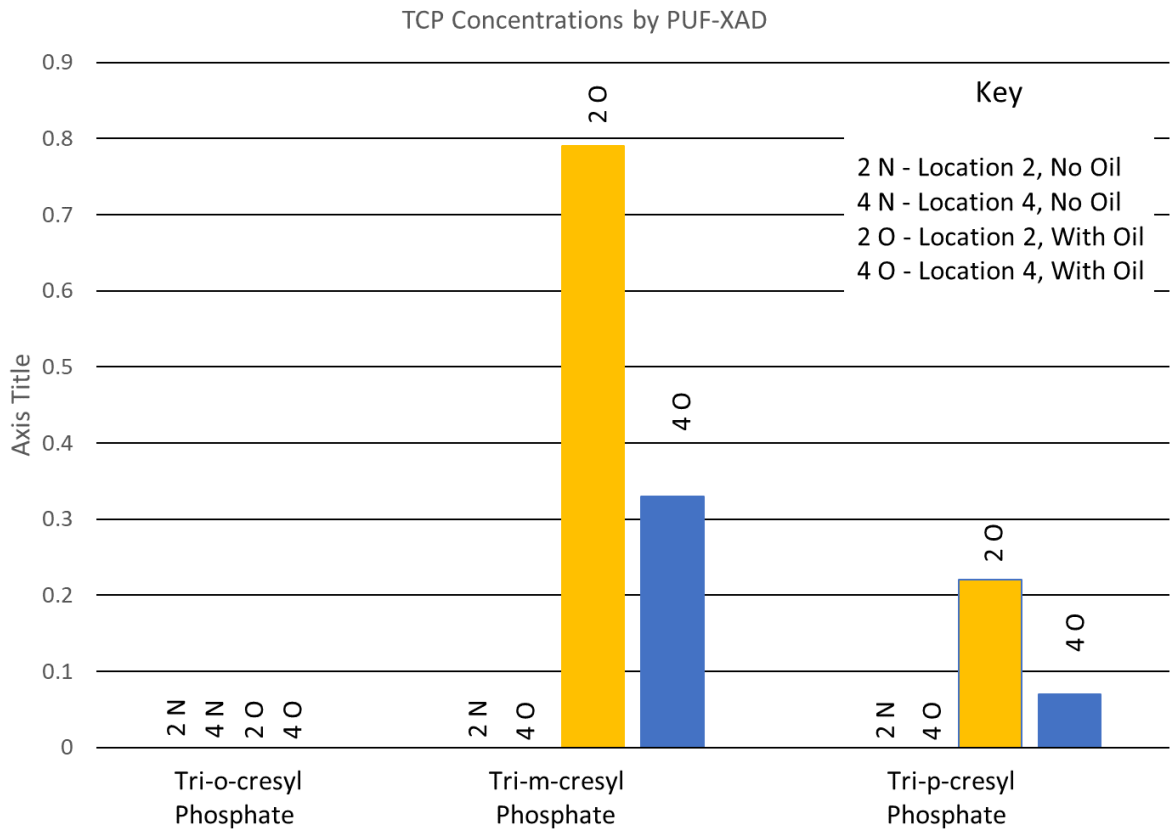

Figure 12. VIPR tri-cresyl phosphate data at 0ppm and 8ppm nominal contamination rates

1.2.4 Assessment of the VIPR data

These data clearly show the potential for ultrafine particles to be a sensitive marker for oil contamination of bleed air. 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 a little 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 the ratio is 10 for particle mass. This huge signal-to-background ratio indicates particle measurement is a very promising marker if appropriate sensors are available. The sophisticated, laboratory-grade instruments used in this project are not suitable for routine aircraft applications.

There are some questions regarding the particulate data. The highly non-linear response with regard to contamination rate is not explained. The Allison 250 data do not exhibit 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. Particularly, the number concentration did not decrease markedly for the Allison data, the size just got smaller and the mass decreased more or less in proportion to the change in contamination rate. It is possible that the size shift is just much greater with the C-17 engine and the bulk of the particles are below the measurement range. Nevertheless, it is difficult to explain the large decrease in mass. These data, therefore, 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. Due to this, there is a question as to the nature of the aerosol that would need to be detected at low engine speeds.

The results of the VIPR project were the main basis for the development of ASHRAE 1830-RP to further explore the suitability of particulate measurements for bleed-air contamination detection. Hopefully, that project will shed some light on these questions.

Finally, it should be pointed out that the VIPR C-17 data and the Allison 250 data collected later only included Mobil Jet Oil II contamination. There is no experimental basis for applying these results to other fluids, especially hydraulic fluid and deicing fluid. These fluids have different compositions and physical characteristics. Preliminary results from the ASHRAE 1830-RP project presented in indicate that, indeed, the hydraulic fluid and deicing fluid behave differently from oil. Thus, it will be important to follow that project closely as more data are collected.

The other real time chemical measurements, carbon monoxide (CO) and total volatile organic compounds (TVOC), had similar results, with signal to background ratios in the range of 1.5 to 2 ([Unpublished data files from the VIPR3 project]). Both clearly responded to the 4 ppm nominal contamination rate but the low signal to background level leaves questions as to their suitability as a primary marker. The assessment is particularly relevant given the possibility of much higher background levels, especially on the ground, in many locations. The environment at Edwards Air Force Base in the high Mojave Dessert is rather pristine compared to many urban airport environments. In addition, the potential background levels of these parameters in the cabin would preclude their use at any locations downstream 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. Both formaldehyde and acetaldehyde have essentially zero background and significant concentrations with the 8 ppm contamination rate. Comparison of the concentrations measured to the TVOC levels show they

are the major component of the observed TVOC increase. While the background levels observed in this experiment are very low, some assessment of the background in the aircraft operational environments needs to be conducted. If cabin or mix manifold measurement locations were to be considered, the background levels in the cabin would need to be assessed.

As noted previously a variety of samples were collected and evaluated for a large number of chemicals and some of those results were shared confidentially with RITE-ACER researchers. In those data shared, nothing stands out as being particularly useful for real time detection other than those already identified. This assessment does not mean there are no other potential chemical markers; just that none have been identified in this process. These data do have another important function, however. An important question that needs to be addressed in the current study is the level of contamination that needs to be detected to ensure the bleed air poses no health risk. Thus, it is important to have information about a wide range of chemicals that result for specific contamination rates to make that determination. Data that tie a broad range of chemical concentrations to a known contamination rate are scarce but are important to implement a sound detection program.

The Aerotracer device also responded to the oil contamination and gave a real time odor indication as shown in Table 4. It should be noted that the odor indication was recorded continuously and there was considerable variation at any given contaminant level. Nevertheless, it 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 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 responses that, qualitatively appeared to have a temporal response similar to the CO and TVOC sensors. It is not known what each individual sensor was detecting or how that information was 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 undoubtedly be a significant event.

1.3 ASHRAE 1262-RP project

1.3.1 Overview of the ASHRAE 1262-RP project

The ASHRAE 1262-RP project, "Relate Air Quality and Other Factors to Comfort and Health Related Symptoms Reported by Passengers and Crew on Commercial Transport Aircraft," was focused on relating substances in the air to health symptoms (Spicer, et al., 2004), (Spicer, et al.,

2018). In the assessment that follows, the focus was to determine what useful information could be gained from that project for the purposes of the current FAA project. Any observations about the limitations or shortcomings of the data reported in this regard are not intended to reflect negatively on the ASHRAE 1262-RP project and the data collected for the intended objectives of the project. It is important to note that the ASHRAE 1262-RP project did not address bleed air, bleed air contamination, or measuring bleed air contaminants.

The assessments that follow are based on the project final report and the database that was generated from the ASHRAE 1262-RP project. Although the report is published and available to the public, the database remains restricted. It was provided by ASHRAE for the purpose of this study in recognition of the FAA's contribution to the original project. The FAA funded data collection by Harvard University through RITE-ACER. The exact limitations on the extent that the information in the database can be reported in a document that may become public has not been made clear. For this reason, detailed presentations of the data from the database are not included in this report. However, some summaries and examples are provided.

1.3.2 Data collected during the ASHRAE 1262-RP project

The following assessment focuses on the environmental data that were collected. It does not address the health symptom data or any other data collected.

Health surveys were conducted on 130 flights spread across three airlines and six aircraft models as noted in Table 5 (Spicer, et al., 2004), (Spicer, et al., 2018). Environmental data were collected on 80 of these flights. The project report does not give a breakdown as to which of these flights included the environmental measurements. It may be possible to extract that information from the database if it becomes important at some future time. The environmental measurements were collected using carry-on instrument packages that were set up on a dedicated seat located near the middle of the economy section of the aircraft. Importantly, all data were collected only at aircraft altitudes above 10,000 feet. Some of the flights were monitored by Battelle, some by Harvard University and some jointly. As a result, there was some variation in the instruments onboard a given flight.

Table 5. Number of flights surveyed

Aircraft	Number of Flights
A340	7
A380	6

Aircraft	Number of Flights
B737	41
B747	24
B767	10
B777	42
Total	**130**

Table 6 (Spicer, et al., 2004), (Spicer, et al., 2018) describes the continuous measurements and associated instruments that were conducted on Airline A and Table 7 (Spicer, et al., 2004), (Spicer, et al., 2018) has the same information for Airlines B and C. The only two continuous variables of relevance to the current FAA study are CO and particulates. All flights used the same make and model of condensation particle counter for these measurements. CO sensor accuracy is a concern as they would not be expected to effectively detect the low levels of CO expected based on the VIPR data, especially the CO sensor used on Airlines B and C.

Table 6. Environmental variables measured continuously on airline A

Variable	**Manufacturer and Model**	**Operating Range**	**Precision**	**Accuracy**
Ozone	2B Technologies Model 202	1.5 ppb -100 ppm	± 1.5 ppb	± 1.5 ppb
Relative humidity, Temperature	Vaisala HHM30C	1-100%	± 3%	± 3%
Carbon monoxide	Draeger PAC III	2 – 2,000 ppm	± 1 ppm	± 3%
Carbon dioxide	Draeger Polytron IR	50 - 10,000 ppm	± 300 ppm at low end of scale	± 5%
Pressure	Vaisala	60 - 1,060 mb	± 0.05 mb	± 0.5 mb
Ultrafine Particles	TSI CPC Model 3781	0 to $5x10^5$ #/cm^3	± 10%	± 10%
Respirable particles (<4 μm)	TSI SidePak AM510	1-20,000 μg/m^3	± 1 μg/m^3	

Table 7. Environmental variables measured continuously and airlines B and C

Variable	Manufacturer and Model	Operating Range	Precision	Accuracy
Ozone	2B Technologies Model 205	1.5 ppb -100 ppm	± 1.0 ppb	± 1.0 ppb
Relative humidity, Temperature	TSI 7565 Q-Trak	0–95% 32-140^{o}F	± 3% ± 1^{o}F	± 3% ± 1^{o}F
Carbon monoxide	TSI 7565 Q-Trak	0 - 500 ppm	± 3 ppm	± 3%
Carbon dioxide	TSI 7565 Q-Trak	0 - 5,000 ppm	± 500 ppm at low end of scale	± 3%
Pressure	TSI 7565 Q-Trak	688 – 1,238 mb	2%	2%
Pressure	Setra 278-500	500 – 1,500 mb	± 0.04mb	± 0.6mb
Ultrafine particles	TSI CPC Model 3781	0 to (5 x10^{5}) pt/cc	± 10%	10%
Respirable particles (<4 μm)	TSI SidePak AM510	1-20,000 μg/m^{3}	± 1 μg/m^{3}	

Integrated air samples were collected during the flight to measure chemicals in the air. The targeted chemical groups and corresponding sampling methods are described in Table 8. The project report provides considerable detail about how the samples were processed in the laboratory but does not detail when during flight the samples were collected. This information is not included in the database. Thus, for purposes of the current FAA project, they can be considered as representative of an averaged in-flight condition.

Table 8. Integrated sample collection

Targeted Chemical Group	Sampling Method
VOCs	Evacuated canister or thermal desorption tubes
Aldehydes	DNPH cartridges
SVOCs	XAD-2 sorbent cartridges or tubes
TCP	Whatman QMA 37 mm quartz filters

1.3.3 Results of the ASHRAE 1262-RP project

Carbon monoxide was measured on 63 of the 80 flights. The report does not document why CO was not measured on the other seven flights. Presumably, it was due to instrument malfunction. Unfortunately, the precision of the sensors, ±3 ppm for one sensor and ±1 ppm for the other one, is not adequate to provide useful data given that the increase seen with substantial oil contamination resulted in an increase of less than 1 ppm in the VIPR project. Nevertheless, data are tabulated and reported. The maximum mean flight average for all flights was 0.1 ppm, essentially nothing. Only two flights reported instantaneous values above 1 ppm, 1.2 ppm, and 1.6 ppm, respectively.

Continuous data for CO are reported in the database and review of individual flight profiles may prove interesting ([Unpublished data ASHRAE 1262-RP Database]). However, given the low values and the limited accuracy, little benefit is seen in reviewing all 63 flights individually since the database is not organized in a manner that makes this evaluation straightforward.

Ultrafine particle measurements were conducted on 56 of the 80 flights. Again, the reason they were not conducted on the other 14 flights is not explained but is likely due to instrument malfunction or availability. Summaries of the data are provided in the project report and are presented in Table 9 (Spicer, et al., 2004), (Spicer, et al., 2018). The database provides continuous recordings for the flights and summary statistics for each flight.

Table 9. Summary of ultrafine particle measurements

	Peak Concentration for Flight	**Mean Concentration for Flight**
	Particles/cm^3	**Particles/cm3**
Mean	25,564	617
Std. Error of Mean	8,708	454
Minimum	0.1	0
10th Percentile	61	20
25th Percentile	131	24
Median	631	35
75th Percentile	5,925	64
90th Percentile	130,000	154
Maximum	382,000	24,600

Four examples are presented in Figure 13-16 ([Unpublished data ASHRAE 1262-RP Database]) that show the variability of results. There appears to be no such thing as a typical flight. The time basis for the data is not documented in the database and flights are categorized only as short, medium, and long. Presumably, the sampling rate is the same from flight to flight and the

sampling interval appears to be one minute. Figure 13-16 all use identical scales on both axes for comparison purposes. Please note that the concentration scale is logarithmic. Each gridline represents an order of magnitude increase in concentration. Flights were randomly assigned numbers and the flight number has no significance other than as an identifier so that data in different files can be tied to the same flight.

It will take some time to thoroughly analyze all of the particulate data in each flight but the continuous data have been examined and it appears that the high concentrations often occur when the readings first start. For example, on flight 104, Figure 15, there are 32 straight readings where the concentration exceeds 10,000 particles/cm^3 at the start and the last 23 of those readings are above 30,000. After a short break in the data, the values are below 10 particles/cm^3 and stay low for the remainder of the flight, typically below 30 particles/cm^3 and never above 200 particles/cm^3. This huge step decrease is not physically possible if the instrument is truly sampling cabin air and points to either instrument error or operator error. To be clear, most flights do not exhibit this behavior and many flights have occasional elevated values as would be expected due to activities in the cabin. Only one flight, flight 005 in Figure 13, appears to have high values throughout the whole flight with values mostly in the range of 25,000 to 30,000 particles/cm^2. Other flights have very low concentrations for the entire flight, as in flight 59, Figure 14. Other flights have a mixture of low, medium, and high values as in flight 008, Figure 16.

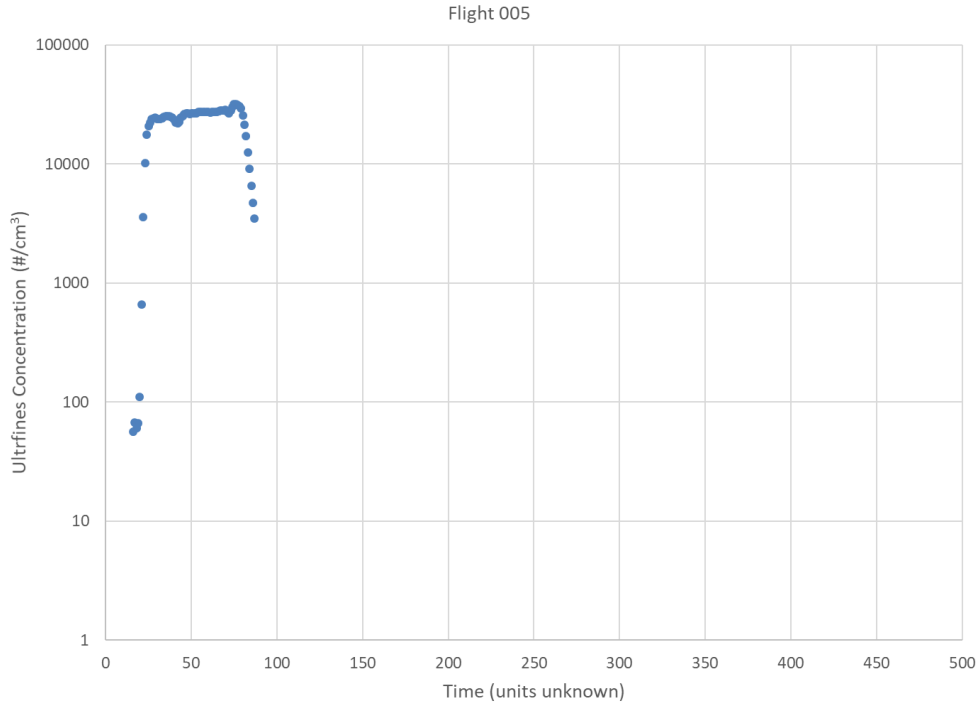

Figure 13. Example of high ultrafine concentrations, short flight

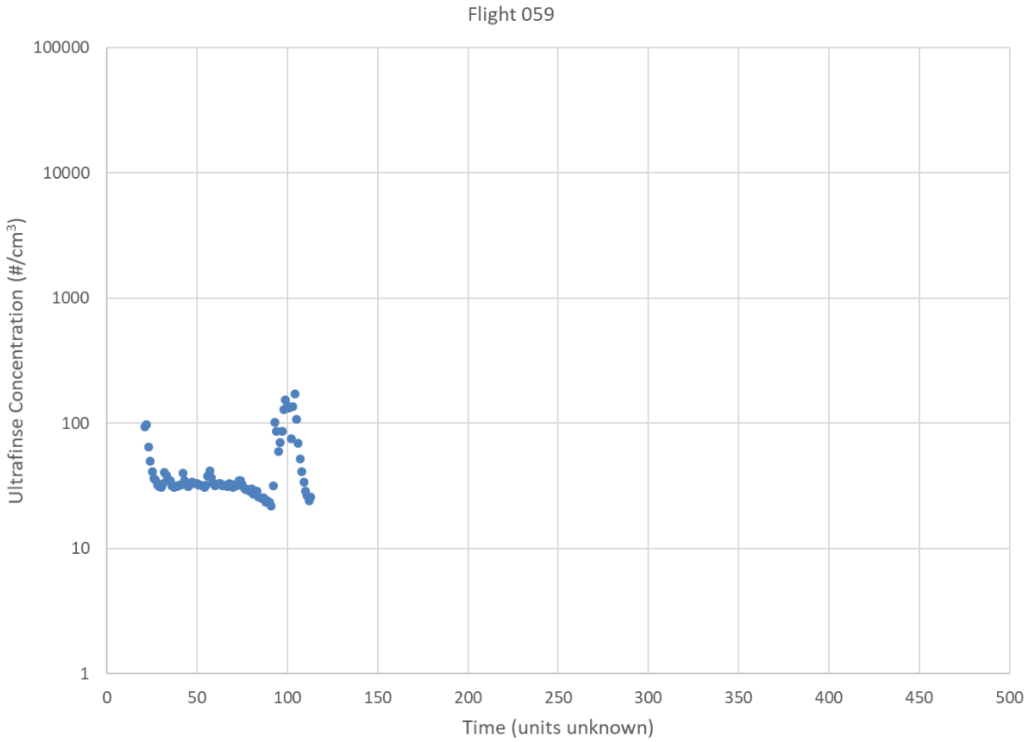

Figure 14. Example of low ultrafine concentration, short flight

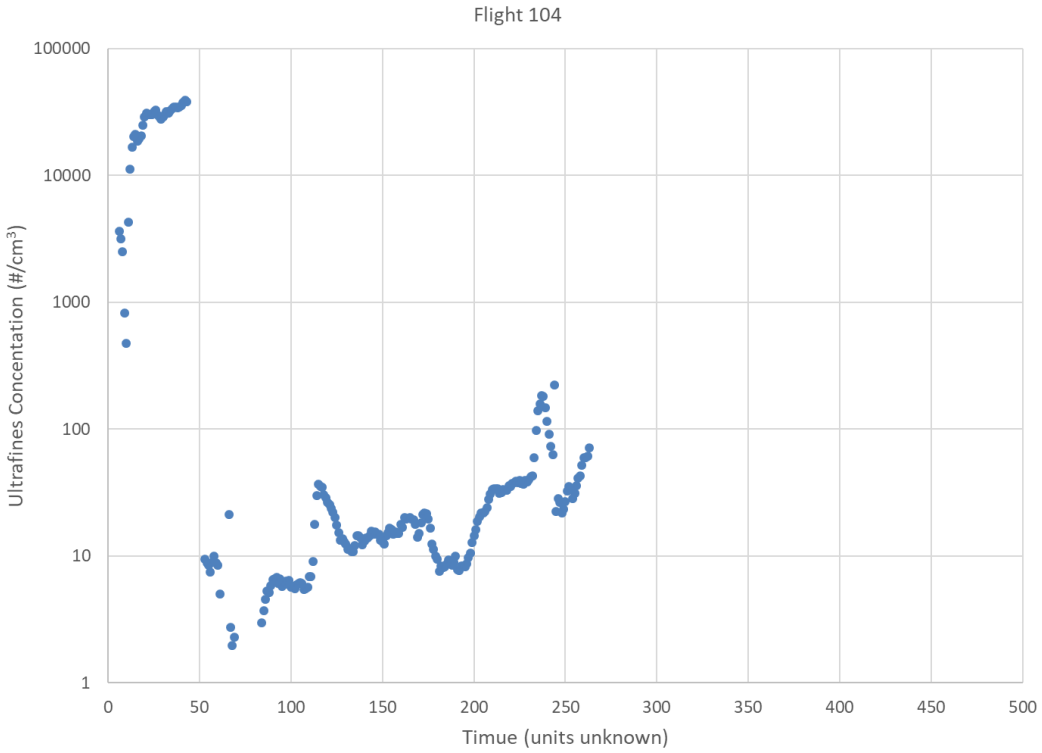

Figure 15. Example of high initial ultrafine concentration, medium flight

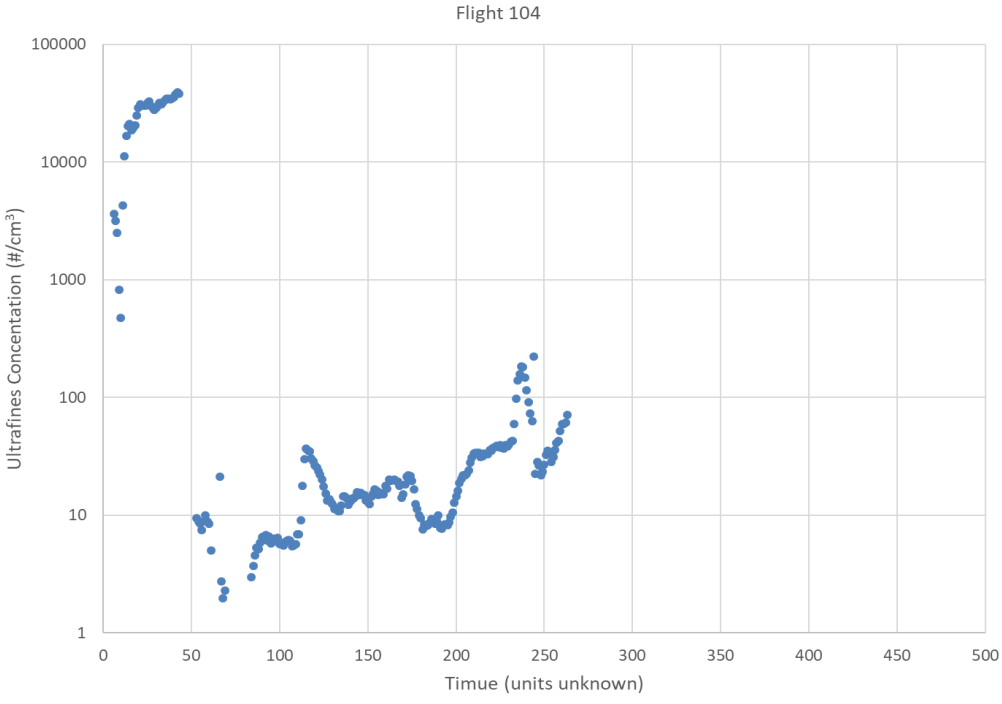

Figure 16. Example of high initial ultrafine concentration, medium flight

Respirable particles were measured on most flights and the results are recorded in the continuous data portion of the database. However, no assessment is provided in the report and it appears ignored in the analyses. For the most part the numbers are quite low.

Samples for semi-volatile organic compounds (SVOCs) were collected on 21 flights. These samples were analyzed for 38 different compounds. Since these substances likely do not provide useful opportunities for real time detection, they are not reviewed in detail here. They are relevant for air quality and at some future time, they should be useful for comparison to amounts generated by bleed air contaminants.

Samples for aldehydes were collected once on all 80 flights and twice on seven of those flights. The samples were analyzed for five aldehydes. The project report provides no summary of the results for these measurements but they are reported in the database. A brief summary is provided in Table 10 ([Unpublished data ASHRAE 1262-RP Database]) using data extracted from the database. Keep in mind that these values are from integrated samples. The peak values do not represent peak instantaneous values but rather represent peak-integrated values for all measured flights.

Samples for VOCs were collected on 75 flights, twice on six of those flights. These samples were then analyzed for 21 different VOCs. Since it is not clear if any of these chemicals have potential as a bleed-air contamination marker and it is not clear as to the confidentiality parameters associated with the database, detailed data for these chemicals are not presented here.

Table 10. Measured aldehyde concentrations ($\mu g/m^3$)

Chemical	**Average Concentration**	**Maximum Concentration**
Formaldehyde	3.0	11.7
Acetaldehyde	13.1	75.8
Acetone	26.3	80.0
Propionaldehyde	2.2	8.9
Acrolein	5.2	52.8

1.3.4 Assessment of the ASHRAE 1262-RP project data

The limited accuracy of the sensors used for CO limits the usefulness of the recorded data except to point out that CO levels are very low on typical flights. The instantaneous peak values measured exceeded 1 ppm on only two of the flights (1.6 ppm and 1.2 ppm). The vast majority of the values recorded were well below 1.0 ppm. However, the $\pm$1 ppm and $\pm$3 ppm accuracy of

the sensors should be kept in mind in assessing those values. Possibly the main conclusion that can be drawn from the CO data is that it is very low on typical flights and although an elevated value does truly represent an anomalous situation, it would not be necessarily bleed air contamination.

The ultrafine particle data from this project are the most useful data from a real time sensing perspective. Most flights had very low values, typically 1 to 2 orders of magnitude below what is typically seen in indoor environments. However, there are periods of elevated concentrations on many flights. These elevated levels are not unexpected since occupant activities such as walking down the aisle can stir up ultrafine particles. The low values are probably the result of a combination of factors including the pristine outside air during flight, the HEPA filtration of the recirculated air, and the low level of activity during much of the flight. The occasional increases seen during long flights, such as in Figure 16, is likely due to activities such as meal service. However, the same result could be attributed to passenger movement just near the measuring instrument.

Too much speculation as to causes of the readings without the corresponding documentation of activities on the aircraft is of little value. However, it should be noted that there is nothing in the report to indicate that, at any time during any flight, there was a clear or even suspected air quality event. The focus of the ASHRAE 1262 project was not air quality events. However, the researchers involved were well attuned to the questions surrounding aircraft air quality and the controversies associated with air quality events. Therefore, it is safe to conclude that any apparent air quality events would have at least been noted. Given this lack of noted air quality events and the frequent high ultrafine concentrations observed, it is clear that *in-cabin* sampling of ultrafine particles is not likely to be a reliable way to detect bleed air contamination even though the VIPR data show ultrafine particles have good promise as a marker of oil contamination. The background levels in the cabin due to other factors could not be easily differentiated from bleed air contamination. Any use of ultrafine measurements to detect bleed air contamination would require sensing in the mix manifold or further upstream.

Since the VIPR data indicate that formaldehyde or acetaldehyde are potential oil contamination markers, the values measured are of interest. The levels shown in Table 10 are in $\mu g/m^3$ while the VIPR data are in parts per billion (ppb). Since the molecular weight of formaldehyde is 30 kilogram/kilomole (kg/kmol), air is 29 kg/kmol, and the density of air is approximately 1.2 kilogram /meters cubed ($kg/m^{3)}$, microgram per meters cubed ($\mu g/m^{3)}$ units for formaldehyde must be multiplied by 0.81 to convert to ppm units. Acetaldehyde, with a molecular mass of 44 kg/kmol, requires a multiplying factor of 0.55. The maximum levels of formaldehyde and

acetaldehyde measured in the ASHRAE 1262 study are then 9 ppm and 42 ppm respectively. The levels of formaldehyde and acetaldehyde measured in the VIPR study with oil contamination were approximately 300 ppb and 200 ppb respectively. These results would indicate that background levels in the cabin may be low enough to use formaldehyde or acetaldehyde measurements in the cabin to detect oil contamination, especially for formaldehyde. However, care must be exercised in drawing a conclusion for two reasons: 1) the values from the ASHRAE 1262 project are integrated measurements and do not reflect instantaneous values which could be much higher and 2) formaldehyde and acetaldehyde generation are not unique to bleed air contamination events. Nevertheless, the data at least do not preclude in-cabin measurements as they do for ultrafine particles.

The various samples collected were analyzed and reported for a total of 64 different chemicals. While it is possible that some of the other chemicals will have potential as markers, it is not yet clear which ones are good markers. As the current research progresses additional potential markers may be identified. The data in the database may be useful for assessing the background levels of those chemicals.

1.4 EASA project

1.4.1 Overview of the EASA project

This review is based on the EASA project's final report and associated data appendixes (Schuchardt, Bitsch, Koch, & Rosenberger, 2014). EASA personnel and the lead researcher were also contacted to discuss the project. After discussion with the lead researcher, it was determined that there is a large, unpublished database underlying the project report. Information in the database was made available to us. However, the database is in a raw data form and not something that can be readily used by other researchers. If it were desired to use this additional data, it would be necessary to hire a researcher from the EASA project to conduct the necessary analysis and extraction. For now, the information in the report was satisfactory.

The primary objective of the EASA study was to determine if there are cabin air contaminants that represent safety and/or potential long/short-term health risks. The study measured in-flight concentrations of a large number of potential chemical contaminants. Special emphasis was given to organophosphate compounds (OPC) in general and to TCP compounds in particular given the issues around TCP and its potential presence in the bleed air. The report and accompanying appendixes contain detailed results from the measurements.

It should be kept in mind that the objectives of the EASA study were different from the objectives of the present FAA project. Comments about the limitations or usefulness of the data collected are in the context of how they can be applied to the present FAA project and are not intended to be criticism of the EASA project.

1.4.2 Data collected during the EASA research

Data were collected on 69 flights. The aircraft were divided into two large groups, non-bleed air aircraft (B787), and bleed air aircraft (all other aircraft). Table 11 and Table 12, reproduced from the report (Schuchardt, Bitsch, Koch, & Rosenberger, 2014), describe the included aircraft.

Table 11. Description of aircraft included in the project other than B787 aircraft

Cycle	Airline	Type	Plane age years	Engines
1	CFG	B767-330ER	22.8	2 x PW PW4062
2	CFG	B767-330ER	22.3	2 x PW PW4062
3	CFG	B767-330ER	23.6	2 x PW PW4062
4	CFG	B767-330ER	25	2 x PW PW4062
5	CFG	B767-330ER	23.8	2 x PW PW4062
6	DLH	B747-830	2.4	4 x GEnx-2B67
7	DLH	A320-211	15.8	2 x CFMI CFM56-5A1
8	DLH	A320-214	2.4	2 x CFMI CFM56-5B4/P
9	DLH	B747-830	1.5	4 x GEnx-2B67
10	DLH	B747-830	3.9	4 x GEnx-2B67
11	DLH	A340-642	9.7	4 x RR Trent 556-61
12	CFG	A321-211	1.1	2 x CFM56-5B3/3
13	CFG	A321-211	1.1	2 x CFM56-5B3/3
14	CFG	A321-211	1.2	2 x CFM56-5B3/3
15	CFG	A321-211	1.2	2 x CFM56-5B3/3
16	CFG	A321-211	1.2	2 x CFM56-5B3/3
17	DLH	B747-830	3.1	4 x GEnx-2B67
18	DLH	A320-211	26.6	2 x CFMI CFM56-5A1
19	DLH	A340-642	12.9	4 x RR Trent 556-61
19a	CFG	B757-330	16.4	2 x RR RB211-535E4B
20	CFG	B767-31BER	22.1	2 x GE CF6-80C2B6F
21	CFG	B767-31BER	22.3	2 x GE CF6-80C2B6F
22	DLH	A340-642	7.4	4 x RR Trent 556-61
23	DLH	A320-211	26	2 x CFMI CFM56-5A1
24	DLH	A340-642	9.7	4 x RR Trent 556-61
25	DLH	B747-830	3.3	4 x GEnx-2B67
26	DLH	A320-214	2.5	2 x CFMI CFM56-5B4/P
27	CFG	B767-31BER	22.3	2 x GE CF6-80C2B6F
28	CFG	B767-330ER	23.6	2 x PW PW4062
29	CFG	B767-31BER	22.3	2 x GE CF6-80C2B6F
30 out	DLH	A320-214	2.8	2 x CFMI CFM56-5B4/P
30 in	DLH	A320-214	3.5	2 x CFMI CFM56-5B4/P

Table 12. Description of B787 aircraft included in the project

Cycle	Airline	Type	Plane age Years	Engines
1	BA	B787-8	3.1	2 x RR Trent 1000
2	BA	B787-8	3.3	2 x RR Trent 1000
3	BA	B787-8	2.2	2 x RR Trent 1000
4	BA	B787-8	3.3	2 x RR Trent 1000

Continuous measurements were conducted on the flights for eight different environmental variables as described in Table 13 (Schuchardt, Bitsch, Koch, & Rosenberger, 2014). Of these variables, only CO, TVOC, and ultrafine particles are of significant interest to the current FAA project.

Unfortunately, the CO measurement had a lower range limit of 0.5 ppm. While this limit is appropriate for health considerations, it does not provide much information about actual CO levels on the aircraft as they are typically below this level.

The ultrafine particles were measured using a newly developed particulate sensing instrument. The instrument itself should be considered experimental. While this instrument may have good potential for aircraft applications, it is unfortunate that more conventional ultrafine particle measurements were not included to provide data that could be more readily compared to other studies and applied in other contexts.

Table 13. Instrumentation for continuous measurements

Variable	**Sensor Type**	**Resolution**	**Range**
TVOC	PID 10.6 eV	1 ppb	5-2,000 ppb
CO2	NDIR	±35 rdg ±50 ppm	0 to 10,000 ppm
CO	Electrochemical	0.01 ppm	0.5 to 5000 ppm (LOD = 0.5 ppm)
O_3	Electrochemical	0.01 ppm	0.02 to 1.0 ppm (LOD = 20 ppb)
Temperature	Not Specified	±0.5C (±0.3°F)	-20 to 65C (-4 to 149°F)
Pressure	Not Specified	±2.5 mbar	0 to 2000 mbar
Humidity	Not Specified	± 2%	0 to 100%
Ultrafine Particles	Custom	2 µg/m^3 (LDL)	Not Specified

TVOC values were measured with an instrument with sensitivity and ranges suitable to provide data useful for the present FAA project. The results are in the ranges that were expected.

Air samples as described in Table 14 (Schuchardt, Bitsch, Koch, & Rosenberger, 2014) were collected for each phase of flight: taxi, takeoff-climb, total flight, and descent-landing. These samples were collected for later laboratory analysis. Detailed information is reported in the report and its appendices on a chemical-by-chemical, flight-by-flight basis for each flight phase.

Table 14. Air sampling methods for integrated measurements

Target Chemical Group	**Adsorbents**	**Flow rate (L/min)**
Organophosphorus Compounds	Gilian 5000, GSA-SG 10, SG- 5100 quartz filter and polyurethane foam, GGP-System (BIA)	10, 3.5, or 1
Volatile Organic Compounds	SG 350 (GSA, Germany) or Tenax TA tubes (Supelco or Perkin Elmer, USA)	0.10 each tube
Aldehydes	SG 350 (GSA, Germany) or DNPH-cartridges (Sep-Pak XPoSure, Sep-Pak ozone scrubber, Waters, USA)	0.30 to 0.50

1.4.3 Results of the EASA project

Table 15 (Schuchardt, Bitsch, Koch, & Rosenberger, 2014) summarizes the CO measurements. Given the, Many of the values were below the 0.5 ppm lower detection limit. The maximum values should be accurate. Figure 17 (Schuchardt, Bitsch, Koch, & Rosenberger, 2014) shows some examples of the continuous measurements of CO. Even though the lower limit for the sensor is listed as 0.5 ppm, values below this limit were recorded.

Table 15. Summary of carbon monoxide measurements

	Main study Flight deck ppm	Main study Cabin ppm	B787 study Flight deck ppm	B787 study Cabin ppm
Mean	< LOD	< LOD	< LOD	< LOD
Min	< LOD	< LOD	< LOD	< LOD
Max	4.8	3.0	0.6	1.6
Median	< LOD	< LOD	< LOD	< LOD
95th-percentile	< LOD	0.6	< LOD	1.06

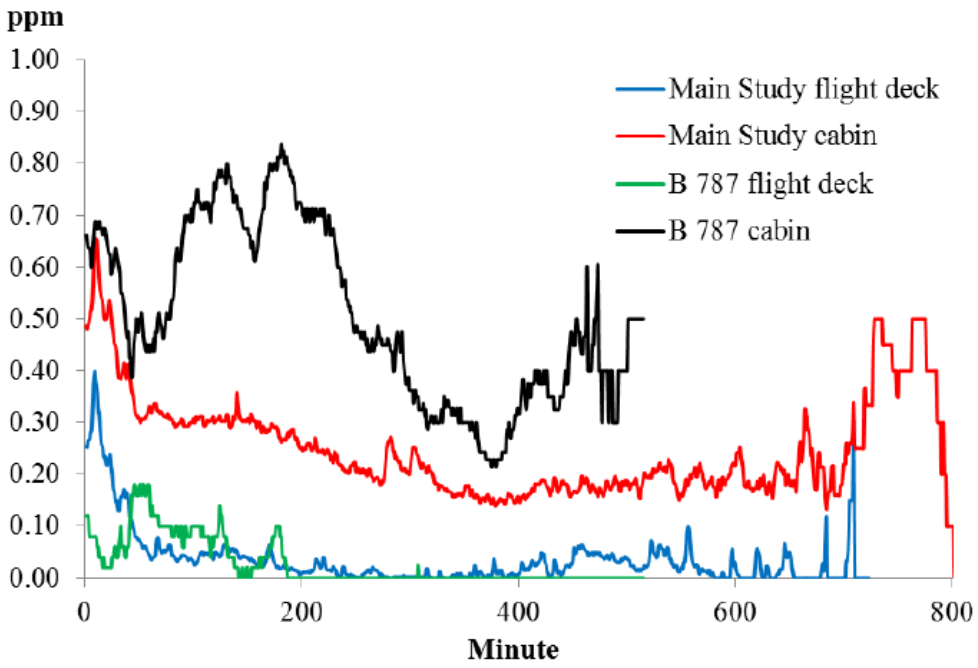

Figure 17. Examples of continuous CO measurement from EASA project report

While continuous TVOC data were evidently collected on all flights, little attention was given to this variable in the report. Table 16 (Schuchardt, Bitsch, Koch, & Rosenberger, 2014), which was copied from the report, summarizes the TVOC data. The reported values are in $\mu g/m^3$ toluene equivalent. To convert them to ppb, divide by approximately 4, which means peak values are on the order of 200 – 300 ppb.

Table 16. Summary of TVOC measurements (toluene equivalent)

	Flight deck Mean µg/m³	Cabin Mean µg/m³
Mean	108	273
Min	59	137
Max	1205	851
Median	84	225
95th-percentile	221	549

The particulate data are only presented as voltages or ratios with no quantitative particulate numbers or mass quantities associated with them. None is presented here, as they are not useful for the current FAA project.

The integrated chemical samples are presented in detail in the report and the number of chemicals measured was over 100. Formaldehyde and acetaldehyde have been suggested as potential markers of oil contamination. Data for these compounds, along with other aldehydes are presented in Table 17 (Schuchardt, Bitsch, Koch, & Rosenberger, 2014). The data are presented in units of µg/m^3. To convert to ppb units, multiply by 0.81 for formaldehyde and 0 .55 for acetaldehyde. Thus, maximum values recorded are approximately 11 ppm for formaldehyde and 5 ppb for acetaldehyde. Keep in mind these values are from integrated samples and instantaneous values could be many times higher.

Detailed chemical analysis was conducted on the air samples collected. Table 18-33 (Schuchardt, Bitsch, Koch, & Rosenberger, 2014) present the results reported for just the VOCs. This level of detail is unnecessary for the current report but are presented here primarily to show the depth of the chemical analysis conducted in this project. Other chemical groups are not reported as they are not expected to play a role in detection at this point in time.

Table 17. Aldehydes for different phases of flight

	Mean			
	µg/m³	µg/m³	µg/m³	µg/m³
Flight phases	taxi-out	take-off/climb	entire flight	descent/anding
Samples *n*	89	91	120	120
	taxi-out	take-off/climb	entire flight	descent/landing
Formaldehyde	13.9	7.0	2.7	4.8
Acetaldehyde	9.1	4.9	2.8	3.4
Acetone	55	31.4	19.5	35.2
Acrolein	1.0	0.8	0.1	0.4
Propionaldehyde	2.1	1.4	0.5	1.0
Crotonaldehyde (cis/trans)	< LOD	0.2	0.1	0.3
n-Butyraldehyde	1.5	0.8	0.4	0.7
Benzaldehyde	4.6	2.0	0.6	2.1
Isovaleraldehyde	2.4	1.2	0.5	3.5
Valeraldehyde	2.7	1.1	0.3	5.5
o-Tolualdehyde	2.5	1.5	0.4	1.2
m-Tolualdehyde	3.3	2.6	1.7	3.8
p-Tolualdehyde	1.8	1.9	1.3	2.7
Hexaldehyde	3.2	1.8	1.1	1.8
2,5-Dimethylbenzaldehyde	2.9	0.5	0.3	0.7
Sum Aldehydes (without acetone)	41.1	21.4	9.9	21.4

Table 18. Summary of acid compounds

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Acetic acid	96.8	11.8	0.1	59.4	9.1	30.1
Benzoic acid	90.9	5.3	0.1	72.8	3.7	14.7
Hexanoic acid	89.4	3.8	0.0	16.6	3.3	9.2
Octanoic acid	75.9	2.1	0.1	8.1	1.7	5.3
Nonanoic acid	80.0	1.9	0.1	6.1	1.7	4.2
Decanoic acid	24.4	0.8	0.0	5.4	0.6	1.9
Formic acid	17.9	0.7	0.0	33.9	0.0	3.5
Phenylmaleic anhydride	7.9	0.3	0.0	6.1	0.1	1.4
Sum Acids		26.6	0.3	185	22.1	57.8

Table 19. Summary of alkanes

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Tetradecane	87.4	2.6	0.0	13.3	2.1	6.3
2,2,4,6,6-Pentamethyl heptane	28.2	1.6	0.0	61.4	0.6	5.3
2,2,4,4,6,8,8-Heptamethyl nonane	55.0	2.4	0.0	49.3	1.2	7.6
Undecane	75.3	2.2	0.0	22.3	1.6	5.7
Nonane	60.0	2.0	0.1	12.9	1.3	6.9
Dodecane	67.9	1.9	0.0	17.6	1.4	4.4
Tridecane	68.2	1.7	0.0	12.2	1.4	4.2
Decane	51.8	1.7	0.1	16.9	1.1	5.1
Pentadecane	64.1	1.5	0.0	6.1	1.2	3.4
Pentane	17.1	1.4	0.0	63.7	0.2	3.9
Hexadecane	53.5	1.2	0.0	3.2	1.0	2.5
Heptadecane	48.2	1.1	0.0	3.1	1.0	2.3
Heptane	24.1	0.9	0.1	24.8	0.4	2.9
Methylcyclohexane	12.9	0.9	0.0	73.8	0.2	2.2
Cyclohexane	14.7	0.8	0.0	48.1	0.2	2.0
Hexane	12.1	0.5	0.0	4.8	0.3	1.7
3-Methylpentane	3.8	0.3	0.0	18.9	0.0	0.5
2,2,4-Trimethyl pentane	1.5	0.1	0.0	2.3	0.0	0.3
Sum Alkanes		24.6	0.8	211	19.5	60.7

Table 20. Summary of aldehydes

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Decanal	85.9	10.5	0.0	54.0	9.3	26.1
Nonanal	84.1	5.4	0.1	31.2	4.5	13.6
Hexanal	90.9	4.4	0.0	14.4	3.9	10.2
Octanal	71.8	2.9	0.0	31.4	2.2	8.5
Heptanal	71.8	2.3	0.1	13.6	1.7	6.0
Benzaldehyde	67.6	2.0	0.0	15.0	1.5	5.6
Undecanal	66.5	1.4	0.1	5.2	1.3	2.6
Butanal	17.1	0.7	0.1	4.5	0.5	1.7
2-Hydroxybenzaldehyde	6.8	0.5	0.0	8.0	0.3	1.3
Sum Aldehydes		30.1	0.2	124	26.8	70.1

Table 21. Summary of alcohols

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Ethanol	100.0	82.3	7.0	616	56.6	246
1-Propanol	97.9	80.7	0.6	1524	16.2	378
1,2-Propanediol	98.2	45.2	0.0	363	22.7	174
Isopropyl alcohol	88.2	12.6	0.1	248	3.5	51.0
1,3-Butanediol	70.0	5.2	0.0	70.2	1.8	24.8
2-Phenoxyethanol	95.0	4.6	0.1	29.4	3.6	11.4
2-Ethylhexanol	93.8	4.0	0.1	14.3	3.6	8.5
1-Butanol	57.6	2.4	0.1	31.5	1.2	9.7
Benzyl alcohol	55.0	1.4	0.0	7.3	1.1	3.3
3-Methylbutanol	23.2	0.8	0.0	10.2	0.5	2.4
Butylated hydroxytoluene (BHT)	16.2	0.6	0.0	12.2	0.3	2.1
Glycerine	1.5	0.4	0.5	127	0.0	0.0
tert.-Butanol	2.6	0.2	0.0	13.6	0.1	0.3
Sum Alcohols		240	12.7	1705	169	639

Table 22. Summary of alkenes

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Isoprene	99.4	9.0	0.1	46.8	6.9	24.4
4-Cy-pentadien-1,3-dion4phenyl	1.8	0.1	0.0	3.6	0.0	0.3
Sum Alkenes		9.1	0.1	47.1	7.1	24.4

Table 23. Summary of aromatics

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Toluene	96.2	11.5	0.0	62.0	8.3	32.4
Benzene	91.2	8.2	0.2	53.4	4.3	32.2
p+m-Xylene	49.4	1.6	0.0	11.7	1.0	5.3
Naphthalene	16.8	1.4	0.0	49.1	0.4	2.6
Phenol	47.4	1.2	0.1	5.0	1.0	2.5
o-Xylene	32.6	1.0	0.0	5.8	0.7	3.0
Ethylbenzene	18.5	0.7	0.0	10.8	0.4	2.0
Styrene	10.3	0.5	0.0	3.8	0.4	1.3
Sum Aromatics		26.1	0.5	174	20.0	67.8

Table 24. Summary of chlorocarbons

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Tetrachloroethene	57.9	3.8	0.0	73.9	1.2	14.6
Dichlormethane	11.2	1.1	0.0	71.9	0.2	2.8
p-Dichlorbenzene	9.7	1.0	0.0	34.1	0.2	4.8
Sum Chlorocarbons		5.9	0.2	75.7	2.4	20.8

Table 25. Summary of esters

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Ethyl acetate	90.3	4.9	0.4	68.1	2.7	16.5
2-Ethylhexyl salicylate	61.8	2.3	0.0	19.1	1.5	7.1
Butyl acetate	55.3	2.2	0.0	44.8	1.2	6.6
Isopropyl myristate	65.3	1.7	0.0	8.6	1.4	4.2
2,2,4-Trimethyl-pentanedioldiisobutyrate	56.2	1.3	0.0	6.7	1.1	2.8
1-Methoxy-2-propylacetate	28.5	1.0	0.0	9.7	0.5	4.5
Isopropyl palmitate	32.9	1.0	0.0	19.3	0.7	2.5
Homosalate	17.9	0.7	0.0	4.1	0.5	2.1
Sum Esters		15.1	0.8	76.7	11.8	37.8

Table 26. Summary of ethers

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Dioctyl ether	93.2	6.4	0.0	42.8	4.5	19.4
Methoxy-bis-1,2'-dipropane-1,2-diol ether	3.5	2.4	18.5	142	0.0	0.0
1,1'-Dipropane-1,2-diol ether	3.5	1.7	9.2	124	0.0	0.0
1,2'-Dipropane-1,2-diol ether	3.5	1.6	8.9	114.8	0.0	0.0
Sum Ethers		12.0	0.0	403	4.5	24.2

Table 27. Summary of ketones

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Acetone	99.7	15.7	0.8	87.2	11.2	44.5
5,9-Undecandien-2-one-6,10-dimethyl	90.9	3.9	0.1	26.4	3.2	8.9
Hydroxyacetone	34.1	3.3	0.0	161.0	0.6	4.8
Butanone	86.2	2.9	0.1	31.8	2.1	7.4
Acetophenone	34.1	1.6	0.0	49.5	0.7	3.7
Sum Ketones		27.3	1.0	319	19.5	66.9

Table 28. Summary of nitrogenous

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Acetonitrile	82.4	19.4	0.2	269	3.2	95.1
Dimethylformamide	3.5	7.7	63.9	541	0.0	0.0
Diethyltoluamide	16.8	0.9	0.0	19.2	0.3	4.3
Sum Nitrogenous		28.0	0.3	610	4.6	132

Table 29. Summary of phosphates

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Tributyl phosphate	38.2	1.1	0.0	6.4	0.8	3.5
Triethyl phosphate	6.2	0.5	0.0	18.4	0.1	1.4
Sum Phosphates		1.6	0.0	21.4	1.0	5.2

Table 30. Summary of phthalates

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Phthalic anhydride	9.1	0.9	0.0	48.9	0.3	2.0
Diethyl phthalate	22.1	0.7	0.0	4.1	0.6	1.7
Diisobutyl phthalate	4.4	0.5	0.0	7.1	0.4	1.0
Dibutyl phthalate	1.5	0.3	0.0	5.3	0.2	0.6
Sum Phthalates		2.4	0.1	62.0	1.5	4.4

Table 31. Summary of siloxanes

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Cyclopentasiloxane	96.5	18.0	0.1	277	11.8	51.4
Cyclotrisiloxane	55.0	1.8	0.0	42.3	1.1	4.7
Cyclotetrasiloxane	62.6	1.8	0.0	35.4	1.2	4.4
Cyclohexasiloxane	30.3	1.0	0.0	9.3	0.7	2.6
Cycloheptasiloxane	18.2	0.7	0.0	3.4	0.5	2.0
Sum Siloxanes		23.2	0.1	288	16.7	59.2

Table 32. Summary of terpenes

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Limonene	93.8	12.3	0.0	216	8.4	29.6
Menthol	95.6	11.6	0.1	60.7	8.6	32.9
Eucalyptol	57.6	2.0	0.0	40.3	1.2	6.7
Menthone	48.5	1.5	0.0	13.5	1.0	4.4
a-Pinene	44.1	1.2	0.0	11.7	0.9	3.3
3-Carene	17.4	1.3	0.0	42.2	0.5	2.5
p-Cymene	7.4	0.8	0.0	33.4	0.4	1.3
b-Pinene	8.8	0.6	0.0	26.1	0.4	1.4
Sum Terpenes		31.3	0.2	265	25.2	72.8

Table 33. Other compounds

Compound	Occurrence (>1 µg/m³) %	Mean µg/m³	Minimum (>0.005) µg/m³	Maximum µg/m³	Median µg/m³	95-percentile µg/m³
Isoalkanes C14 - C20	82.9	62.4	0.2	355	45.8	207
Perfluoro derivates	14.4	5.5	1.1	110	0.0	43.6

1.4.4 Assessment of the EASA project data

No air-quality events were noted on any of the flights monitored in the EASA study. Given that the study was focused on air quality and air contamination, one can be certain any such events

would have been featured prominently in the report. Thus, all of the data collected should be regarded as representing normal, non-event conditions.

The limitations of the CO data were noted previously. Most of the CO data are not particularly important other than noting that the values are typically low, below 1.0 ppm. The maximum values are somewhat useful as they should be reasonably accurate and represent the maximum levels encountered over a substantial number of flights. Thus, these maximum levels can be considered representative of normal, non-event flights. Given that instantaneous values in the 1-5 ppm range were observed shows that in-cabin measurements of CO are not likely to be very useful for detecting bleed air contamination events, at least for oil, as the VIPR data indicate that, even with substantial oil contamination, bleed air levels would not be this high.

Similar conclusions can be drawn about TVOCs. The maximum levels recorded are on the same order as the levels measured in the bleed air with a substantial oil contamination event in the VIPR project.

As noted previously, there appears to be no data on particulates that were useful for the current FAA project.

The formaldehyde and acetaldehyde levels reported are all an order of magnitude or more less than the levels measured in the bleed air with substantial contamination in the VIPR project. While these results do not preclude the use of in-cabin measurements of formaldehyde or acetaldehyde to detect bleed air oil contamination, they do not validate such usage. These values are from integrated samples and instantaneous values could be much larger. Additionally, events not associated with bleed air contamination could produce these compounds.

These two compounds are the only ones specifically identified as promising as markers of oil contamination in bleed air. If at some point in the future other compounds prove to be potential markers for bleed air contamination, it is likely there will be data from the EASA study that will allow the evaluation of background values in the cabin.

1.5 Cranfield project

1.5.1 Overview of the Cranfield project

This project 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. Technically, it is called the "Cabin Air Sampling Study" but is popularly known simply as the "Cranfield Study." The study was established due to health concerns crewmembers potential exposure to substances in the cabin air. Unique to this project, as compared to the EASA and ASHRAE studies, was the focus on fume events with both the researchers and crewmembers identifying the occurrence of fume events (Crump, Harrison, & Walton, 2011), (Crump, Harrison, & Walton, 2011). Many flights are designated as having fume events. Unique to this project is the inclusion of the Bae 146 aircraft, which has a reputation for fume events. Given the health focus of this project and the focus on 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. Finally, sampling was conducted throughout all phases of flight from boarding to deplaning.

It should be kept in mind that the objectives of the Cranfield study were different than the objectives of the FAA project. Comments about the limitations or usefulness of the data collected are in the context of how they can be applied to the current FAA project and are not intended to be critical of the Cranfield project.

1.5.2 Data collected during the Cranfield research

The reports do not specifically state but based on various comments made in the project report, it is believed that all physical measurements were conducted in the aircraft cockpit.

Data were collected on five aircraft types and on 20 flights for each type for a total of 100 flights as described in Table 34. Data are associated with 10 different flight phases starting with boarding and ending with deplaning as described in Table 35 (Crump, Harrison, & Walton, 2011). A separate category is designated for an air quality event, which could be associated with any of the flight phases.

Table 34. Aircraft included in the study and the number of flights

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

Continuous measurements were collected for TVOC, CO, and particulates. Air samples were collected for later analysis in the laboratory. The associated instrumentation is described in Table 36 (Crump, Harrison, & Walton, 2011). The particulate data were collected with a condensation particle counter that counted particles in the 0.020 to 1.0 μm range. This range includes part of what is normally considered ultrafine particles, <0.10 μm, and part of what is normally considered fine particles, i.e., 0.10 μm to 2.5 μm.

Table 35. Summary of specific flights phases identified for data collection

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

* Reproduced with permission of (Crump, Harrison, & Walton, 2011)Copyright 2011, Institute of Environment and Health, Cranfield University.

Table 36. Summary of instrumentation use in the aircraft for measurements

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

The air samples were analyzed for a limited number of targeted compounds as described in Table 37 (Crump, Harrison, & Walton, 2011). When compared to the ASHRAE and EASA studies, the number of compounds evaluated is small and appears to have been selected because of the potential association with a wide range of fume events and their potential for health effects. None has been specifically identified as having high potential as a bleed-air contamination marker.

Table 37. Targeted chemical compounds for laboratory analysis

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

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 primarily subjective on the part of the researcher based primarily on smell. However, an “abnormal” increase in TVOC or

particulates also could be an indication of an air quality event. It appears objective criteria were not established for designating a fume event.

1.5.3 Results of the Cranfield project

For the continuous measurements, the reports 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 Figure 18– 20 (Crump, Harrison, & Walton, 2011). Unfortunately, the flight phases are not designated on the graphs so some judgement must be used when viewing the data. Additionally, the scales change from flight to flight so direct comparisons between plots, particularly for particulates, which range over several orders of magnitude, must be approached with care. For example, Figure 21 (Crump, Harrison, & Walton, 2011) has a peak particle concentration about an order of magnitude lower than for the flight shown in Figure 20. Thus, the particulate variation during the in-air portion of the latter flight can be seen much more readily.

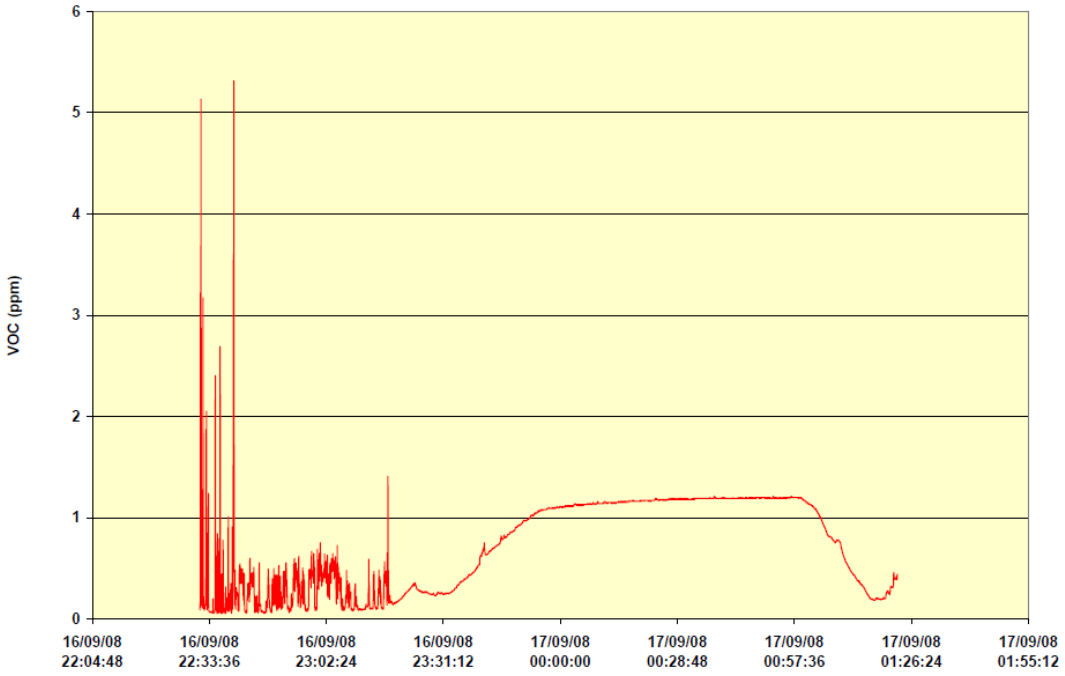

Figure 18. Example of TVOC data recorded for one flight.

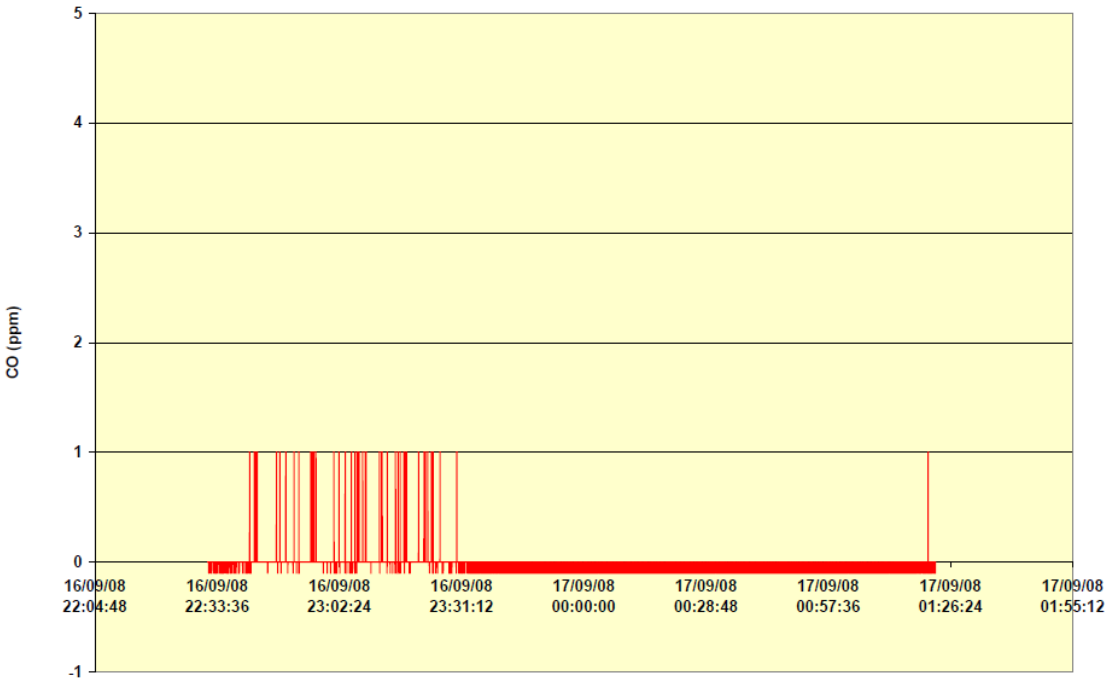

Figure 19. Example of CO data recorded for one flight
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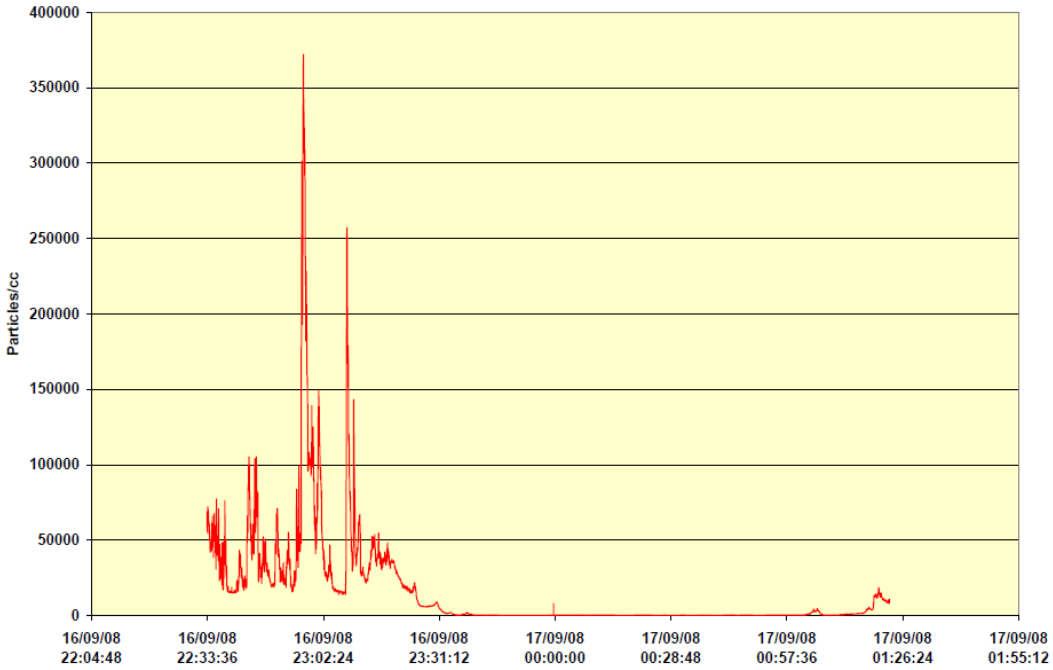

Figure 20. Example of particulate data collected for one flight

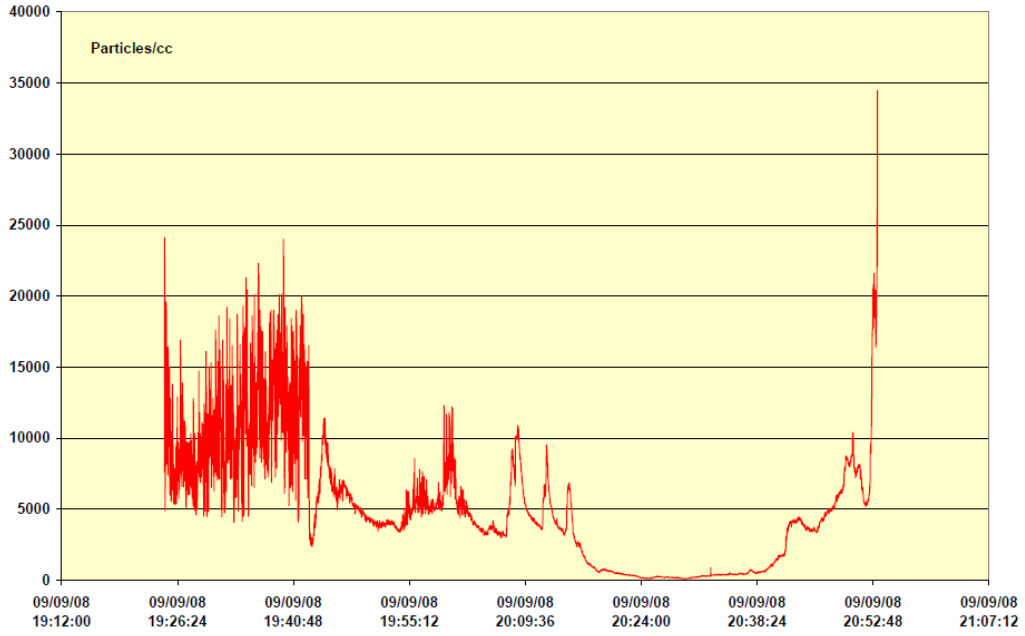

Figure 21. Example of flight with lower peak particulate levels
Reproduced with permission of (Crump, Harrison, & Walton, 2011). Copyright 2011, Institute of Environment and Health, Cranfield University.

In general, the highest particulate concentrations are seen during the boarding phase and, to a lesser extent, the deplaning phase as seen in both Figure 20 and Figure 21 Generally, during the in-air portion of the flight, the values are low with occasional peaks as seen in Figure 21, likely due to physical activity in the vicinity of the instrument. However, there is no such thing as a true "typical" flight as particle concentrations and time characteristics varied considerably from flight-to-flight and the concentration varied considerably during most flights as well. Table 38 (Crump, Harrison, & Walton, 2011) summarizes the levels that were measured for all flights and Table 39 (Crump, Harrison, & Walton, 2011) contains the same information for those flights identified as event flights. There is no discernable difference in the patterns between the two tables. The reports do not parse the particulate data by aircraft or by phase of flight.

Table 38. Summary of flights with different levels of particulate concentration

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 39. Particle counts for aircraft with air quality events

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

Like particulates, the highest levels of TVOC were often observed at the beginning of a flight, presumably during boarding. Figure 6 is representative of such cases. Unlike particles, which usually had higher values at the beginning and sometimes at the end than the rest of the flight, TVOC was not consistent in this respect and many flights had low initial values as shown in Figure 22 (Crump, Harrison, & Walton, 2011). The levels during what appears to be the in-air portion of the flights showed a lot more consistency from flight to flight. The project report does not provide much summary data for TVOC measurements. Peak values are characterized in Table 40 (Crump, Harrison, & Walton, 2011). The reports do no parse the TVOC data by aircraft or by phase of flight.

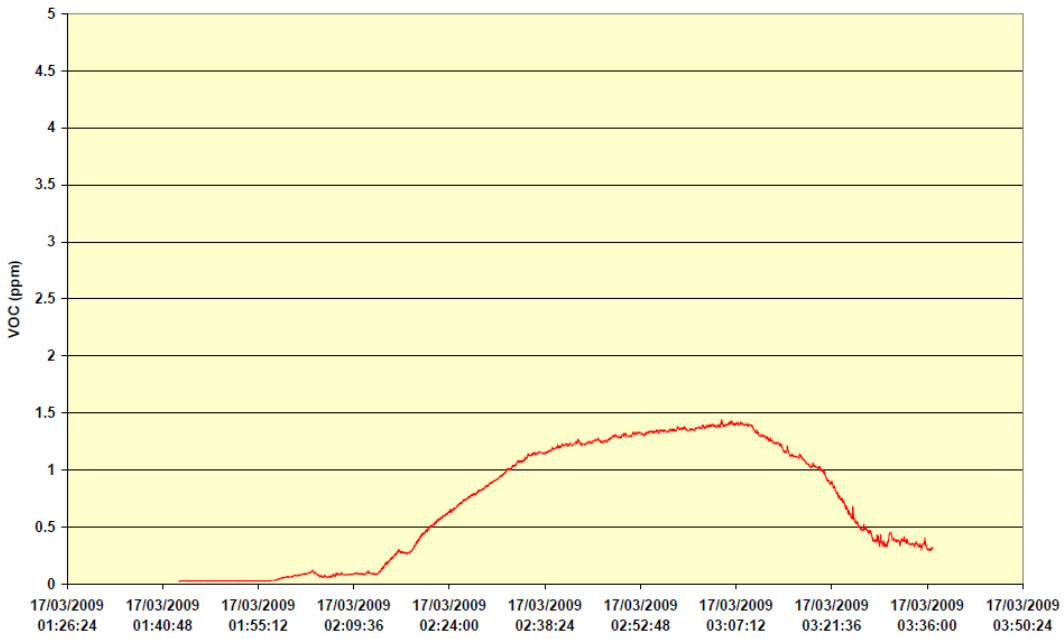

Figure 22. Example of low initial value of TVOC
Reproduced with permission of (Crump, Harrison, & Walton, 2011). Copyright 2011, Institute of Environment and Health, Cranfield University.

Table 40. TVOC maximums (the term "sectors" is equivalent to "flights")

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

Given the 1 ppm resolution of the CO data, there is little useable CO information. Figure 19 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 occasional brief peaks of a few ppm at most. Table 41 (Crump, Harrison, & Walton, 2011) summarizes the number of such peak values. Given the resolution of the sensor, it is questionable whether values of 2 ppm represent a true peak. Values greater than 2 ppm likely do reflect an elevated CO level. All such excursions were brief, approximately minutes. The reports do not parse the CO data by aircraft or by phase of flight.

Given the focus on health impacts, considerable attention was given to the chemical data and detail chemical data by phase of flight and flight-by-flight are provided in the data appendix in Part 2 of the project report. At this point, none of the chemicals included have been identified as likely markers for detection so only an overview is provided here. Table 42 (Crump, Harrison, & Walton, 2011) provides summary statistics for all samples collected on all flights, 981 total, but some of the TCP data may be in error (Wolkoff, Crump, & Harrison, 2016). Table 43 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 44 presents the toluene results as an example.

Table 41. Carbon monoxide peak values (the term “sectors” is equivalent to “flights”)

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

Table 42. Summary of chemcial data for all flights, Based on all 981 samples collected (AM- arithmetic mean, SD- standard deviation, ND not detected).

Compound (n)	Concentration µg m^{-3}							
	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 43. Summary of chemical database on flight mean values (Wolkoff, Crump, & Harrison, 2016).

Compound (n=100)	Concentration µg 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 44. Summary statistics for toluene by phase of flight (Wolkoff, Crump, & Harrison, 2016). Reproduced with permission.

Phase of flight	Toluene concentration µg 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

Researchers identified 30 events on 25 different flights over the course of the project. The results are summarized by flight phase in Table 45 (Wolkoff, Crump, & Harrison, 2016). Events identified by researchers were spread throughout all phases of flights but most common during engine start, takeoff, and taxi back. Crewmembers identified 57 air quality events. Table 46 presents the same information for events identified by crewmembers. The events identified by the crewmembers tend to be clustered in the earlier phases of the flights, engine start, taxi, and takeoff. The events identified by crewmembers were based on post flight surveys. The reports do not show whether or not there is any correlation between when researchers identified events and when crew members identified events. The reports do not parse the event data by aircraft, which is somewhat surprising given the reputation of the Bae 146 aircraft for fume events.

The study was divided into five parts and “part” refers the part of the study.

Table 45. Number of air quality events identified by researchers

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

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Table 46. Air quality events identified by crewmembers

	Phase of flight										
Part	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

* Plus one report of smell of human waste throughout flight

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The only summaries comparing data during event times with non-event times is for particulates as referenced previously and shown in Table 39 and Table 40. No chemical data are reported in this manner. While some of the events were associated with increased levels of TVOC, particularly those that were identified by such an increase, the general conclusion of the study is that there was no association between concentrations of chemicals or other variables and the identification of an event. Perhaps importantly, none of the events rose to the level of requiring follow up reporting or actions by the airline.

1.5.4 Assessment of the Cranfield project data

The particulate data reported in the Cranfield project are useful for the FAA project. Concentrations are typically low compared to those measured in the bleed air with significant oil contamination levels in the VIPR project. However, there are numerous cases of highly elevated

levels particularly during the boarding phase. These cases show 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.

Similarly, the TVOC data are informative. The background levels of TVOC measured in the cabin in the Cranfield Project are normally well above the levels seen in the intentionally contaminated bleed air in the VIPR Project. Clearly, attempting to use TVOC measurements in the cabin to identify bleed air contamination will not be practical.

The low resolution of the CO 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 adequate 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 value for detecting bleed air event based on the levels measured with significant contamination in the VIPR project.

While the number of compounds for which chemical data were collected is limited, the results are well documented in the reports and readily available for use later, if needed. At this point none of the compounds evaluated have been identified as a likely candidate as a marker for bleed air contamination. However, if interest in these compounds increases in the future, the Cranfield project provides good background data.

The number of air quality events identified was surprising and indicates a very low threshold for defining an event. The fact that none of the events rose to a level that would require any kind of follow up action by the airline reinforces the observation that the threshold used was very low. Similarly, the lack of association with any physical measurements further reinforces this observation. It also points to the difficulty 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.

Whether or not the inclusion of the Bae 146 aircraft had any influence on the high frequency of defined air quality events cannot be determined from the reports as the event information is not presented or documented in a way that makes this association possible. Whether this lack of association was a necessary part of the study or is just a coincidence was not documented

1.6 Other data

1.6.1 ASHRAE 959-RP

ASHRAE 959-RP project “Determine Aircraft Supply Air Contaminants in the Engine Bleed Air Supply System on Commercial Aircraft” (Nagda, Rector, Li, & Hunt, 2001) was a precursor to ASHRAE 1262-RP and was conducted on a small number of aircraft. This project is unique from the three large cabin air projects reviewed above in that it focused on measuring the supply air rather than the cabin air. As such, the research may provide information about supply air contaminants not found in the larger studies. The primary objective of the project was to develop and demonstrate measurement techniques and not to generate a database. Thus, the data collected are not intended to be representative of the fleet in general. The ASHRAE 959-RP project was not included in the current review.

1.6.2 Thermal decomposition database

A series of experimental measurements have been conducted by industry over a number of years to evaluate the thermal decomposition products of a number of fluids, mostly engine oils. In addition to a number of engine oils, some of the data are for hydraulic fluids and deicing fluids. Typically, data were collected at 200^{o}C (392^{o}F) and 370^{o}C (698^{o}F) which more or less represents the range of temperatures encountered in bleed air. The database was originally proprietary but parts of it has been made public. The number of chemicals included in the analysis is extensive.

It is believed that this database will provide an important supplement to the data available from the VIPR project given that it addresses a dozen different oils and aircraft relevant fluids as opposed the single oil included in the VIPR project. While thermal decomposition in a steady state laboratory environment is much different than in the bleed air environment, the fact that certain compounds are generated through thermal decomposition is an indication that they are likely to be present in bleed air under some conditions. Additionally, the data are quantitative and describe the mass of each contaminant generated per mass of test fluid. Thus, information in this database can be used to estimate the levels that are potentially present for given levels of contamination by oil or other fluids. The temperature range of the database may also present a limitation as most of the data are collected at one of the two temperatures. Most bleed air extraction temperatures are intermediate between these two temperatures and, thus, may not be reflected accurately at the either of the test conditions.

1.7 Discussion and conclusions

This summary is from the same perspective as the review. That is, it addresses what information from the reviewed studies is useful for the FAA Project. In particular, what can be learned from these studies about bleed air contamination and its detection?

Between the three cabin air studies, the chemical constituents in the cabin air for routine operation are well characterized. The EASA project included 69 flights, the ASHRAE 1262 project included 80 flights, and the Cranfield project included 100 flights. Combined, the projects conducted measurements on 11 different aircraft models: A319, A320, A321, A340, A380, B737, B747, B767, B777, B787, and BAe146.

Additionally, there are multiple subtypes included for some of the models. Both the EASA project and the ASHRAE 1262 project evaluated the air for a large number of chemical compounds, hundreds of compounds between the two projects. The EASA project further evaluated four different phases of flight. The Cranfield project addressed a much more targeted set of chemicals but collected data for 10 different phases of flight.

No air-quality events were reported for either the EASA project or the ASHRAE 1262 project. The Cranfield project focused on air quality events and identified over 25 such events. However, the definition and threshold for an event was very low. None of the events identified rose to the level of requiring follow up reporting or other actions by the airlines and there was no correlation between identified events and measurement results. It is reasonable to conclude that the identified events would not normally be considered air quality events and that the Cranfield data are representative of normal operation. As a result of this review, the following items were noted.

1. For the purpose of the current FAA Project, the background chemical levels of aircraft cabins during normal, non-air quality event, operation can be considered well characterized and there is no present need for additional data in this regard in the near future.
2. While this review was focused on bleed air and the adequacy of the characterization of background chemical levels, it is worth noting that the chemicals related to air quality in general for aircraft cabins appear to be well documented for normal operation. No need is seen for further large-scale cabin air chemical measurement projects for evaluating normal operations at this time.
3. The same conclusions cannot be drawn about the chemicals that may be present in bleed air because of contamination by the substances of concern: engine oil, hydraulic fluid,

and deicing fluid. The VIPR project provides considerable valuable information in this regard. Even so, these data were collected for one contaminant (Mobil Jet Oil II), at one contamination level (8 ppm), for one operating condition (simulated cruise but on the ground), and for one engine (F117/PW2000).

4. Compared to the breadth of the cabin air combined chemical database, the chemical database for contaminated bleed air is very narrow and represented a challenge for the FAA Project.

5. It is hoped that the thermal decomposition database will help provide guidance for other contaminants but that guidance will be by inference, which should not be confused with actual measurements with contaminated bleed air. Some information from test flights from the FACTS program may become available. However, given the challenges of conducting controlled bleed air contamination in actual aircraft engines under actual operating conditions, it is unlikely that extensive additional chemical data for controlled bleed air contamination on aircraft will become available in the near future. Well-designed bleed air simulators may be able to fill this gap. Likewise, test stand engines may be able to provide useful information.

The VIPR project was not focused on developing real time detection. However, the results of the project did provide useful information on several potential markers for real time detection. These variables include: ultrafine particles, formaldehyde, acetaldehyde, TVOC, and carbon monoxide. After reviewing these variables in light of the cabin data, the following observations can be made.

1. The VIPR Project showed that ultrafine particles are a very sensitive indicator of engine oil contamination in bleed air. The cabin air quality studies show that ultrafine particles in the cabin are usually very low compared to the levels seen 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.

2. Ultrafine particles remain a prime candidate for detection of oil contamination but the sensing needs to be upstream of the cabin in the supply air stream to ensure particles detected are from contaminated bleed air and not from other sources.

3. 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. The background levels measured in the cabin were all well below the elevated levels measured with oil contamination.

4. Formaldehyde and acetaldehyde remain promising candidates for detection of oil contamination and their location in the cabin has not been ruled out.
5. Carbon monoxide and TVOC responded to oil contamination in the VIPR Project. However, those responses were not well above background levels and their usefulness as markers for the detection of oil contamination appears questionable based on these data. The cabin air studies make it clear they are not suitable for use in the cabin for detecting bleed air contamination since background levels are often above the levels measured in VIPR in the case of TVOC and occasionally above the levels measured in VIPR in the case of CO.
6. Carbon monoxide and TVOC are questionable indicators of oil contamination in any case and definitely cannot be used to detect oil contamination by measurements of the cabin air.
7. No specific task within the FAA project included comparing the thermal decomposition data to the chemicals measured in VIPR with oil contamination. However, such a comparison may prove insightful.
8. This review was the beginning of a process not the end of a process. Following this review, additional data and information was obtained through collaboration with the ASHRAE 1830-RP research project and through collaboration with the SAE E31B committee. This additional information is reflected in Section 4 of this report.

2 Assessment of sensor technology

2.1 Introduction

The preliminary review of potential means of detecting bleed air contamination is presented in this section of the report. This assessment was based on the review presented in Section 1 of this report, evaluation of off-the-shelf sensor technology, and collaboration with sensor manufacturers and users. Recommendations for specific instruments and sensors that should be evaluated experimentally are presented in Section 5 of this report. These tasks are an integrated effort with the goal of assessing potential bleed-air contamination detection technology and sensors and the sensor manufacturers willing to collaborate in the research.

Two, interrelated approaches were used in this assessment. The first approach was to identify substances in the bleed air that result from contamination and then identify sensors that may be able to sense those substances at levels relevant to bleed air applications. The second was to

identify sensors that have been developed to detect contaminants in bleed air or that can be adapted to this purpose. Typically, these instruments have multiple sensors and details may be proprietary.

The VIPR project provided detailed information about the substances that result from engine oil contamination of bleed air and this information is the starting point for our assessment. Thermal decomposition data is also available for several engine oils and these data were assessed to supplement the VIPR data. Additionally, experiments were conducted on an auxiliary power unit and a test-stand engine as part of the ASHRAE 1830-RP project. These experiments included two types of hydraulic fluid and two types of deicing fluid. In addition, several sensor companies provided sensors to supplement the particle measurements originally planned. This information will assist with the ongoing assessment both of the substances that result from contamination and the performance of the instruments included. Some of this data is still under review. Additionally, thermal decomposition data available for hydraulic fluid and deicing fluid were reviewed to identify potential marker substances. The experimental data collected in collaboration with the ASHRAE 1830 research project are discussed further in Section 3 and Section 5 of this report. An accompanying electronic data set includes detailed data from these experiments. This data set is described in Appendix B.

2.2 Sensing technology

This section of the report provides general assessment of types of sensing technology that may prove useful for detecting bleed air contamination. Recommendations for specific sensors and instruments in test stand engine experiments are presented in Section 5 of this report. For the application as envisioned in this project, a key requirement is that the measurement be close to real time, perhaps 10 minutes maximum, and be suitable for implementation on aircraft. These limitations substantially reduce the types of sensing that are available. Additionally, the sensors must be able to detect marker substances at levels expected with bleed air contamination. The VIPR data helps establish the required levels for engine oil. At this point, sensor cost was not taken into consideration. Eventually, it will be a factor but the goal is not to find a low-cost sensor but rather to identify effective detection methods. The SAE E31b committee has conducted extensive work in this regard and much of their work has been incorporated into this assessment.

As shown in Table 47, several chemicals have been identified as having potential as markers for oil contamination.

Table 47. Potential marker chemicals representative of bleed air contamination

Chemical	**Potential**
Formaldehyde	Good
Acetaldehyde	Good
Carbon Monoxide	Fair
TVOC	Fair
Carbon Dioxide	Good
*Note: Good as a discriminator but not for primary detection	

Various methods can be used to detect these gasses. These methods can be divided into four broad categories: 1) electro-chemical sensors, 2) metal oxide sensors, 3) photo ionization detectors, and 4) spectrometers.

The electrochemical sensors and the metal oxide sensors are relatively inexpensive and can be designed to target a variety of specific compounds. They have the potential for detecting low concentrations. Multiple sensors can be combined and tuned to detect specific substances. Some disadvantages include a tendency to drift over time, poisoning of the sensing medium, and slow recovery after exposure. Various measures may be employed such as cleaning cycles and calibration to address these concerns.

Photo ionization detectors (PID) use UV light to generate ions. The flow of ions depends on the gasses present and their concentrations. They can be very sensitive but are not highly selective. In this application, they would be primarily used for non-selective measurements such as TVOC.

The term spectrometer is used in a very broad sense here to describe instruments that have a signal that is altered by different chemicals by different amounts and these differences are used to identify the presence of a substance or substances. Common spectra are based on wavelength specific attenuation or absorption and on time of flight. They can be designed to detect a single substance such as with a non-dispersive infrared sensor for carbon dioxide or can be used to identify multiple gasses such as with a proton transfer mass spectrometer (PTRMS).

Table 48 lists the measurement methods identified for each of the marker chemicals. This assessment is based partly on results from work performed by the SAE 31B committee in the development of AIR6418, *Transient Measurement Method Development for Aircraft Propulsion Engine and Auxiliary Power Unit Generated Contaminants in Bleed Air* and shared with the research team through the collaboration with this committee. However, that work is still in

progress at the time this report is being written and information included here should not be considered as endorsed by SAE.

Table 48. Measurement methods for the various potential marker chemicals

Chemical	**Measurement Methods**
Formaldehyde	TILDAS, CRDS, SIFT-MS, TOF-PTRMS, MIRL
Acetaldehyde	TILDAS, CRDS, SIFT-MS, TOF-PTRMS, MIRL
Carbon Monoxide	Metal Oxide, Other
TVOC	PID
Carbon Dioxide	NDIR, CRDS, TILDAS

Several companies have developed instruments that use multiple sensors that respond differently to different gasses and then combine that information to identify specific contaminants. Generally, the details of the sensors and, especially, the algorithms used to process the data are proprietary.

The presence of ultrafine particles was been shown to be a promising means to detect engine oil in the bleed air. The ongoing ASHRAE 1830-RP is focused specifically on ultrafine particles.

Preliminary data to date from this project are consistent with the VIPR data in that oil contamination produces very large numbers of ultrafine particles < 100 nm in size. Also, results from these experiments showed that ultrafine particle concentrations were two orders of magnitude greater than ambient concentrations even with oil contamination levels as low as 1 ppm by mass. See section 5 Data from this project show that ultrafine particles are not good indicators of deicing fluid or hydraulic fluid. Fine particles show some promise for hydraulic fluid. Table 49 summarizes the technologies available for detection of ultrafine particles and provides comments relevant to their possible usage for real-time bleed air detection.

Table 49. Technologies for detection of ultrafine particles

Technology	**Comments**
CPC	Requires fluid reservoir and regular attention
Electrical Impactor	Applies charge to particles and measures resulting current
Optical Counters	Generally not applicable for sizes below about 300 nm

The above technology can be combined with particle size “filtering” technology to create a mass spectrometer that provides size distribution information. This size discrimination can be achieved by a differential mobility analysis (DMA), which applies a charge to each particle and then discriminates by how rapidly they move through the air when subjected to an electrical field. It can also be achieved by differences in time of flight when subjected to accelerating flow. The latter method generally is not used for ultrafine particles.

2.3 Sensor manufacturers

From the initiation of the project, sensor manufacturers and other companies and organizations in the industry were invited to collaborate in the research. In addition to contacts from the previous ACER Industrial Advisory Board and additional personal contacts, participation was solicited through several ASHRAE, SAE, and ASTM committees. Over 300 people were contacted through this process. An industry workshop webinar was conducted. This workshop was designed to be a broad-based outreach effort to inform the industry about this project and to invite participation. It was considered highly successful from a participation standpoint, as 101 individuals registered for the webinar not including project personnel. The registrants represented 76 different companies and organizations. A list of the companies and organizations registered is presented in Appendix B. Ninety people, not counting project personnel, participated in the webinar. Thus, the vast majority of the people registered actually participated in the event.

While the webinar was valuable for informing the industry about the project, it became apparent that this large webinar format was not an effective approach for a focused working group. Sensor companies in particular indicated they were not comfortable working in such a large public group setting. During the webinar and again following the webinar, an open invitation was provided for companies to collaborate on the project. The working group was built around those companies that indicated an interest in collaborating and that had the potential to provide value to the project, as opposed to just observing. The makeup of the working group varied some over the course of the project. Over 18 companies were identified for the working group. The companies that have been identified are divided into several categories below.

Table 50 summarizes the status of companies currently or potentially participating in this project. The types of companies (sensor vs. non-sensor) are listed as well as their level of participation and/or interest. A number of the companies supported the experiments by providing sensors and instruments as shown in Table 50.

Table 50. Collaboration with private sector companies

Company	**Sensor/Non-Sensor**	**Interest Status**
Aeris Technologies	Sensor	Specific interest
Airbus	Non-sensor	General interest
Airsense	Sensor	Provided sensors
American Airlines	Non-sensor	General interest
Astronics	Sensor	Provided sensor
Boeing	Non-sensor	General interest
CH Technologies	Sensor	Provided sensors
Collins Aerospace	Sensor	Specific interest
Honeywell	Sensor	Provided equipment
Interscan	Sensor	Provided sensors
IPVideo	Sensor	Provided sensors
L2 Aviation	Sensor	Provided sensors
Naneos	Sensor	Provided sensors
Pall Aerospace	Sensor	Provided sensors
Pegasor	Sensor	Provided sensors
Piera Holdings	Sensor	Provided sensors
Teledyne	Sensor	Provided sensors
TSI	Sensor	Provided sensors

Finally, several important non-sensor companies have worked with us and assisted with the experimentation. These companies were Airbus, American Airlines, and Boeing. American Airlines provided the test facility for the ASHRAE 1350-RP APU experiments and allowed the expansion of the scope of those experiments to include additional instrumentation. Boeing and American Airlines participated in engine experiments conducted at Kansas State University.

2.4 Promising technology

The potential markers for hydraulic fluid and deicing fluid in bleed air were not determined experimentally prior to the current project. Thus, there was limited information for the preliminary review for these contaminants and the focus was on engine oil.

Deicing fluid is composed of a mixture of propylene glycol and water, typically about half-and-half, or full strength, depending on the type, plus a small amount of additives. Also, bleed air temperatures and pressures are such that much, if not all, of the propylene glycol is expected to

vaporize. Thus, propylene glycol is expected to be a strong marker for deicing fluid. However, no real time off-the-shelf propylene glycol sensor or instrument suitable for this application was identified. Likely, some of the laboratory grade spectrometer-type instruments could detect it. The potential for detecting deicing fluid is further examined in Section 5 of this report based on data that were collected.

Hydraulic fluid is intended for lower temperature service applications than engine oils and there is every reason to believe that a variety of substances is generated when it is heated to bleed air temperatures, perhaps even more so than for engine oil. The thermal decomposition data review supports this assessment. Nevertheless, data specifically for hydraulic fluid contamination in bleed air were not available prior to this project. The potential for detecting hydraulic fluid is further examined in Section 5 of this report based on data that were collected.

Potential markers for engine oil and applicable measurement methods are identified in the following subsections of this report. Most of the measurement technology identified available off the shelf is expensive, large, laboratory-grade instrumentation that may be suitable for ground-based measurements but is unsuitable for measurements during routine in-flight operations. Some of the multiple sensor systems being developed may have scaled-down adaptations of some of these technologies.

Each of the markers is addressed below.

2.4.1 Carbon monoxide

Carbon monoxide sensing is widely employed and there are many sensors available. However, most of these sensors are intended for personal protection or chemical processing applications where low-level measurements are not required. The VIPR project showed that to be useful, CO had to be measured with resolutions and accuracy well below 1 ppm and it is likely that a resolution of 50 ppb is needed. The VIPR project utilized the Alphasense CO-B4 carbon monoxide sensor and it was shown to perform well. While there are certainly other comparable sensors on the market, additional time was not spent researching CO measurement technology as it is clear it can be measured, if needed. The real question with CO is whether it is a useful marker.

2.4.2 TVOC

Like CO, there are a large number of TVOC sensors on the market as TVOC is widely measured for indoor environmental evaluations. Many of these sensors are metal oxide based and are of questionable utility for this application. There are also a number of PID-based instruments

available. Hand held devices generally do not have the resolution and detection limits needed for this application. Some of these PID instruments, such as the ppbRAE 3000 instrument, have specifications that indicate they are capable of detecting and resolving TVOC in the necessary range but need to be evaluated in actual bleed air experiments. Like CO, the bigger question is not so much the availability of TVOC sensors but the suitability of TVOC as a marker, especially as a standalone marker.

2.4.3 Formaldehyde

Formaldehyde appears to have promise as a marker. In addition, because formaldehyde is a common indoor pollutant of interest, there are a number of portable formaldehyde sensors. The laboratory grade sensors identified certainly have the capability to measure formaldehyde at the levels needed. Some of the multiple sensor instruments may include formaldehyde sensing.

2.4.4 Acetaldehyde

Acetaldehyde is measured much the same way as formaldehyde. The primary difference is that there are not nearly as many sensors on the market as there is considerably less interest in acetaldehyde measurement in the indoor environment.

2.4.5 Carbon dioxide

There are a large number of carbon dioxide instruments available off-the-shelf and there is little concern about identifying suitable CO_2 sensing technology should it be desired. Carbon dioxide is not a viable marker for bleed air contamination. However, some of the other markers for bleed air contamination are also generated by combustion and the presence of elevated CO_2 levels can be used to identify ingestion of combustion products as the contaminant source rather than working fluid bleed-air contaminant sources. For this application, resolution approximately 40 ppm or better should be adequate and there are a number of instruments available with this capability. Non-dispersive infrared (NDIR) based CO_2 instruments should be suitable for this application.

2.4.6 Ultrafine particles

Ultrafine particles are normally measured with a condensation particle counter (CPC) but this technology is unsuitable for aircraft applications due to the need for liquid reservoirs that have to be filled regularly and sensitivity to orientation. Some hand-held models have minimized the orientation sensitivity but still have the reservoir issue. Laboratory grade electrical impactors are large and very expensive. However, the basic technology is well suited for this application as it is relatively rugged, is fast responding, and has the needed size range. The Protector instrument is a

scaled-down device based on this same principle and has excellent potential for this application. The Protector was effective at detecting the ultrafine particles created by oil contamination in the APU and test stand engine experiments.

2.5 Road map

As indicated in Section 2.3 of this report, while participating aircraft manufacturers and airlines were comfortable working in a large-group setting, most sensor manufacturers were more interested in collaborating singly. The interest in this approach is understandable. Proprietary information is a factor in some cases but probably is not the driving consideration in most cases. In general, sensor companies are interested in seeing their technology considered and fairly evaluated. In addition, they are interested in seeing how their technology performs in the "real world." A number of companies have technology they believe has potential application to bleed air contamination but the technology has not been tested in a true bleed air application.

Because of these considerations, the path taken had two key components: 1) one-on-one interactions with companies and 2) experimental evaluation of sensors. The APU tests were something of a test case for this approach. Four different sensor companies loaned us instruments to evaluate. We were then able to piggyback evaluations of these instruments on the experiments already being conducted for particulate measurements. No additional run time was required but considerable extra data were collected to the benefit of both the ASHRAE project and the FAA project. The sensor manufacturers also benefited, as they were able to see how their instruments performed with known contamination. This approach was followed in test stand engine experiments with even more companies participating.

Single chemical gas sensors, e.g. formaldehyde sensors, are relatively straightforward to evaluate when there are reliable specifications and there are data on the levels of chemicals to expect. Nevertheless, since the opportunities arose to evaluate such sensors and obtain data on the chemical levels present, it made sense to take advantage of those opportunities.

As our work proceeded, it became increasingly evident that lack of bleed air chemical data for hydraulic fluid and deicing fluids was a limiting factor for the project. The ASHRAE 1830-RP project is providing considerable information about the particulates that result in the bleed air with these contaminants but the intention of the ASHARE 1830-RP project was not to generate a chemical database. The collaboration described above is expected to provide some chemical data but likely will be limited. Additionally, chemical decomposition data were reviewed to identify potential chemicals that will result from these contaminants. However, the pressure and temperature conditions for the chemical decomposition data are not the same as in bleed air

systems. While the decomposition data can provide guidance, they are not expected to provide accurate data on the concentrations of these chemicals. Thus, some limited sampling and laboratory analysis was included in test-stand engine experiments conducted through collaboration with ASHRAE 1830-RP.

3 Establishment of a cross functional working group for sensor technologies, standards and experiments

3.1 Introduction

As part of the overall goals to gather and assess available information that will be useful in identifying and evaluating technology with potential application for detecting bleed air contamination by engine oil, hydraulic fluid, and deicing fluid, the project was tasked with forming two working groups. One working group was to be with the sensor industry and the other focused on specific organized activities, i.e., SAE E31B, ASHRAE 1830-RP, and EASA-FACTS. As the project progressed, it became evident that there was considerable overlap between these two groups. That is, many of the companies that produce potential sensing technology or are potential users of this technology are also active in SAE E31B or ASHRAE 1830-RP. (EASA FACTS is not currently active). Thus, a single industry group was formed.

The activities of the overall working group are described followed by a review of the status of the sensor evaluations. This review is then followed by a description of the activities related to ASHRAE 1830-RP and SAE 31B. Finally, some implications of findings to date are discussed.

3.2 Working group

The project statement of work envisioned two working groups, one group associated with the sensor industry and the air transportation industry (subtask 2.1) and a second group associated with the ASHRAE 1830-RP project, the SAE E31B committee, and the EASA FACTS project (subtask 2.2). It became evident that there was considerable overlap between the two groups and that it would be counterproductive to attempt to form a working group specifically for the organized activities. Both the sensor industry and the organized activities are represented in the single working group that was established. However, separate from the working group, collaborations with ASHRAE 1830-RP and SAE E31B were established. Those activities are reported in sections 3.3 and 3.4 of this report.

The EASA FACTS project was conducted during 2017-2020. Dr. Byron Jones, from the Kansas State research team, served on the Scientific Advisory Committee for the FACTS project.

Additionally, Dr. Sven Schuchardt of Fraunhofer Institute for Toxicology and Experimental Medicine was contacted. Fraunhofer was the lead organization for the EASA FACTS project and Dr. Schuchardt is very familiar with the project. He is also familiar with the EASA planning for a follow-on project.

Twenty-one companies were identified as being part of the working group and are listed in Section 3.2. Of these companies, 14 are sensor manufacturers, three are aircraft manufacturers, two are engine manufacturers, two are environmental control system (ECS) manufacturers, one is an airline, and one is a research laboratory (one company has multiple functions). Several additional companies participated later on in the project as indicated in Table 50.

A webinar was held on November 2, 2020. This webinar was aimed at a very broad audience and was intended to inform people about the project and to gain industry support and collaboration for the project. This webinar was discussed in Section 3.6 of this report and will not be discussed further here. A second webinar was held on January 14, 2021 and was limited to the working group, the FAA, and the ACER team[2]. The companies invited and the companies that participated are listed in Table 50. The second webinar was used both to share relevant data with the working group (including the most recent data collected in collaboration with ASHRAE 1830-RP) and to hear from industry about available technology as well as get industry input on the current project. Several important takeaways from the webinar and the SAE E31B committee were identified and described below.

- None of the measurements conducted in the phase 3 of the VIPR project (VIPR3) nor in the ASHRAE 1830-RP project at the time of the webinar have specifically addressed contaminants in combination. That is, only one contaminant at a time, either engine oil, hydraulic fluid, or deicing fluid, had been addressed. As was shown in the data presented in the second webinar for the current project, different contaminants have different characteristics with respect to both the particulates and gasses seen in the bleed air. Mixtures of these contaminants may reflect the characteristics of the individual contaminants or may be completely different. It all depends upon the mechanisms involved in forming the substances seen in the bleed air, which are not fully understood. Thus, it is important to address mixtures. A single mixture experiment with engine oil and hydraulic fluid was conducted in collaboration with ASHRAE 1830-RP. This

[2] The "ACER team" refers to the research team conducting the current project and consists of Byron Jones (PI), Kansas State University, Ruel A. Overfelt, Auburn University, Sin Ming Loo, Boise State University, and Richard Fox, Aircraft Environment Solutions. All were participants in the original FAA Air Transportation Center of Excellence for Airliner Cabin Environment Research, which is now a graduated center.

experiment showed that this mixture behaved very similar to engine oil by itself at least with respect to particle markers. Additional mixture experiments may be warranted.

- While deicing fluid is difficult to detect and likely is not as serious a concern as oil and hydraulic fluid, industry participants in the webinar indicated it may cause other contaminants that have been deposited on ECS surfaces (i.e., heat exchanger surfaces in particular) to be released. Presumably, this information is based on their own observations. This phenomenon is something that was not evaluated fully in the current project, but it should not be overlooked in future research.
- Similarly, changes in the operating mode of the ECS can result in release of contaminants that have been previously deposited on ECS heat exchanger surfaces. In particular, when the ECS goes from cooling mode to heating mode, contaminants that have condensed or otherwise deposited onto ECS surfaces can be driven off. While not long lived, the result can cause fume events in the aircraft. These contaminants would be expected to have come from the bleed air originally, but the deposition and release process can increase the intensity of the fume event. This phenomenon is also a factor in deciding where to locate sensors. In general, the further upstream the sensors are located the better they are at identifying the source of any contamination detected. However, if low-level contamination from an engine (below a sensor's detection limit) accumulates in the packs and is then released rapidly from the pack to create a fume event, sensors upstream of the pack would incorrectly indicate that the resulting fume event is not bleed air based when it actually is. Limited investigation of this phenomenon was conducted in collaboration with ASHRAE 1830-RP. It is something that should be considered in any future research.
- Carbon dioxide is often mentioned as a potential means to address the confounding that can occur from ingestion of aircraft and other engine exhaust fumes. That is, engine exhaust can be ingested into the engine and result in markers in the bleed air that may be similar to those that result from oil and hydraulic fluid contamination. Available data show pretty clearly, that measurable increases in CO_2 do not result from these latter contaminants in the bleed air. Engine exhaust measurements have clearly measurable elevation of CO_2. However, it has not been shown whether CO_2 measurement will actually be sufficiently sensitive to identify markers resulting from exhaust ingestion. Since this resolution between bleed air contaminants and exhaust ingestion is important, especially for ground operations, it is important to answer the question as to whether or not CO_2 measurements can resolve the confounding. The ASHRAE 1830-RP experiments showed that CO_2 does respond substantially to engine exhaust ingestion and

does not respond to the contaminants assessed. Thus, increases in CO_2 over background appears to be a good way to discriminate exhaust ingestion from engine oil and hydraulic fluid contamination.

- The discussion of exhaust ingestion has also led to the conclusion that we need to routinely measure CO_2 in the bleed air on the KSU test engine as it sometimes ingests exhaust under certain wind conditions. The CO_2 measurement can help to ensure data integrity particularly for low-level oil contamination measurements when the oil-generated markers do not overwhelm the ingestion effects.
- The effect of humidity may be important. In general, airlines find that they have more odor problems in high humidity situations. In addition, some sensors have problems in low humidity environments, such as in an aircraft cabin in-flight. It will be difficult to experimentally evaluate sensors in low humidity environments with the planned experiments, but it may be feasible to add water spray to the engine inlet air to create high humidity. It is unclear whether the humidity impacts the amount of contamination, affects the substances that result in the bleed air from the contamination, or just affects the odor sensitivity of people. Elevated humidity may also have the effect of releasing contaminants accumulated on ECS surface similar to the effect of deicing fluid described previously.
- Pall Aerospace has developed an advanced cabin air quality measuring instrument, the Pall CAQS MK-1 Sensor, which may be effective for bleed air contamination detection and identification. It will still need to be tested or test data provided but, initially, it appears promising. This instrument uses a measurement principle that was not previously considered.

As discussed in Section 2 of this report, multiple companies provided sensors to include in the ASHRAE 1830-RP APU and test stand engine experiments. That work helped gain valuable information as to what sensors worked well for APU conditions.

3.3 Experimental sensor evaluation ASHRAE 1830-RP

The collaboration with ASHRAE 1830-RP allowed for more experimental evaluation of sensors than was originally envisioned. Otherwise, manufacturer data and specifications would have been our primary basis for sensor evaluation and the decomposition data would be our primary means of assessing what needs to be sensed and the likely concentrations that need to be detected for chemical markers. Most sensor manufacturers have not evaluated their sensors in an actual bleed-air contamination environment. The collaboration with ASHRAE 1830-RP was mutually

beneficial as it provided information about chemical markers as well as particulate markers. Likewise, collaborations with sensor companies were mutually beneficial. This activity provided the project with data on how a variety of sensors responded to different contaminants at various concentrations and over a range of engine speeds. Most sensor companies would not otherwise have the opportunity to collect such data. For rather obvious reasons, the sensor evaluation is important for this project. Much of the experimental evaluation that was previously anticipated to occur during the next phase of the project was completed through the collaboration with ASHRAE 1830-RP.

As reported previously, data were collected with seven different contaminants in the ASHRAE 1830-RP APU and test stand engine experiments as described in Table 51. In addition, a wide range of contaminant concentrations was evaluated, ranging from 1 ppm by mass to 10 ppm by mass. Figure 23-31 present selected results from these experiments and are representative of the results observed for the contaminants addressed.

Table 51. Contaminants included in the APU and test stand engine experiments

Contaminant	**Concentrations in Inlet Air (ppm by mass)**
Eastman 2197 Engine Oil	1, 3, 5
Eastman 2389 Engine Oil	3,5
Mobil Jet II Engine Oil	1, 2, 3, 5
Skydrol LD4 Hydraulic Fluid	3, 5, 10
Skydrol PE5 Hydraulic Fluid	3, 5
Deicing Fluid Type 1 (50-50 with water)	10
Deicing Fluid Type 4 (full strength	10

All three engine oils have a large response for ultrafine (<100nm) particles. The results for all three oils were similar with Eastman 2389 having a somewhat lesser but still large response. Figure 23 shows the size distribution for Eastman 2197 as measured on the APU. Figure 24 shows the size distribution for both Eastman 2197 and Mobil Jet II as measured on the test stand engine. Results indicated that the number of particles present in the general range of about 50nm was two to three orders of magnitude greater than with zero contamination. This response of the engine oils extends up to fine particles (>100nm) as well but at a lesser relative magnitude as seen in Figure 23. This strong response continues up to about 1μm as seen in Figure 25 and Figure 26.

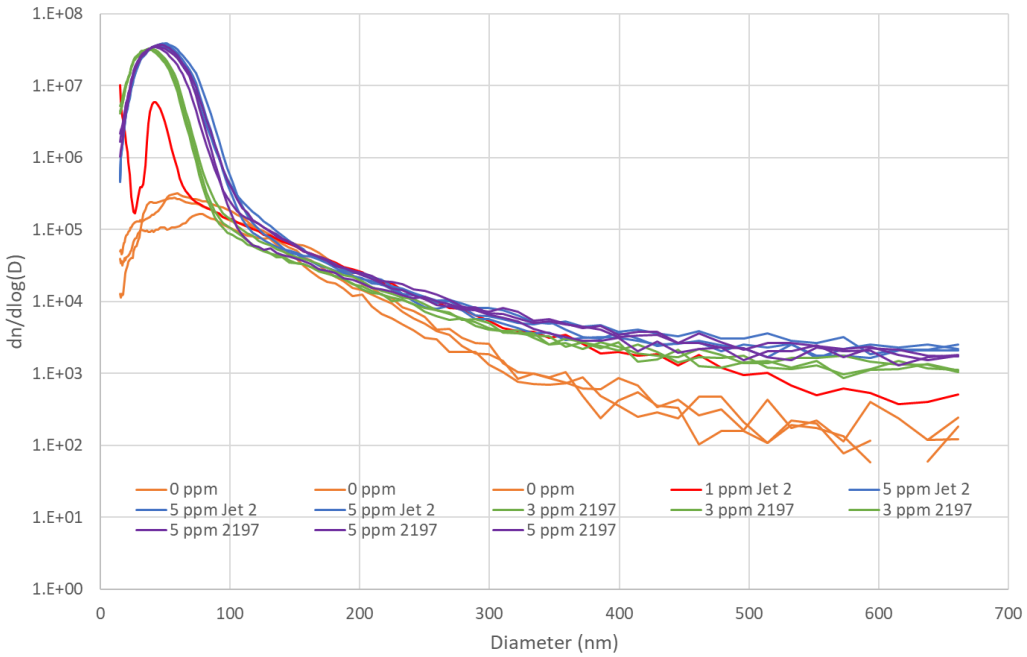

Figure 23. Size distribution for Mobil Jet II and Eastman 2197, measured by SMPS on test stand engine.

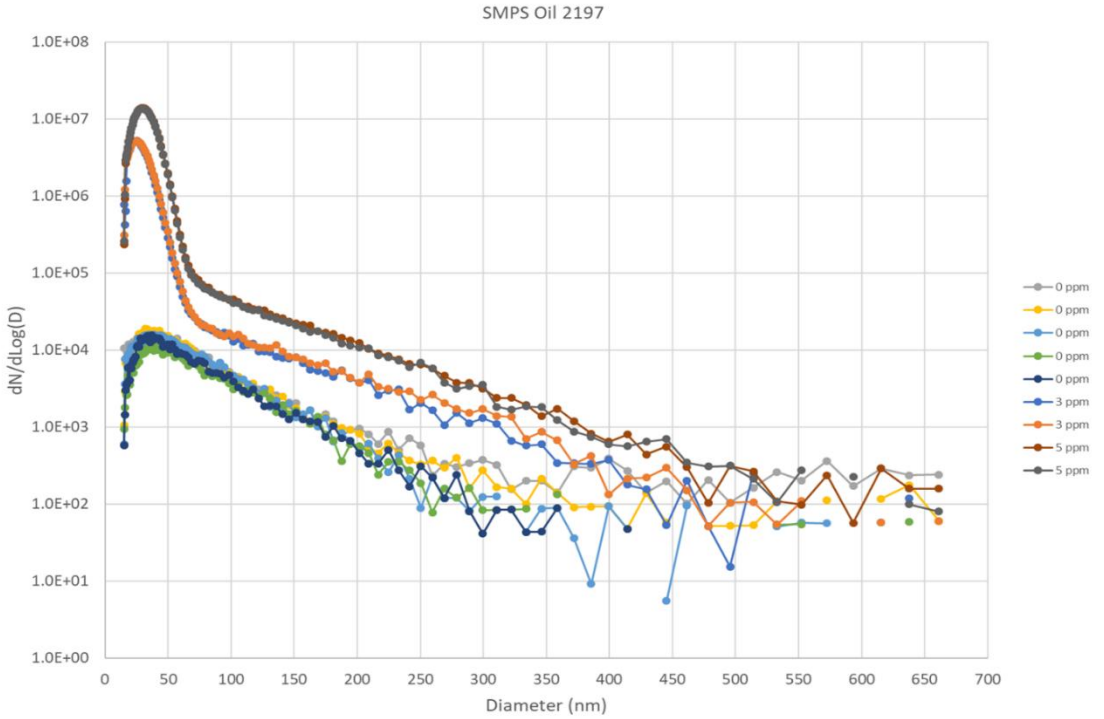

Figure 24, Particle size distributions for Eastman 2197 engine oil, measured by SMPS on APU.

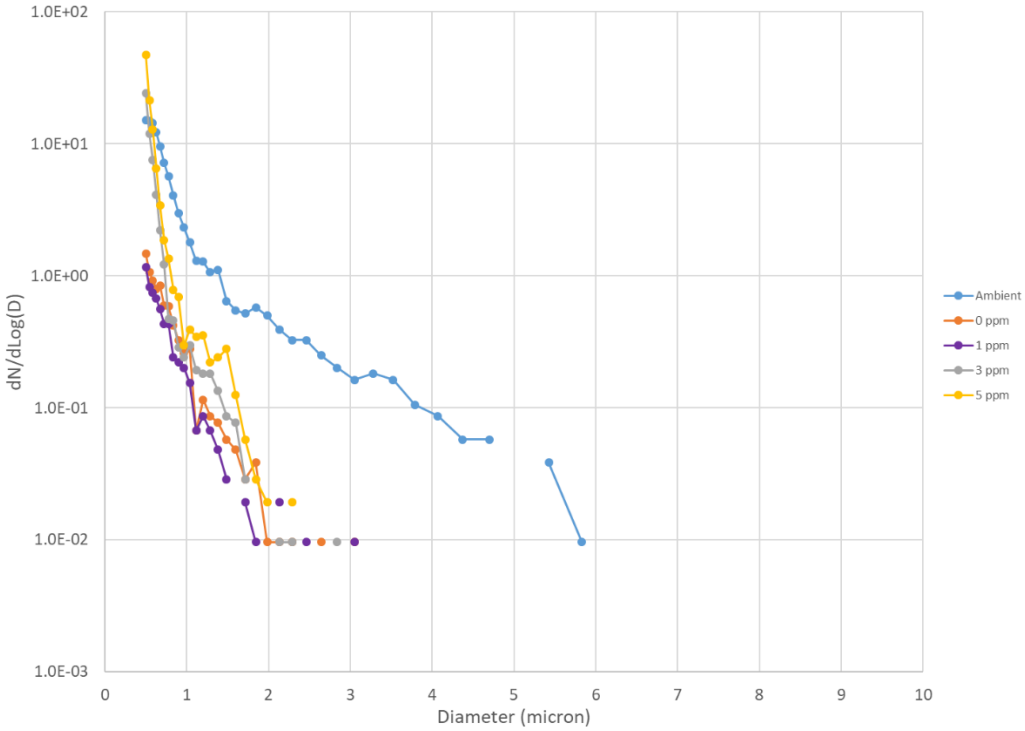

Figure 25. Particle size distribution for Eastman 2197 engine oil, measured by APS on APU.

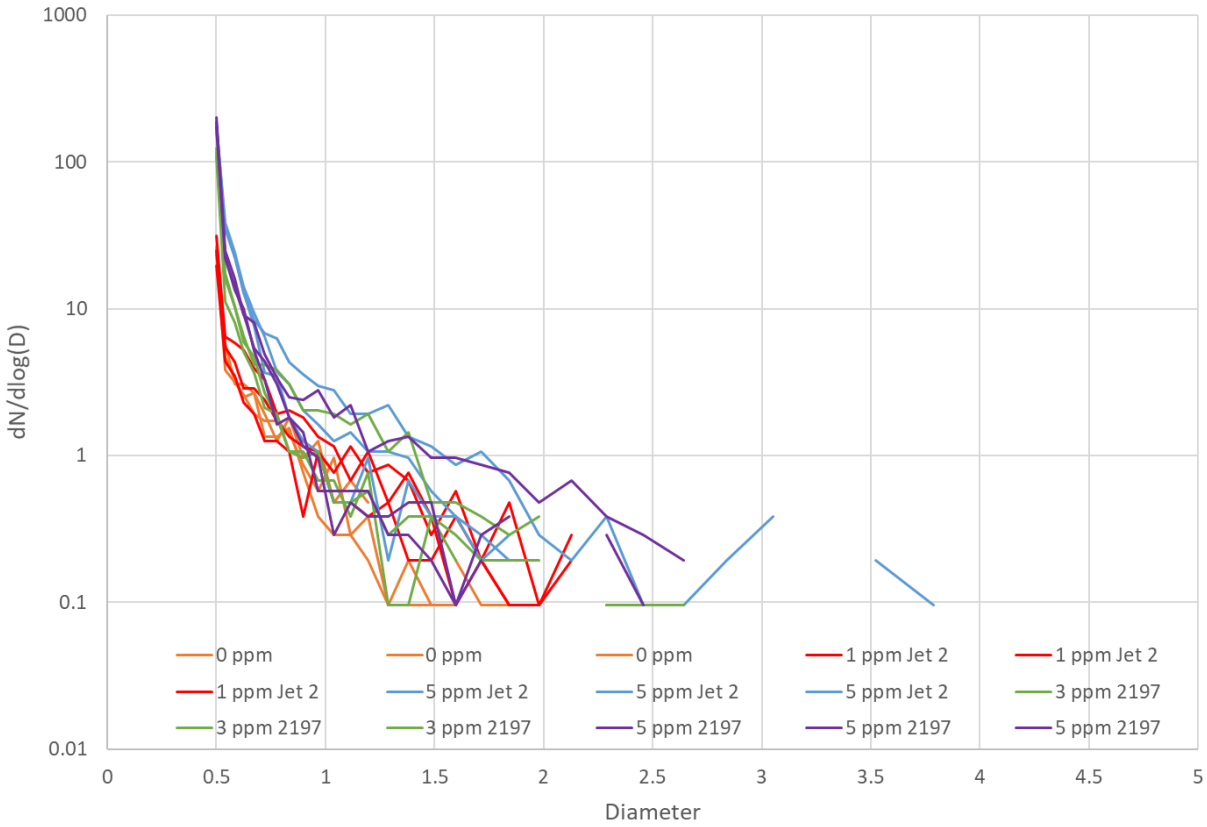

Figure 26. Particle size distribution for Mobil Jet II and Eastman 2197, measured by APS on test stand engine.

In comparisons, hydraulic fluids show no clearly measurable response for ultrafine particles for the APU experiments as seen in Figure 27. For the test stand engine experiments, there was a modest increase in ultrafine particles as seen in Figure 28 but not nearly as much for the oils. However, the hydraulic fluids have responses were similar to or greater than the response for oils in the fine particle range, again up to about 1μm as shown in Figure 27 to 30.

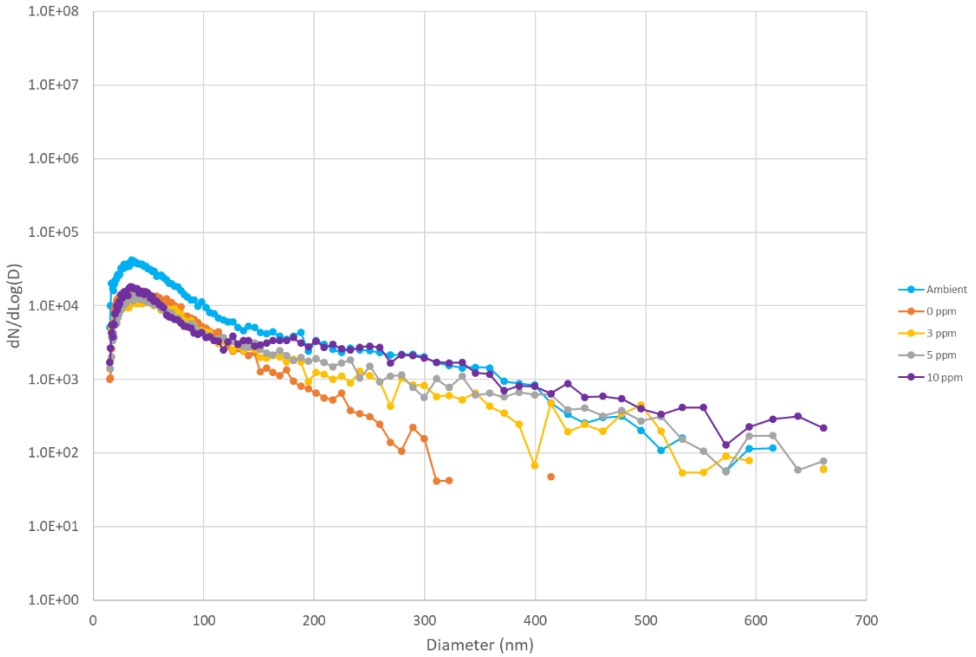

Figure 27. Particle size distribution for Skydrol PE-5, measured by SMPS on APU

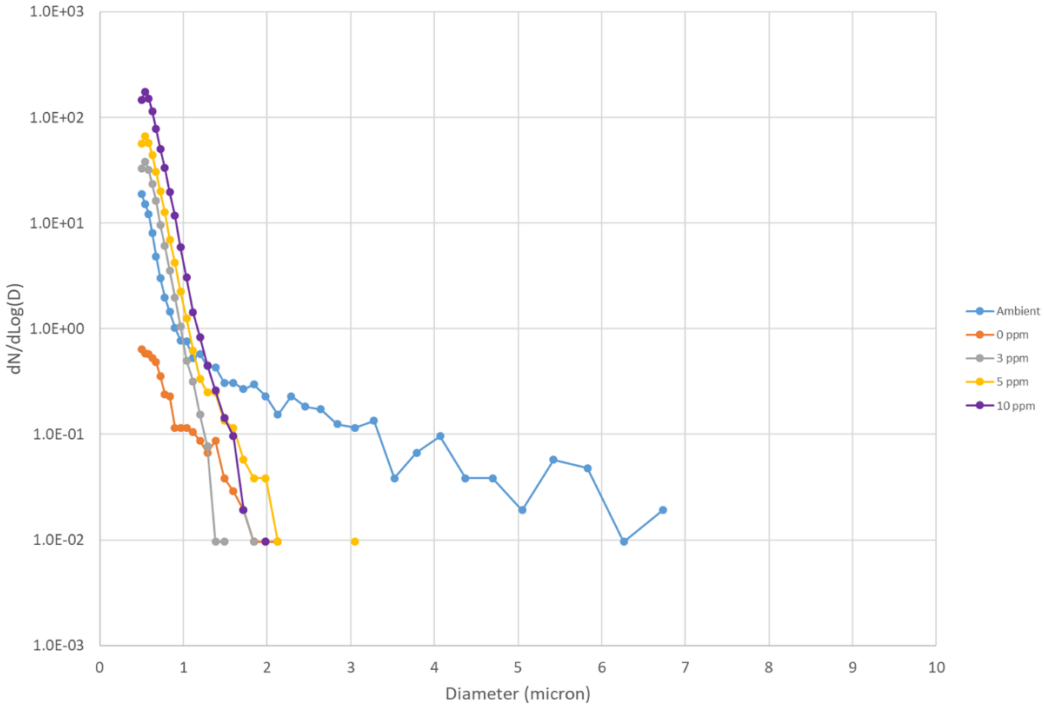

Figure 28. Particle size distribution for Skydrol PE-5 hydraulic fluid, measured by APS on APU

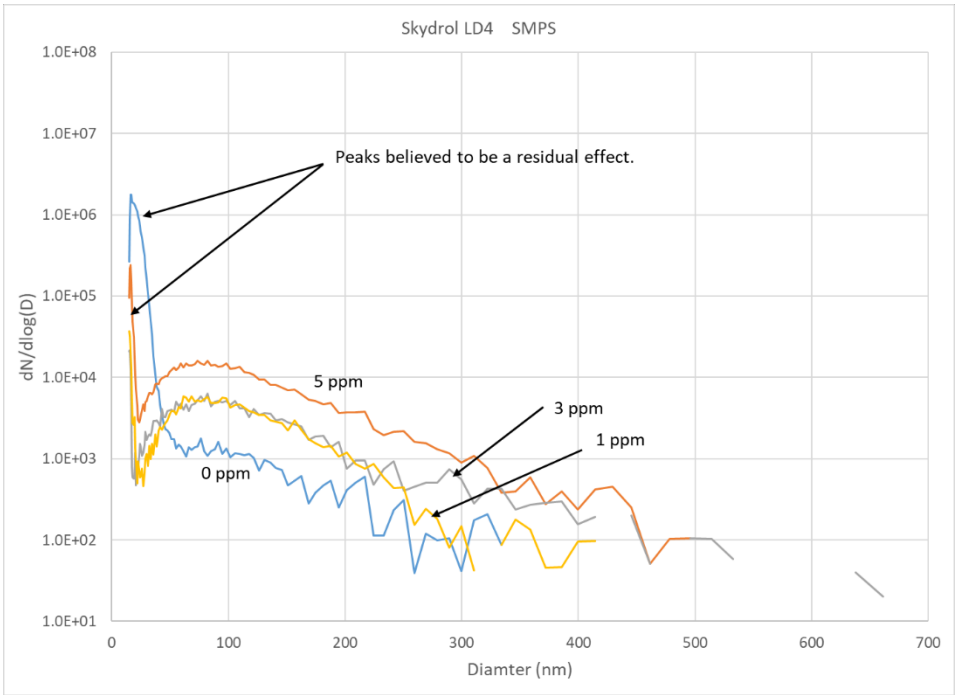

Figure 29. Particle size distribution for Skydrol LD-4 hydraulic fluid, measured by SMPS on test stand engine.

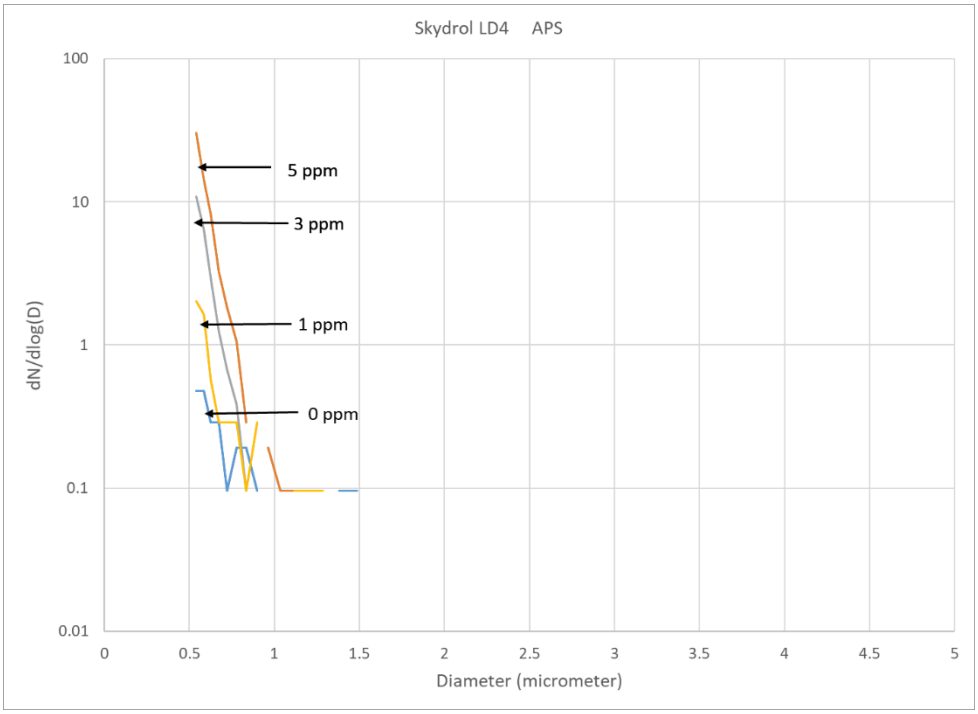

Figure 30. Particle size distribution for Skydrol LD-4 hydraulic fluid, measured by APS on test stand engine.

No consistently measurable increases in particles of any size were observed with either of the deicing fluids tested as shown in Figure 31 and Figure 32. This response is not surprising since the deicing fluids tested are comprised of propylene glycol or an approximately 50-50 mixture of water and propylene glycol with only a small fraction of additional additives. Both water and propylene glycol boil at the temperatures and pressures present in the bleed air and, thus, they would be expected to become gasses and not form particles. It was concluded from these experiments that neither fine nor ultrafine particles are a useful marker for deicing fluid contamination.

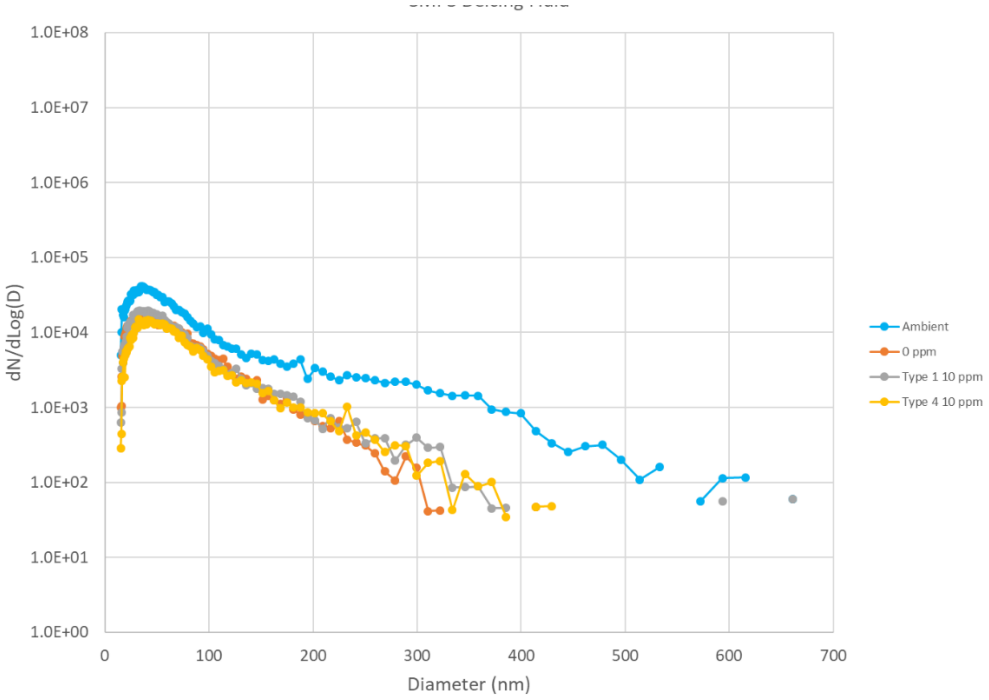

Figure 31. Particle size distribution for deicing fluids, measured by SMPS on APU

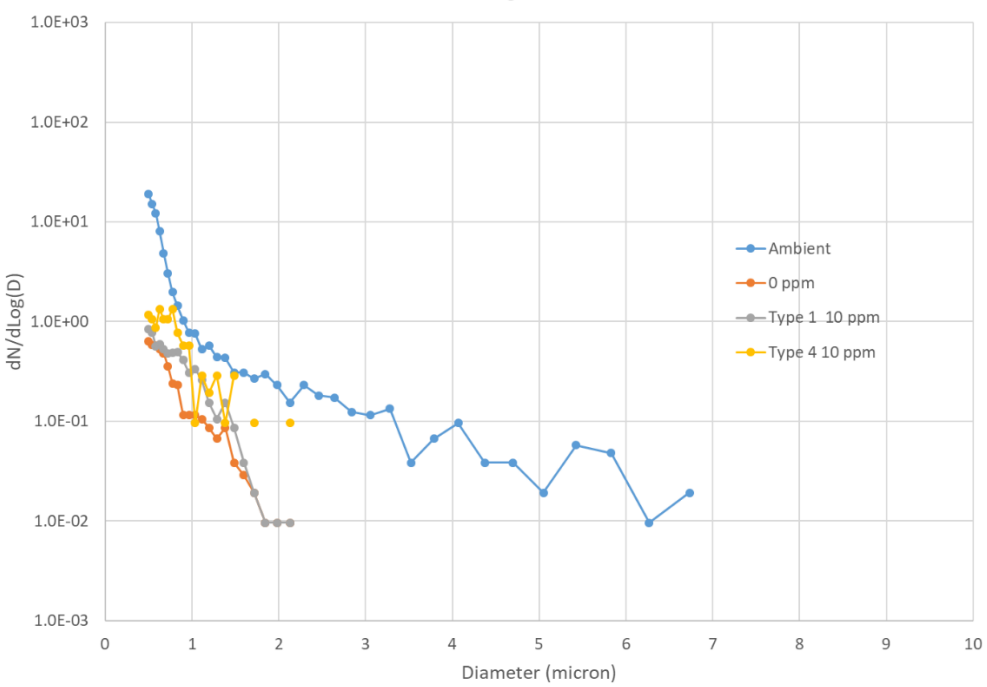

Figure 32. Particle size distribution for deicing fluids, measured by APS on APU.

It is important to note that the baseline condition with zero contamination is well below ambient particle concentrations for the fine particles. Sometimes, even with substantial contamination, the concentrations are below ambient conditions. This result is very important as it shows that comparison to ambient air is not a valid approach to detecting contamination using fine particles. The exact consequences of this result have not been fully assessed but it could result in the need for an engine specific baseline for fine particles. The fact that the engine compressor removes most of the larger particles from the air is nothing new as suspended particle impaction and deposition is a common problem in gas turbine engine operation. However, these results of these experiments clearly document the extent to which liquid particles are removed by the compressor. The exact particle generation and particle removal phenomena involved are not well defined. It was postulated in the VIPR3 project that the particles are generated because of an oil-film building up on the compressor blades and other engine surfaces. Particles are then sheared off from the firm surfaces by the high shear forces due to the high velocity air, or are generated as droplets when the film flows off the trailing edges of the blades. The experiments conducted on the APU, as part of ASHRAE 1830-RP (where it took a very long time for particles to appear in the bleed air at very low contamination rates) is consistent with this explanation. The very different behavior of hydraulic fluid suggests a different mechanism. The ability to form a film on surfaces to provide lubrication is a critical attribute for engine oil. However, hydraulic fluid

serves a very different function and consequently may not have the same film forming and droplet shedding properties. Hydraulic fluid particle (droplet) generation may be a result of large droplets affecting high-speed blades and being broken into smaller particles.

The hypothesis that the ultrafine particles are generated by shearing effects within the compressor was brought into question by experiments conducted in collaboration with ASHRAE 1830-RP. Since the bleed air is hot when it is extracted from the engine, 200^{o}C – 300^{o}C (400^{o}F – 570^{o}F), it must be cooled before it is supplied to the various instruments. This arrangement is not totally unlike an aircraft where the bleed air flows directly to the pre-cooler before being ducted to other parts of the aircraft. It was hypothesized that some contaminants may condense or otherwise deposit on the bleed air cooler and then be released upon temperature changes such as occurs when bleed air temperature increases. Several experiments were conducted to explore this effect. Figure 33 shows the results for an experiment where the cooling air to the bleed air heat exchanger was restricted, which resulted in the heat exchanger warming. It is seen that both ultrafine and fine particles very similar to those seen with engine oil resulted. It is also seen that the effect is transient. There is a big surge in particles upon initial heating but the concentration had already dropped substantially before the maximum temperature was achieved. Clearly, these particles were not generated by shearing from surface films by high speed airflows.

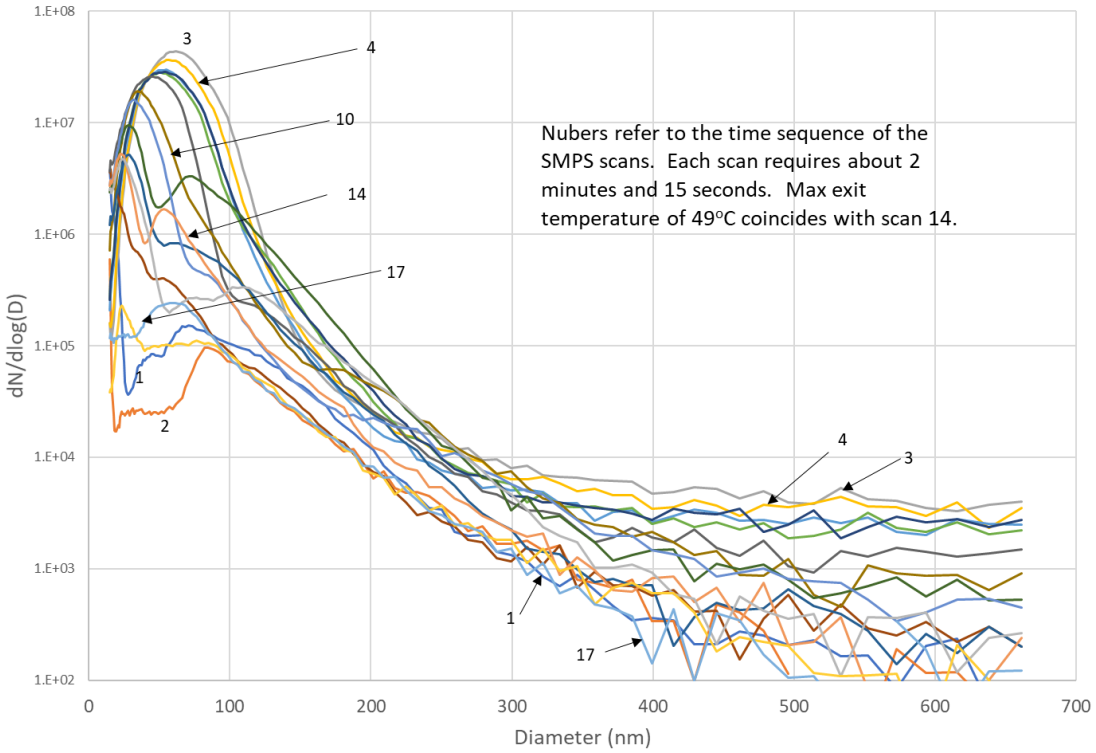

Figure 33. Size distribution of particles generated by allowing the bleed air heat exchanger on test stand engine to warm, measured by SMPS.

Whether or not the shearing hypothesis is correct has little bearing on this project. It is not as important as to how particles are generated. The important consideration is whether particles are reliably generated. The experiments do clearly show that heat exchanger surfaces can be a source of particles and, likely, can be the source of fume events. Presumably, the original source of the substances being released were from bleed air contaminants, likely oil. However, these experiments show that there may not be a one-to-one correspondence between the presence of particulates and contamination in the current source of bleed air. Accumulated contaminants can be released when bleed air temperature increases or even when there is a switch to APU air from ground air sources. The fact that particles are released when a heat exchanger temperature increases is not necessarily bad since they can serve as a marker for this contamination and a possible fume event that may result. : It does mean that the bleed-air fume event process may be more complex than originally thought and may also make the detection of the underlying contaminant more complex.

The data collected in VIPR3 and ASHRAE 1830-RP to date do not show evidence of smoke particles being generated from contaminants. The removal of ambient air particulates is likely due to impaction and sticking of particles on compressor blades. Ambient air particles are believed to be mostly solids, which would be expected to behave differently than liquid contaminants; that is, they do not form liquid films on the surfaces. In addition, dust fouling of compressor blades for land-based turbine engines is a long-standing operational issue. It should be no surprise that the aircraft engine compressors also remove particles from the air. They just spend most of their operational hours in pristine air with minimal dust as compared to land-based engines so it is not as much of a problem. It should be understood that this discussion of particle generation and removal is speculative in nature. Experiments to provide clarity about these phenomena likely would be challenging and expensive. Given that the goal of the current project is detection, describing the result is more important than fully exploring the phenomena that generate that result.

The strong response of fine particles greater than 300 nm is a good outcome as particles of this size and larger can be detected with the simpler and more flexible optical methods. In general, optical techniques are more adaptable and do not require a complex condensation particle counter. One additional instrument with optical detectors was included in the experiments and responded similarly to the APS in response to the oils and hydraulic fluid. Another instrument used a corona discharge method to detect ultrafine particles without resorting to a CPC. It responded to the oils similarly to the SMPS. Thus, it appears promising instruments are available that can detect both oil and hydraulic fluid and, potentially, discriminate between them.

Deicing fluids were only evaluated at five and 10 ppm concentrations as previous KSU engine experiments produced no clearly measurable particle concentration increases in response to deicing fluid contamination as shown in Figure 31. The APU experiments also found no measurable increase in particle concentrations with the deicing fluids. Thus, it is clear that particulates are not a good marker for deicing fluid.

The instrumentation provided by the sensor manufacturers included a wide variety of chemical sensors including photoionization detectors (PID), ceramic metal oxide sensors (CMOS), metal oxide sensors (MOS), and an ion mobility spectrometer (IMS). These types of sensors come in a wide variety of configurations. Sensor sensitivity can be adjusted to specific response ranges. Thus, one sensor of a given type is not necessarily representative of all sensors of that same type. This uniqueness is one reason why it is important to evaluate specific instruments rather than generic instruments.

The temperatures for APU bleed air are low, typically in the 200C-220ºC (392-428ºF) range, and are not expected to generate significant decomposition of oil or hydraulic fluid based on the decomposition data reviewed. On the other hand, the temperature is sufficient to vaporize deicing fluids, which are primarily propylene glycol and water. In general, the responses of the chemical sensors individually did not reliably detect the contaminants under these conditions. Nevertheless, the Aerotracer instrument, which uses multiple sensors and proprietary software to analyze the outputs, was able to detect all of the contaminants and responded differently at the different contamination levels. Aerotracer's positive ion IMS sensor exhibited a significant response to deicing fluids.

The bleed air temperatures for aircraft propulsion engines are much higher some of the time, typically around 300ºC maximum. The decomposition data indicate that the off-gassing from oils and hydraulic fluids will be several orders of magnitude higher at these temperatures. Thus, it is anticipated that chemical sensors will be much more responsive to oil and hydraulic fluid contamination at these temperatures.

As with all ASHRAE research projects, a project monitoring subcommittee (PMS) was established to oversee the conduct of this project. Most decisions related to the collaboration, sharing of information, and such are in the hands of the PMS. The PMS for 1830-RP consists of Dr. Richard Fox, Stephen Trent (Boeing), and Ben Thiesse (American Airlines). Dr. Fox is a member of the research team for the current project and Mr. Trent and Mr. Thiesse are both part of our working group. This close association between the ASHRAE PMS and participants in the current project has facilitated the collaboration and eliminated a lot of delays and bureaucracy. The interaction between the two projects was seamless.

3.4 SAE 31B

While there are no formal collaborative agreements between the SAE E31B committee and the current project, there has been collaboration with individual committee members. Dr. Fox chairs the SAE E31B committee and Byron Jones is a committee liaison so both are fully aware of the activities and information developed by the committee. In addition, several companies that participate in SAE E31B are represented on the working group. The collaboration is a two-way arrangement. On January 12, 2021, Byron Jones provided a detailed presentation to the committee describing the current project and collected data. This presentation resulted in considerable feedback from committee members, which paralleled the webinar feedback. This is not surprising since a number of the same people were involved. Feedback was not differentiated from the two sources in Section 3.2 of this report, and is not repeated here.

3.5 Looking forward

The results of the ASHRAE 1830 project thus far are promising, at least for engine oils and hydraulic fluids. Data continue to become available through the collaboration with ASHRAE 1830-RP. As an example, it appears the Partector instrument, which detects both fine and ultrafine particles, should be able to detect oil and hydraulic fluid with minimal adaptation. This particular product is not pointed out here to recommend it over other instruments, rather, it is identified to make the point that there is every reason to believe that instruments and measurement methods will be identified that can detect bleed air contamination at low levels. As indicated previously, the Pall instrument appears to be promising and was able to detect contaminants in the test stand engine experiments. The Aerotracer is able to detect contamination but it requires a skilled operator for effective use and also can be overly sensitive if not operated properly. Nevertheless, the Aerotracer does show that appropriate chemical sensors can detect the contaminants. At higher temperatures, it is anticipated that a variety of sensors will be able to detect the contaminants. The key point here is that the current project, and future phases, can focus on the best ways to detect contamination and not be overly concerned about whether or not detection is feasible.

There is a wide range of envisioned detection implementation scenarios. These scenarios range from simple binary detection, much like a smoke detector, that indicates there is contamination present somewhere in the bleed air stream, to very sophisticated systems that identify the contaminant (e.g., oil, hydraulic fluid, etc.), the source location (e.g., left engine, right pack, etc.), and the severity of the contamination. The options, of course, depend on instrumentation capabilities. Results to date are encouraging and a wide range of options may well be feasible. It probably is not necessary to down select to a single scenario for the current project; however, different instruments may be more appropriate for different scenarios and recommendations for the instruments to be addressed for future research depend on the specific scenarios envisioned.

As the ASHRAE 1830-RP project proceeded and, particularly, as minimum detection levels were better understood, the importance of a “clean” engine became apparent. The test engine must be in excellent operating condition with respect to compressor seals and other potential sources of bleed air contamination. If the test engine itself is generating contaminants, then it is difficult to evaluate the effect of the controlled contaminants injected, especially at low concentrations. This need for a clean engine should be addressed when testbed selections are made for future phases. As the project moves to on-aircraft experiments in future phases, it is not only the engine that needs to be clean, but the entire air path from engine to cabin needs to be clean as well, as accumulated contaminants in the packs and elsewhere can be released under some operating

conditions. These considerations may place limits on the aircraft that can be used for such experiments.

3.6 Industry webinar registration and attendance

As part of the interaction with the Industry Working Group, a webinar was held in January of 2020. The workshop was used to explain the project to the working group, to present preliminary results that had been obtained, and to obtain feedback and other information from industry participants. A list of the industry participants may be found in Table 52. This list does not include ACER and FAA participation.

Table 52. Industry webinar registration and attendance

Company Name	**Business Type***	**Attendance**
Aeris Technologies	Sensor Manufacturer	**
Airbus	Aircraft Manufacturer	X
Airsense Analytics	Sensor Manufacturer	X
Alphasense	Sensor Manufacturer	**
American Airlines	Airline	X
Boeing	Aircraft Manufacturer	X
CH Technologies	Sensor Manufacturer	X
Collins Aerospace	Sensor Manufacturer	X
Embraer	Aircraft Manufacturer	**
Enmet	Sensor Manufacturer	**
Fraunhofer	Research Laboratory	X
Honeywell	ECS Manufacturer Engine Manufacturer Sensor Manufacturer	X
IPVideo	Sensor Manufacturer	X
L2 Aviation	Sensor Manufacturer	X
Liebbherr	ECS Manufacturer	X
Naneos	Sensor Manufacturer	X
Pall Aerospace	Sensor Manufacturer	X
Pratt & Whitney	Engine Manufacturer	X
TDG Aerospace	Sensor Manufacturer	X
Teledyne	Sensor Manufacturer	X
TSI	Sensor Manufacturer	X

* Business type with regard to this project. Some companies have additional business functions.
** Participation records are unclear as to whether this company participated.

4 Plan engine stand tests

4.1 Introduction

The objective of the test stand engine plan is to provide the range of contaminants, contamination rates, and the range of conditions that are recommended for evaluation by engine-stand testing.

There is an infinite number of combinations of possible test conditions and contaminants that could be examined. The three primary factors considered in developing the test plan were: (1) determining the specific contaminants to be included in the testing, (2) determining the concentrations of these contaminants to be used in the testing, and (3) determining the engine operating conditions for the testing. A number of other factors that must be considered in developing a test plan. In addition to presenting a test plan for test stand engine testing, this section discusses these factors and explains the rationale for the plan developed. The specific instrumentation to be included are addressed in Section 5.2 of this document.

4.2 Contaminants

The focus of this project is on engine oil, hydraulic fluid, and deicing fluid. While this direction may appear focused, there are still many possibilities. For example, Table 53 lists examples of turbine engine oils from three of the major brands and Table 54 lists examples of hydraulic fluids from four major brands. These lists are not all-inclusive and are provided to illustrate the numerous engine oils and hydraulic fluids available. Not all oils are intended for the same purpose. Some are for APU applications, some for turboprop engines, some for helicopter engines, and some are oils for aircraft jet propulsion turbine engines.

Table 53. Example oils from three major brands

Brand	**Product Names**
Mobil	Jet Oil II
	Jet Oil 254
	Jet Oil 387
BP Eastman	Turbo Oil 2197
	Turbo Oil 2380
	Turbo Oil 2389 (APU)

Brand	Product Names
Shell	Ascender
	EO 750 (turboprop)
	EO 555 (helicopter)
	EO 500
	EO 560
	EO 390 (APU)
	EO 308

Table 54. Examples of hydraulic fluids from four major brands

Brand	Products
Phillips 66	X/C 5606A
	X/C 5606H
Shell	Fluid 31
	Fluid 41
BP Eastman (Skydrol)	LD-4
	PE-5
	5
	500B-4
Mobil	HFA
	HyJet IV-A
	HyJet V

Deicing fluids typically are not branded and are purchased by airlines in truckload quantities given the large-volume nature of their use. Deicing fluids are divided into four generic types, Types I – IV. The following descriptions are from NASA training materials (National Aeronautics and Space Administration, 2016).

- Type I fluids are the thinnest of fluids. As such, they can be used on any aircraft, as they shear/blow off even at low speeds. They also have the shortest hold-over times (HOT) or estimated times of protection in active frost or freezing precipitation.
- Type II and IV fluids add thickening agents to increase viscosity. The thickeners allow fluid to remain on the aircraft longer to absorb and melt the frost or freezing precipitation. This translates to longer HOT, but it also means a higher speed is required to shear off the fluid.
- Type III fluids are relatively new and have properties in between Type I and Type II/IV fluids. Type III fluids also contain thickening agents and offer longer HOTs than Type I, but are formulated to shear off at lower speeds. They are designed specifically for small commuter-type aircraft, but work as well for larger aircraft.

The deicing fluids may be propylene glycol or ethylene glycol based with propylene-based fluids dominating in the United States as shown in Table 55 (U.S. Environmental Protection Agency, 2012). Type I and Type IV are used predominantly in the United States. Type I is typically diluted approximately 50:50 with water while Type IV is used full-strength. In addition to the glycol base and water, where applicable, the deicing fluids will contain small amounts of additives for corrosion inhibition, thickening, wetting agents, etc. (U.S. Environmental Protection Agency, 2012).

Table 55. Use of aircraft deicing fluids in the United States

Fluid type	**Fraction**	**Annual amount**
Type I Propylene Glycol	77.1%	19,305,000 US gal ($73,077\ m^3$)
Type IV Propylene Glycol	11.4%	2,856,000 US gal ($10,811\ m^3$)
Type I Ethylene Glycol	10.3%	2,575,000 US gal ($9747\ m^3$)
Type IV Ethylene Glycol	1.2%	306,000 US gal ($1158\ m^3$)

4.3 Operating conditions

Aircraft operate in a wide variety of ambient conditions. Ambient temperature may range from near 50°C (122°F) on the ground in hot desert environments to -60°C (-76°F) at higher altitudes. Similarly, they operate with ambient pressures ranging from one atmosphere at sea level to about 0.20 atmospheres at the higher altitudes. Propulsion engines operate over wide range of power levels from idle to "full-throttle."

The thermal, chemical, and mechanical processes that lead to various potential markers in the bleed air, whether those markers are fine particles, ultrafine particles, or various gasses or liquids are not fully understood. Certainly, temperature and pressure will affect vaporization and thermal decomposition processes. The speed of compressor blades and the airflow over those blades may affect aerosol generation and the characteristics of those aerosols. The pressure and temperature increases above ambient for bleed air are determined by the engine speed (power level). The temperature and pressure increases at a given point in the compressor are determined by engine speed for a given ambient condition. Most propulsion engines have two bleed air ports, a high pressure port and a low pressure port, to allow bleed air to be extracted at different locations in the compressor depending upon engine speed. That is, the high-pressure port will be used at low engine power and the low-pressure port will be used at high engine power to offset the speed effect to some extent. Nevertheless, the temperature and pressure of bleed air will vary considerably during a flight. Table 56 presents representative bleed-air temperatures and pressures (National Research Council, 2002). Some smaller engines do not have a low-pressure port, which will result in higher maximum temperatures.

The APU is simpler in this regard in that it is a constant speed engine that is either on or off. It is used primarily for ground operations but may be operated during flight in some aircraft. There will still be some variations in temperature and pressure of the "bleed" air it generates, depending upon ambient conditions but the variations are not expected to be as wide as for propulsion engines. Table 56 (National Research Council, 2002) shows a typical bleed air temperature for ground operations of 170°C (338°F). The temperature measured during the ASHRAE 1830-RP [3] project was a little higher, 185-195°C (365-383°F) with ambient temperatures of approximately 15°C (59°F). The APU used for this test was an "integral" APU where both the engine air and the pneumatic (bleed) air provided to the aircraft are compressed

[3] ASHRAE 1830-RP, Experimental Characterization of Aircraft Bleed Air Particulate Contamination" a research project funded by the American Society of Heating, Air-Conditioning, and Refrigerating Engineers (ASHRAE) and conducted by Kansas State University (KSU).

by the same compressor. It is expected that the temperature of the air with a “separate” APU, where the compressor for pneumatic air is separate from the engine compressor, will be lower.

Table 56. Typical bleed air conditions

Mode of Operation	**Temperature ºC (ºF)**	**Absolute Pressure, kPa (psi)**	**Extraction Stage**
Takeoff-maximum power	350 (662)	1170 (170)	Low Pressure
Top of Climb	310 (590)	690 (100)	Low Pressure
Cruise	250 (482)	340 (49.3)	Low Pressure
Initial Descent	185 (365)	200 (29.0)	High Pressure
End of Descent	230 (446)	460 (66.7)	High Pressure
Switch Over High to Low	280 (536)	480 (69.6)	High Pressure
Ground Operations	170 (338)	Not specified	APU

4.4 Other factors

The collaboration with ASHRAE RP-1830 has pointed out several other factors that need to be addressed and which were not specifically foreseen when the initial work statement for the current FAA project was formulated. The following items are not intended to be a comprehensive list of all other factors that need to be addressed but rather are ones that have been identified through the collaboration with ASHRAE RP-1830.

4.5 Environmental control system (ECS) surfaces

Environmental control systems, in particular the heat exchangers in environmental control systems, can alter the markers of contaminants, and perhaps the contaminants themselves. When heat exchangers are cold, volatile chemicals may condense on the surfaces. In addition, aerosols may deposit on heat exchanger surfaces. Under different ECS operating conditions, the heat exchanger surfaces may be allowed to get hot. As a result, some of the substances may be driven off the surfaces and back into the bleed air. This phenomenon has two important consequences. One, markers of contamination may be removed by the heat exchanger surfaces and not be detected by sensors downstream of these heat exchangers at the time the contaminants are being introduced into the engine. Two, when the accumulated contaminants are later released into the air supply, sensors upstream of the heat exchangers will not detect their presence and give a false negative indication. Sensors downstream of the heat exchangers may give a false indication of

the source engine. For example, if the contaminants accumulate during APU operation but are not released until the APU is off and the bleed air is coming from a propulsion engine, the contamination may be incorrectly attributed to the propulsion engine. This ECS effect has major implications for practical application of bleed air contamination sensing.

4.6 Contaminant mixtures

Contaminants may not necessarily occur in isolation. There may be more than one contamination source at a given time. One contaminant may accumulate over a period of time from low-level or intermittent contamination and another contaminant may cause the accumulated contaminant, whether on interior compressor surfaces or heat exchanger surfaces, to be rapidly released causing an air quality event. This releasing phenomenon is mostly speculation at this time. However, the experiments conducted in collaboration with ASHRAE 1830-RP appear to show that hydraulic fluid does clean oil from the engine and, possibly, deicing fluid does too. Whether this releasing effect would be sufficient to result in an oil-based event through the introduction of hydraulic fluid or deicing fluid is unknown. However, some data indicate there may be an initial surge of particulates when hydraulic fluid is first introduced in some cases. In other cases, it appears the hydraulic fluid just hastens the decline in particulates following cessation of oil contamination. Since these data have not been fully assessed, they are not presented at this time.

4.7 Transient response

Contamination markers do not necessarily respond immediately when contamination is introduced. This effect was seen clearly with the APU experiments for ASHRAE 1830-RP. Starting with what appeared to be a very clean engine, the initial contaminant was engine oil at a concentration of 1 ppm by mass. After about 20 minutes with no apparent response on the particulate sensors, it was initially concluded that the oil was not detectable at the 1 ppm level. Subsequent data later showed that oil was clearly detectable at the 1 ppm level. Analysis of the data is not 100% conclusive but the tentative conclusion is that some minimal oil accumulation on interior compressor surfaces is required before particulate markers are generated. It is unclear whether other potential markers such as volatile organic compounds respond more quickly.

4.8 Engine cleaning

In addition to delayed response upon introduction of contaminants, there is a similar delayed response after contaminants are no longer introduced. Data collected in collaboration with ASHRAE 1830-RP have shown that approximately 30 minutes or more of engine operation is required for markers of engine oil contamination, ultrafine particulates in particular, to return to

clean engine baseline levels. It appears that engine washing between contaminants may be necessary. However, an engine wash with soap and water conducted during the APU experiments appeared to leave a residue that took some time to clear based on particulate measurements. Since then, pure water and hydraulic fluid have also been used to clean oil from the engine. The results from these experiments have not been fully analyzed but it appears both are beneficial. Hydraulic fluid may be somewhat more effective as it acts as a solvent on the oil. However, the hydraulic fluid may take time to clear from the engine.

Initial engine cleaning prior to experimentation may also be important, especially for an engine that has operated for many years that has been exposed to unknown contaminants and contaminant levels.

4.9 Baseline conditions

Evaluating the response of sensors requires establishing a valid baseline condition for the no-contamination case. For particulate markers, especially fine particles 0.3 μm and larger, ambient conditions are not a good baseline as the compressor removes this size of particles from the air passing through it. It is unclear if this same consideration applies to chemical based markers. Even though ambient air is not a valid baseline, it can have a large impact on the baseline as gasses and ultrafine particles will pass through the compressor in many cases. Turbine engine exhaust and other engine exhaust can have a large impact on what is present in the bleed air for the no-contamination case and can be quite variable depending on wind conditions and operation of engines near the test engine. Thus, it is important to check baseline conditions frequently and long enough to establish good values and variations in those values so that contamination effects can be differentiated from changing baselines. Limits on that differentiation should established.

The engine itself is also a factor in establishing baselines. It must be established whether the engine is generating any contaminants, with oil being the only contaminant that is likely to be generated internally. In addition, its own exhaust will usually be a concern. A test engine needs to be operated over the full range of operating conditions planned for bleed air experiments to establish whether it is a source of contaminants. It may be impossible to completely isolate internal contamination from exhaust ingestion.

It should be kept in mind that the real world is not clean and any bleed air contamination sensing system will have to work in the real world, not just in an artificial pristine environment with a perfect engine. Thus, the goal with the test stand engine is not to establish a perfectly clean engine operating in a perfectly clean environment where the slightest contamination of bleed air can be detected. The ability of sensing systems to detect contamination in that setting may yield

unrealistic expectations as to how well they will perform in realistic applications. On the other hand, the engine cannot be so dirty and the operating environment cannot be so dirty that only extreme contamination can be differentiated from background levels. The goal is to have both an engine and an operating environment that are sufficiently clean that background levels are representative of actual aircraft operations.

4.10 Confounding

While the current study is focused on oil, hydraulic fluid, and deicing fluid, they are not the only causes of cabin air quality events. A recent study identified over 13 different causes. Where the cause was identified, less than half were from causes that could potentially be associated with the bleed air supply, including the ECS. Nearly half were associated with electrical systems and fans (Anderson, 2021). Bleed air contamination detection systems that sample air from the cabin could easily confuse these events with bleed air events if the markers are similar. In most aircraft, cabin air passes through HEPA particulate filters before being supplied to the mix manifold. Thus, bleed air contamination detection systems located in the mix manifold that use particulates or particulate material, as markers would be immune from this confounding but not sensing systems that use gas sensors. Sensors located upstream of the mix manifold in the supply air stream would be immune to this confounding regardless of the similarity of markers.

The preceding discussion only addresses an actual air quality event. There are numerous potential sources of confounding markers in the cabin unrelated to bleed air contamination or even air quality events in general. For this reason and for the reasons discussed in the preceding paragraph, the cabin appears to be an undesirable location for sampling any marker to detect bleed air contamination. Nevertheless, several potential sensing systems under consideration are intended to be cabin air-quality sensors and sample air from the cabin. For this reason, some knowledge of contaminants generated by electrical and fan failures and how markers or sensors respond to them would be useful to determine whether these sensing systems can differentiate bleed air contamination from oil, hydraulic fluid, and deicing fluid from these other sources.

4.11 Test plan

With so many contaminant variants, so many potential operating conditions, and the numerous other factors that need to be considered, it is clear that there is not a perfect test plan. Different knowledgeable people could arrive at very different, practical test plans. Fortunately, many of these considerations went into developing the test plan for ASHRAE 1830-RP. There was considerable industry input that went into developing that plan. We can use that test plan to

provide insights for the test stand engine test plan. Additionally, input was obtained from our industry-working group to guide the development of a reasonable test plan.

It should be noted that, given the collaboration with ASHRAE 1830-RP, a significant portion of the test plan has already been conducted. Thus, there is the advantage of hindsight in developing the test stand engine test plan. The test plan outlined in Appendix C is not formulated simply to match what has already been completed. Where different conditions are needed, where different approaches are required, and, where additional tests are needed, the test plan has been defined accordingly. The intent is to benefit from the work already completed and not to simply mimic that work.

In devising the test plan, several objectives were considered. The purpose of the test stand engine experiments is to evaluate the ability of sensors and sensing systems to detect the three contaminants in bleed air. The purpose is not to evaluate what chemicals actually end up in the bleed air or their health effects. The focus is strictly on the sensing and the ability to detect, and possibly distinguish between, engine oil, hydraulic fluid, and deicing fluid in the bleed air. This focus does not mean that it does not make sense to collect bleed air samples for various chemical analyses in conjunction with these experiments. However, the planning should be based on sensor and sensing system evaluation, not on characterizing bleed air.

The VIPR project showed that, at least for oil, concentrations of approximately 9 ppm by mass are readily detectable. Experiments conducted for ASHRAE 1830-RP also show that hydraulic fluid is detectable at these levels. Thus, there is no reason to spend time and resources examining these levels. The real question is the ability to reliably detect at lower levels and determining the minimum levels of contaminants the can be detected with reasonable certainty. The minimum detection requirement is an important question but is a separate question from the minimum detection limit. Given the minimum detection limits established by these experiments, future work may be required to determine whether they are adequate for a practical bleed-air contamination detection system.

Deicing fluid is different from engine oil and hydraulic fluid in that the primary constituent, propylene glycol (and water in Type 1), evaporates completely at the temperatures and pressures normally encountered in bleed air. Thus, particle sensors or chemical sensors that respond to liquid droplets are not expected to detect deicing fluid. In most situations, any substantial deicing fluid ingestion is expected to occur only during operations on the ground when bleed air is being supplied by the propulsion engines operating at low power or the APU. Consequently, the bleed air temperatures are not expected to be high enough to cause any thermal decomposition in these cases. Sensing deicing fluid in these cases is primarily a matter of sensing propylene glycol fumes

and nothing else. It is possible that propulsion engines will ingest some residual deicing fluid during takeoff when the engines are operating at high power. The resulting higher bleed air temperatures may result in some thermal decomposition. Given these differences, it makes sense to include higher concentrations of deicing fluid.

The complete plan is presented in Appendix C. Explanations for the rationale for specific conditions follow.

4.11.1 Bleed air temperature

The bleed air temperature is believed to be the best control parameter for engine power setting. The primary consideration is whether the engine is operating with a high enough bleed air temperature to generate thermal decomposition. It is believed that significant thermal decomposition starts when the temperature reaches 300°C (572°F) ([Unpublished data files from the VIPR3 project]). Thus, it is desired to have the high temperature tests at or above 300°C. However, as seen in Table 56, most operating conditions stay below 300°C and it is only for very brief periods that the temperature is much above 300°C. Thus, there is no reason to conduct testing much above 300°C. It is also believed that 250°C (482°F) is well below the temperature where any significant thermal decomposition occurs, at least for oil ([Unpublished data files from the VIPR3 project]). Thus, this temperature is set as an upper limit for low temperature tests. APU air will be well below this temperature as will the propulsion engine bleed-air when on the ground.

The temperatures are shown in the plan as >300°C and <250°C. However, the actual temperature should be reasonably constant from test to test, $\pm$2°C ($\pm$3.6°F). The low temperature tests shown as completed in the test plan were at a nominal value of 230°C (446°F). This value should be used for completion of these tests. When test stand engine experiments were conducted in March 2021, the maximum bleed air temperature that could be achieved was approximately 275°C (527°F) due to cool ambient temperatures. This temperature is not sufficiently high enough to expect thermal decomposition; thus, these tests should be rerun at the desired conditions.

4.11.2 Contaminants to include

It is impossible to include all of the different varieties of oil, hydraulic fluid, and deicing fluids described in Section 3 of this report. Considerable attention was given to this question in the development of ASHRAE 1830-RP and it was decided to use three engine oils, two hydraulic fluids, and two deicing fluids. The same fluids are recommended for the test stand engine tests. Explanation of this rationale follows.

Mobil Jet II and Eastman 2197 are engine oils widely used in propulsion engines. Others that are used are expected to have similar characteristics. However, using two oils will help verify that different oils of this type will indeed behave similarly. Eastman 2389 is widely used for APUs. Oils formulated for this purpose have somewhat different characteristics and potentially will behave differently as a bleed air contaminant. Thus, this oil was also included to determine if there would be a substantial difference. The APU experiments showed that Mobil Jet II and Eastman 2197 behave almost identically at least with respect to particulates generated. Eastman 2389, the APU oil, behaved similarly but some with noticeable differences.

Skydrol LD-4 and Skydrol PE-5 are both widely used in commercial aircraft with LD-4 being increasingly replaced with PE-5 according to industry sources. Unlike different engine oils for different types of engines, hydraulic fluid requirements are uniform. Thus, there is no inherent reason to expect different fluids to have substantially different characteristics. However, two different hydraulic fluids are included to verify characteristics are the same from one fluid to the next. At least for particulates, LD-4 and PE-5 respond nearly identically in tests conducted to date.

Table 55 shows that deicing fluids used in the United States are predominantly propylene glycol based Type I and Type IV. For this reason, testing is limited to these two types. Since they have different additives to achieve different properties, there is some possibility they will behave differently in bleed air but not likely. Since propylene glycol and water evaporate when subjected to bleed air conditions, they were not expected to generate particles and tests to date demonstrate that particles are not a useful marker for deicing fluid. Chemical sensors that are sensitive to propylene glycol are the only likely means of detecting deicing fluids. Both fluids are included but it is expected that the response will be similar after accounting for the different concentrations of propylene glycol.

The most likely scenarios for ingestion of APU engine oil or hydraulic fluid are through the APU. There are few scenarios where hydraulic fluid or APU engine oil will be ingested into the propulsion engine and, if they are, it likely will occur on the ground when propulsion engines are operating at low power. Similarly, the likely scenarios for ingestion of deicing fluid are during or immediately after deicing either through the APU or through a propulsion engine operating at low power. For these reasons, there is limited interest in the characteristics of these fluids in the bleed air for the higher bleed air temperatures associated with propulsion engines in flight. Hence, very few tests with these fluids are included at the higher temperature.

4.11.3 Heat exchanger

A test stand engine is not the best venue for assessing the effect of the ECS surfaces on bleed air contaminant storage and release unless it is equipped with air-conditioning packs and other ECS systems, which is unlikely for most test stand engines. Likely, fully addressing this question will have to wait on tests performed with actual aircraft. However, even on a test stand engine, the bleed air must be cooled before it is sampled or analyzed by the various instruments. One particulate sensor that can work with sample streams at bleed air temperatures was to be incorporated into the ASHRAE 1830-RP experiments but no data were obtained for it. All other sensors and instruments identified must operate at or near room temperature. For these instruments and sensors, there will always be some form of heat exchanger through which the bleed air passes prior to being sensed. Some limited assessment of the storage-release phenomenon is possible with this heat exchanger by allowing its temperature to rise after it has been subjected to contaminated bleed air. Several experiments of this nature were completed in collaboration with ASHRAE 1830 and contaminants were clearly released when the heat exchanger temperature rose. However, this heat exchanger had been in operation without cleaning for many years and subjected to known contaminants as well as unknown contaminants. For the tests included in the test plan, the heat exchanger is to be first cleaned and tested in the cleaned condition and then subjected to known bleed air contamination for known duration and then tested when contaminated.

4.11.4 Other tests

Limited tests are included for electrical insulation, as they were not part of the research requirement. In addition, a simulated fan rub is included where the fan blade material is heated to the point of smoking.

5 Develop instrument tests

5.1 Introduction

The objective in developing the instrument tests was to identify which sensing technology and instrumentation should be evaluated in the engine tests stand experiments as described in Section 4. This section of the report presents those instruments and sensors recommended to be included. Through the collaboration of a number of participating companies and in collaboration with ASHRAE 1830-RP, a significant portion of the test stand evaluations recommended was completed. The data analysis is ongoing, but some of the preliminary results are included herein.

5.2 Instruments and sensors

Instruments and sensors were selected based on three primary criteria as follows.

The first criterion is applicability of an instrument or sensor(s) to respond to bleed air contamination or its markers. For primary sensors (i.e., those sensors designed to measure a specific substance), this criterion is based on whether the substance was previously identified as a likely marker of bleed air contamination.

The second criterion was whether the manufacturer demonstrated an interest in collaborating with the project and supporting the evaluations. Several instruments were identified that were developed specifically for aircraft air-quality applications. Those manufacturers have all been eager to support the evaluations. Instruments and sensors that are not designed for this purpose likely would require some adaptation for onboard aircraft applications. If the manufacturer is uninterested in such applications, then there is little reason to pursue application of that equipment. In general, the response of manufacturers has been good and no promising technology has been excluded due to lack of interest on the part of its manufacturer.

In addition to evaluating specific instruments and sensors, it is also important to collect measurements during test stand engine experiments to document what actually ends up in the bleed air with different contaminants and conditions. Thus, the third criterion was whether an instrument or sensor provides this information. This information will assist in further identifying and selecting sensors and instruments and will assist in assessing impacts of bleed air contamination in future phases of the FAA Aircraft Air Quality and Bleed Air Contamination Detection research program. For these latter instruments and sensors, it is not essential that the manufacturer be involved but it is helpful.

Instruments and sensors can be categorized in a number of different ways. For the purpose of this report and the following discussions, instrument and sensors were divided into four groups: cabin air quality monitors, troubleshooting, particle detectors, and gas detectors.

It should be noted that equipment does not always fit neatly into one of these categories. For example, the air quality monitors typically have a number of gas sensors of various types and may have particle detectors as well.

Table 57 provides an overview of all of the sensors and instruments identified. Each instrument or sensor is described briefly in the following sections.

Table 57. Summary of instruments and sensors

Category	**Instrument**	**Substance Measured**	**Temp. Limits[1]**
CAQM	Teledyne ACES	Multiple Sensors	Not specified.
CAQM	Pall Aero MK-1	Multiple Sensors	Not specified.
CAQM	L2 Aviation-IPVideo HALO	Multiple Sensors	0-50°C (32-122°F).
Troubleshooting	Airsense Aerotracer	Multiple Sensors	32-113°F (0-45°C)
Particle Detector	TSI 3080L Electrostatic Classifier	Particle Spectrometer (Part A)	50-104°F (10-40°C)
Particle Detector	TSI 3775 Condensation Particle Counter	Part of particle spectrometer (Part B)	50-100°F (10-38°C)
Particle Detector	TSI 3321 Aerodynamic Particle Sizer	Particle Spectrometer	50-104°F (10-40°C)
Particle Detector	TSI 3007 Condensation Particle Counter	Ultrafine particles	10-35°C (50-95°F)
Particle Detector	Naneos Partector 2	Ultrafine and Fine Particles	0-40°C (32-104°F)
Particle Detector	Piera Systems IPS-7100	Fine Particles	-10 to 60°C (14-140°F)
Particle Detector	Pegasor Mi3	Ultrafine particles	Up to 300^{+o}C (570°F)
Gas Detector	PP Systems WMA-5 CO_2 Analyzer	CO_2	0-50°C (32-122°F)

Category	Instrument	Substance Measured	Temp. Limits[1]
Gas Detector	Honeywell ppbRae 3000 VOC Monitor	Volatile organic compounds	-20 to 50°C (-4 to 122°F)
Gas Detector	Interscan 8160-2000b	Formaldehyde	0-45°C (32-113°F)
Gas Detector	Astronics Smart Aircraft System Gas Sensor	Unspecified Gas(es)	Not Specified
Gas Detector	TSI Q-Trak Indoor Air Quality Monitor 5757	Up to six different user selected gases	-10 to 60°C (14-140°F)
Particle Detector	Piera Systems IPS-7100	Fine Particles	-10 to 60°C (14-140°F)
Particle Detector	Pegasor Mi3	Ultrafine particles	Up to 300+ °C (570°F)

1) All can operate at typical occupied aircraft cabin temperatures as a minimum.

5.2.1 Cabin air quality monitors

Aircraft air quality monitors are instruments that were developed specifically for onboard monitoring of air quality in aircraft cabins. These instruments have functionality that extends beyond just bleed air contaminants. However, addressing bleed air contamination is within the realm of their functionality. All of these instruments have multiple sensors and, in some cases, it is possible to access the response of individual sensors. This access is a useful feature for test stand engine experiments as it gives further insights into what types of sensor do and do not respond to individual contaminants. All of these units were developed by their manufacturers for operation in the aircraft cabin and not at other locations at this time. It is feasible that they could be adapted to other locations within the aircraft in the future.

Teledyne has developed its Aircraft Cabin Environment Sensor (ACES) system (Teledyne ACES) and is currently marketing it. It is type certified for use on Boeing 737 aircraft. It monitors a variety of environmental variables related to cabin air quality and specifically references oil, hydraulic fluid, and deicing fluid in its product literature. The device uses multiple sensors but the details of the sensors, and how the generated signals are used in the detection process, are proprietary.

Pall Aerospace is developing its MK-1 Cabin Air Quality Sensor. It is not publicly marketed at present and there is no available online information. Pall did make a presentation about the

sensor at the 2021 International Aircraft Cabin Air Quality Conference. Pall has been working with one or more airlines in its use and they provided two of the sensors for use in the test stand engine experiments that were conducted in March 2021 for ASHRAE 1830-RP. It uses multiple sensors to detect various contaminants. The details of the sensors, and how the generated signals are used for substance detection, are proprietary.

The IPVideo HALO unit by L2 Aviation is a general-purpose indoor environmental monitor (https://ipvideocorp.com/halo/). It monitors a number of variables related to air quality including CO, CO_2, NO_2, NH_3 and particulates. It is also used for security applications and measures variables related to noise and light. In its current form, it does not claim to detect contaminants specifically related to bleed air (e.g., oil, hydraulic fluid, and deicing fluid); however, given the sensors included there is potential for it to be adapted to this purpose. L2 Aviation is currently marketing a version of the HALO for aircraft applications. The details of the sensors, and how the generated signals are processed, are proprietary.

5.2.2 Troubleshooting

Troubleshooting refers to instruments designed to be used to investigate an aircraft fume event or other air quality issues after the aircraft has landed. . Only one instrument in this category was identified, the Airsense Analytics Aerotracer (https://airsense.com/en/products/aerotracer). The Aerotracer has been available on the market for several years and some airlines and manufacturers use it routinely. It was developed in collaboration with the air transportation industry. It is designed specifically to detect the presence of substances of interest to aircraft operation including potential bleed air contaminants oil, hydraulic fluid, and deicing fluid. It is a handheld unit that contains an extensive array of sensors. The details of the sensors, and how the generated signals are used in substance detection, are proprietary. Working in collaboration with the manufacturer, it has been possible to extract signals from individual sensors which is useful for engine test stand experiments as it helps identify which types of sensors respond to bleed air contaminants and which types do not. The instrument is very sensitive, requires a skilled operator to be used effectively, and is subject to sensor saturation. It likely would not be used as an onboard, unattended sensor in its current form but it is useful for test stand engine work for the reasons explained above. It is possible that future adaptations could be developed for routine real time monitoring.

5.2.3 Particle detectors

Particle detection continues to be a leading candidate for engine oil detection and shows promise for hydraulic fluid detection as well. Thus, it is recommended that any test stand engine

experiments include the capability to fully characterize the particulates generated in the bleed air. In addition, specific instruments that have potential to be adapted to on-aircraft bleed air contamination need to be included.

A laboratory-grade particle spectrometer or combination of spectrometers should be included in test stand engine experiments to fully characterize particle size distribution and concentration. At a minimum, the spectrometer(s) should cover particles size from 15 nm to 4 μm with at least 25 size bins logarithmically spaced over this size range. The instruments described below worked well in test stand engine experiments. There are other commercially available instruments, which can also serve this purpose. The TSI 3080L particle classifier, paired with a TSI 3775 condensation particle counter, can detect particle size and concentrations from10 nm to 700 nm depending upon the instrument configurations. The TSI 3321 aerodynamic particle sizer provides concentrations and size distributions from 0.5 μm to 20 μm.

Condensation particle counters (CPC), in general, are good at detecting ultrafine particles and ultrafine particles appear to be a good marker of oil contamination in bleed air. Most CPCs are for laboratory use. They require a “condensation fluid," generally an alcohol, that is evaporated into the air stream and which then condenses onto the ultrafine particles in the air in a cooling process growing them to a size where they can be detected by optical sensors. The TSI 3007 hand-held condensation particle counter (Condensation Particle Counter 3007 | TSI) is a handheld CPC for field use. Whether it could be adapted for real time, unattended use onboard an aircraft is problematic due to the condensation fluid requirement. However, the device provides a good measure of what can be accomplished with ultrafine particle detection with regard to bleed air contamination.

The Naneos Partector 2 https://www.naneos.ch/partector.html) is a promising instrument that measures particle concentrations over the range of 10 nm to 10 μm, which covers the full range of interest. It uses corona discharge technology for the particle counting and, thus, is 100% solid state and requires no condensing liquid. It is well suited for standalone operation and should be readily adaptable to aircraft applications. It provides some limited size information, e.g. average particle size. Whether this information would allow it to differentiate between engine oil and hydraulic fluid is not yet clear.

The Pegasor Mi3 instrument (Q-Trak Indoor Air Quality Monitor 7575 | TSI) is designed to measure ultrafine particles in vehicle engine exhaust. This instrument was identified recently and has not yet been fully vetted. It has not been included in any experiments conducted to date. However, an aircraft engine manufacturer has used it for bleed air applications, and the manufacturer has provided the instrument for use in experiments that have not been completed at

the time of report preparation. The Mi3 measures particles down to 10 nm, which makes it well suited for detection of engine oil. Unique to this instrument is its ability to sample high temperature gas streams. It should be able to sample bleed air directly from the engine prior to the pre-cooler, which eliminates the problems associated with contaminant deposition and release from heat exchanger surfaces. It could potentially measure unaltered bleed air. The instrument, in its current form, appears to be a bit complicated to operate and probably could not be used as an unattended on-board bleed-air contamination detection device without modification. For test stand engine experiments, it could prove to be valuable for identifying contaminant deposition and release in the bleed air cooler. Additionally, potential future adaptations open up important options due to its ability to accept high temperature air from anywhere along the bleed airflow path.

The Piera Systems IPS-7100 Intelligent Particle Sensor (Q-Trak Indoor Air Quality Monitor 7575 | TSI) is another sensor that has not yet been fully vetted. but the manufacturer has indicated interest in collaboration. Perhaps the most interesting feature of this device is its low cost (<$100) for the sensor and less than $200 for a complete instrument that can be plugged into a laptop computer. It also provides some limited sizing information (7 bins). The IPS-7100 uses optical counting technology. Generally, optical methods are not seen as applicable below about 500 nm, 300 nm at the minimum. However, the manufacturer claims it counts particles down to 100 nm. This size range is at the upper end of what is expected to be useful for oil contamination detection but may work. It is well within the range that is expected to work for hydraulic fluids.

5.2.4 Gas detectors

Data to date indicate that CO_2 may be useful for detecting engine exhaust ingestion that may be confounding other measurements. Engine exhaust may also contain ultrafine particles and products of combustion such as formaldehyde that could be misinterpreted as markers of bleed air contamination by oil or hydraulic fluid. There are then two reasons to include a CO_2 sensor with test stand engine experiments: 1) to evaluate whether or not there is inadvertent exhaust gas ingestion during an experiment and 2) to evaluate how well CO_2 identifies instances of exhaust ingestion. Data to date show small but measurable increases in CO_2 with exhaust ingestion even though that ingestion results in readily measurable increases in ultrafine particles. Carbon dioxide is not expected to be a useful indicator of bleed air contamination in and of itself. Several of the other instruments listed include CO_2 sensors, or equivalent CO_2 (eCO_2) sensors.[4]

[4] Carbon dioxide equivalent or eCO_2 indicates the number of metric tons of CO_2 emissions with the same global warming potential (GWP) as one metric ton of another greenhouse gas, and is calculated using US EPA 40 CFR Part 98 Greenhouse Gas Reporting Program (GHGRP) Equation A-1.

However, it is recommended that dedicated CO_2 sensors be used for the test stand engine experiments since the accuracy of the other CO_2 measurements may not be sufficient and the data may not be available in real time. It is also recommended that intake air CO_2 and bleed air CO_2 be measured simultaneously with identical instruments to verify that any increases seen in the bleed air are, in fact, due to ingestion and not due to some bleed air contaminant. There are a number of CO_2 measurement instruments available. The instrument used should have a repeatability of 10 ppm or better for the measurement range of 400-600 ppm. The PP Systems WMA-5 CO_2 Detector (https://ppsystems.com/wma-5/) is an example of a suitable detector for this purpose. The eCO_2 sensor approach was developed in the building industry as a low cost means to comply with the ASHRAE Standard 62.1 Indoor Air Quality Procedure (ASHRAE, 2019). The eCO_2 sensor is a metal oxide type sensor that measures volatile organic compounds (VOCs) and related odors in the parts per billion range. Therefore, the output of the eCO2 sensor is not a true CO_2 sensor, which is highly specific, but rather is a type of VOC sensor.

Total volatile organic compounds (TVOC) are a possible marker for bleed air contamination. The Honeywell ppbRae 3000 VOC Monitor (ppbRAE 3000 + | Honeywell) is one of the most accurate, if not the most accurate, hand-held monitor designed for field use. While it would take some adaptations for it to be used in routine, unattended monitoring in aircraft, it should be able to provide a good indication as to whether or not TVOC is a useful indicator of bleed air contamination. The Honeywell ppbRae uses a photoionization detector that detects a limited number of VOCs at a variety of response levels, based on type and size of the molecule, and how well the molecule is excited by light energy. Other TVOC sensors with appropriate specifications probably could be used, such as metal oxide sensors or ion mobility spectrometry. For this application, a TVOC sensor should measure at least in the range from 0 to 1000 ppb and have resolution of at least 10 ppb.

The Interscan 8160-2000b instrument is a general purpose, laboratory-grade gas sensor (https://cat.gasdetection.com/product/gasd-8000-series-portable-gas-analyzers-formaldehyde-8160-2000b). It can be equipped with a variety of sensing modules to measure different gas concentrations. For test stand engine experiments, formaldehyde is the gas of interest as it has shown good promise as a bleed-air contamination marker. The 8160 instrument is not suitable for routine, unattended monitoring in aircraft without some modification. However, it should be able to provide a good indication as to whether or not formaldehyde is a useful indicator of bleed air contamination. Interscan has also been supportive of the project to date. Another instrument with appropriate specifications could be used but it should measure at least in the range of 0 - 1000 ppb and have a resolution of 10 ppb. There are a number of formaldehyde sensors on the market, but most are intended for higher concentration applications.

The Astronics Smart Aircraft System (Smart Aircraft System | Astronics) is a broad-range smart system information-gathering platform for aircraft and addresses a wide range of parameters from seat back positions to left-on-board luggage. For this project, the gas-monitoring instrument for the system could potentially be a means of detecting bleed air contamination. Astronics has been willing to provide the gas-sensing module as a standalone device for test stand engine experiments. The details of the sensor, and how the information is used in Smart Aircraft System, are proprietary.

The TSI Q-Trak Indoor Air Quality Monitor 5757 (Q-Trak Indoor Air Quality Monitor 7575 | TSI) is a general-purpose air quality assessment instrument that can be equipped with a number of different sensing modules to allow a variety of different environmental variables to be measured, including fine particles and various gas concentrations. Gas sensing modules for CO, CO_2, TVOC, Formaldehyde, NO, NO_2, O_3 are available and up to six gas concentrations can be measured simultaneously. In its current configuration it is a portable user operated instrument and is not intended for extended unattended use. However, for test stand engine experiments, it is very useful for collecting real time data on specific variables that may be useful for bleed-air contamination detection.

5.3 Data assessment

The objective of the data assessment is to identify sensors and instruments to be included in test stand engine experiments. Some of the experiments needed to evaluate these sensors were conducted in collaboration with the ASHRAE 1830-RP research project. Specifically, data were collected in November 2020 using a Honeywell (Garrett) GTCP85-98DHF APU and in March 2021 and June 2021 using the Allison 250 C28B test stand engine. The APU experiments were well instrumented for particulates in the bleed air but included limited instrumentation for other variables. Representative particulate data are presented in Section 3 of this report. The Allison 250 experiments conducted in March 2021 in collaboration with ASHRAE 1830-RP included all of the instruments listed in Table 57 except for the Pegasor and Piera Systems particle detectors. The Piera Systems sensor was included in the June 2021 experiments. The primary limitation of the March 2021 experiments was the inability to achieve high bleed air temperatures equivalent to propulsion engine takeoff and climb power settings. It is desired to include experiments with bleed air temperatures of 300°C (570°F) which is representative of the higher limit of bleed air temperatures achieved in a typical aircraft during a typical flight profile. It is believed substantial decomposition of the bleed air contaminants may occur at this temperature. Additional experiments at higher temperatures were conducted in June of 2021 in collaboration with ASHRAE 1830-RP.

Currently, specific instruments and sensors tested have not been fully evaluated with regard to their ability to detect engine oil, hydraulic fluid, or deicing fluid contamination in bleed air. Data remains to be fully analyzed and, as noted above; important data remain to be collected before this assessment is made. Some preliminary assessments have been made about markers as opposed to specific instruments. The assessments may change when additional high temperature bleed-air data are collected. In addition, some of the markers were assessed with extensive instrumentation (e.g., fine particles), and some substances were evaluated with only a single instrument (e.g., H_2S).

The assessments are grouped into the six categories as listed in Table 58. “Oil” includes all three engine-lubricating oils included in the experiments, Mobil Jet II, Eastman 2389, and Eastman 2197. “Hydraulic Fluid” includes both fluids evaluated, Skydrol LD-4 and Skydrol PE-5. “Deicing Fluid” includes both Type 1 and Type 4 deicing fluids evaluated. “Heat Exchanger” refers to experiments where the cooling air was shut off to the bleed air cooler allowing it to rise in temperature. “Heated Wire” refers to experiments conducted where electric wire was heated to the point that the aircraft grade high temperature PYRE-ML urethane insulation began smoking. Whether or not the dilution with ambient air was representative of an aircraft event is unknown. The assessment here addresses the response of the sensors for this test and may not be representative of the ability to detect onboard fume events. “Heated Fan” refers to one experiment where the wiring of an avionics-cooling fan motor was deliberately burned out. This failure test was not representative of the more likely failure mode in which the synthetic fan material rubs against the fan housing during a bearing failure. Experiments were also conducted with heated fan blade material. The way the sampling was conducted likely resulted in contaminant concentrations that would be much higher than in likely onboard failure scenarios. The assessment here addresses the response of the sensors for these tests and not for their ability to detect an onboard fume event.

Table 58. Assessment categories

Category	**Sub-categories**
Engine Oil	Mobil Jet II
	Eastman 2197 Eastman 2389
Hydraulic Fluid	Skydrol LD-4
	Skydrol PE-5
Heat Exchanger	

Category	Sub-categories
Heated Wire	
Heated Fan	

Table 59 defines the terms used in Table 60. Table 60 presents a tentative subjective summary based on the real time measurements collected to date. In assigning an evaluation term, consideration is given not only to the magnitude of the response, but also the repeatability of the response, where the repeatability can be evaluated, and the stability of the reference baseline. For example, hydraulic fluid typically resulted in a one to two orders of magnitude increase in fine particles at the higher concentrations. Such a large response would normally be seen as a "high" response. However, uncertainty in the baseline reduced the assessment to "medium." Baseline variability for the gas sensors appears to be a significant limiting factor for using specific chemicals for real time detection of bleed air contaminants.

Table 59. Definition of terms for table 60

Term	Definition
None	No consistent response above baseline observed.
Low	Appears to respond to contaminant but it is questionable whether or not it is sufficient for reliable detection
Medium	Clear response to contaminant and sufficiently large that it may be a useful marker of contamination.
High	Large response to contaminant and expected to be a reliable marker.
Mixed	Inconsistent or unclear results typically in the Low to Medium category.

Figure 34 to 52 are presented to support the basis for the assessments made in Table 60. Color-coding is used to identify the different markers and geometric symbols are used to identify the different contaminants. These colored symbols are then placed on the figures to show were a specific contaminant and marker combination is being evaluated. For example, Figure 35 looks at fine particle responses (purple symbols) for reference conditions (diamond symbols), hot heat exchanger contaminants (circle symbols), and oil contaminants (star symbols). Additionally, the relevant figure numbers for each contaminant and marker combination are identified in Table 60.

Four of the instruments evaluated use multiple sensor arrays and proprietary processing to identify specific substances. Some of these instruments record the output of individual sensors, which provides some insight as to how different sensors respond to different contaminants. As an

example, Figure 53 shows the response of individual HALO channels to different test conditions. In preparing this figure, the signals from seven sensors for 21 test conditions were plotted on a logarithmic scale. Figure 53 is not intended to present numerical results for the different contaminants. Each numbered test is for a different contaminant but the timing of the injection is not resolved. The purpose of this figure is to show the variety of responses from the different sensors for different contaminants. Table 61 describes the type of sensors corresponding to the letters on Figure 53 and the type of contaminant corresponding to the numbers in Figure 53. The HALO instruments uses metal oxide chemical sensors. Each sensor is directed at a given chemical as identified in Table 61. However, most metal oxide sensors are sensitive to multiple chemicals and the responses seen in Figure 53 may not actually be a response to the chemical listed in Table 59.

Even though the HALO appears to be able to detect specific contaminants when there is sufficient concentration, the results indicate that no one channel responds consistently for all contaminants. Multiple sensors are necessary to differentiate between contaminant sources. This is true of other sensor suites, including the Airsense Aerotracer, Pall MK-1, and Teledyne ACES sensor suites. Some sensor suites, such as the HALO and ACES use chemical and particle sensors, while Aerotracer and MK-1 use gas sensors only. The common denominator is that all sensors use, or will require, data analytics to correlate sensor response to contaminant source. The details of the analytics are proprietary.

Table 60. Tentative subjective evaluation of suitability of substances as markers of bleed air contamination

Substance Sensed	Empty Tube (Reference)	Oil	Hydraulic Fluid	Deicing Fluid	Hot Heat Exchanger	Heated Wire	Heated Fan Impeller
Ion Mobility Spectrometer		High Fig 34	High  Fig 34	High  Fig 34	High  Fig 34	High  Fig 34	High  Fig 34
Fine Particle		Medium  Fig 35, 36, 39, 40	Medium  Fig 35, 36, 39, 40	None  Fig 35, 36, 39, 40	Medium  Fig 35, 36, 39, 40	None  Fig 35, 36, 39, 40	High  Fig 35, 36, 39, 40
Ultrafine Particles		High  Fig 37 -40	Low  Fig 37 ,-40	None  Fig 37 -40	High  Fig 37 ,-40	None  Fig 37 ,-40	Low  Fig 37 ,-40
TVOC		Mixed  Fig 41-45	Low  Fig 41-45	Medium  Fig 41-45	High  Fig 41-45	Medium  Fig 41-45	High  Fig 41-45
CH_2O		Mixed  Fig 46-49	Medium  Fig 46-49	Mixed  Fig 46-49	Medium  Fig 46-49	High  Fig 46-49	High  Fig 46-49
CO_2		None  Fig 50-51	None  Fig 50-51	None  Fig 50-51	None  Fig 50-51	None Fig 50-51	Low Fig 50-51
CO		Mixed Fig 52	None Fig 52	Mixed Fig 52	Mixed Fig 52	None Fig 52	High Fig 52
NO and NO_2, SO_2 O_3, H_2S, & SO_2 ,		No Response	No Response	No Response	No Response	No Response	No Response

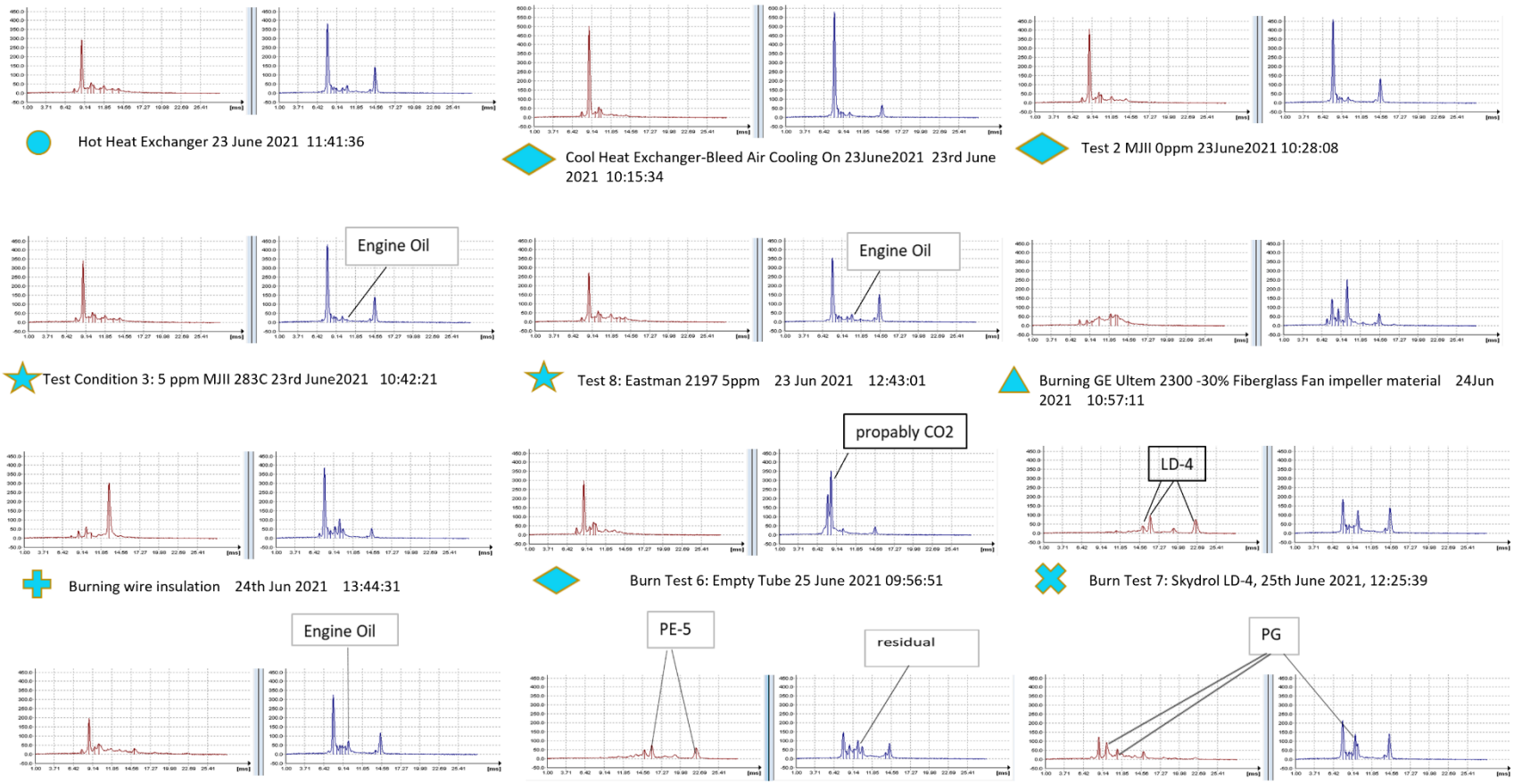

Figure 34. Ion mobility spectrometer response & substance identification

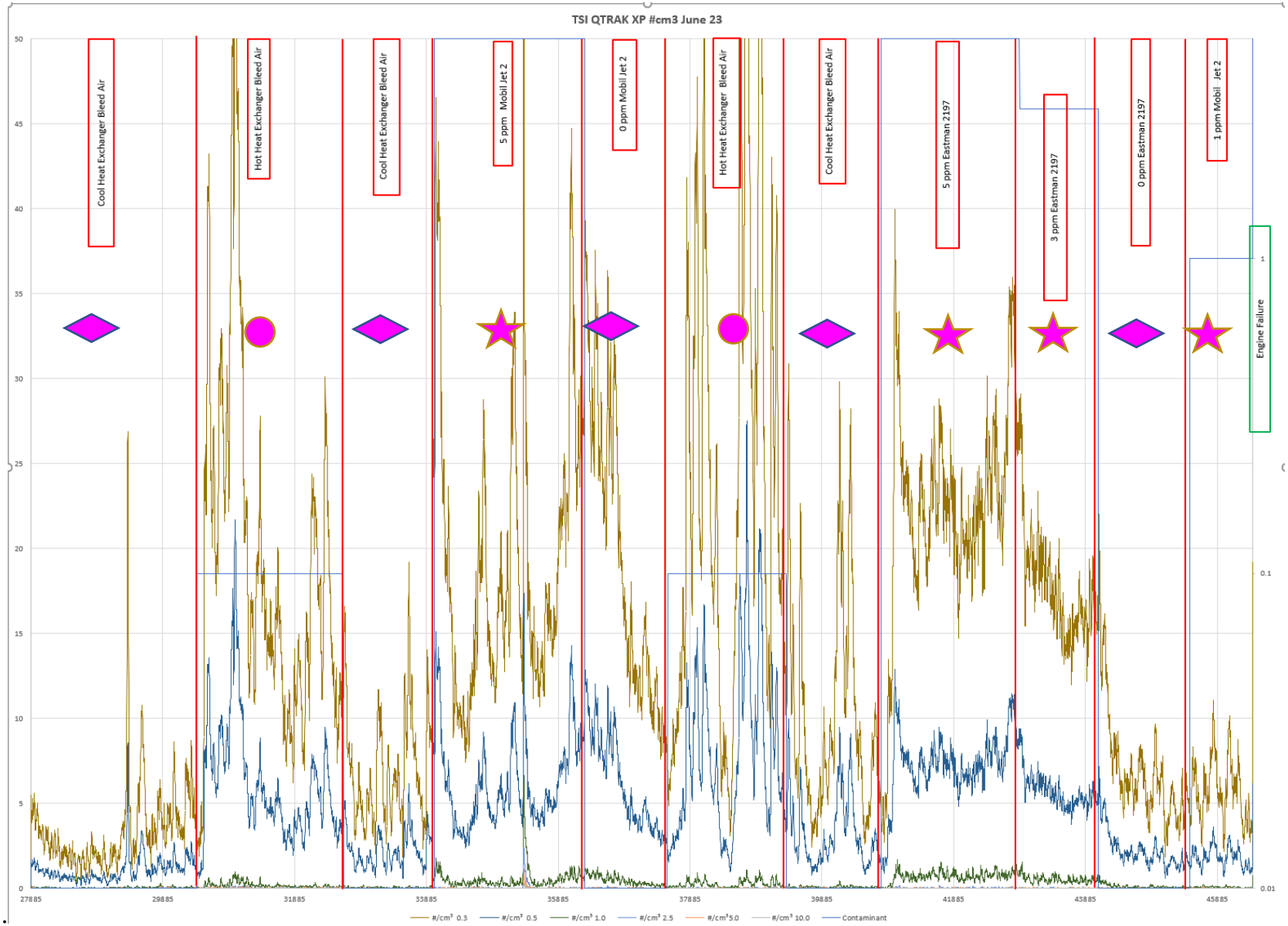

Figure 35. Fine particle (red laser) sensor response

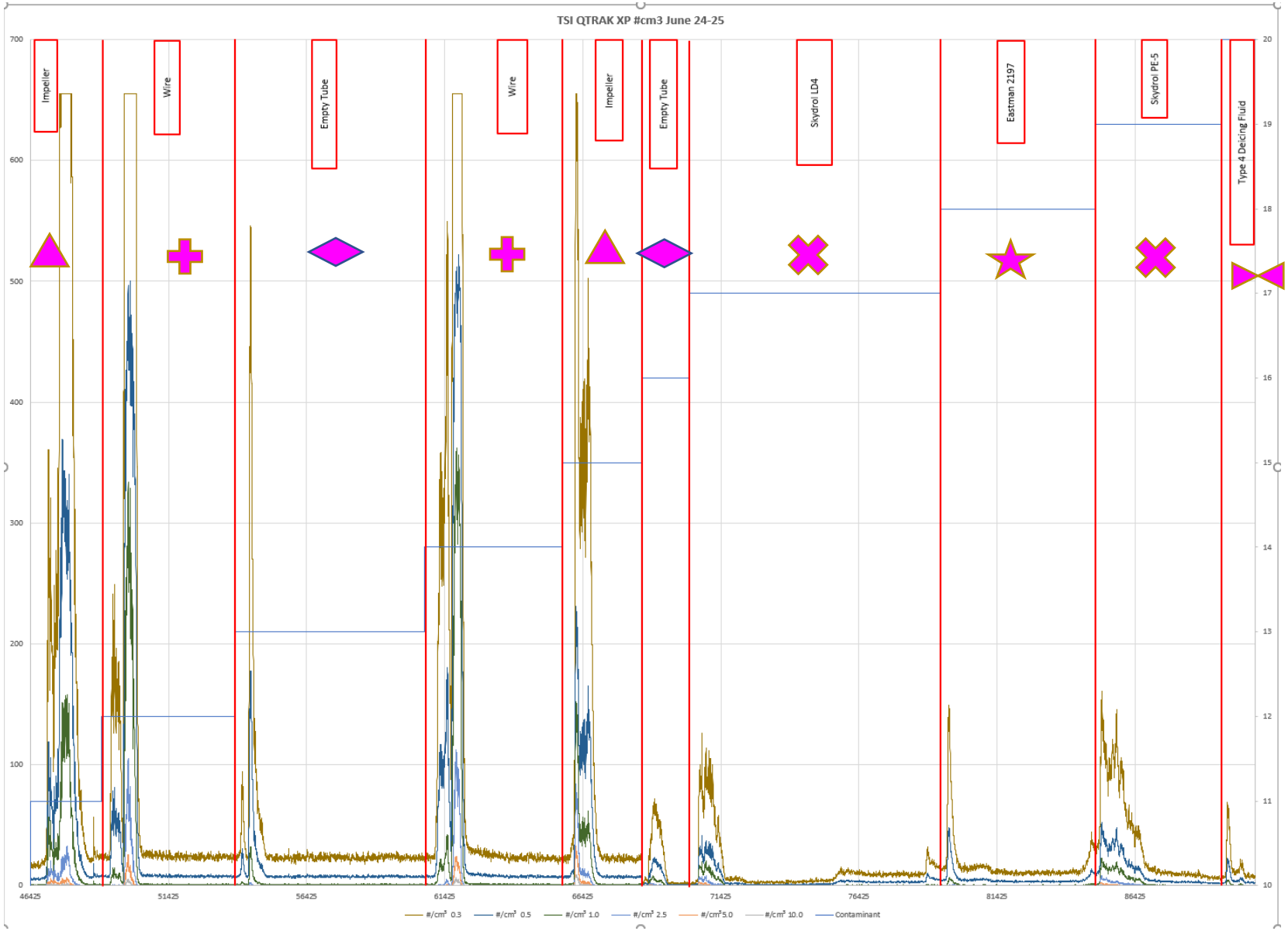

Figure 36. Fine particle (red laser) sensor response

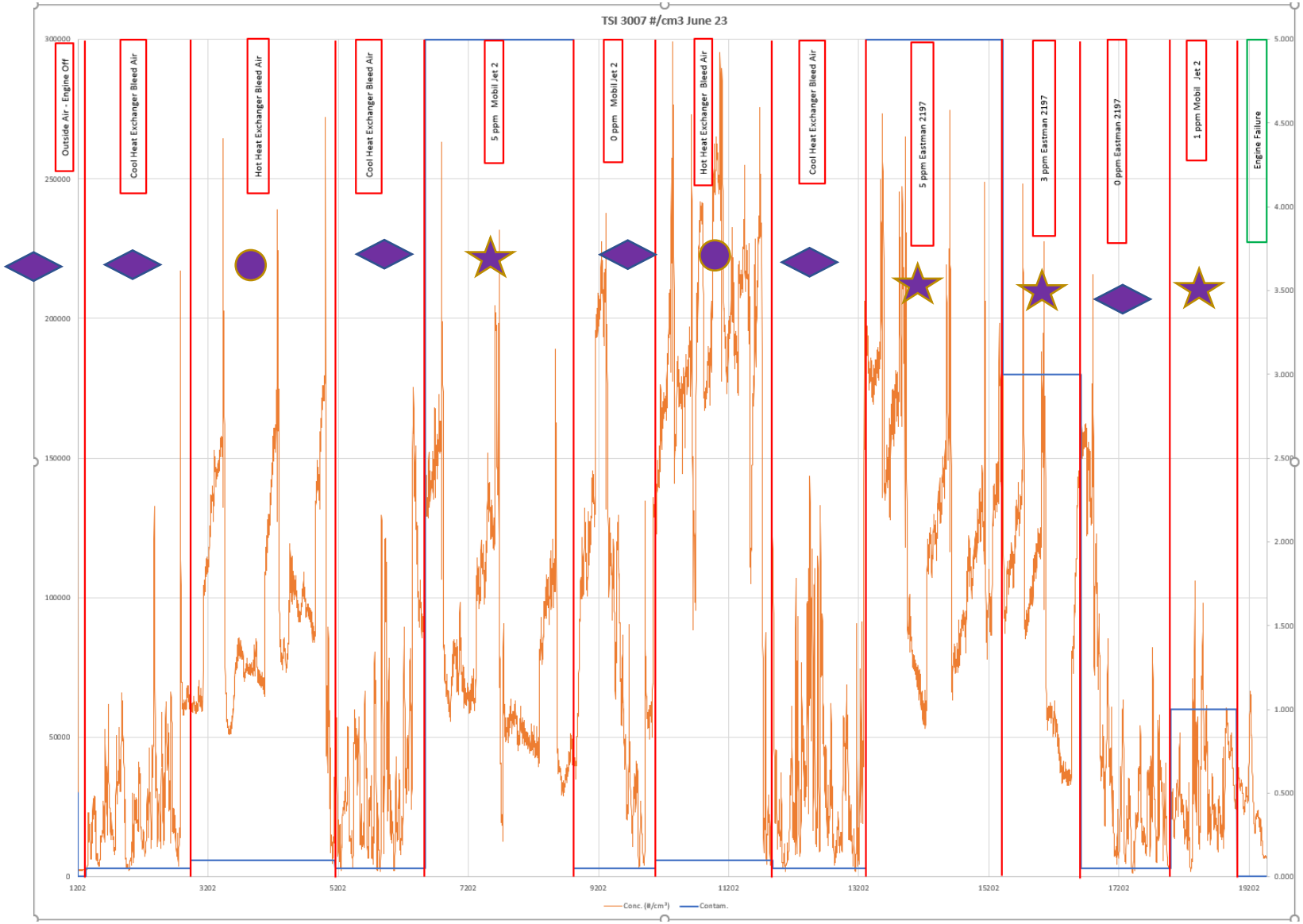

Figure 37. Ultra-fine particle (condensation particle counter) sensor response

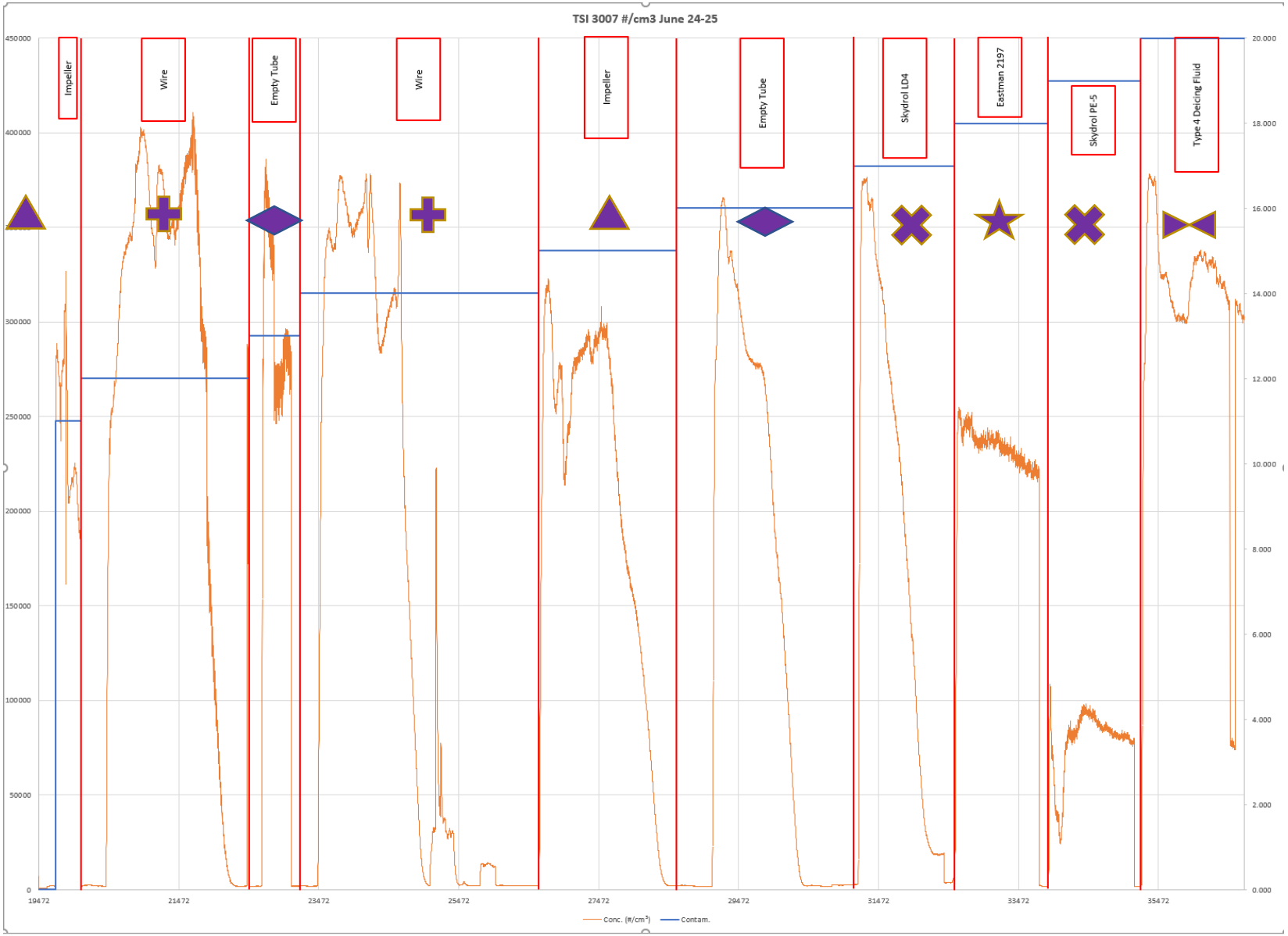

Figure 38. Ultra-fine particle (condensation particle counter) sensor response

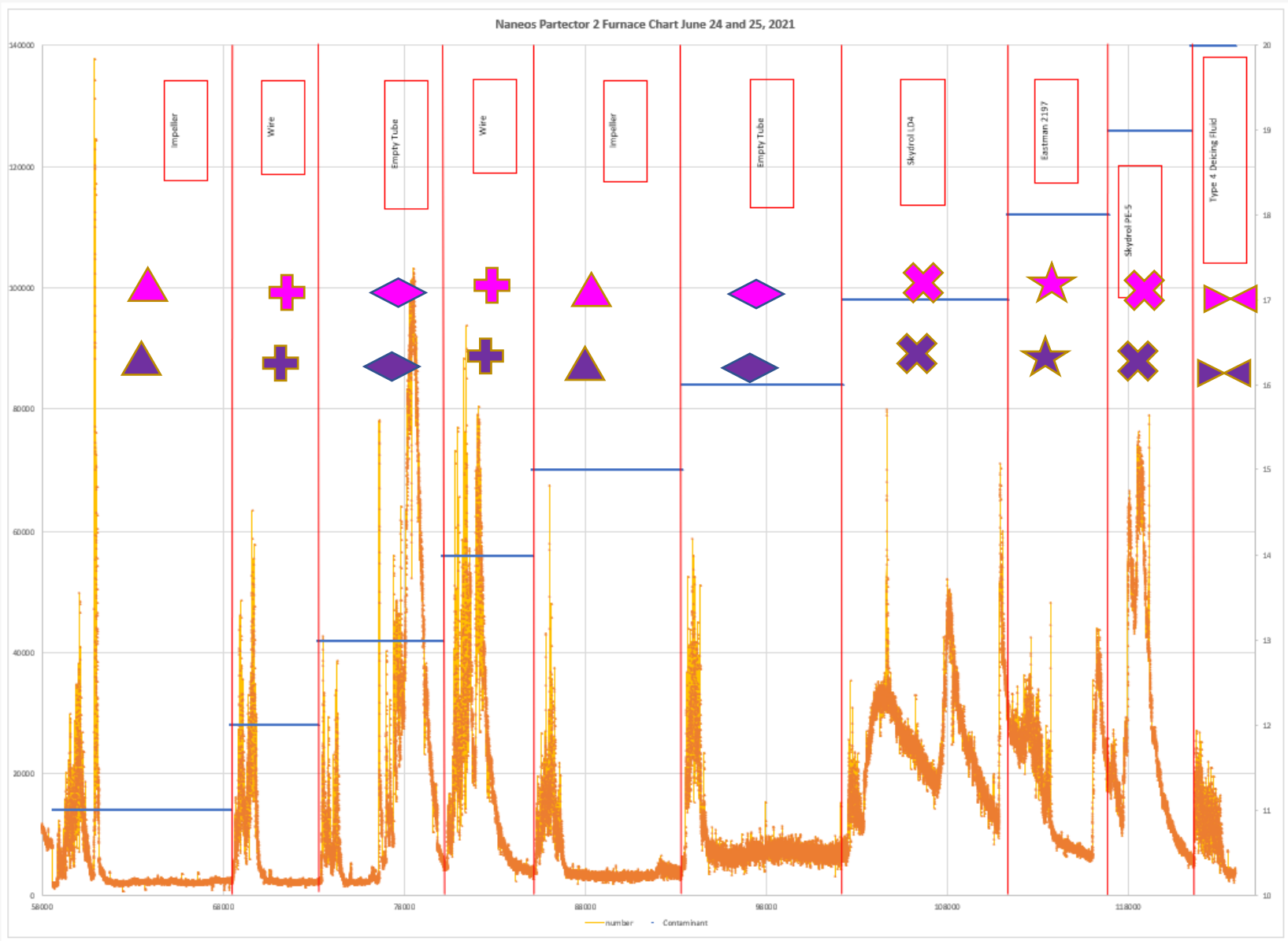

Figure 39. Fine and ultra-fine particle (corona discharge) sensor response

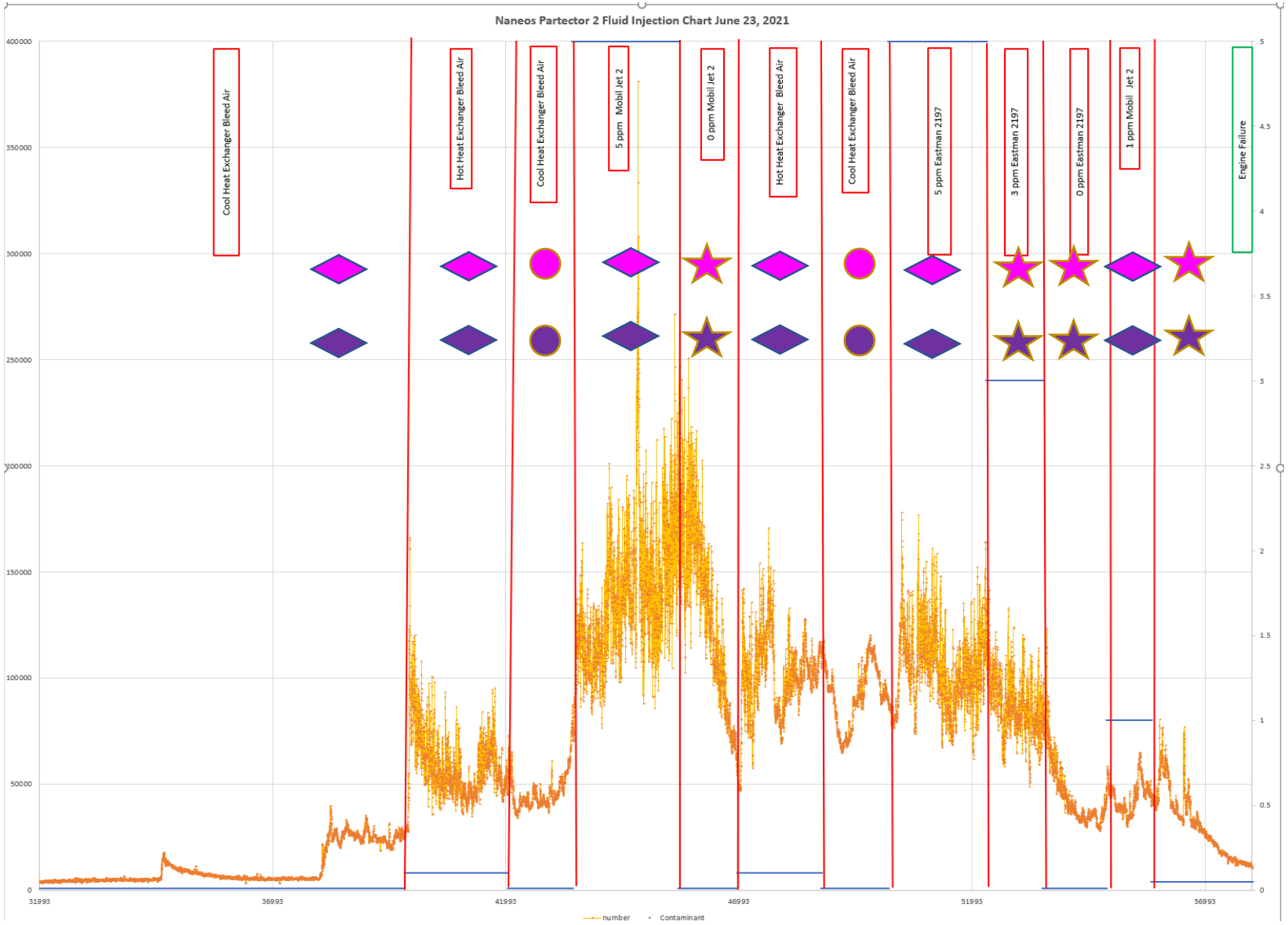

Figure 40. Fine and ultra-fine particle (corona discharge) sensor response

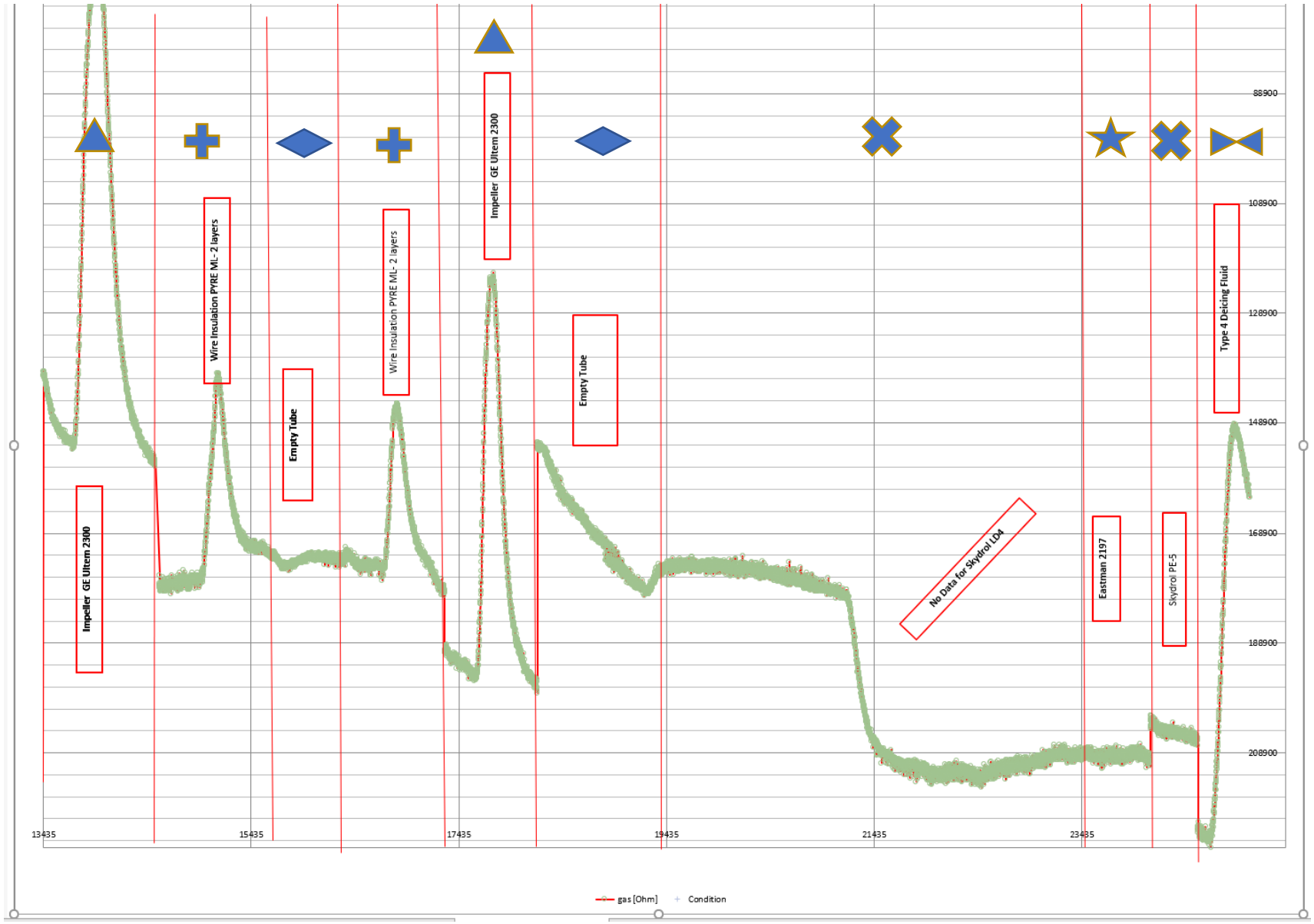

Figure 41. VOC (metal oxide) sensor response

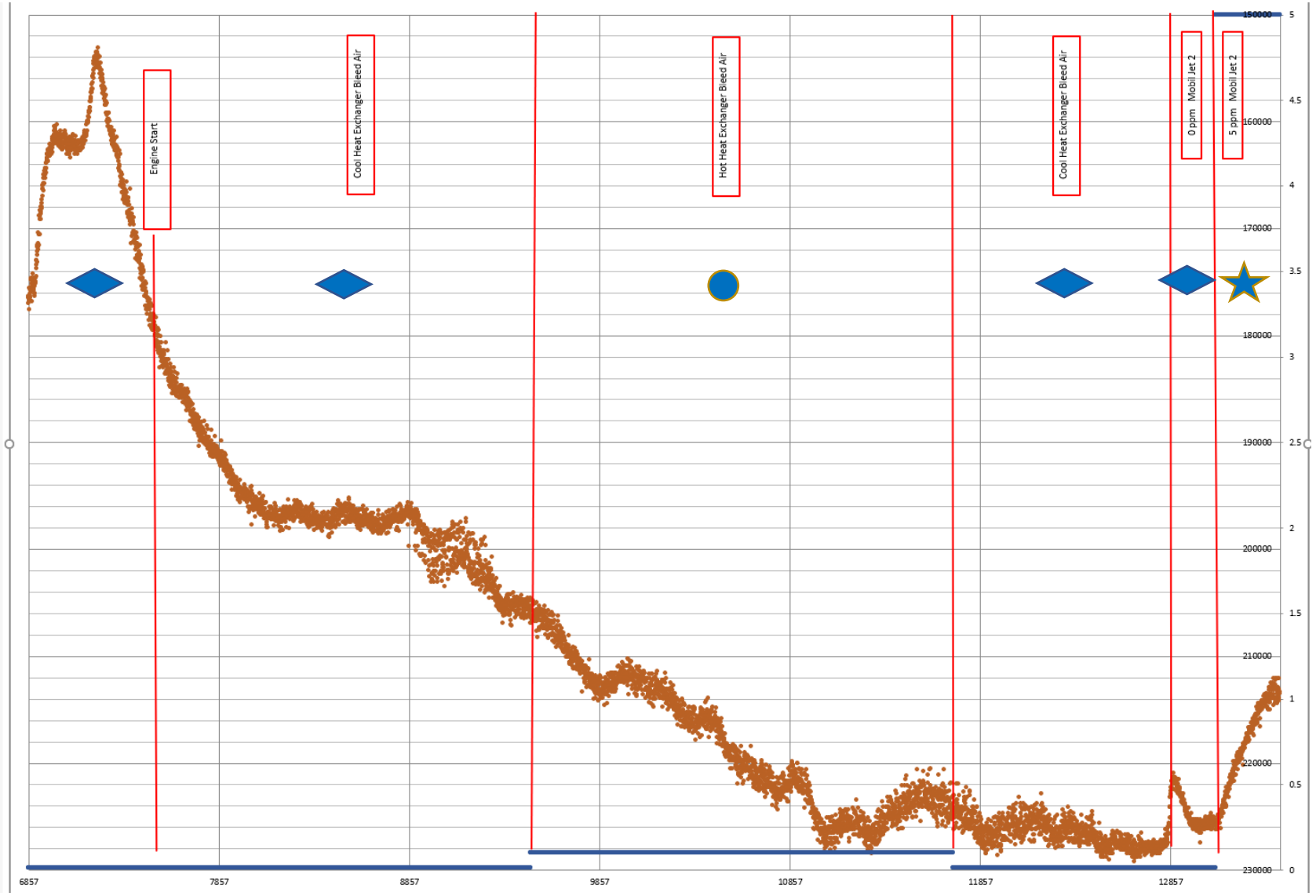

Figure 42. VOC (metal oxide) sensor response

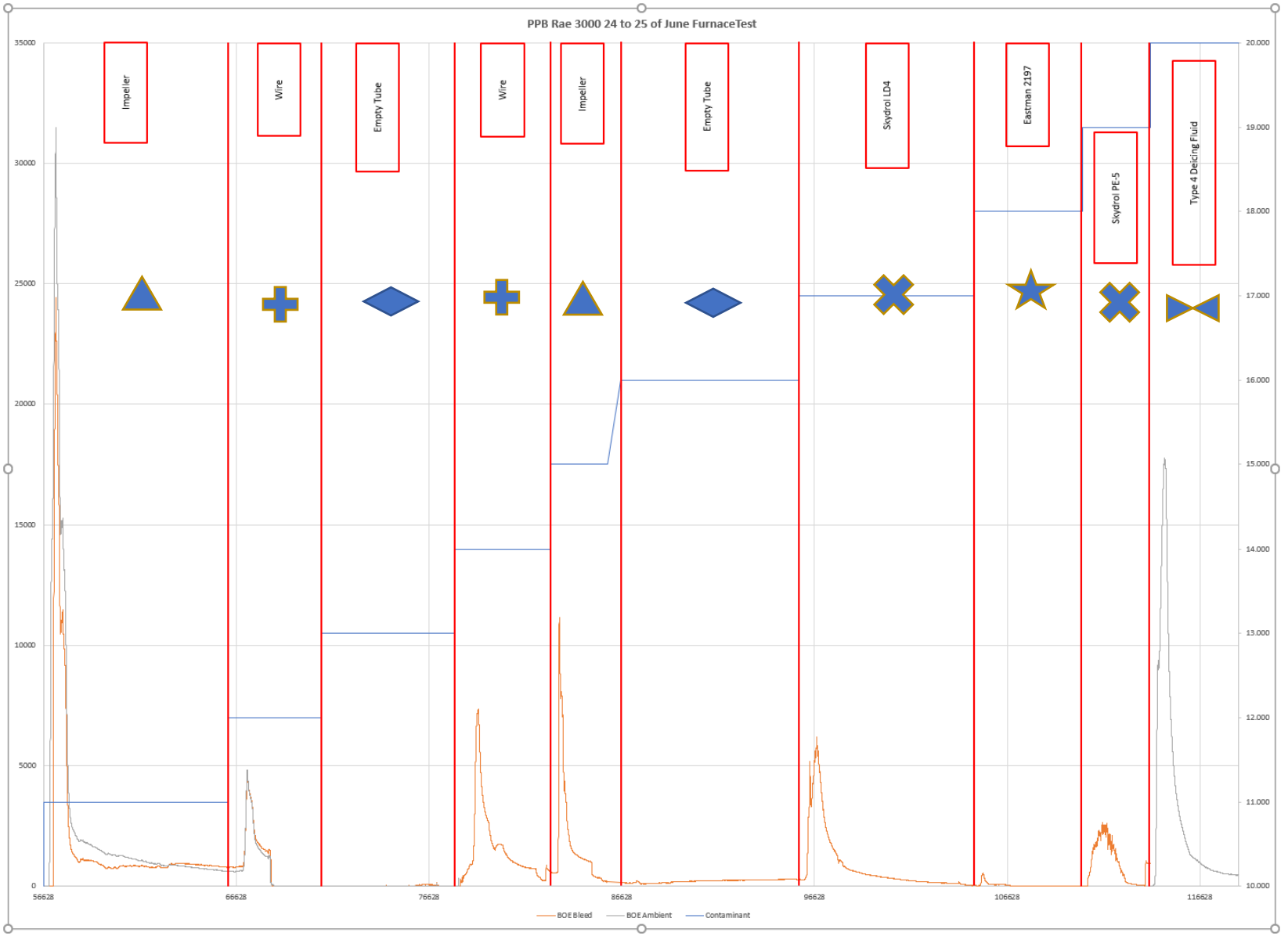

Figure 43. VOC (photoionization detector) sensor response

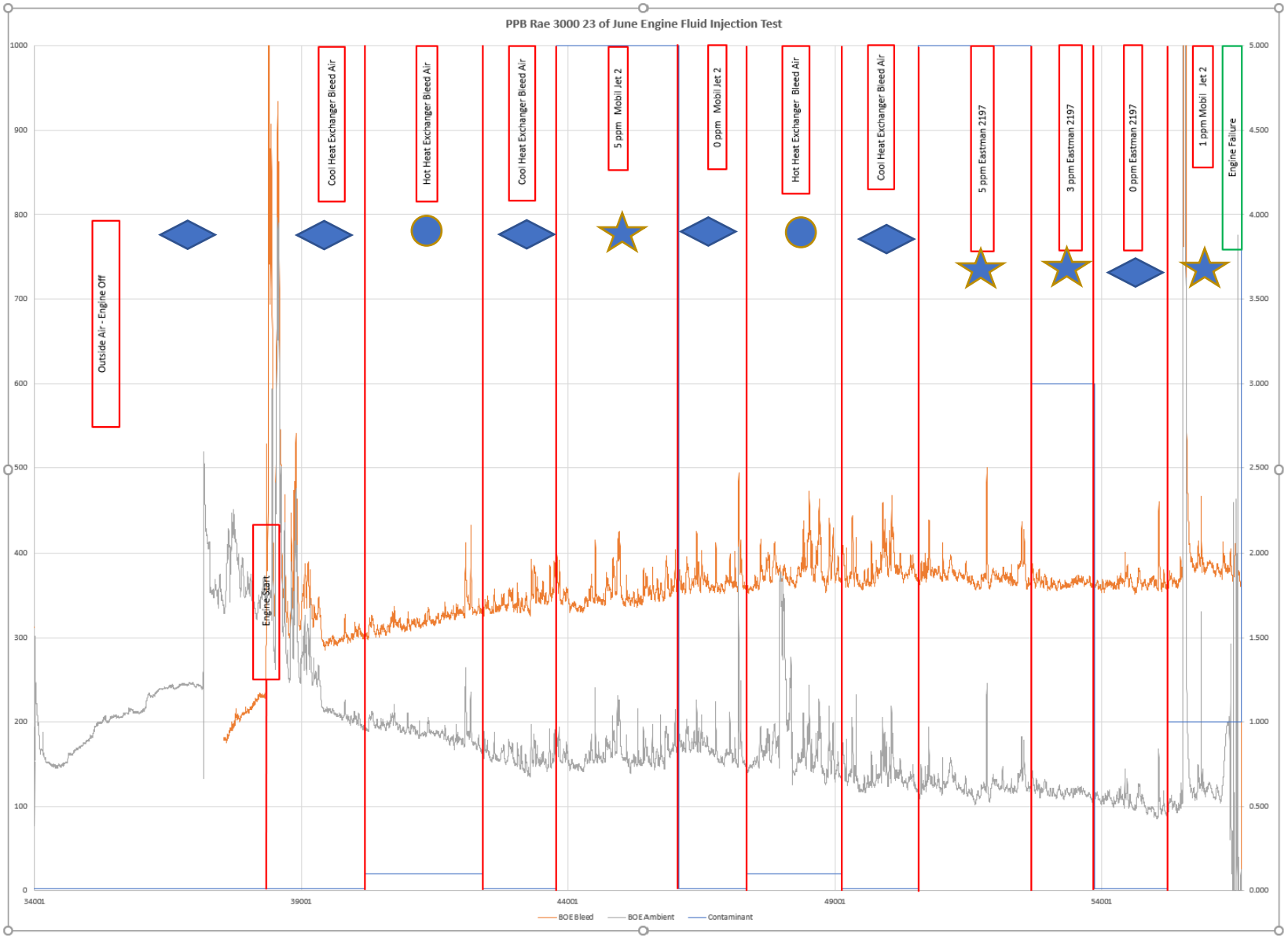

Figure 44. VOC (photoionization detector) sensor response

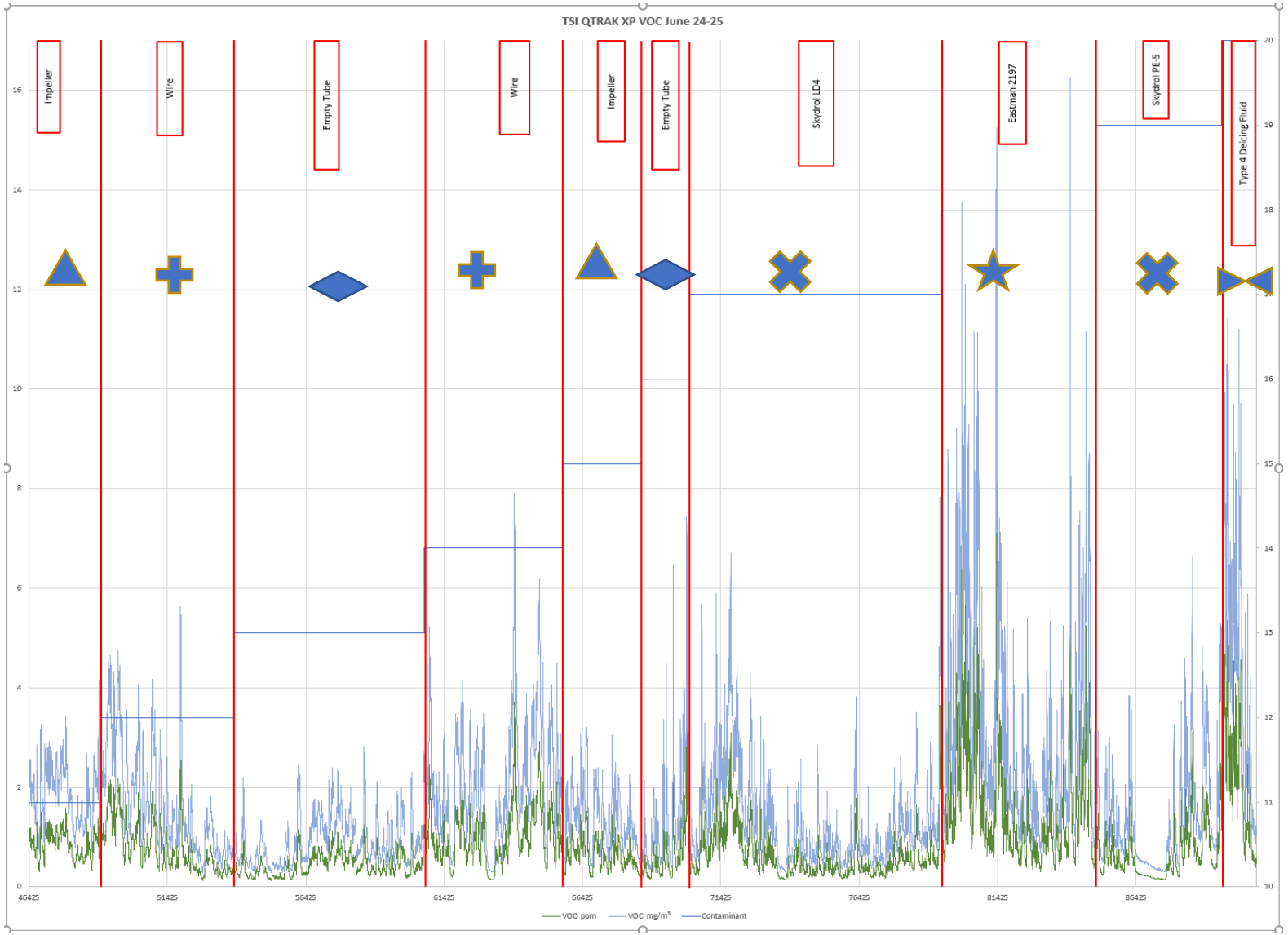

Figure 45. VOC (photoionization detector) sensor response

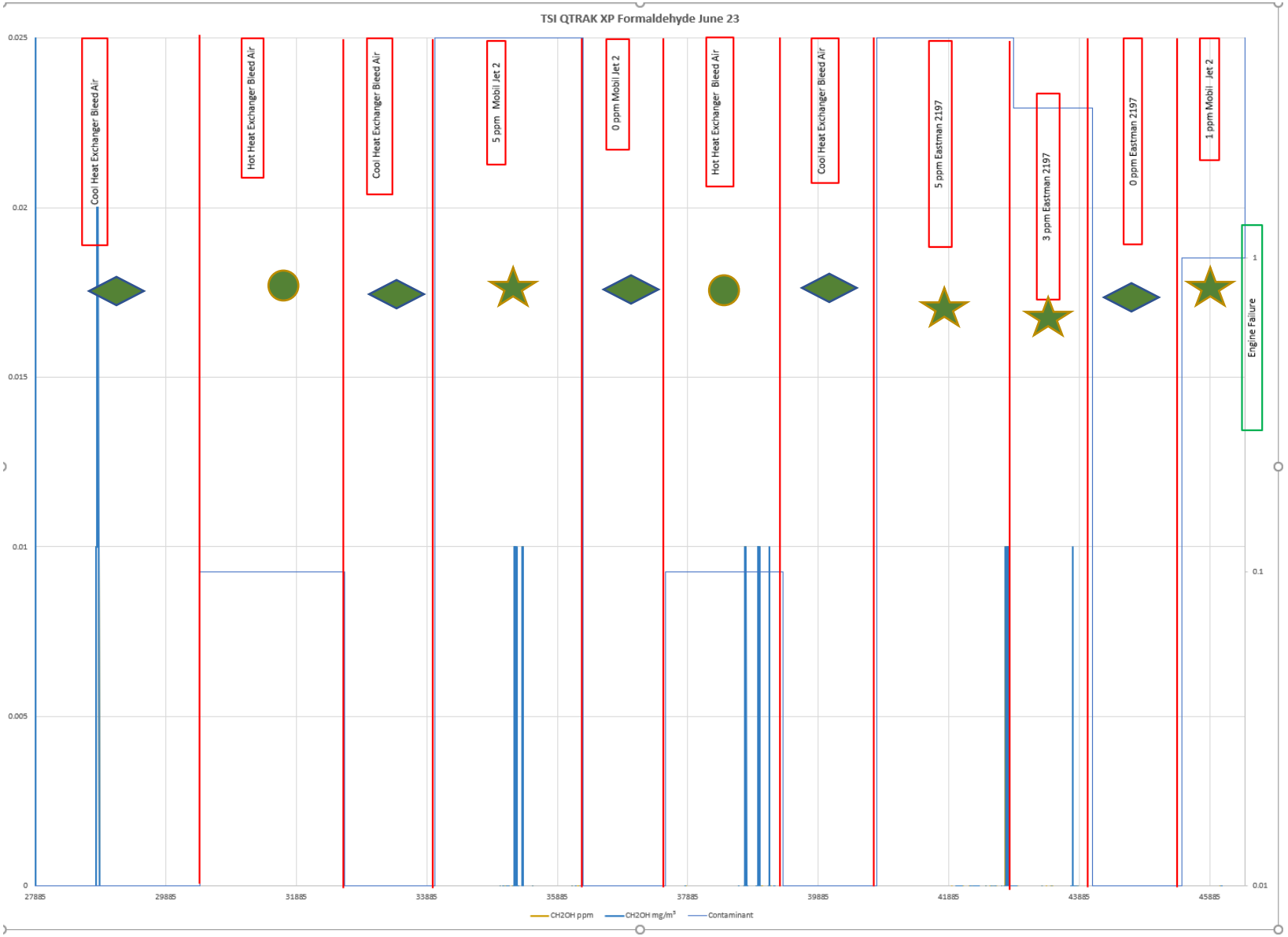

Figure 46. Electrochemical CH2O (formaldehyde) sensor response

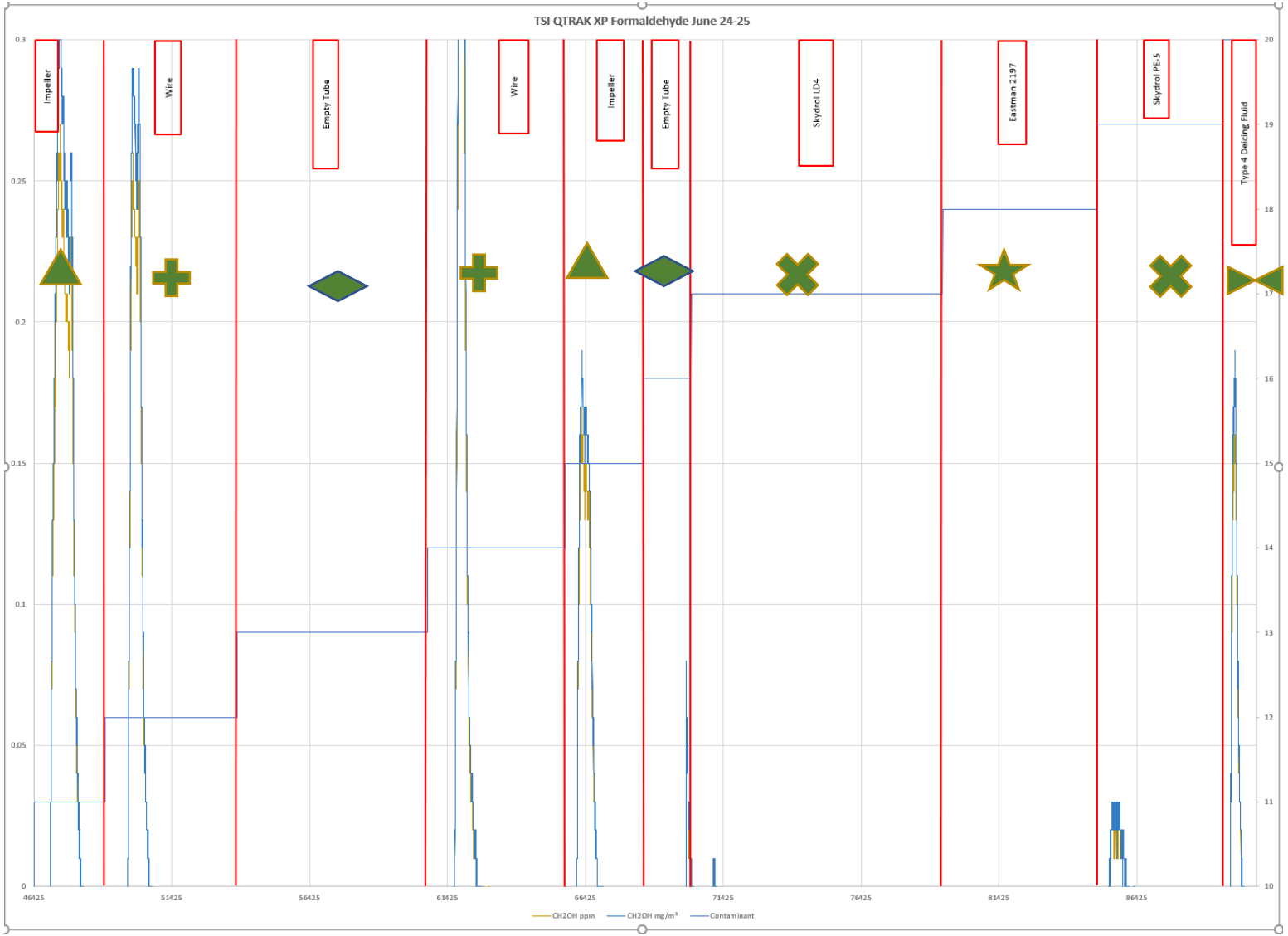

Figure 47. Electrochemical CH2O (formaldehyde) sensor response

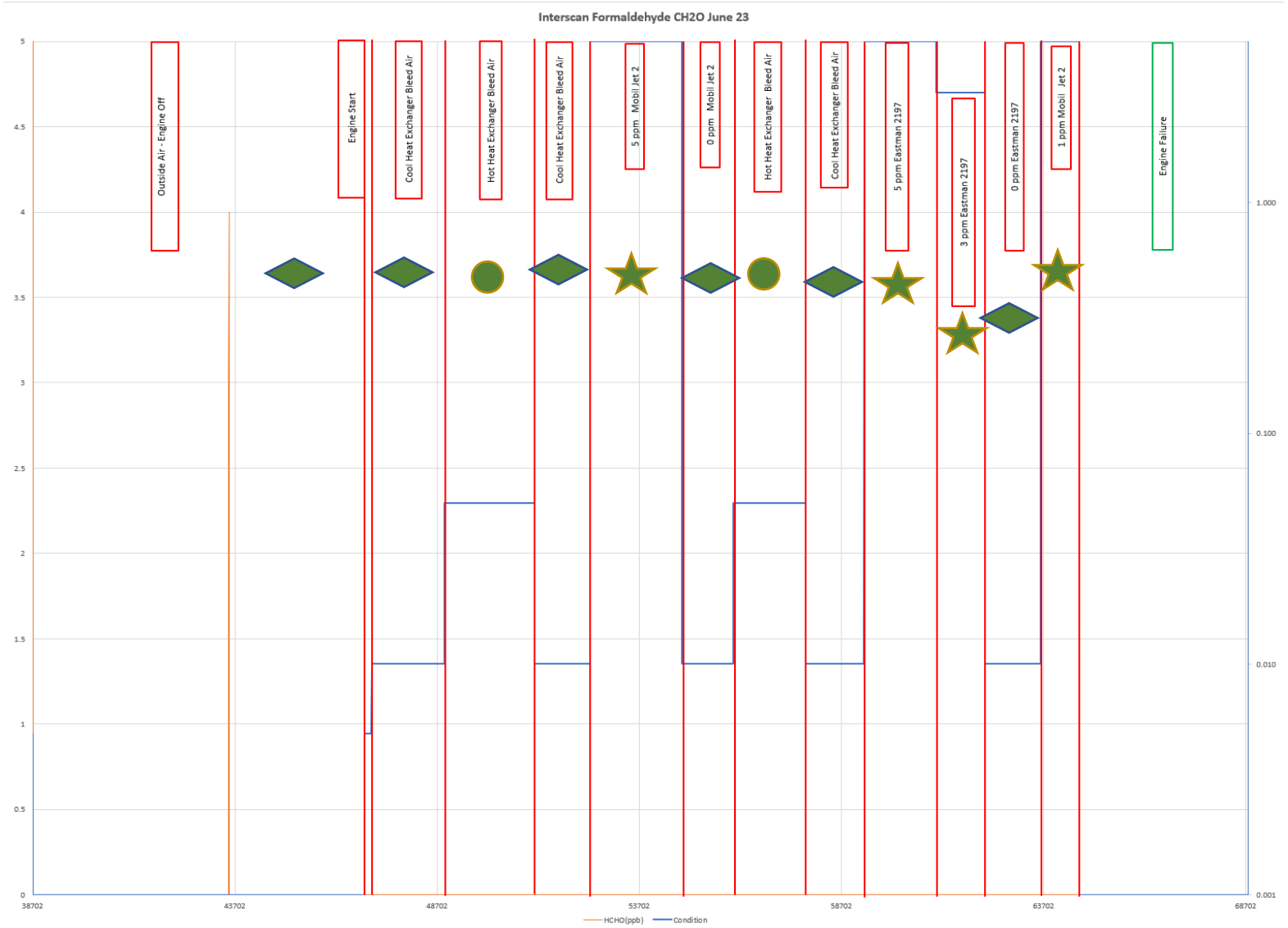

Figure 48. Electrochemical CH2O (formaldehyde) sensor response

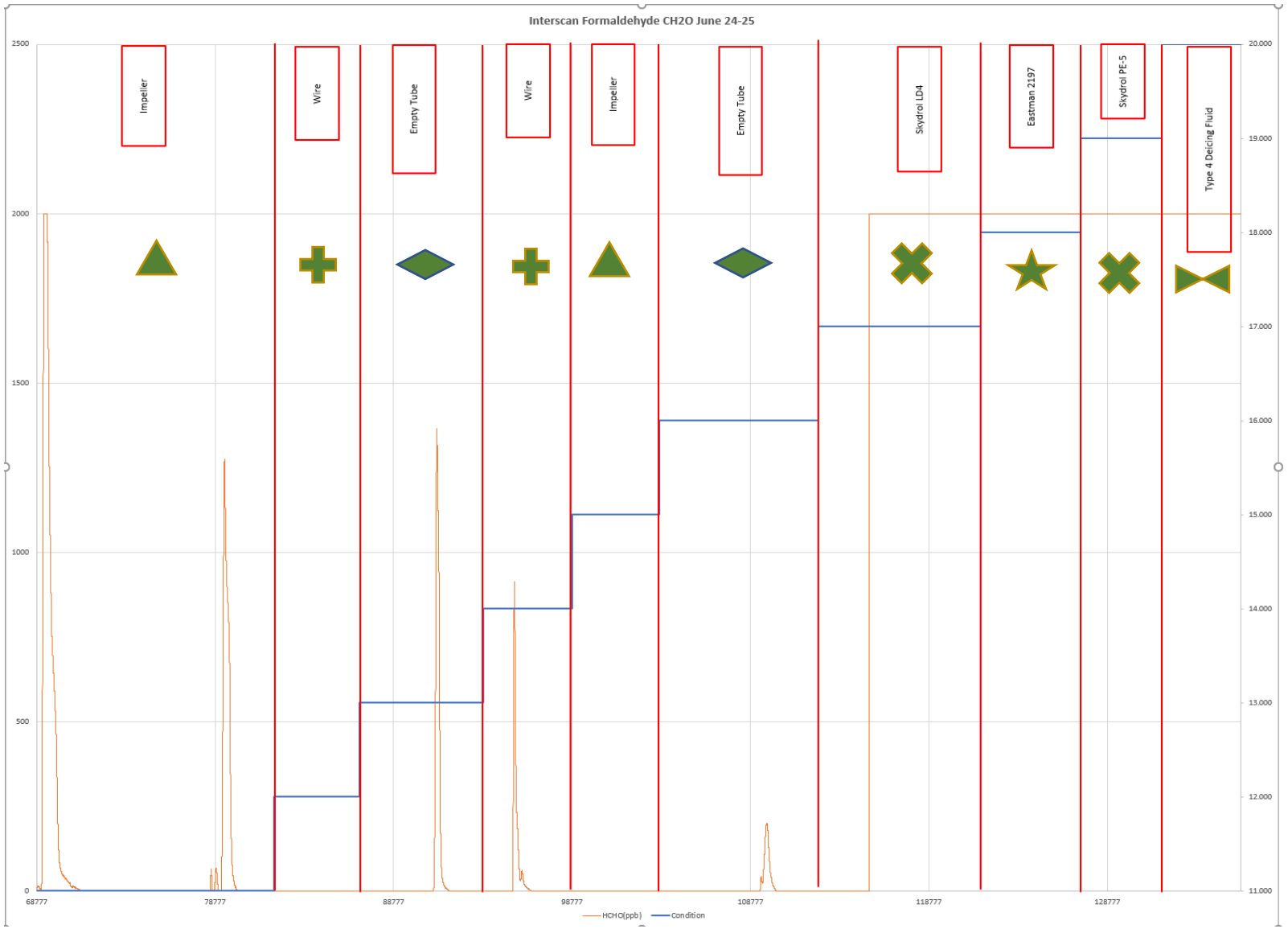

Figure 49. Electrochemical CH2O (formaldehyde) sensor response

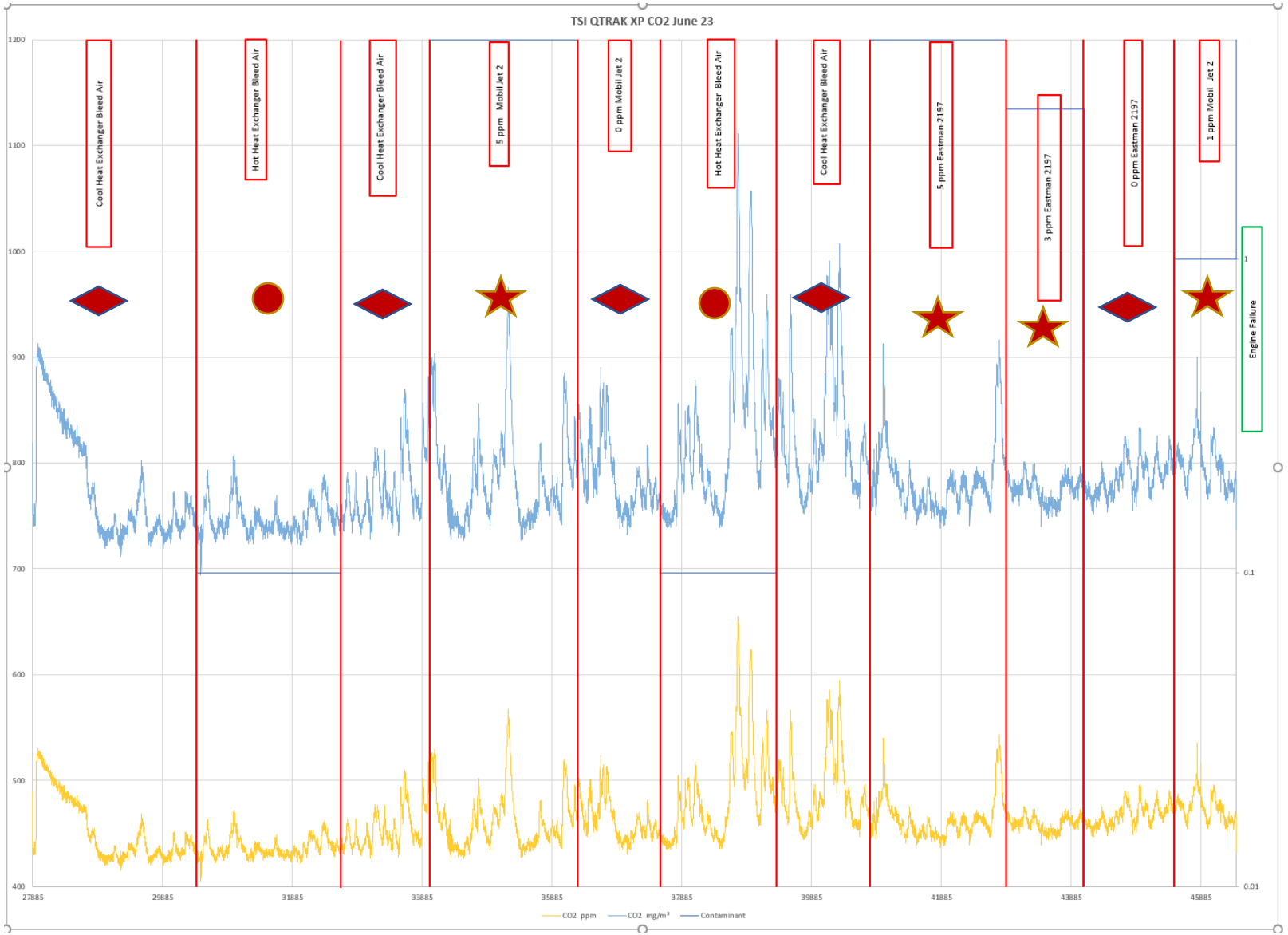

Figure 50. NDIR CO2 sensor response

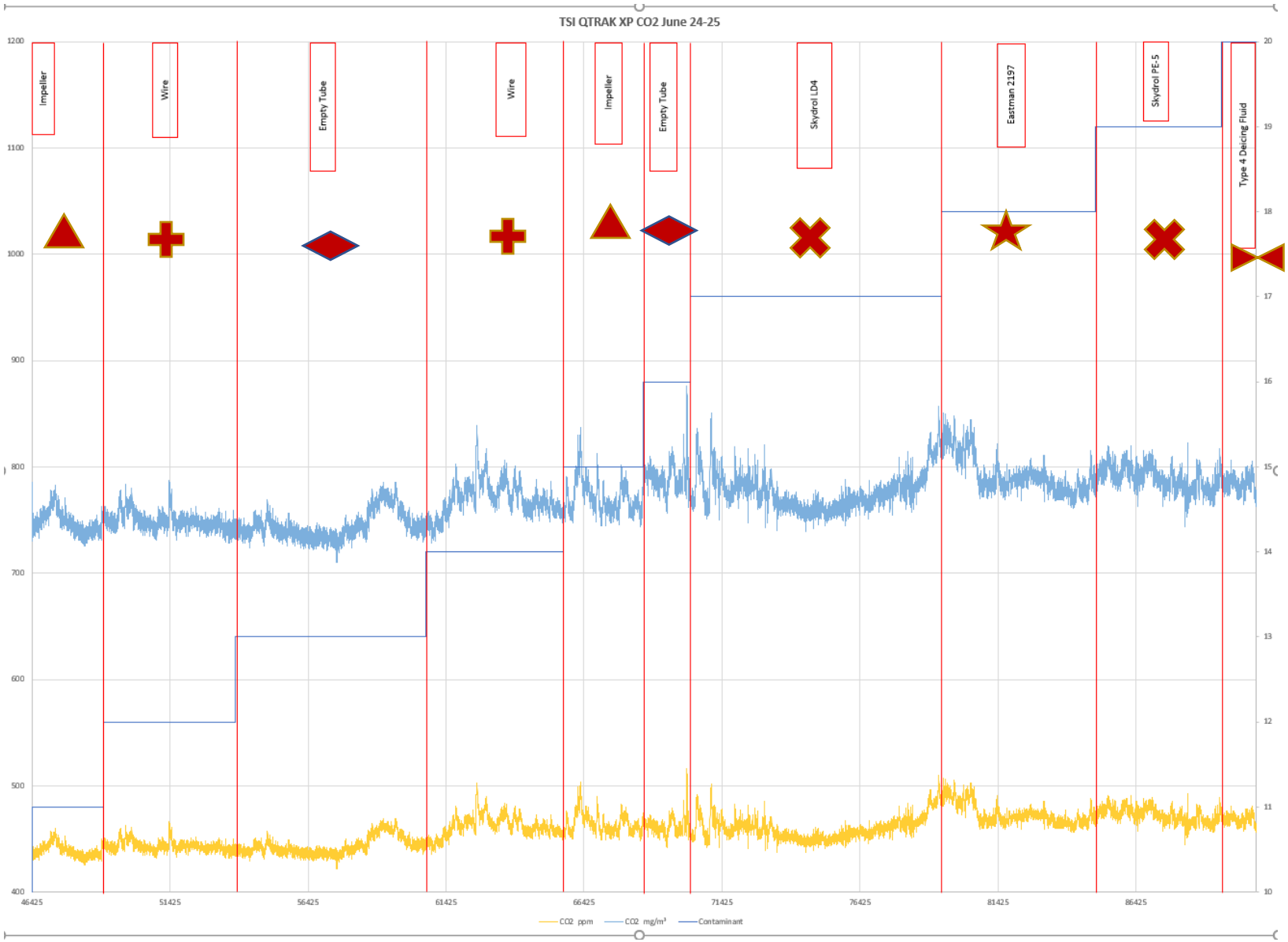

Figure 51. NDIR CO2 sensor response

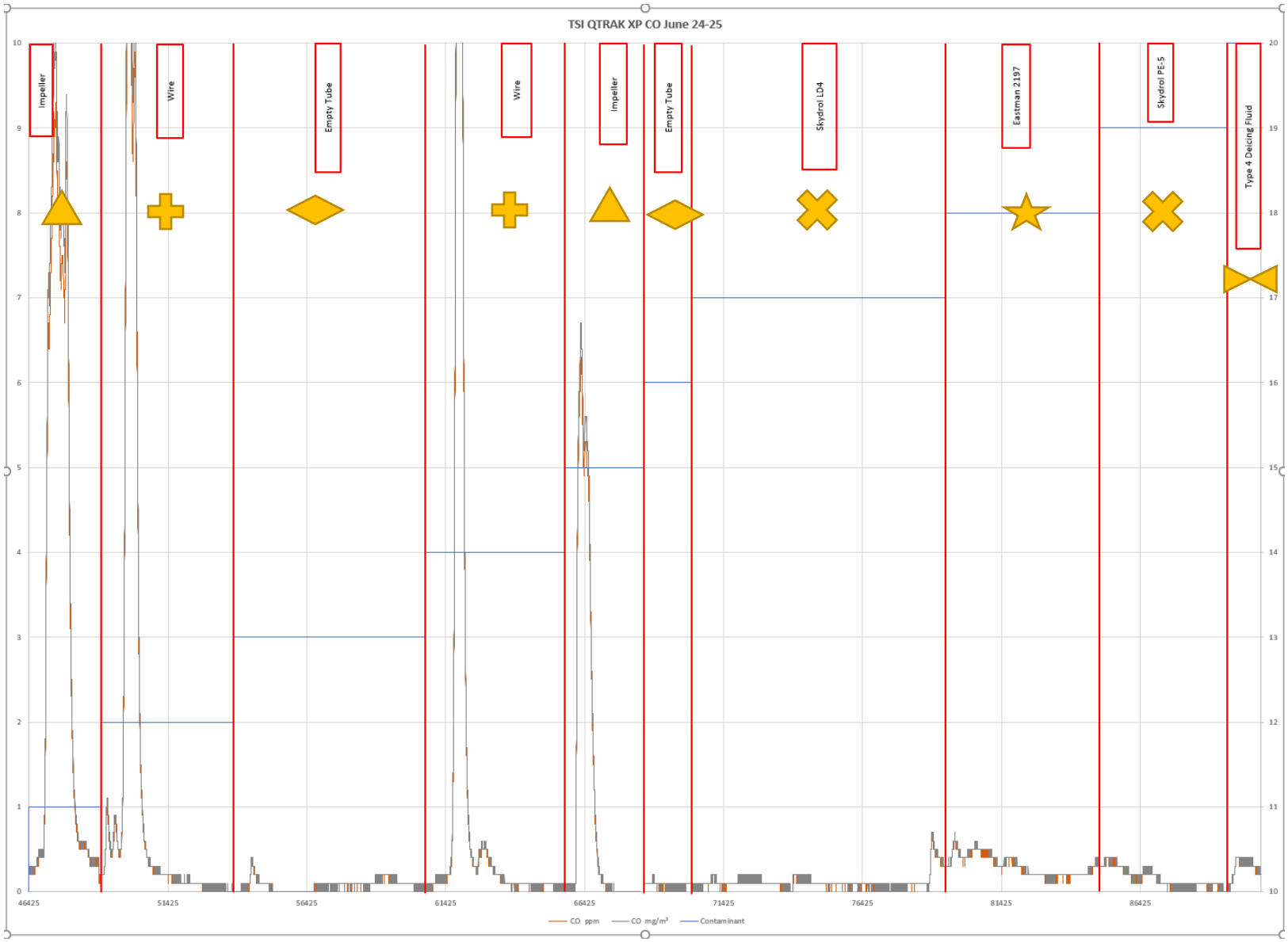

Figure 52. Electrochemical CO sensor response

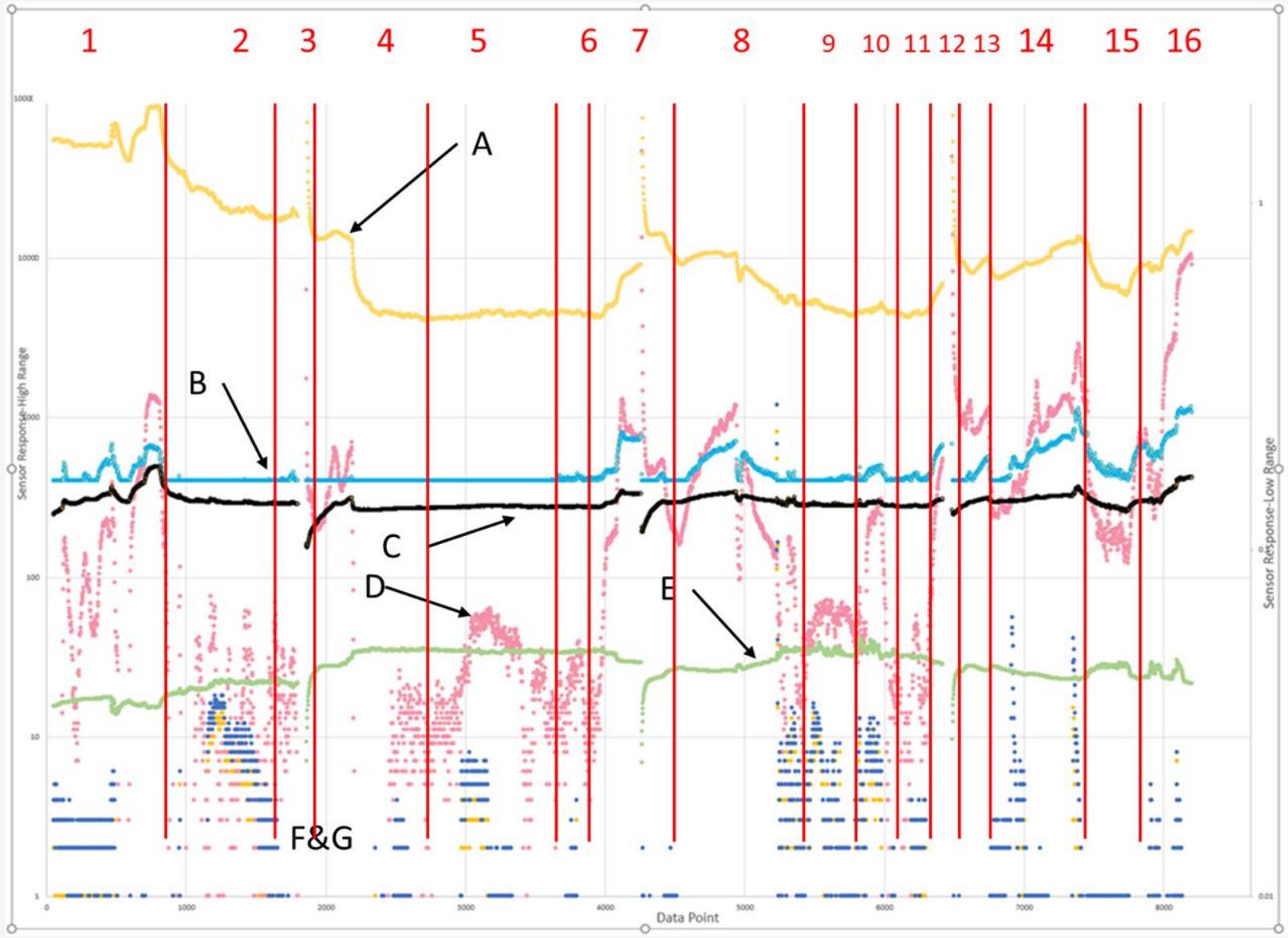

Figure 53. Response of individual HALO channels to different test conditions

Table 61. Figure 55 key

Identifier	**Explanation**
A	“Ammonia” (metal oxide sensor)
B	“eCO_2” (metal oxide sensor) CO_2 VOC equivalent
C	“CO” (metal oxide sensor)
D	“TVOC” (metal oxide sensor)
E	“NO_2 (metal oxide sensor)
F	$PM_{1.0}$ (laser optical sensor) orange symbol
G	$PM_{2.5}$ (laser optical sensor) dark blue symbol
1	Type 1 Deicing Fluid 230^{o}C
2	Mobil Jet II 230^{o}C (high to low)
3	Heat Exchanger Fan Off
4	Eastman 2389 230^{o}C
5	Skydrol LD4 230^{o}C
6	Mobil Jet II 230^{o}C (1ppm low to high)
7	Type 1 Deicing 230^{o}C (10 ppm low to high)
8	Outside Air (diesel engine exhaust ingested)
9	Mobil Jet II 275^{o}C
10	Skydrol LD- 275^{o}C
11	Skydrol PE-5 275^{o}C
12	Outside Air (engine exhaust ingested)
13	Burning Wire
14	Burning Fan Wiring
15	Outside Air
16	Type 4 Deicing Fluid 230^{o}C

6 Research conclusions

- Some sensors did not appear to provide significant response to bleed air generated contaminants: H_2S, SO_2, NO_2, O_3, and CO_2
- Carbon dioxide was not a bleed-air contaminant indicator, but did increase with exhaust ingestion and may be an effective means to identify contamination from turbine engine and ground equipment exhaust.
- Formaldehyde was a marker for exhaust ingestion.
- The hot heat exchanger samples had three orders of magnitude more particles than cool heat exchanger samples.
- Gas sensors do have known cross sensitivities; so a range of substances present during contamination events may be measured by a single sensor type.
- Contaminants released from heat exchangers also generate elevated ultrafine particles concentrations.
- Given the multiple heat exchangers in an ECS, an effective detection strategy needs to address them as a sink and a source for contaminants and for markers.
- Fine particles may be a useful marker for both oil and hydraulic fluid but, likely, will not discriminate between the two contaminants.
- Ultrafine particles and fine particles (and perhaps other sensors) combined may be able to detect and distinguish between oil and hydraulic fluid.
- Ultrafine particles are an effective marker for oil contamination.
- Particles are not an effective marker for deicing fluid, which evaporates.

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Appendix A: November 2020 Workshop Representation

Affiliation
1) AAF Flanders
2) AerNos
3) Aero Data Science, LLC
4) AeroMed Technologies LLC
5) Association of Flight Attendants
6) Airbus
7) Aircraft Cabin Air Conference Director
8) Airsense Analytics
9) Allied Pilots Association
10) American Airlines
11) Ansys Engineering Software
12) Asher Inc.
13) AVSA (France)
14) BASF
15) BASSA H&S Principle
16) Boeing
17) Bombardier Aviation
18) Canadian Union of Public Employees Air Canada
19) Civil Aviation University of China, College of Aeronautical Engineering,
20) Collins Aerospace
21) Dassault Aviation
22) EASA
23) Eastman Chemical Company
24) Eaton Aerospace- Ducting, Sealing, & Sensing Group
25) ENEA
26) Environmental International
27) ES3AERO LLC
28) Exxon Mobil Fuel and Lubricants Company

29) Federal Aviation Administration (FAA)
30) Fraunhofer Institute for Building Physics IBP
31) Fraunhofer Institute for Toxicology and Experimental Medicine (ITEM)
32) French Agency for Food Environmental and Occupational Health and Safety
33) French Airline Pilot Union
34) Freudenberg-NOK Sealing Technologies
35) GE Aviation
36) German Aerospace Center
37) Honeywell Aerospace
38) Honeywell Engineering
39) Hummingbird Aero, LLC
40) Institute of Atmospheric Science & Climate National Research Council of Italy
41) Institute of Occupational Safety & Health of the German Social Accident Insurance
42) Liebherr-Aerospace Toulouse SAS
43) Lufthansa Airline & Lufthansa Group
44) Mitsubishi Aircraft
45) NAWCAD Aeromedical Division
46) NuSil Technology LLC
47) NYCO America, LLC
48) Pall Aerospace
49) ASHRAE Passenger Rep. on SSPC161 Cabin Air Quality Committee
50) Patient Initiative Contaminated Cabin Air e.V. Germany, Vice Chairwoman
51) Performance Sealing Inc.
52) Pratt & Whitney
53) Pratt & Whitney
54) Propulsion Lubricants
55) PTI Technologies, Inc.
56) Rolls-Royce Corporation
57) SAE AC9 Committee, AC-9 Liaison Member
58) SAE Former Chair of E31
59) Safran Filtration Systems

60) Saint-Gobain Performance Plastics
61) SAREL Consult
62) SNPL France ALPA
63) Southwest Research Institute
64) Southwest Research Institute
65) Textron Aviation
66) Transport Canada
67) Trelleborg Sealing Solutions
68) U.S. Air Force
69) UILTRASPORTI - Italy
70) United Airlines
71) University of Manchester, UK
72) University of Stirling (UK)
73) Vereinigung Cockpit
74) VMAN Consulting Services
75) Undesignated

Appendix B. Data set

An electronic data set accompanies this report. This data set documents the experimental data that were collected in collaboration with ASHRAE 1830-RP. The electronic data set is organized by instrument with a separate folder for each instrument. Each instrument has its own data recording format and files, for the most part, are in the format provided by that instrument. The files are all synchronized to the same time and data are organized in the files by time. There is a folder containing experiment logs that document the experimental conditions for each date and time. Through the recorded time and the experiment logs, data can be related to any test condition. The only exception is for the experiments conducted prior to the APU experiments in November of 2020. Only SMPS data are available for those experiments and test conditions are documented internally in the data files.

These data files are presented to document the experiments conducted and to document the basis for the evaluation of instruments and sensor that may be used for detecting markers of bleed air contamination. Any use of this data for other purposes should be conducted with caution. Researchers who use these data need to be familiar with the operation and limitations of the experiment instruments, . Researchers must be familiar with the formats of the data files generated by the instruments and how to interpret the recorded data.. Similarly, any data interpretation needs to be done in the context of the experiments from which they were generated. The user needs to be familiar with the experiment apparatuses used, the conditions under which the experiments were conducted and the confounding factors potentially present. Failure to follow this guidance could result in misleading and erroneous interpretations and conclusions.

The following lists identifies data files or folders that are available for each set of experiments for each instrument.

Test Stand Engine Experiments, Preliminary

a) SMPS
    - 2020-07-24a SMPS
    - 2020-07-24c SMPS
    - 2020-08-06a SMPS
    - 2020-08-07a SMPS
    - 2020-08-13a SMPS
    - 2020-08-14a SMPS
    - 2020-08-31a SMPS
    - 2020-09-18a SMPS

APU Experiments November 2020

a) SMPS
   - 2020-11-12 SMPS
   - 2020-11-13 SMPS

b) APS
   - 2020-11-12 APS
   - 2020-11-13 APS

c) Halo
   - Halo November 12 and 13

d) Naneos
   - Partector November 11
   - Partector November 12
   - Partector November 13

e) Logs
   - 2020-11-12-13 Log

Test Stand Engine Experiments, March 2021

a) SMPS
   - 2021-03-23 SMPS
   - 2021-03-24 SMPS
   - 2021-02025 SMPS

b) APS
   - 2021-03-23 APS
   - 2021-03-24 APS
   - 2021-03-25 APS

c) Aerotracer
   - Aerotracer Summary for March Experiments

d) MOS1
   - MOS1 March 22-26

e) Halo
   - Halo March 22-26

f) Interscan
   - Interscan March 22-26

g) Lab Results
   - Lab March 22-26

h) Naneos Partector II
   - Partector March 22-26

i) ppbRAE
   - ppbRAE March 22-26

j) TSI 3007
   - TSI 3007March 22-26

k) TSI QTRAK
- TSI QTRAK March 22-26

j) Logs
- 2021-03-23 Log
- 2021-03-24 Log
- 2021-03-25 Log

Furnace Experiments, March 2021

SMPS
- 2021-03-26 SMPS

APS
- 2021-03-26 APS

Logs
- 2021-03026 Log

Test Stand Experiments, Intermediate

a) SMPS
- 2021-04-12 SMPS
- 2021-04-15 SMPS
- 2021-04-16 SMPS
- 2021-04-28 SMPS
- 2021-05-12 SMPS

b) APS
- 2021-04-12 APS
- 2021-04-15 APS
- 2021-04-16 APS
- 2021-04-28 APS
- 2021-05-12 APS

c) Logs
- 2021-04-12 Log
- 2021-04-15 Log
- 2021-04-16 Log
- 2021-04-28 Log
- 2021-05-12 Log

Test Stand Engine Experiments, June 2021

a) SMPS
- 2021-06-22 SMPS
- 2021-06-23 SMPS

b) APS
- 2021-06-22 APS bleed

- 2021-06-22 APS outside
- 2021-06-23 APS bleed
- 2021-06-23 APS outside

c) Piera
- 2021-06-22 Piera outside
- 2021-06-22 Piera bleed
- 2021-06-23 Piera outside
- 2021-06-23 Piera bleed

d) CO_2
- 2021-06-22 CO_2
- 2022-06-23 CO_2

e) SD
- 2021-06-22 SD
- 2021-06-23 SD

f) Airsense Aerotracer
- Aerotracer Summary for June Experiments

g) MOS1
- MOS1 June 21-25

h) Halo
- Halo June 21
- Halo June 22
- Halo June 23
- Halo June 24-25

i) Interscan
- Interscan June 21-25

j) Lab Results
- Lab June 21-25

k) Naneos Partector II
- Partector June 21-25

l) ppbRAE
- ppbRAE June 21-25

m) Pegasor
- Pegasor IAQ Monitor June 21-25

n) TSI 3007
- TSI 3007 June 21-25

o) TSI QTRAK
- TSI QTRAK June 21-25

p) Logs
- 2021-06-21 Log
- 2021-06-22 Log
- 2021-06-23 Log

Furnace Experiments, June 2021

a) SMPS
   - 2021-06-24-SMPS
   - 2021-06-25 SMPS

b) APS
   - 2021-06-24 APS bleed
   - 2021-06-24 APS outside
   - 2021-06-25 APS bleed
   - 2021-06-25 APS outside

c) Piera
   - 2021-06-24-Piera bleed
   - 2021-06-24-Piera outside
   - 2021-06-25-Piera bleed
   - 2021-06-25-Piera outside

d) CO_2
   - 2021-06-24 CO2
   - 2021-06-25 CO2

e) SD
   - 2021-06-24 SD
   - 2021-06-25 SD

f) Temperature
   - 2021-06-24 TEMP
   - 2021-06-25 TEMP

g) Logs
   - 2021-06-24 Log
   - 2021-06-25 Log
   - 2021-06-21-25 Log

Follow on Furnace Experiments

a) SMPS
   - 2021-07-16 SMPS
   - 2021-08-02 SMPS
   - 2021-08-03 SMPS
   - 2021-08-04 SMPS

b) APS
   - 2021-07-16 APS bleed
   - 2021-08-02 APS bleed
   - 2021-08-02 APS outside
   - 2021-08-03 APS bleed
   - 2021-08-03 APS outside
   - 2021-08-04 APS bleed
   - 2021-08-04 APS outside

c) Piera
    - 2021-08-04 Piera bleed
    - 2021-08-04 Piera outside
d) CO_2
    - 2021-07-16 CO_2
    - 2021-08-02 CO_2
    - 2021-08-03 CO_2
    - 2021-08-04 CO_2
e) TEMP
    - 2021-07-16 TEMP
    - 2021-08-02 TEMP
    - 2021-08-03 TEMP
    - 2021-08-04 TEMP
f) SD
    - 2021-07-16 SD
    - 2021-08-02 SD
    - 2021-08-03 SD
    - 2021-08-03 SD
g) Logs
    - 2021-07-16 Log

Appendix C Test Plan

This appendix presents the detailed test plan for test stand engine experiments described in Section 4.

Contaminant	Concentration	Bleed Air Temp
Low Temperature Test 200C - 250C		
Mobil Jet II	0 ppm	<250C
Mobil Jet II	5 ppm	<250C
Mobil Jet II	3 ppm	<250C
Mobil Jet II	2 ppm	<250C
Mobil Jet II	1 ppm	<250C
Mobil Jet II	0 ppm	<250C
Eastman 2389	0 ppm	<250C
Eastman 2389	5 ppm	<250C
Eastman 2389	3 ppm	<250C
Eastman 2389	1 ppm	<250C
Eastman 2389	0 ppm	<250C
Skydrol LD4	0 ppm	<250C
Skydrol LD4	5 ppm	<250C
Skydrol LD4	3 ppm	<250C
Skydrol LD4	1 ppm	<250C
Skydrol LD4	0 ppm	<250C
Deice Type 1	0 ppm	<250C
Deice Type 1	5 ppm	<250C
Deice Type 1	10 ppm	<250C
Deice Type 1	0 ppm	<250C
Deice Type 4	0 ppm	<250C
Deice Type 4	5 ppm	<250C
Deice Type 4	10 ppm	<250C
Deice Type 4	0 ppm	<250C
Skydrol PE5	0 ppm	<250C
Skydrol PE5	5 ppm	<250C
Skydrol PE5	3 ppm	<250C
Skydrol PE5	1 ppm	<250C
Skydrol PE5	0 ppm	<250C
Mobil Jet II	0 ppm	<250C
Mobil Jet II	1 ppm	<250C
Mobil Jet II	0 ppm	<250C
Skydrol LD4	0 ppm	<250C
Skydrol LD4	1 ppm	<250C
Skydrol LD4	0 ppm	<250C

Completed Tests

Completed, May Require Repeat

Tests Not Conducted

Deice Type 1	0 ppm	<250C
Deice Type 1	1 ppm	<250C
Deice Type 1	0 ppm	<250C

High Temperature Tests >300C

Mobil Jet II	0 ppm	>300C
Mobil Jet II	5 ppm	>300C
Mobil Jet II	3 ppm	>300C
Mobil Jet II	1 ppm	>300C
Mobil Jet II	0 ppm	>300C
Eastman 2197	0 ppm	>300C
Eastman 2197	5 ppm	>300C
Eastman 2197	3 ppm	>300C
Eastman 2197	0 ppm	>300C
Skydrol LD4	5 ppm	>300C
Skydrol LD4	0 ppm	>300C
Mobil Jet II	0 ppm	>300C
Mobil Jet II	1 ppm	>300C
Mobil Jet II	0 ppm	>300C

Special Tests

No Bleed Cooling	0 ppm	<250C
Cleaned Heat Ex	0 ppm	<250C
Dirty Heat Ex	0 ppm	<250C
Cleaned Heat Ex	0 ppm	>300C
Dirty Heat Ex	0 ppm	>300C
Water Wash	0 ppm	<250C
Turbine Exhaust	NA	<250C

Non-Engine Tests

Insulation Smoke	Fan	NA
Fan Rub Smoke	Fan	NA
Insulation Smoke	Wire 1	NA
Insulation Smoke	Wire 2	NA
LD-4		NA

PE-5	NA
Jet II	NA
2197	NA
Deice 4	NA
Empty Furnace	NA