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The Nature of Particulates in Aircraft Bleed Air Resulting from Oil Contamination

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ABSTRACT

ASHRAE Standard 161, Air Quality within Commercial Aircraft, includes a requirement for bleed air sensors to detect contamination from lubricating oil. One potential approach to meeting this requirement is through particle detection. A four-part experimental program was conducted to develop a detailed characterization of particles that result when bleed air is contaminated with lubricating oil. The first part of the program utilized a bleed air simulator. A reciprocating compressor follow by a heated tube was used to create controlled temperature and pressure conditions representative of bleed air from an aircraft engine. Aerosolized lubricating oil was injected into the airflow upstream of the compressor and the particulate characteristics were measured downstream of the heated tube. The second and third parts of the program used turbine shaft engines mounted in a test stand and connected to a dynamometer for controlled loading. Aerosolized oil was mixed into the inlet air and the resulting particle characteristics in the bleed air were measured. The compressor for the second part utilized both axial and centrifugal compression stages while the compressor for the third part utilized a single centrifugal stage. The fourth part of the program utilized an engine on an US Air Force C-17 military transport aircraft. Oil was injected into the first stage of the compressor and the bleed air from the engine was diverted to a test platform where it was cooled and sampled. Particulate size distributions and concentrations were measured with aerodynamic particle sizing and scanning mobility particle sizing. Collectively, these instruments could measure concentrations and size distributions for particles ranging from 10 nanometers to 20 microns. The measurements showed that oil contamination in the compressor will result in a fog of very fine droplets in the bleed air under most operating conditions. Typically these droplets are in the 10-150 nanometer range. With very low contamination rates, it appears that many of the droplets may be even smaller than 10 nanometers. This research shows that development of sensors for detecting oil contamination in aircraft bleed air should focus on ultrafine particle detection and sensing of low contamination levels may require sensitivity to extreme ultrafine particles 10 nanometers and smaller.

INTRODUCTION

The vast majority of commercial aircraft utilize bleed air from the propulsion engine compressors for ventilation and pressurization during flight. They may also use an auxiliary power unit for this purpose during ground operations and some phases of flight. If there is contamination from lubricating oil or other fluids ingested into the engine air intake or through bearing seal leakage, then the air supplied to the aircraft will also be contaminated. Additionally, the temperatures achieved in the engine compressor at the bleed air extraction location can be high enough under certain operating conditions to present the possibility of thermal decomposition (NRC 2002). Low levels of bleed air contamination present the potential for chronic, unidentified exposure. Higher levels of contamination create what is referred to as a fume event where there is an obvious odor or sometimes visible smoke or mist in the aircraft. In the case of visible smoke, the flight crew must make critical decisions. An onboard fire is a

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clear emergency requiring immediate landing perhaps at a less than ideal runway. If the smoke is from oil in the bleed air from a compressor seal leak, the situation is managed by source isolation and the flight can normally continue without urgency to a safe landing point. Unfortunately, aircraft are not normally equipped with instrumentation that allows bleed air contamination to be detected. Consequently, flight crew may waste critical time trying to isolate a bleed air source when, in fact, there is an onboard fire. Or, they may make an unnecessary emergency landing with its inherent risks when the source could have been isolated with minimal disruption of the flight. In less extreme cases, oil contamination of bleed air may result in turn backs or unscheduled landings with their inherent costs and disruptions (Shehadi et al 2015a, Lebbin 2013). The probability of a bleed air fume event on any random flight is very low; Shehadi et al (2015b) estimated the frequency to be approximately one in 5000 flights and lubricating oil is just one of several causes. Nevertheless, the ability to detect oil contamination in bleed air and to identify the source engine of this contamination would be a valuable asset in minimizing aircraft occupant exposure to contamination and aid in critical decision making in the case of a serious smoke in the cabin event. This need is recognized in ASHRAE Standard 161 (ASHRAE 2013) which calls for sensors to detect bleed air contamination. Unfortunately, there are no sensors readily available with demonstrated ability to reliably detect oil contamination of bleed air.

A series of projects was conducted to assess the nature of contaminants that result from oil in bleed air. These experiments addressed the chemical nature and the particulate (droplet) nature of the contamination that eventually ends up in the bleed air. There were multiple objectives for the projects including quantification of the chemical exposure that results, identification of chemical tracers for detection, and characterization of the particulates that result. This paper addresses only the particulate characterization results from these experiments.

EXPERIMENTAL APPARATI

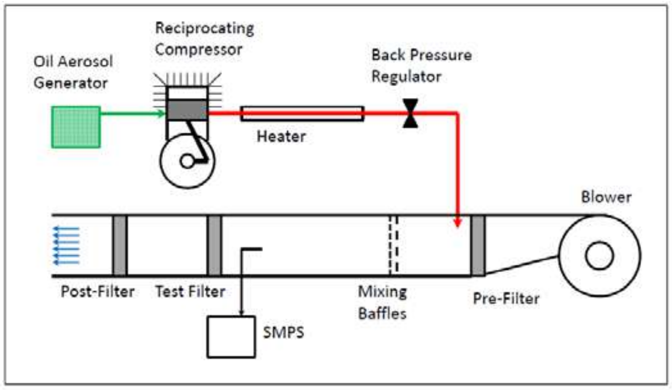

Figure 1. Bleed air simulator.

The first project used a bleed air simulator (BAS) to provide air representative of oil contaminated bleed air. This apparatus was developed for a previous project which required exposing aircraft recirculation filter media to controlled contamination representative of what would be expected in the case of aircraft cabin contamination (Eckels et al 2014). A simplified diagram of the apparatus is presented in Figure 1. A bank of aerosolizing nozzles was used to generate a fine oil mist. The resulting mist laden air was compressed in a reciprocating compressor to a controlled pressure. Following the compressor, a heater raised the temperature of the air stream to a controlled value. This apparatus allowed pressure and temperature to be controlled more or less independently and allowed examination of both temperature and pressure effects on the chemical makeup and particulate characteristics of the contaminated, simulated bleed air. Previously published results showed that optical particle detection and sizing did not work well in this application due to the small particle size (Mann et al 2014). Additionally, a water-based condensation particle counter did not work well presumably due to the difficulty in condensing water onto an oil particle. A scanning mobility particle sizing system (SMPS) and an aerodynamic particle sizing system (APS) were both shown to work well and provided consistent results. Together, these measuring devices allow size distributions to be characterized over the range of 10 nanometers to 20 microns. The same SMPS and APS used for the BAS experiments where used for the other three projects as well. Since the vast majority of the particles detected with oil contamination were in a size range below the sizing limits of the APS, only the SMPS data are presented in this paper. More detailed descriptions of the BAS experimental setup are provided by Mann et al (2014) and Magoha (2012).

While the BAS provided a means to conveniently and economically generate controlled conditions for assessing oil contamination of bleed air, it has limitations on the fidelity with which it simulates bleed air. In particular, it utilizes a reciprocating shop compressor to compress the air. Since this type of compressor is purposely cooled to increase the efficiency of compression, the temperature of the air from the compressor is not representative of aircraft bleed air. Thus, a separate heater was required. Aircraft engines use high speed turbo machinery to compress the air and there is no cooling of this air internal to the compressor. The shear mechanisms responsible for aerosol generation may be very different in a reciprocating compressor as compared to a turbo compressor. Additionally, the BAS heater raises the temperature through a heat transfer process whereas the temperature increase for aircraft bleed air is due to adiabatic compression. For these reasons, it was desired to confirm the results of the BAS with bleed air from a turbine engine. Large commercial aircraft engines are extremely expensive to obtain and operate and were out of the question. However, a small turbo shaft engine was available to use for this purpose. This engine has a nominal power rating of 300 HP (220 KW), utilizes six stages of axial compression and one stage of centrifugal compression. It is typically used for small helicopters as well as stationary applications. It is designated as the C-18 engine in this paper. The engine was mounted on a test stand and configured as shown in Figure 2. It was connected to a dynamometer to provide controlled loading. Bleed air was pulled off the engine bleed air port and passed through an aircraft precooler prior to being sampled. The same bank of aerosolizing nozzles used for the BAS was used to generate an oil mist that was injected into the engine inlet air. Sampling ports were available to allow the air to be sampled both upstream and downstream of the oil injection. A more detailed description of the experimental apparatus is presented by Roth (2015).

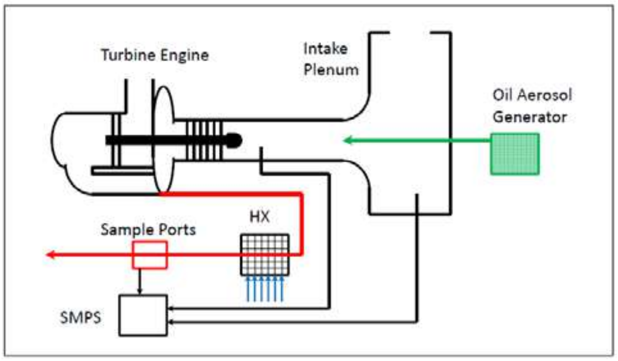

Figure 2. Test stand engine configuration.

It turned out that the C-18 engine was not capable of generating the pressures and temperatures of most interest for bleed air contamination studies. Consequently, a more powerful version of the same engine was obtained. This engine had a nominal power rating of 500 HP (370 KW). It is designated as the C-28B engine in this paper. The C-28B engine design is the same as the C-18 except that it utilizes a single stage centrifugal compressor with no axial compression stages. It was mounted on the same test stand with the same sampling setup as for the C-18 engine.

The C-18 and C-28B engine projects provided very useful data for bleed air oil contamination. By utilizing test stand engines, conditions could be controlled and it was possible to run experiments for many conditions. However, there was still the question as to whether or not the results are representative of the contamination in a large commercial airliner engine that is orders of magnitude larger than the C-18 and C-28B engines. Through fortuitous circumstances, the opportunity to participate in the NASA Vehicle Integrated Propulsion Research (VIPR) program to test and evaluate new engine health management technologies arose. VIPR was a very large program which involved not only NASA but also the U.S. Air Force, the FAA, and several private companies. Experiments were conducted on the engine on an Air Force C-17 transport aircraft. The VIPR program provided an opportunity to collect bleed air oil contamination data that otherwise

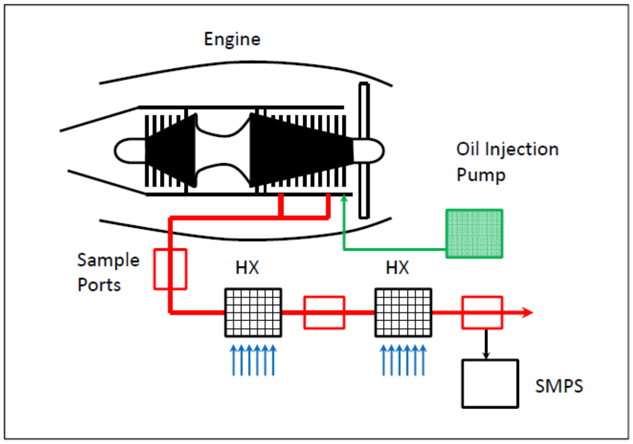

Figure 3. Configuration for VIPR experiments.

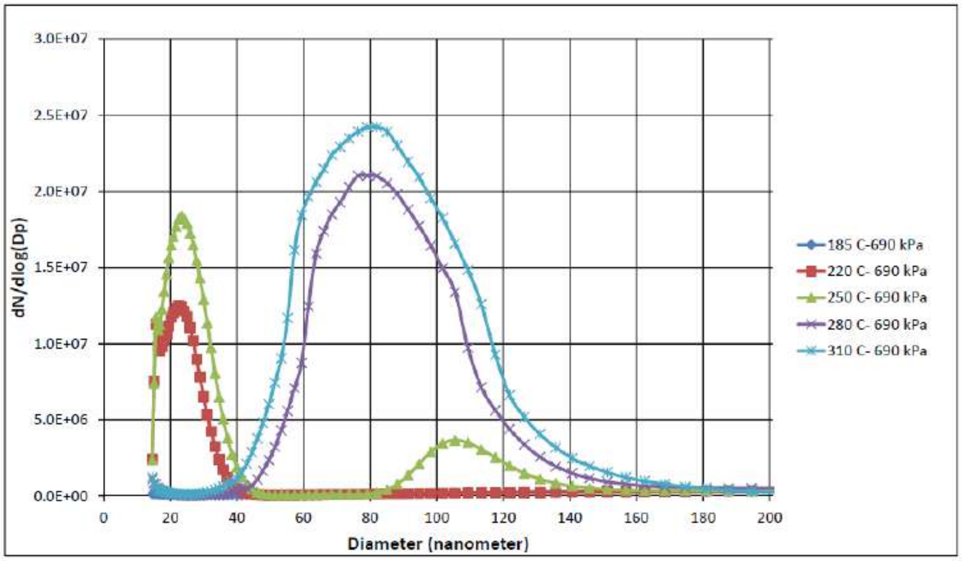

Figure 4. Bleed air simulator results.

would have been prohibitively expensive to obtain. The bleed air aspect of the experiments was only a small part of the overall VIPR program. The data were collected on the ground from an engine mounted on an operational aircraft. A simplified diagram of the experimental setup is shown in Figure 3. Atomized liquid oil was injected via a nozzle mounted in an inspection port near the front of the compressor. There are two bleed air ports on the engine, the low pressure port and the high pressure port. The engine and bleed air manifold were modified so the bleed air port selected could be controlled remotely. The bleed air was diverted to an instrumentation platform located on the ground beneath the engine. The bleed air was cooled in two stages to allow sampling at different temperatures representative of different locations in the bleed air system. The bleed air was cooled using aircraft bleed air pre-cooler heat exchangers. The particulates were measured at the last stage were the bleed air had been cooled to levels acceptable for the SMPS and APS. The engine was operated at a power level intended to give bleed air conditions representative of cruise engine operation.

EXPERIMENTAL RESULTS

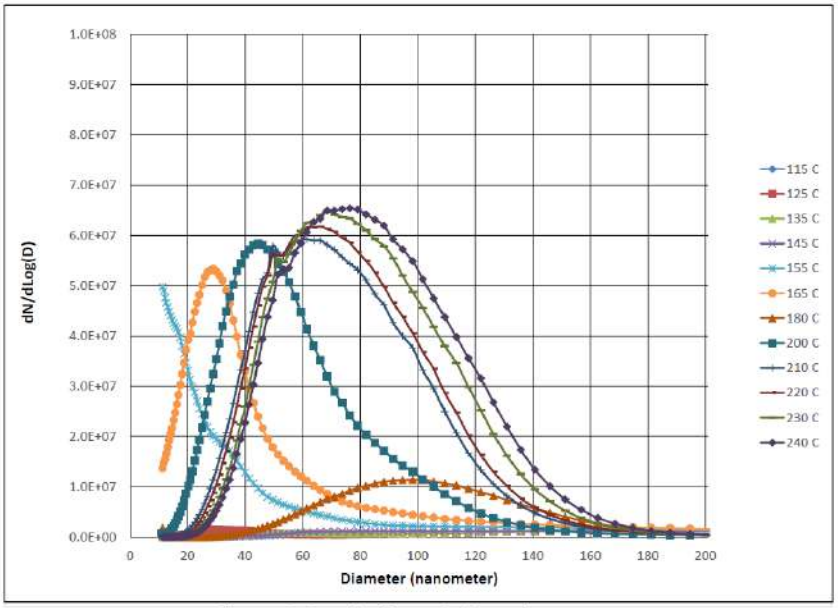

Figure 5. Results from C-18 engine.

A large amount of data was collected in the four projects and only representative results are presented in this paper due to space constraints. With the BAS, data were collected by holding pressure constant and varying temperature and by holding pressure constant and varying pressure. Figure 4 shows the results for one pressure typical of aircraft bleed air. Temperature is seen to have a substantial effect on the both the size distribution and the total number of particles. It appears there is a change in particle formation mechanism that starts at about 250C (480F). It had been expected that there would be an increase in ultrafine particles as the temperature increased above the point that oil starts to char, around 280C

(530F). Whether or not the increase seen at the higher temperatures is due to this effect is strictly speculative at this point. The key conclusion from these data is that the bulk of the particles in terms of numbers are very small with most being less than 150 nanometers in diameter.

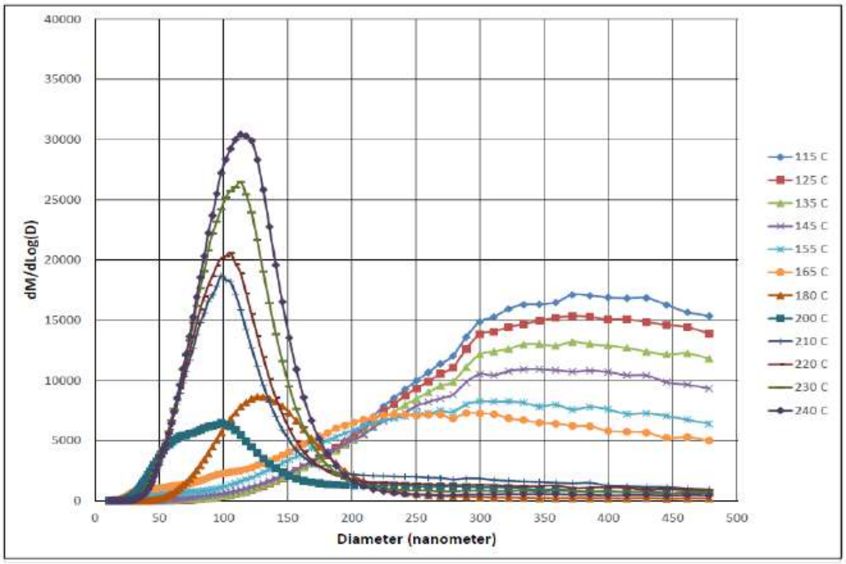

Figure 6. Mass distribution with C-18 engine.

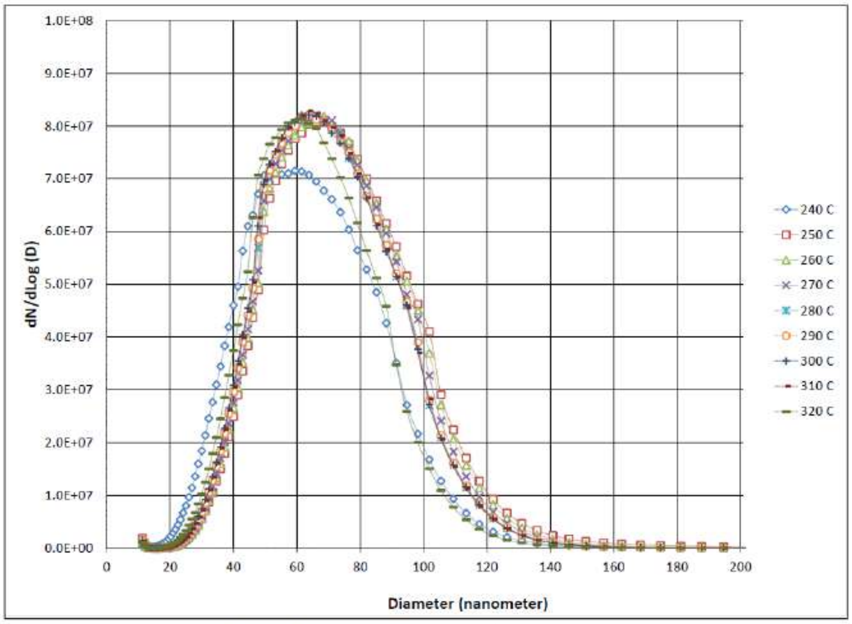

Figure 7. Results from C-28 engine.

Figure 5 presents data from the C-18 engine. In some sense, a phenomenon similar to that seen in the BAS data is present. That is, the number of particles present increases greatly with temperature. It also appears that this phenomenon levels out at some point and the concentration does not change much with further temperature increases. The bleed air temperatures for the C-18 engine are all well below the point that charring of the oil would be expected. Thus, it is reasonable to conclude that the increasing number of particles with increasing temperature is not due to that effect. With any turbine engine, temperature and pressure in the compressor are not independent as both variables increase together with engine speed which, in turn, increases with power. Figure 6, which shows the mass distribution, helps explain why the concentration increases with temperature or speed. At low speeds the mass is located in larger particles and then, as the speed increases, the larger particles are evidently sheared into smaller particles. Given the cubic relationship between mass and diameter and the size change, the same amount of mass can result in a couple of orders of magnitude increase in particle numbers when they are sheared into the smaller particles. As with the BAS data, one of the key findings with the C-18 engine is that the bulk of the particles, by number, are less than 150 nanometers in diameter.

The C-18 engine data provided useful insights into the nature of particles that can be expected in bleed air and the phenomena whereby the very small particles are generated, the temperature conditions that could be achieved with this engine were below those that would be expected in large commercial aircraft bleed air systems and are also below those where charring of the oil is expected to occur. Since the chemical nature of the bleed air contaminants under these conditions was important to determine, the C-28B version of this engine was obtained and data were collected on the same test stand. The C-28B engine was able to achieve bleed air pressures and corresponding temperatures that pretty well cover the range expected from most large aircraft engines. As seen in Figure 7, temperatures up to 320C (610F) were achieved. The data from the C-28B engine match well with the C-18 engine and appear to confirm that further increases in speed and temperature have little effect on the size distribution of the particles generated.

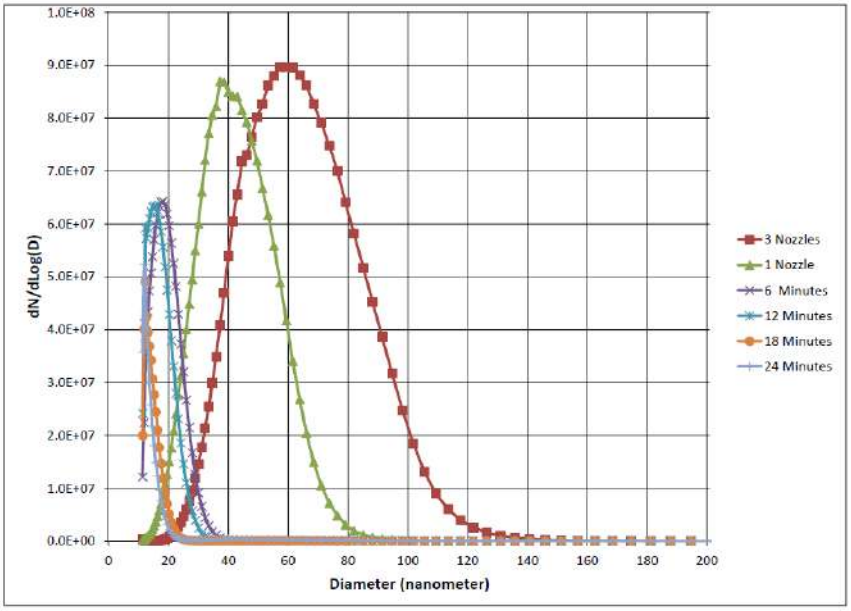

Figure 8. Decay behavior with C-28 engine.

As part of the experimental procedure, tests were conducted to determine how quickly the particle size distribution changed after the oil injection was turned on or off. This information is needed to determine how much time is required to ensure stable, steady state measurements. The results from one of these tests are shown in Figure 8 and they provide further insight into the particle generation phenomena inside the engine. The oil aerosol generator consisted of a bank of three identical venturi aerosolizing nozzles and could be operated with one, two, or three nozzles generating aerosols. Unless stated otherwise, all data collected for the BAS, C-18 engine, and the C-28B engine were collected with all three nozzles operating. The test shown in Figure 8 started with all three nozzles operating and then two were turned off and the conditions allowed to stabilize. The peak concentration shifted from about 60 nanometers to about 40 nanometers with only a modest change seen in the concentration. However, the cube of 40/60 is about 0.3 so a decrease in size from 60 to 40 nanometers results in approximately the same number of particles with 1/3 the mass. After the single nozzle data were collected, all of the nozzles were turned off and a size scan was performed every six minutes for 24 minutes. As expected, the number of particles decreased. Interestingly, the particle size also decreased and the decrease in mass present was more from the size decrease than the number decrease. The C-18 data and the C-28B data lead to the hypothesis that, at the power levels of most interest, the vast majority of the oil droplets do not pass through the compressor without impacting a surface within the compressor. These impacting droplets form an oil film on the surface and new droplets are sheared from this film. The thicker the film the larger the droplets sheared from the film. Thus, the droplets are larger for the higher injection rates and get progressively smaller as the film is dissipated when the oil injection stops. This phenomenon, if correctly hypothesized, has important consequences for sensing of oil contamination in bleed air. Large numbers of particles are expected even at low contamination rates but the ability to detect very small particles, perhaps 10 nanometers and less, would be required for sensing low contamination rates.

Data collected from the VIPR experiments are shown in Figure 9. These data were collected under steady state operating conditions with the engine set at power levels intended to yield bleed air conditions representative of cruise conditions. The SMPS takes approximately 2 minutes to collect data and generate a size distribution. The curves in this figure are from consecutive measurements. It is seen that the conditions were quite stable and consistent data were obtained. While somewhat boring in nature, these data are perhaps the most important of all of the data presented as they were collected on an actual large aircraft engine operating at typical flight conditions. In fact, the engines on the Air Force C-17 aircraft are essentially the same engine as used on the B-757 aircraft. It is reassuring to see that the data collected on this large engine match very closely with the data collected on the test stand engines. Not only are the particle size distributions nearly the same, the number concentration is about the same as well. This consistency in results gives confidence that the data collected on the test stand engines, the C-28B engine in particular, are representative of large aircraft engines.

An important consideration for oil contamination detection is how these particle concentrations compare to background concentrations with no oil injection. The total particle concentration for the data shown in Figure 9 is approximately $2x10^7$ particles/cm^3. By comparison, the total particle concentration measured in the ambient air at the time of the experiments was approximately $1x10^4/cm^3$ and the concentration in the bleed air with no oil injection was approximately $1x10^3$ particles/cm^3. Thus, the concentrations measured when the oil contamination was present were approximately four orders of magnitude greater than when it was not present. The concentration in the bleed air being lower than the ambient concentration was somewhat surprising at first. However, the particles in the ambient air were much larger than those seen in the bleed air and most likely are composed of solids, not liquid. It is likely they impact surfaces in the compressor or otherwise do not make it to the bleed air port. The VIPR experiments were conducted at Edwards Air Force Base on the dry lake bed in the Mohave high dessert. Except possibly for some dust from the lake bed, the air is pristine and free of industrial contaminants. Also, the VIPR test engine was fully overhauled prior to the beginning of the VIPR experiments and, presumably, was in top operating condition with no seal leaks. The no-oil total particle concentrations in the bleed air for the C-28B and C-18 engines were not as low as for the VIPR engine. The test stand for these engines was located in an industrial park and the configuration was such that re-entrainment of the engine exhaust could not be totally avoided. Measurements in the air plenum with the C-18 engine showed that the particle concentration in the air plenum upstream of the oil injection increased several orders of magnitude with engine operation as compared to the ambient concentrations prior to engine operation. Nevertheless, the overall particle concentrations in the bleed air with oil injection were still about one to two orders of magnitude greater than steady state values with no oil injection.

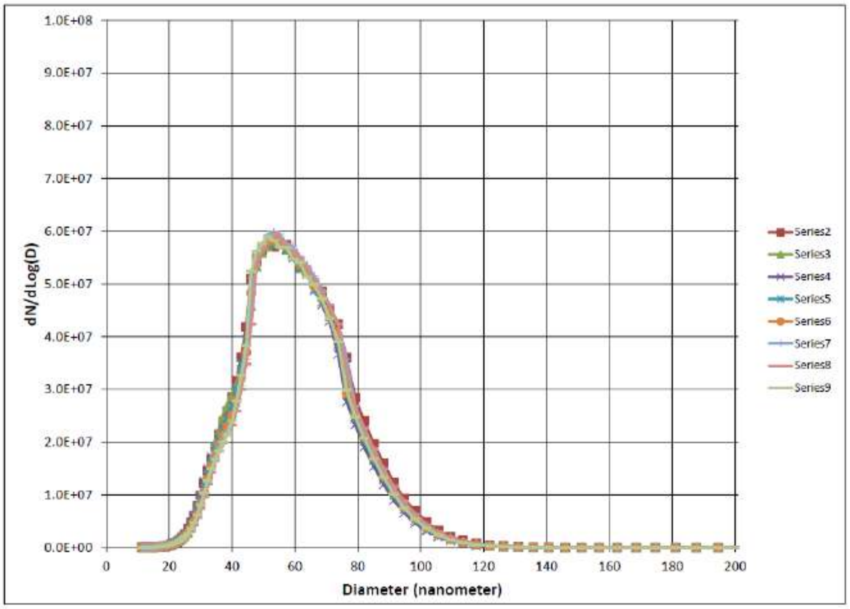

Figure 9. Results from VIPR experiments.

CONCLUSIONS AND RECOMMENDATIONS

It is clear from these experiments that oil contamination leads to a large number of particles in the bleed air. Additionally, the signal to noise (background) ratio is very high making particle detection a promising method for detection of oil contamination in the bleed air.

It is also clear from these experiments that the particles generated will be very small with peak concentrations likely in the range of 50-70 nanometers with substantial oil contamination. The data collected came from four very different systems. The BAS utilized a reciprocating compressor and heater to generate simulated bleed air conditions. The C-18 engine had a compressor with 6 axial stages and one centrifugal stage. The C-28B engine compressor had a single centrifugal stage. The VIPR engine had a fan plus two-part compressor with multiple axial stages in each part. Given that these diverse systems gave similar results gives good confidence the data are representative of aircraft turbine engines in general and are not unique to a specific make and model of engine or engine design.

Detecting oil contamination during acute fume events is important and these data indicate there should be no problem detecting contamination via particles present during these events. Detecting low-level chronic leakage is important to avoid prolonged exposure and to identify a developing malfunction before it creates a critical flight situation. The experiments reported here did not specifically target this low-level contamination. However, some useful insights were gained. It appears that particle numbers will still be large with lower levels of contamination but the particle size gets increasingly small with low contamination rates, possibly in the 10-20 nanometer range and even smaller. Thus, detecting low levels of contamination using particles likely will require sensors that can detect these very small particles.

The SMPS system used to collect the particle size distribution and concentration data reported in this paper worked well. However, it is laboratory instrumentation that is expensive, requires stable operating conditions, and requires a knowledgeable researcher to operate the equipment and process and interpret the data. Thus, it is not a candidate for routine in-flight monitoring of bleed air for oil contamination. Now that the nature of the particulates that result from bleed air contamination has been determined, it is recommend that research be conducted to indentify reasonable-cost, rugged, and reliable sensing technology that could be deployed widely in the aircraft fleet to detect oil contamination. The requirement to detect ultrafine particles limits the technology that may be applicable. A condensation particle counter (CPC) is the particle sensing device in the SMPS and clearly is able to detect particles in the size range of interest. However, substantial modifications would be required to make available CPCs suitable for routine aircraft monitoring. Another promising technology is the ionization-based particle detection this is widely used in home smoke detectors. This technology is effective at detecting particles in the size range of interest and is simple and reliable.

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