SAE Aerospace
An SAE International Group

AEROSPACE INFORMATION REPORT

SAE AIR5892
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Nonvolatile Exhaust Particle Measurement Techniques

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1. SCOPE:

This SAE Aerospace Information Report (AIR) addresses procedures applicable to quantifying the emission of nonvolatile particulate matter at the exit plane of aircraft gas turbine engines. While both volatile and nonvolatile particulate matter (PM) are present in aircraft gas turbine exhaust, the methods used to measure nonvolatile particles are farther advanced and are addressed here.

Existing PM measurement regulations employ the SAE Smoke Number measurement (Reference 2.1.1), a stained filter technique used in evaluating visible emissions. The environmental and human health issues associated with submicronic PM emissions require more detailed measurement of the mass, size, and quantity of these particle emissions.

Responding to regulatory agency requests, this AIR describes measurement techniques that are well developed and could be applied to the measurement of aircraft engine particulate matter. The techniques discussed here are considered relevant for measuring particle parameters identified with environmental and health concerns.

The discussion that follows is based on research made while developing measurement techniques and in scientific and engineering experiments regarding PM emissions. The techniques are not yet used in routine aircraft engine certification. Future use in regulatory testing is likely to involve further refinements in methodology and application. It is planned that these refinements will be included in the subsequent publication of an Aerospace Recommended Practice.

The distinction between nonvolatile and volatile particle types is a critical task in the measurement of particles in aircraft engine exhaust. Appendix A, SAE E-31 Position Paper on Particle Matter Measurements, provides additional technical bases for the scope of this AIR. The measurement methods for volatile condensed particles in turbine exhaust will be covered in a subsequent report. Observations to date show that volatile particles occur mainly at diameters less than 10 nanometers (<10 nm) but may dominate in particle number density (PND).

2. REFERENCES, DEFINITIONS, NOMENCLATURE:

2.1 SAE Publications:

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

2.1.1 ARP1179 Aircraft Gas Turbine Engine Smoke Measurement Practice

2.2 Other Applicable References:

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2.3 Definitions:

AIRCRAFT GAS TURBINE ENGINE: Any gas turbine engine used for aircraft propulsion or for power generation on an aircraft, including those commonly called turbojet, turbofan, turboprop, or turboshaft type engines.

CLASSICAL AERODYNAMIC DIAMETER: The diameter of an equivalent unit density sphere with the same settling velocity in still air as the particle in question.

ELEMENTAL CARBON (PARTICULATE MATTER): The refractory carbon found in combustion-generated particulate matter. Also known as graphitic carbon.

EMISSION INDEX (MASS): The mass of emissions of a given constituent per thousand mass units of fuel burned (e.g., g/kg fuel).

ENGINE EXIT PLANE: Any point within the area of the engine exhaust nozzle at an axial distance within 0.5 diameters (or equivalent, if not circular) downstream from the outer edge of the nozzle.

NONVOLATILE PARTICLES: Particles that exist at engine exit plane temperature and pressure conditions.

ORGANIC CARBON (PARTICULATE MATTER): All carbon-based particulate matter resulting from condensation and chemical reaction after the combustion process. Organic carbon contains volatile components of carbon combined with hydrogen and other elements.

PARTS PER MILLION (ppmv): The unit volume concentration of a gas per million unit volumes of the gas mixture of which it is part. (Also applicable to mass measurements and referred to as ppmm).

2.3 (Continued):

PM-2.5: Particulate matter ≤ 2.5 µm in classical aerodynamic diameter.

PM-10: Particulate matter ≤ 10 µm in classical aerodynamic diameter.

TOTAL CARBON (PARTICULATE MATTER): The sum of elemental carbon (EC) and organic carbon (OC).

VOLATILE PARTICLES: Particles formed from condensable gases after the exhaust has been cooled to below engine exit conditions (e.g., sulfuric acid particles).

2.4 Nommenclature and Abbreviations:

2.4.1 Nomenclature (all units are SI):

g = grams

mg = milligrams

µg = micrograms

m = meters

cm = centimeters

µm = micrometers

nm = nanometers

P = pressure, hPa

V = volume

T = temperature, degrees Kelvin

t = time, seconds, hours

2.4.2 Abbreviations:

CO_2 = carbon dioxide

EC = elemental carbon

N = number of particles

OC = organic carbon

PM = particulate material

PND = Particle number density

TC = total carbon

SN = smoke number per ARP1179

Other symbols are defined in the text as applicable to the mathematical expression at hand.

3. INTRODUCTION:

3.1 Background:

As scientific understanding of the effects of small microscopic-sized particles on environment and human health (Reference 26) has increased, regulatory agencies have become more concerned about the production, emission, and dispersion of such particles. As a result, more restrictive regulations have been implemented, a notable example being the United States Environmental Protection Agency's (USEPA) consideration of PM-2.5 (particulate matter less than or equal to 2.5 micrometers in diameter) as a refinement of the PM-10 (10 micrometers in diameter) standard (Reference 26). The potential impact of aviation emissions on the global atmosphere has been assessed recently by an Intergovernment Panel on Climate Change (IPCC) (Reference 15). Aviation particle emissions were identified as a potentially strong contributor to changes in cloud formation and in radiative forcing of the atmosphere and, consequently, to global climate change, although large uncertainties are associated with these estimated impacts. The IPCC assessment was requested by the International Civil Aviation Organization (ICAO), which underscores the interest of the international aviation community in these potential effects and in possible limitations and control.

3.1 (Continued):

Agencies responsible for regulating and certifying aviation operations have begun to examine methods for measuring particle emissions from aircraft engines. There is general consensus and concern that the regulations regarding the emission of visible smoke for aircraft engines, which have been in place for decades, do not address the measurement of particles responsible for health effects and environmental impacts.

Working Group 3 of the ICAO Committee on Aviation Environmental Protection (CAEP) has asked the SAE E-31 committee and European Commission AERONET Group for technical assistance in developing appropriate particulate characterization techniques for routine certification of aircraft turbine engines. The SAE E-31 committee has specified measurement techniques and protocols for aviation emission measurements for many existing regulations. The committee has accepted these requests for the specification of small particle emissions measurement and is responding by the writing of this Aerospace Information Report, AIR5892.

3.2 Particulate Emissions:

Aircraft gas turbine engines emit small particles (<<10 µm) as a result of the combustion of hydrocarbon fuels. These are classified into two groups, nonvolatile and volatile. The nonvolatile particles are comprised mostly of carbonaceous particles (from fuel combustion), particles ingested in the engine inlet, and metals and are addressed in this AIR. In addition, volatile particles composed of sulfur compounds and organics are formed as the engine exhaust cools in the ambient air. The measurement of volatile particles will be addressed in a subsequent AIR.

The nonvolatile emissions include carbon-based particle products from incomplete combustion in an engine. These products consist of pure (optically black) carbon, nonvolatile (gray) organic compounds, and metal particles resulting from engine erosion and the combustion of fuels containing trace metal impurities. Metal particle concentrations are several orders of magnitude smaller than those of carbonaceous particles.

Modern turbo-fan engines ingest large quantities of air. Particulate material contained in the ambient air that enters the engine should not be considered as part of the engine emissions. Careful analysis and identification of PM in the ambient air entering the engine is a mandatory requirement in measuring engine particulate emissions.

3.3 Measurement Methods:

Nonvolatile PM measurement methods can be divided into two general approaches: measurement of the total particle mass and measurement of size and number density of particles.

3.3.1 Mass Measurement: The first approach includes methods that measure the total mass of emitted particles without distinguishing size or number of particles emitted. One technique samples the exhaust stream and collects particulate matter on a filter, which is analyzed for the collected particle mass. Another technique probes the exhaust flow optically to quantify scattering material in situ without requiring the exhaust to be sampled and transported to the measurement system. Other techniques use oscillating microbalances, which measure particle mass based on the change in the natural frequency of the vibrating element as particles are collected. These total mass measurement systems are discussed in Section 5.

Current regulatory interest in stationary source particle emissions is directed toward total mass measurements and the total mass measurement techniques are discussed in the context of this regulatory interest.

3.3.2 Particle Size and Number Density Measurement: The second general approach distinguishes the size and number of individual particles. The techniques for measuring number and size distribution have been used extensively in atmospheric research and have been refined for use in measuring aircraft engine exhaust. This type of measurement provides a number density and a particle size distribution derived from a sampled exhaust stream. The measurement of these parameters can be used, with a value of particle density and information on the particle morphology, to estimate the total mass of the particles. This approach offers considerably more information about the emitted particles, but it comes at the expense of a more complex and costly measurement system. The number density and size distribution measurements are discussed in Section 6.

3.4 Sampling:

The sampling of a particle-laden stream and transportation of the sample to a measurement instrument must be done carefully to minimize loss of particles or change in particle size and composition before measurement. Sampling probe design and sample transport are important for most of the techniques discussed in this report and must be tailored to the specific requirements of temperature, velocity, and particle number densities associated with aircraft engine exhaust.

Except for optical non-intrusive techniques, all measurements discussed in this AIR require extractive sampling from engine exhaust and transportation through sampling lines to measurement instruments. Section 7 discusses the requirements for optimal operation of sampling probes and transfer lines.

4. DESCRIPTION OF EMITTED PARTICLES:

4.1 Mass:

The amount of particulate matter emitted from aircraft engines can be quantified in terms of mass of particles per volume of gas. Typical units are mg m^{-3} or µg m^{-3}. Reference conditions for the gas volume have to be specified, e.g., T = 273.14 K, p = 1013.25 hPa for Standard Temperature and Pressure (STP) conditions or T = 288 K, p = 1013.25 hPa for Sea Level Static (SLS) conditions. Unless stated otherwise, the particle mass concentration does not refer to a specific range of particle sizes.

4.2 Size:

Current size-related standards of particle mass measurements refer to particles with aerodynamic equivalent diameters less than 10 µm (US EPA PM-10) or with aerodynamic equivalent diameters less than 2.5 µm (US EPA PM-2.5) (Reference 6). Particles emitted from combustion sources such as aircraft engines are usually significantly smaller than 1 µm in diameter. Size distributions reported from aircraft engine test rig experiments and in-flight studies show a modal diameter of 0.03 to .06 µm with an average lognormal geometric standard deviation of 1.6 (References 9, 10, 28, 29, 43). A second, but weaker mode was found at a modal diameter of 0.15 to 0.2 µm.

4.3 Composition:

The particulate matter emitted from aircraft engines is composed primarily of nonvolatile particles that form inside the engine combustor and secondarily of the volatile particles that nucleate in the cooling exhaust gas from gaseous precursors. The emission of primary particles (treated in this report) is related to the design and operating conditions of the investigated engine and to fuel properties. The formation of secondary particles (to be treated in a subsequent report) depends on the time-temperature history of their formation, the sampling conditions, and the fuel properties.

Similar to particles emitted from diesel engines (Reference 19), nonvolatile particles emitted from aircraft engines can continue to grow by adsorption and condensation of organic and water-soluble inorganic (e.g. sulfates) compounds. The organic compounds are reactive and may be volatile or semi-volatile; i.e., they oxidize at temperatures as low as 400 K. As shown in Figure 1, elemental carbon (EC) is chemically almost inert at low and moderate temperatures and thermally stable up to temperatures of about 700 K. The elemental carbon fraction is the most stable fraction of combustion particulate matter in terms of particle aging and temperature change during sampling.

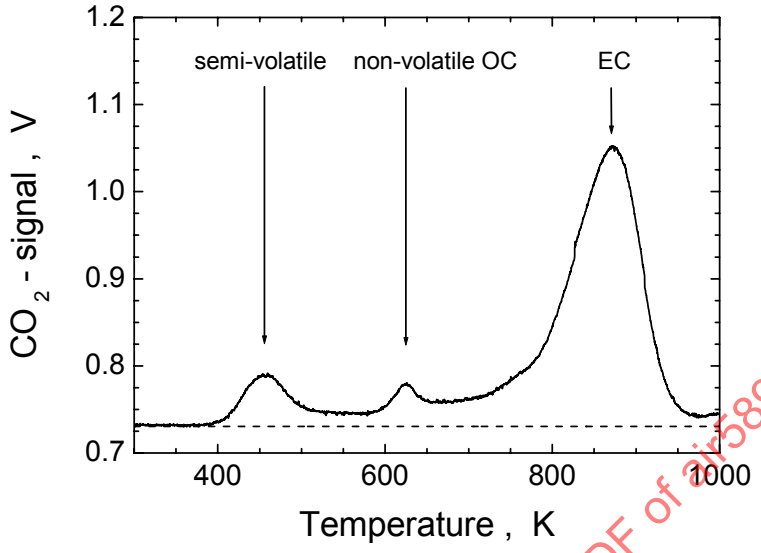

FIGURE 1 - Evolving CO_2 as a function of the sample heating temperature for a combustor particulate matter sample; semi-volatile OC oxidizes at 450 K, nonvolatile OC at 600 K, and elemental carbon above 700 K (Reference 34)

4.3 (Continued):

The distribution between organic carbon (OC) and EC depends on the operating conditions of the engine. The fractions may vary from 10% EC and 90% OC at idle conditions to ≅ 100% EC at take-off thrust conditions (Reference 28). An example is given in Figure 2. At common cruise conditions in modern engines, 60 to 80% of the emitted particulate matter is elemental carbon. Usually, the light absorbing material, termed black carbon, is strongly correlated to the elemental carbon fraction of the aerosol. The most significant feature of the black carbon fraction is its graphite-like structure. These particles can absorb light in the whole visible spectral region very efficiently and appear as black. Figure 3 illustrates this strong relationship between aerosol light absorption and EC mass concentration.

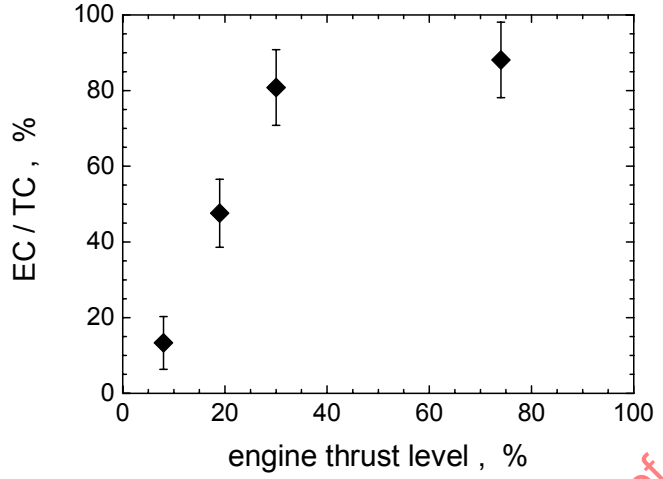

FIGURE 2 - Elemental carbon (EC) fraction of total carbon (TC) for an aircraft engine combustor particulate matter sample as a function of the engine thrust level (Reference 28)

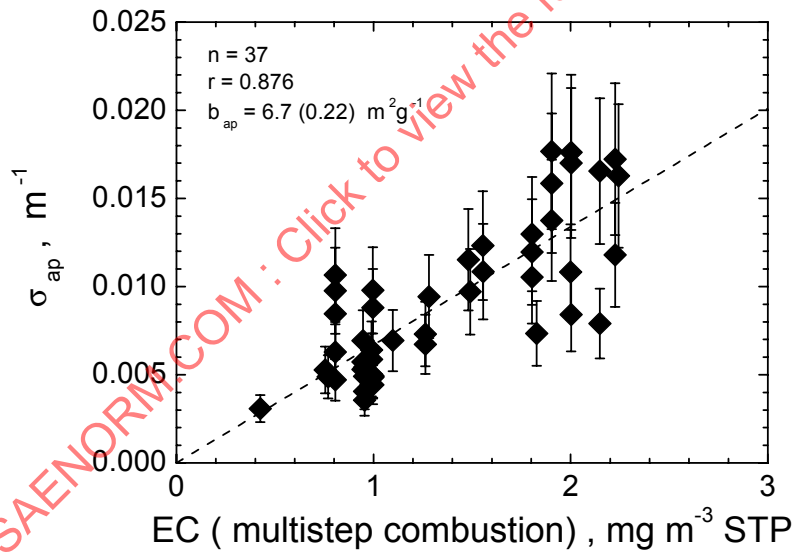

FIGURE 3 - Particle-related absorption coefficient σ_{ap} at a wavelength of 550 nm in an aircraft engine combustor exhaust gas as a function of the elemental carbon mass concentration; the correlation analysis indicates a mass specific absorption coefficient $b_{ap} = 6.7 \pm 0.22\ m^2\ g^{-1}$ (Reference 33)

5. PARTICLE MASS MEASUREMENT:

Measuring the mass of emitted particulate matter may be performed in several ways, as summarized in Table 1 and described in detail below. Filter methods are the oldest and most well known but are being replaced by optical methods that are non-intrusive and provide immediate results. Microbalance methods also provide immediate results. However, as the filter methods, they require extractive sampling.

TABLE 1 - Methods for the Measurement of Particle Mass Concentrations in Aircraft Engine Exhaust

Measurement Method	Measurement	Analysis
Gravimetric analysis	Total particulate matter, total mass	off line, filter samples
Combustion of filter samples and CO_2 detection	Total carbonaceous mass, TC	off line, filter samples
Combustion analysis including OC/EC separation	Organic carbon (OC),elemental carbon (EC), OC + EC = TC	off line, filter samples
Optical absorption photometry	Black carbon (BC), BC ≅ EC	on-line, filter samples time resolution ≥ 1 min
Laser induced incandescence	Black carbon (BC)	on-line, in situ
Transmissometry	Opacity	on-line, in situ
Light scattering	Forward scattering	on-line, in situ
Microbalance	Total particulate mass	on-line, extractive

5.1 Gravimetric and Chemical Filter Methods:

5.1.1 Introduction: Time-averaging methods are used to sample the emitted particles on appropriate fibrous filters or membrane filters (Reference 6). Since a considerable fraction of aircraft engine exhaust particles is smaller than 0.1 µm in diameter, filter materials of high sampling efficiency in this size range are required. Common practice is to use glass fiber, quartz fiber, or Teflon filters for exhaust particle sampling that show a filtration efficiency of >99% in the relevant size range. Cellulose fiber filters like Whatman No. 4, used for the current Smoke Number method (Reference 2.1.1), show a significantly lower filtration efficiency for particles smaller than 0.1 µm in diameter (Reference 6). To determine particulate matter, the technique used must specify both temperature and filter face velocity for the sampling system.

5.1.2 Method: The sampled particulate matter can be analyzed gravimetrically by weighing the filter before and after loading, which yields the total particle mass. Combustion of the particle-loaded filter with subsequent detection of the loss in mass or the evolved CO_2 is used to measure the total mass of carbonaceous material as shown in Figure 1. The separation between elemental and organic carbon can be achieved by pre-treatment of the filter sample before combustion. There is no general agreement on separation methods. An overview and comparison of applied separation methods is given in Reference 36. Measuring the modification of the filter optical properties caused by the deposited particles yields the amount of light-absorbing particulate matter on the filter and is discussed in 5.2.

Gravimetric and chemical analyses of the deposited particulate matter are time consuming, expensive, and of limited temporal resolution. However, filter-based methods show almost no limitations in collecting a minimum deposited mass of particulate matter. The amount of deposited material can be controlled by the time of exposure and the sample flow through the filter.

The SAE ARP1179 Smoke Number measurement is a reflectance method that measures the deposited material. Others (Reference 14) have adapted this method using a gravimetric calibration to infer a mass concentration.

5.2 Optical Methods Based on Filter Samples:

5.2.1 Introduction: In contrast to off-line methods like gravimetric, chemical or combustion techniques, the measurement of filter optical properties can be conducted continuously. Optical methods are suitable for the measurement of particles on a filter because carbon is a very efficient light absorber, and optical methods are simple. These methods analyze the modification of filter optical properties such as transmittance or reflectance caused by the deposited particles.

5.2.2 Filter Transmission: The aethalometer (Reference 11) is a commonly used optical instrument, which measures the change in filter transmission caused by the deposited particles. This particle-related attenuation (ATN) of transmitted light is related to the black carbon mass loading of the filter S_{BC} via the relationship

$$ATN \equiv -100 \ln \frac{T}{T_0} = b_{ATN} S_{BC} \qquad \text{(Eq. 1)}$$

where T and T_0 denote intensities of transmitted light with respect to the particle-loaded filter and the blank filter. The property b_{ATN} is a proportionality factor that links the attenuation to the black carbon mass loading, in $m^2\ g^{-1}$. The factor b_{ATN} depends on the microphysical and chemical properties of the deposited particles, e.g. on the amount of organic material. Thus, the aethalometer is not directly applicable to pure carbonaceous particles like the particulate matter emitted from a gas turbine engine due to these dependencies on particle properties.

5.2.3 Filter Reflectance: In a manner similar to the aethalometer, the measurement of the change in filter reflectance has been shown to be applicable in determining filter mass loading. The relationship between filter reflectance REF and filter black carbon mass loading, S_{BC} can be defined as:

$$REF = -100 \ln \frac{R}{R_0} = 2\, b_{REF}\, S_{BC} \qquad \text{(Eq. 2)}$$

In analogy to Equation 1 R and R_0 denote the reflectance of a particle-loaded and a clean filter, the coefficient b_{REF} is again given as a mass specific cross section. The factor 2 appears because in reflectometry the light beam crosses the particle layer deposited on the filter twice before measurement. A study on the dependence of b_{REF} on particle composition and size (Reference 21) showed that the reflectance coefficient is not strongly influenced by the light-scattering particle fraction but there is still a measurable dependence.

An experimental method that analyzes the modifications of filter optical properties by deposited particles but reduces cross-sensitivities to "white" and "gray" light-scattering particulate matter constituents was evaluated (Reference 30). This method uses radiative transfer methods to include light scattering effects in the analysis of the filter optical properties. Measurements of aircraft particulate matter emissions were successful. The data analysis is complex and cannot be reduced to simple equations.

5.2.4 Multi-angle Absorption Photometer: The multi-angle absorption photometer samples the particles continuously from the exhaust gas stream on glass fiber filters. The requirements for sampling are similar to the Smoke Number Test (Reference 2.1.1). Sampling can be performed either for a short duration using an undiluted exhaust gas or continuously using diluted exhaust gas. In the latter case, information on the variability of the particle emission at constant operation conditions is obtained. The measurement during transient operation conditions is also possible at a time resolution ≥1 min.

The modifications of the filter optical properties are analyzed on-line parallel to sampling. The application of radiative transfer to the analysis of a particle-loaded filter requires knowledge of the radiation fields in the forward and back hemisphere of the particle-loaded-filter. An optical sensor is used capable of simultaneously measuring both radiation fields. This sensor has one detector for the measurement of the transmitted and forward-scattered radiation and two detectors for the measurement of the back-scattered radiation. Figure 4 summarizes schematically the optical set ups for attenuation and reflectivity measurements and compares them with the developed multi-angle absorption photometer (MAAP).

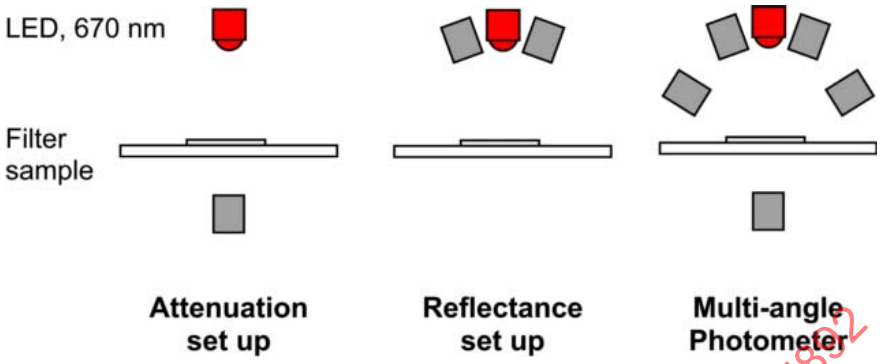

FIGURE 4 - Schematic Set Up for Attenuation and Reflectivity Measurements Compared to the Multi-angle Absorption Photometer (MAAP) Set Up (Reference 30)

5.2.4 (Continued):

Inputs required to determine the radiative transfer are the measured ratios of radiation transmitted through the filter and radiation reflected back from the filter for particle-loaded and particle-free filter samples. The algorithm outputs are optical thickness τ_L and the single scattering albedo SSA_L of the particle-loaded filter, i.e., the ratio between light extinction and light scattering by the particle-loaded filter. From these values the absorbance ABS of the particle-loaded filter can be derived as

$$ABS = 100\left(1 - SSA_L\right) \quad \tau_L = b_{ABS}\, S_{BC}\,. \qquad \text{(Eq. 3)}$$

Equation 3 is similar to the relationships given in Equations 1 and 2 but includes the consideration of multiple scattering effects via the parameters τ_L and SSA_L. The black carbon mass concentration c_{BC} is calculated from $S_{BC,}$ the respective sample volume V, and the filter spot area A according to Equation 4.

$$c_{BC} = \frac{S_{BC}\, A}{V} \qquad \text{(Eq. 4)}$$

This method was used to determine the carbon mass concentration in the exhaust of an aircraft engine combustor. The reference method used during the evaluation experiments was the combustion analysis of sampled filters to separate the elemental carbon (EC) and organic carbon (OC) fractions. The separation between elemental and organic carbon was obtained by oxidizing the organic carbon at temperatures below 600 K and measuring the elemental carbon at temperatures above 600 K (Reference 36).

5.2.4 (Continued):

A correlation analysis of the MAAP optical method and a filter catch based on the smoke number (SN) combustion method is given in Table 2. The MAAP shows a very strong correlation with the EC value of the reference filter sample combustion method. However, the major contribution of uncertainties in the linear regression analysis is expected from the thermal EC determination rather than the optical method. The correlation with total carbon (TC) is weak because TC also contains transparent organic compounds. Respective correlation analysis data for the SN method are added for comparison. The correlation of the SN method with total carbon and elemental carbon is in both cases weaker than the respective correlation of multi-angle photometry with TC and EC.

TABLE 2 - Correlation of Smoke Number (SN) method and Multi-angle Absorption Photometry (MAAP) BC (b_{ap} = 6.7 m^2 g^{-1}) vs. TC (combustion method) and EC (multistep combustion)

	SN vs.		MAAP vs.	
	TC	EC	TC	EC
number of samples	38	36	39	37
correlation coefficient r	0.384	0.608	0.507	0.876
slope of regression line	0.612 ± 0.046	0.947 ± 0.057	0.635 ± 0.042	0.988 ± 0.033

Figure 5 illustrates the application of the multi-angle absorption photometer to an aircraft engine combustor exhaust sample. Sampling from diluted exhaust gas is preferable because of the reduced particle mass concentration level. The particle emission properties of the combustor showed a distinct variation during the measurement cycle, as seen in the number concentration of combustion particles, N. The on-line MAAP responds well to varying particle emission. The present Smoke Number method yields only an average mass concentration value, as indicated by the dashed line in Figure 5. The time resolution of the MAAP is set to one minute; the detection limit at a standard volume flow rate of 1 m^3 h^{-1} is ≤ 0.1 µg m^{-3}.

The advanced multi-angle absorption method appears to be an appropriate filter-based technique for the on-line measurement of primary combustion particles in the exhaust of an aircraft engine. It is under consideration to become an optical reference method for the measurement of carbon for anthropogenic combustion particle emissions in air quality monitoring networks.

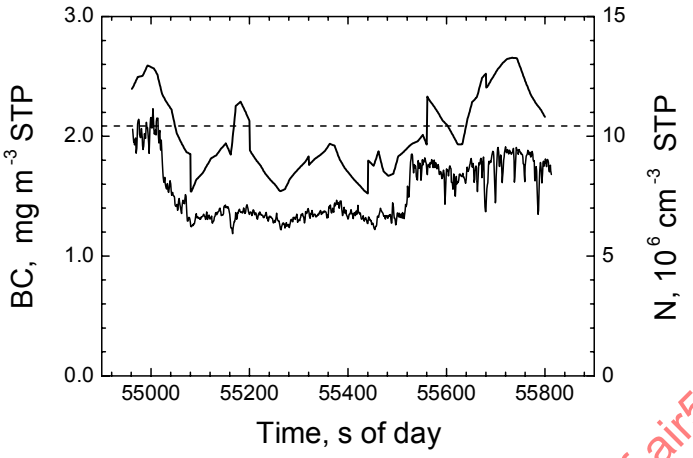

FIGURE 5 - Carbon mass concentration measured with the Multi-Angle Absorption Photometer (solid line) and with the Smoke Number method (dashed line) in an aircraft engine combustor exhaust; the lower full line indicates the number concentration of combustion particles (Reference 33)

5.3 Non-intrusive Sampling:

5.3.1 Introduction: Non-intrusive measurement techniques have the principal advantage of avoiding errors incurred in collecting and transporting combustion particles through sample lines. Optical techniques require knowledge of the refractive index and other properties of the measured particles to calculate particle mass, but often the desired quantity can be inferred from the measurement. Optical line-of-sight averaging techniques require a well-mixed exhaust (homogeneous measurement volume) unless the measurement is traversed and an inversion technique applied to the data. Simple inversion techniques usually require symmetry assumptions unless distribution information is known (or measured otherwise) and factored into the inversion. Non-intrusive methods require a separate calibration to determine carbon mass loading.

Some non-intrusive techniques are point measurements. Other non-intrusive-measurements provide spatially resolved information along a path (such as a laser beam) or over a cross-sectional plane. These measurement techniques overcome data inversion issues but are inferred measurements and can require assumptions about the particle refractive index.

5.3.2 Laser-induced Incandescence (LII): To overcome the limitations of extractive sampling, laser-induced incandescence has been developed and demonstrated to measure the volume fraction of nonvolatile particles in turbine engines (Reference 16). LII provides real-time spatial profile measurements of nonvolatile particles in a hot exhaust stream during engine operation. Important advantages include significant reduction in test times, the ability to quickly track variations in mass for on-line monitoring during test programs, and spatial resolution capabilities that reveal variations in black carbon mass across a plume.

LII involves heating particles with laser radiation to the vaporization temperature and measuring the resulting incandescence with a light-sensitive detector (Reference 23). The resulting signals are sensitive to the particle volume fraction and, to a lesser degree, particle size. Quantitative mass concentration measurements of high accuracy can be elusive due to unwanted effects of particle size and shape. These errors can be minimized with the proper choice of system parameters. LII methods are becoming popular for measuring particle mass distributions in flames (References 38, 4) because of their potential for high spatial resolution. LII measurements have been applied to diesel (Reference 39) and aircraft engine exhausts (References 1, 35).

In practice, a short laser pulse causes particles to rapidly reach vaporization temperature, as depicted in Figure 6(a). The resultant incandescence tracks particle temperature, and the LII signal is integrated over the duration of the camera gate, as depicted in Figure 6(b). With judicious selection of camera delay, gate duration, and spectral detection window, the incandescence intensity gives an accurate measurement of particle volume fraction (Reference 24). Using a pulsed laser and an intensified charge-coupled detector (ICCD) camera, the benefits of LII applied to an aircraft engine test were demonstrated (Reference 17).

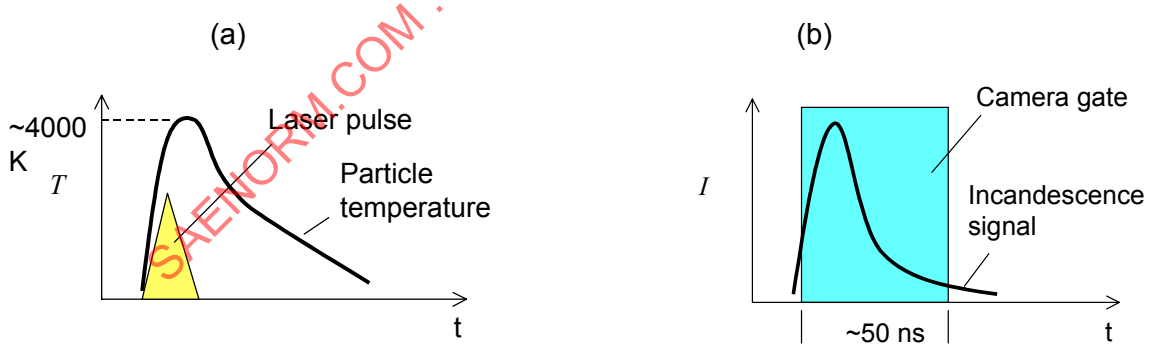

FIGURE 6 - The LII concept involves (a) heating particles via a laser pulse to about 4000 K, then (b) subsequently detecting the resulting incandescence with a gated camera

5.3.2 (Continued):

The measured radiation is modeled using Planck's blackbody formula. For the small particles observed in turbine engine exhaust, the radiation is directly proportional to the volume fraction times the length of the measurement volume. The length is fixed by the field-of-view of the detection optics. Assuming the mass density of the particles is constant, the measured radiation is directly proportional to the particle mass. The detection system is calibrated in situ for absolute intensity by passing a known flux of black carbon particles through the measurement volume. This establishes the detection system calibration factor that is used to reduce camera data to particle volume fraction, or mass concentration, for a given density of the particulate matter.

An illustration of an LII system on an engine test stand is shown in Figure 7. The laser system was located in a room remote from the test tunnel, and the entire system was controlled remotely using a personal computer. A series of turning mirrors directed the laser beam to the LII transmitter/receiver unit and launched it across the exhaust plume. The beam was safely terminated in an anodized aluminum beam dump. To minimize vibration-induced relative motion between the transmitter and the receiver, the camera and imaging optics were mounted on the same rigid platform as the final laser beam turning mirror. The receiver system was oriented at an oblique angle that allowed the entire chord of the exhaust plume to be illuminated by the laser beam. The capability to investigate spatial nonuniformities in the particle mass profile of the exhaust plume is a feature not available to extractive sampling point measurement methods unless multiple points are sampled.

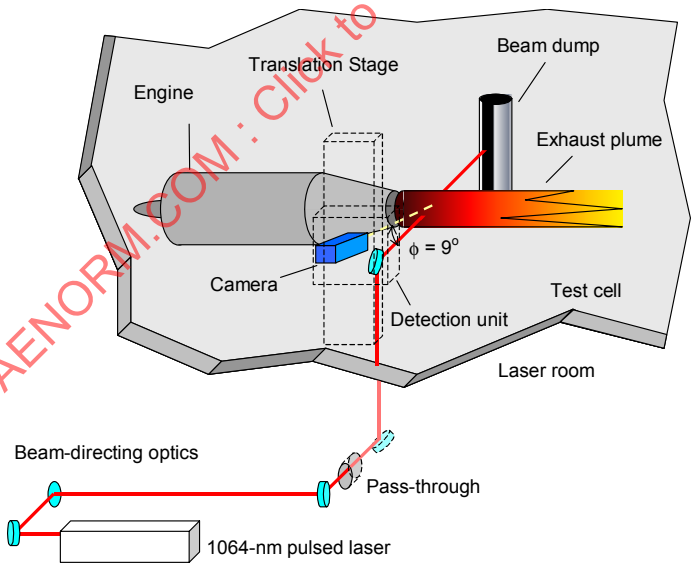

FIGURE 7 - LII System Mounted in an Engine Test Cell for Measuring Particle Mass Concentration in Exhausts

5.3.2 (Continued):

Data produced by this system consists of consecutive images of the incandescing particles in the exhaust plume. In all tests, LII data were recorded at the rate of one frame per second, where each frame was an accumulation of ten laser shots. Figure 8 shows a sample of LII data recorded during a 45-minute test. Superimposed on the data set is the actual throttle history. In all cases, the LII signal indicated a change in mass with a change in engine settings. At transitions from low to high power, a characteristic spike in the mass profiles was observed consistently. This spike in the mass concentration was observed to fall quickly to a steady state value after transitions. The system's spatial resolving capability was demonstrated by a characteristic asymmetry that was observed across the exhaust plume with higher concentrations located in an outer annulus. Both the temporal and spatial characteristics are shown in the multi-dimensional data sets of Figure 9, where distance across the exhaust plume is plotted on the x-axis, mass concentration on the y-axis, and time on the z-axis.

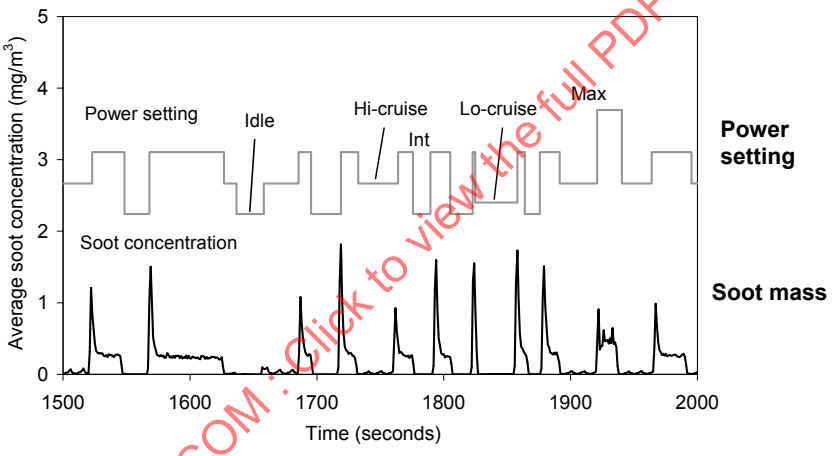

FIGURE 8 - Particle Mass Concentration Averaged Across the Plume During an Engine Test Mission

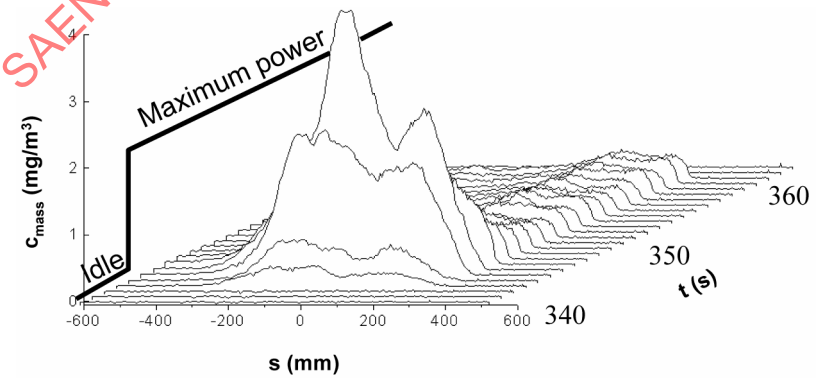

FIGURE 9 - Particle Mass Profiles in an Engine Exhaust During a Transition in Throttle Setting from Idle to Maximum Power

5.3.3 Transmissometer:

5.3.3.1 Method: A common method for continuous monitoring of particle emissions is the opacimeter or transmissometer. In this method, a light beam traverses the exhaust duct and the attenuation of the beam is measured. The initial light intensity is I_0, final intensity is I after traversing a path length, and the Beer-Lambert law applies

$$I = I_0 \exp(-bl) \quad \text{(Eq. 5)}$$

where b is the extinction coefficient and includes contributions from both scattering and absorption due to the particles. The value of b is linearly related to particle mass concentration if

- the size distribution is fixed, and
- the opacity is less than 0.1, i.e. a transmittance greater than 0.9 (Reference 40).

The latter condition arises because scattering intensity is proportional to the number of particles, provided only single scattering occurs. For 0.1 < opacities < 0.3, this relationship is lost due to double scattering, i.e. particles are sufficiently close together so that scattered light is re-scattered. The connection between transmittance and mass loading for engine exhaust smoke has been further refined (Reference 8).

$$I = I_0 \exp\left(-\frac{L\gamma_s}{K\rho} \times 10^{-3}\right) \quad \text{(Eq. 6)}$$

where L is the path length in meters, K is a constant dependent on smoke size distribution, ρ is the density of the particles, and γ_s is the mass loading in mg/m^3.

5.3.3.2 Application: In determining the path length of the light beam needed for measuring the particles in the plume of a gas turbine, a value of 0.02% opacity for a one meter plume defines the limit of visibility. Therefore, for modern engines, transmittance values of 0.99 are expected. A single pass through the plume requires measuring the difference between two large transmittance values, which limits accuracy. Multiple passes through the plume achieve improved accuracy.

Red light sources are preferred since (1) for a given power input, they give a higher power output than other wavelengths and (2) low cost silicon photodiode sensitivity peaks in the red light spectrum. Lasers are a popular source since they avoid collimating optics but have associated safety problems which can be overcome by using a light emitting diode (LED) array as the light source. However, these light sources have the disadvantage of being diffuse and require focusing optics for multiple passes.

Only the intensity ratio is measured and calibration consists of measuring the transmittance through clean gas. Because of the possibility of optic degradation due to fouling of the source or detector and other errors (see below), a continuous 100% transmittance reading is preferable. A carbon mass loading calibration requires gravimetric sampling in parallel with transmittance measurements.

The principal instrument sources of error and their remedies are as follows:

- Beam steering due to variations of refractive index in the plume. This can be overcome by ensuring that the beam diameter is sufficiently large to counteract any displacement and by using a detector with a large effective diameter or by using a large diameter uncollimated source.

- Source instabilities occur due to variable power supply and due to physical displacement resulting from vibration. Both effects can be mitigated but not completely removed. If the source output is continuously monitored, any remaining instability can be compensated in post processing.

- Detector instability can also be caused by window fouling or temperature fluctuations. Window fouling is best overcome by recessing and purging with clean air. Photodiode response temperature dependence is approximately 0.1% of full scale per degree centigrade. Use of Peltier-cooled photodiodes can reduce this to 0.0001% per degree.

- Nitrogen dioxide in the exhaust absorbs some of the beam. Since extinction coefficients for mixtures are additive, a knowledge of the NO_2 concentration allows this error to be corrected in post processing unless NO_2 dominates the absorption.

5.3.3.2 (Continued):

Sample error sources include scintillation due to turbulence-induced inhomogeneities, density fluctuations, and incomplete mixing. Providing the detector bandwidth is sufficient, turbulence effects and density fluctuations can be corrected in post processing. Only moving the instrumentation can solve incomplete mixing. If the plume temperature is below the dew point of volatile particle precursors scattering due to droplets will cause an error. Provided the plume is well mixed and the particle size distribution is effectively constant, a transmittance measurement provides a measurement of carbon mass loading.

5.3.4 Light Scattering:

5.3.4.1 Method: In light scattering, a beam of light shone across the engine plume is scattered in all directions but preferentially in the forward direction. The intensity of the scattered light is dependent on the viewing angle with respect to the beam (higher intensities with low angles) and the size distribution of the particles in the beam. Like transmittance, for a given size distribution, the intensity of scattered light is proportional to carbon mass loading (Reference 40). The method has the advantages of being a direct measurement, not a difference, that requires only one pass through the plume. There are two principal disadvantages. The signal is weak and hidden to some extent by the background scintillation, and it is a point measurement and relies on the plume being uniformly mixed.

5.3.4.2 Application: The weak scattering signal is enhanced and the background noise suppressed by modulating the source and synchronously recording and adding the scattering signal. A fundamental calibration requires the use of mono-dispersed particles and is normally conducted by the instrument manufacturer. For routine calibrations, a surface that scatters a known amount of light is placed in the beam and the detector span adjusted. Zero readings would be obtained with clean air. A carbon mass loading calibration would require parallel gravimetric sampling and scattering measurements.

Instrument sources of error and their resolution are similar to those for transmittance measurements, with the exception of NO_2, which does not scatter the beam. The sampling errors are similar except that point measurement requires greater sample homogeneity. Provided the plume is well mixed and the particle size distribution is effectively constant, a scattering measurement provides a direct value for carbon mass loading.

5.4 Microbalance Methods:

5.4.1 Introduction: Other on-line methods have been used for the determination of total particulate matter (PM) mass emissions that may have potential application to aircraft engine testing. These methods are the tapered element oscillating microbalance (TEOM) and the quartz crystal microbalance (QCM). Each is described briefly below. Both these methods have been used successfully in similar evaluations of automotive internal combustion engines, with the TEOM also recently introduced for measurements in the aerospace industry.

5.4.2 TEOM: In the TEOM instrument, a hollow vibrating tube equipped with a small in-line filter is installed inside a heated chamber. The change in harmonic oscillation measured by a sensitive frequency counter over a prescribed averaging time is proportional to the additional PM mass collected on the filter. The TEOM was originally designed to monitor PM ambient air quality but has been adapted for use in automotive engine testing (References 18, 25, 3). The TEOM mass values must be corrected for pressure loss across the filter and total sample flow throught the TEOM. In general, the TEOM has been shown to correlate reasonably well to the total filter method as determined over extended averaging periods, but it has high instrumental noise making shorter term measurements problematic.

5.4.3 QCM: An older instrument, which has been reintroduced to automotive engine testing, is the QCM. The harmonic oscillator principal used in the QCM is similar to the TEOM except that the collected PM is actually deposited on the crystal element itself using an electrostatic precipitator (Reference 3). Due to its higher frequency operation, the QCM exhibits far less instrumental noise than the TEOM but can overload in a relatively short period of time. To offset this problem, either a diluter or multiple elements mounted in a rotating carousel are used where the carousel supplies a fresh element when the loading exceeds a predetermined limit. Agreement between QCM measurements and traditional PM mass methods was found in recent testing conducted in the UK (Reference 3).

6. SIZE AND NUMBER DENSITY METHODS:

6.1 Introduction:

Physical characterization of particles from gas turbine engine exhaust can be achieved with the use of commercially available particle size and number density measurement systems. These instruments are widely accepted by industry, academia, and government research organizations. They can be operated as laboratory or mobile systems under the difficult conditions encountered near the exit planes of combustors or turbine engines. These instruments provide real-time or near real-time results for size distribution and on-line data to assess particle loading. The concerns of sample mishandling and extensive time delays associated with off-line, post-test analysis have been eliminated. With this extractive sampling technique, special consideration must be given to the sampling systems to minimize modification of the exhaust particles as they are transported to the diagnostic instrumentation.

Measurement of the physical characteristics of combustion particles from aircraft turbine engines and research combustors requires that the diagnostic instruments be designed to sample from a wide range of pressure (1 to 62 atm) and temperature conditions (220 K to 2400 K). They must be capable of measuring particle number densities (PND) (number of particles per unit volume of exhaust gas) that range from background levels as low as 0.5 cm^{-3} to exhaust emission levels as high as 1.0×10^{9} cm^{-3} and particle diameters ranging from a few nanometers (~3 nm) to >10 µm. Instrumentation used to measure these parameters for aircraft engine emissions is described below and in-depth in Reference 6.

6.2 Particle Number Density (PND):

The PND in turbine engine exhaust is determined by using one or multiple condensation nuclei counters (CNC). These counters provide real-time particle number density measurements and a means of rapidly assessing particle emissions from a combustion source.

In a CNC, a particle-laden sample is passed through a heated saturator where an alcohol (usually butanol) evaporates into the sample stream and saturates the flow. The saturated sample passes through a cooled condenser where the alcohol condenses on the particles to generate larger particles (droplets) that can be counted with an optical detector. The detector counts the particles in either the single-pulse mode for number densities of less than 10^{4} particles per cm^{3} or in the photometric mode (light scattering) for particle number densities of 10^{4} to 10^{7} particles per cm^{3}. The sample entering the counter is usually diluted with particle-free air that is added to the sample flow at or within a few centimeters of the probe tip. This dilution minimizes particle-to-particle interaction (coagulation), and gas-to-particle conversion (nucleation, condensation) and prevents the saturation of the PM instrumentation. The CNC data have to be corrected for this dilution to obtain the actual particle concentration in the exhaust gas. The dilution and sample flows are

6.2 (Continued):

monitored and controlled with flow controllers. The flow controller-based dilution ratios are validated by comparing them to dilution ratios determined from the CO_2 concentration in the diluted and undiluted sample trains. Leaks in the dilution flow or sample lines or dilution air escaping through the tip of the probe may contribute to differences between the flow controllers and CO_2 methods of determining dilution ratios.

6.3 Particle Size Distribution:

A differential mobility analyzer (DMA) in combination with a CNC can be used to determine particle size distributions in turbine engine exhaust. An exhaust sample is passed through a bipolar ion charger, that imparts a Boltzmann charge distribution to the particles. The charged and neutral particles enter the DMA, which contains a high voltage rod charged to provide a precise negative potential. The particles are separated or classified by size according to their mobility in the electric field. By changing the voltage in the DMA, a size spectrum is acquired. Bipolar charger/DMA/CNC systems are commercially available as a Scanning Mobility Particle Sizer (SMPS) and can measure particle sizes from 2-1000 nm in diameter using analyzers with different ranges. The size distribution for larger diameter particles (>300 nm) is determined with a laser particle counter (LPC) that uses light scattering techniques. Using a diffusion battery, small diameter particles are removed from the sample before entering the LPC. Most particles in turbine engine exhaust are smaller than 300 nm in diameter (Reference 32).

The direct measurement of particle size distribution and number density allows the determination of the mean geometric diameter and the particle distribution width. In addition, emission indices with respect to particle number, surface area, and mass can be computed. The particle surface area and mass require assumptions of morphology and density, which may be a source of error in mass calculation.

Recent physicochemical characterization of particles emitted from an aircraft engine combustor (Reference 32) show close agreement between the average particle sizes obtained from DMA measurements and those calculated from mass and number density data. These data indicate an average particle density of 1.0 g cm^{-3}. Other studies report densities ranging from 0.8 to 1.8 g cm^{-3}. The size range of particles also was reported. It was observed that for a typical aircraft engine, combustion particles with diameters <10 nm contributed less than 10% to the total number of particles, and particles with diameters >300 nm contributed less than 0.01%.

6.4 PM Measurement System:

The CNC and variations of the DMA systems described above are widely used and accepted by academia, industry, and government organizations for the characterization of exhaust particles from diesel and turbine engines. Organizations using these techniques include:

- University of Missouri-Rolla (UMR)
- University of Minnesota
- Air Force Research Laboratory (AFRL)
- NASA Glenn Research Center
- Southwest Research Institute (SwRI)
- United Technologies Research Center (UTRC)
- German Aerospace Center (DLR, Germany)
- Paul Scherrer Institute (PSI, Switzerland)
- Rolls Royce (Derby, UK)

Figure 10 is a schematic of a typical particle size distribution and number measurement facility (References 37, 27, 31, 13, 2, 7).

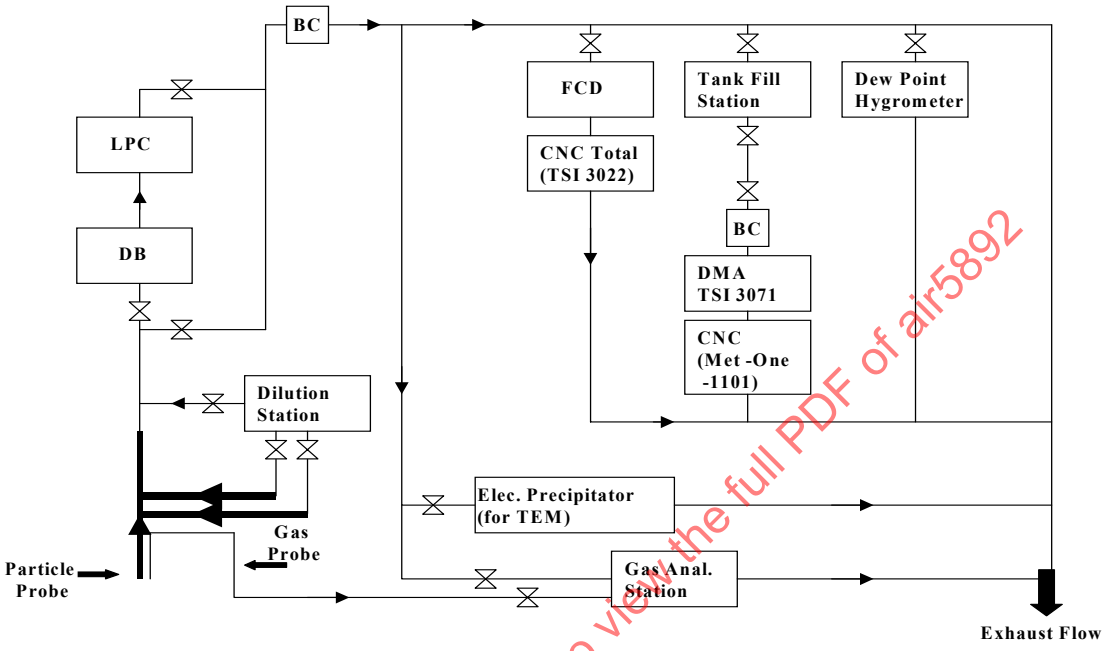

FIGURE 10 - Schematic of a size distribution and number density measurement facility. DB=Diffusion Battery, LPC=laser particle counter, BC=Bipolar Charger, FCD=Filter Capillary Diluter, CNC=condensation nuclear counter, DMA=differential mobility analyzer, TEM=transmission electron microscope

6.4 (Continued):

In this facility engine exhaust products are extracted through a particle probe and transported to the instrumentation by the sampling system (see Section 7). If the diluted sample exceeds the capacity of the CNC, the dilution flow is increased to further reduce particle concentration. For more detailed size information or to obtain time-averaged size distribution in an unstable source, samples may be collected in tanks for off-line DMA analysis. The relative humidity in the diluted sample is measured with a hygrometer and controlled to below 40% to prevent water condensation. Information on particle structure and morphology is gathered by collecting sample particles on grids in an electrostatic precipitator for off-line analysis.

6.5 Typical Particle Size Distribution and Number Density Data:

Examples of data generated by a typical size and number measurement system are presented in Figures 11 and 12. Figure 11 shows the measured size distribution (diamonds) and its lognormal curve fit (solid line).

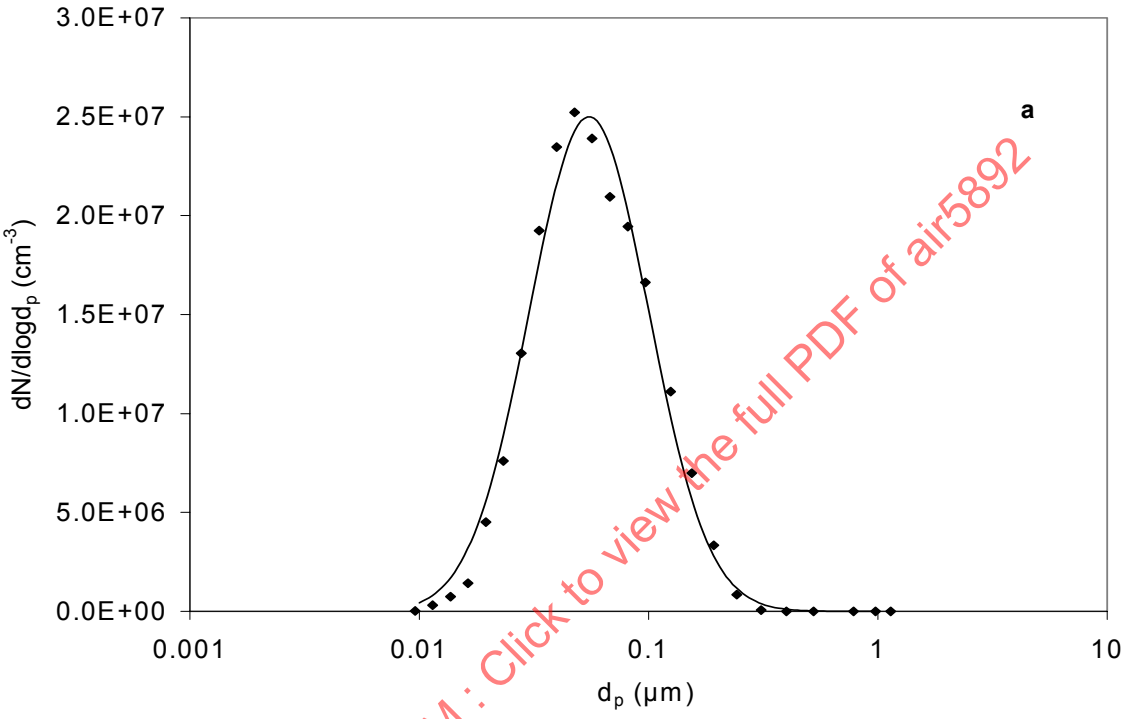

FIGURE 11 - Size Distribution Data for Turbine Engine Exhaust

Similarly, Figure 12 depicts data and curve fits of surface area (diamonds, solid line) and mass (triangles, dotted line). The three data points at the large end of the size distributions (780, 980, and 1140 nm) were taken with an LPC. As shown and mentioned previously, the contribution of the LPC size range (>300 nm) to total particle number is negligible.