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Superseding AIR5892A

Nonvolatile Exhaust Particle Measurement Techniques

RATIONALE

AIR5892A documents the non-volatile particulate matter (PM) measurement technologies that were mature and had aviation measurement experience as E-31 began its first steps in moving toward a non-volatile PM Aerospace Recommended Practice (ARP). In addition to documentation of these potential candidate measurement techniques, AIR5892A includes an appendix which discusses the context and approach that E-31 planned on using in developing a non-volatile PM ARP. For these reasons, it will be useful and important for future SAE documents to be able to cite AIR5892A as a review of measurement techniques and of the context for making non-volatile measurement decisions. Since no equivalent document exists in the archival technical literature, having a stable SAE AIR5892A document available for citation will be useful for the future development of the anticipated ARP and for the future application of this ARP once it is published.

The International Civil Aviation Organization (ICAO) has a Committee on Aviation Environmental Protection (CAEP) that has great interest in the development of a non-volatile PM measurement methodology. CAEP has shown significant and specific interest in both AIRs and ARPs in the area of non-volatile PM measurement. As such, ICAO's CAEP would also benefit greatly from having a stabilized, citable version of AIR5892A available.

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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:

2.2.1 General References: The following general references are provided for information purposes only and are not a required part of this SAE Aerospace Information Report.

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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 $\leq 2.5 \mu\text{m}$ in classical aerodynamic diameter.

PM-10: Particulate matter $\leq 10 \mu\text{m}$ 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 Nomenclature 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:

CO₂ = 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 ($<10\ \mu\text{m}$) 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 $\mu\text{g m}^{-3}$. Reference conditions for the gas volume have to be specified, e.g., $T = 273.14 \text{ K}$, $p = 1013.25 \text{ hPa}$ for Standard Temperature and Pressure (STP) conditions or $T = 288 \text{ K}$, $p = 1013.25 \text{ hPa}$ 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 $10 \mu\text{m}$ (US EPA PM-10) or with aerodynamic equivalent diameters less than $2.5 \mu\text{m}$ (US EPA PM-2.5) (Reference 6). Particles emitted from combustion sources such as aircraft engines are usually significantly smaller than $1 \mu\text{m}$ in diameter. Size distributions reported from aircraft engine test rig experiments and in-flight studies show a modal diameter of 0.03 to $.06 \mu\text{m}$ 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 $0.2 \mu\text{m}$.

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.

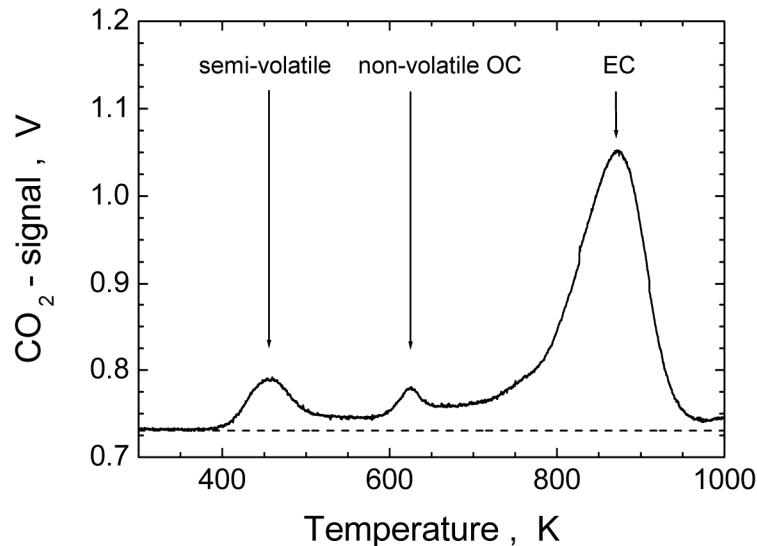


FIGURE 1 - Evolving CO₂ as a function of the sample heating temperature for a combustor particulate matter sample; semi-volatile OC oxidizes at 450 K, nonvolatile OC at 600 K, and elemental carbon above 700 K (Reference 34)

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 $\approx$ 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.

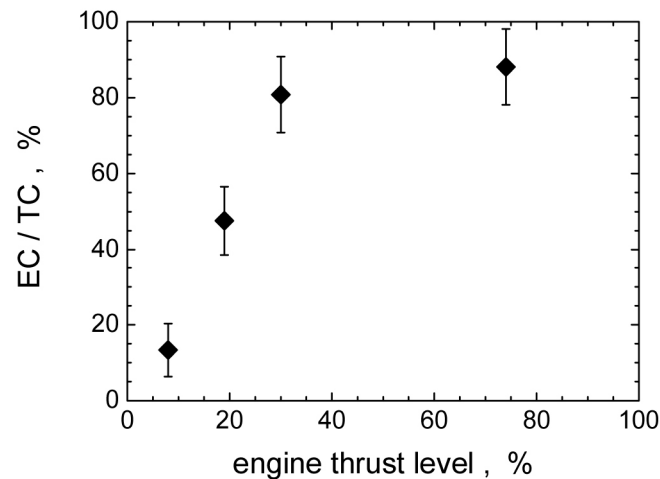


FIGURE 2 - Elemental carbon (EC) fraction of total carbon (TC) for an aircraft engine combustor particulate matter sample as a function of the engine thrust level (Reference 28)

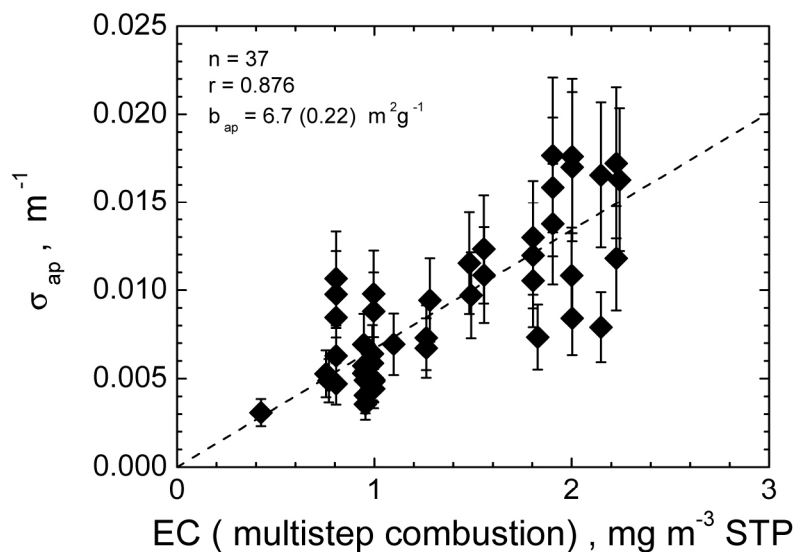


FIGURE 3 - Particle-related absorption coefficient σ_{ap} at a wavelength of 550 nm in an aircraft engine combustor exhaust gas as a function of the elemental carbon mass concentration; the correlation analysis indicates a mass specific absorption coefficient $b_{ap} = 6.7 \pm 0.22 \text{ m}^2 \text{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