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AEROSPACE RECOMMENDED PRACTICE

ARP 1179 A

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AIRCRAFT GAS TURBINE ENGINE EXHAUST SMOKE MEASUREMENT

1. SCOPE

This Aerospace Recommended Practice (ARP) standardizes test equipment and procedures for the measurement of smoke emission from aircraft gas turbine engines. The procedures included are for determining and reporting the amount of smoke emission. Tests have indicated that the practically achieveable precision of the smoke number is within ±3 when the system is properly used as outlined herein. This procedure is not intended for in-flight testing, nor does it apply to afterburning engines.

This ARP is divided into the following sections:

2. Definitions and Terminology
3. Equipment
4. Test Procedures
5. Information and Data to be Recorded
6. Data Reduction and Analysis
7. Presentation of Results
8. Comments

2. DEFINITIONS AND TERMINOLOGY

The following apply to the terms indicated as they are used in this ARP:

2.1 A: Area of the smoke filter spot.

2.2 Aircraft Gas Turbine Engine: Any gas turbine engine used for aircraft propulsion or power generation, including those commonly called turbojet, turbofan, turboprop or turboshaft type engines.

2.3 Filter Material: Filter material shall be Whatman No. 4 filter paper.

2.4 Power Setting: A value of the quantity used to rate the power output of an engine. The power setting of turbojet and similar engines should generally be expressed in terms of net thrust (corrected). For turboprop and similar engines, power setting should generally be in terms of shaft horsepower.

2.5 SN: Smoke Number, the dimensionless term quantifying smoke emission. SN increases with smoke density and is rated on a scale from 0 to 100. SN is evaluated for a sample size of 0.0162 grams of exhaust gas per sq. millimeter (0.0230 lb. per sq. in.) of filter area.

2.6 SN': Smoke number obtained from an individual smoke sample. SN' is defined in 6.2, and is evaluated from the spot reflectance irrespective of the sample size.

2.7 Sampling: The collection of an exhaust sample under controlled conditions for the purpose of analysis.

2.8 Smoke: Small gas-borne solid particles, including but not limited to black carbonaceous material from the burning of fuel, which in sufficient concentration create visible opacity.

2.9 Standard Volume: A standard volume of gas defined as the volume at 25° C (77° F) and 101.32 kPa (29.921 in. Hg Abs.).

2.10 V: The measured sample size (volume).

2.11 W: The calculated mass of the measured sample volume.

3. EQUIPMENT

3.1 System Scheme: Fig. 1 is a schematic diagram of a proper system.

3.2 Sample Size Measurement: A wet or dry positive displacement meter shall be used to measure the sample volume needed to satisfy the requirements of 4.2 to an accuracy of ±2%. Pressure and temperature shall be measured immediately upstream of the meter. Pressure shall be measured to an accuracy of ±0.2% of the absolute pressure value. Temperature shall be measured to an accuracy of ±2° C (3.6° F). If a dry type meter is used, it may be located between the filter holder and the vacuum pump.

3.3 Sample Flow Rate Measurement: Sample flow rate shall be measured with a rotameter or equivalent flow measuring device. Accuracy shall be within ±5%.

3.4 Filter Holder: The filter holder shall firmly clamp the filter material so that overall system leakage is in accordance with 4.7. Suggested and required elements of the filter holder design are given in Fig. 2. The filter holder shall be made of corrosion resistant material.

3.5 Sampling Probe: The probe shall be made of stainless steel. If a mixing probe is used, all sampling holes shall be of equal diameter and total probe orifice area shall be such that at least 80% of the pressure drop through the probe assembly (from free stream to probe outlet) shall be taken at the orifices. Probe orientation and sampling locations shall be as follows:

(a) A minimum of 12 sampling points shall be used. Either mixing or individual probes are acceptable.

(b) The axial location of the sampling plane shall be as close to the plane of the exit nozzle as engine performance parameters permit but in any case shall be held within 0.5 exit nozzle diameter of the exit plane.

(c) The sampling points shall be arranged over the exhaust nozzle exit area for straight turbojet, turboprop, turboshaft, and mixed flow (or confluent flow) fan engines, and over the core nozzle exit area for nonmixed fan engines.

(d) In order to promote uniformity of smoke measurements, a specific probe design should be standardized for use with a given type or series of engines. It must be demonstrated, by means of detailed traverse measurements in the sampling plane, that this probe design provides a representative smoke sample.

3.5 (Continued)

(e) As a test of representative sample collection, the fuel-air ratio calculated from average measured CO_2 values obtained in accordance with the procedures given in SAE ARP 1256 (latest version) shall agree within 15% at idle and 10% at higher power settings with values calculated from air and fuel data. The fuel-air ratio may be adjusted for estimated exhaust carbon monoxide and hydrocarbon concentrations. Fuel flow and CO_2 measurements should be taken at the same time. Air flow data preferably are from direct measurements but if such measurements are impractical, the data may be taken from air consumption curves generated for the particular model of the engine under test, corrected to actual temperature and pressure conditions. Total air flow shall be used for straight turbojet, turboprop, turboshaft and mixed flow fan engines. Core airflow shall be used for nonmixed flow fan engines. This test for a representative sample need be conducted only at the power setting giving the highest or near the highest smoke level for the particular engine model under test.

(f) If it is desired to draw a higher sample flow rate through the probe than through the filter holder, an optional flow splitter may be located between the probe and Valve A (Fig. 1), to dump the excess flow. The dump flow may also be sent to the CO_2 analyzer or complete emissions analysis system thus eliminating the need for Valve E.

If a flow splitter is used, a test shall be conducted to demonstrate that the flow splitter does not change the smoke level passing to the filter holder. This may be accomplished by reversing the outlet lines from the flow splitter and showing that, within the accuracy of the method, the smoke level does not change.

3.6 Sampling Lines: The sampling lines including the lines up to the filter holder entrance shall be straight through with no kinks or loops, and no bends having a radius of less than 10 line diameters. Sampling line inside diameter shall be 4.0 to 8.5 mm (0.16 to 0.33 in.). The sampling line section from the probe exit to filter holder entrance shall be of minimum length, not greater than 25 metres (82 ft.), with no unnecessary fittings or other breaks. Line material shall be such as to not encourage build-up of either particulate matter or static electric charge. Stainless steel, copper and carbon loaded grounded PTFE (Polytetrafluoroethylene) line meet these requirements.

3.7 Valving: Five valve elements shall be provided. Valves A and E shall be quick acting, full-flow, flow diverter valves with "closed", "sample", and "by-pass" positions. Valve A may consist of two valves, provided that they are interlocked so that one of the pair cannot act independently of the other. Valves B and C shall be throttling valves used to establish a system flow rate. Valve D shall be a shut-off valve used to isolate the filter holder. All valves shall be made of corrosion resistant material. If an optional flow splitter is used, Valve E is not required.

3.8 Sample Pump: The sample pump shall have a no-flow capability of at least 75 kPa vacuum (22 in. HgV), and full flow rated capacity of 28 standard litres/min (1.0 scfm) minimum.

3.9 Reflectometer: A reflectometer conforming to American National Standards Institute (ANSI) PH 2.17-1977, "Annular 45°: 0° (or 0°: 45°) Optical Reflection Measurements (Reflection Density)", shall be used. The diameter of the reflectometer light beam on the filter paper shall be within 0.1 and 0.5 D, where D is the diameter of the smoke stain. The allowable range of D is given in Fig. 2.

4. TEST PROCEDURES

4.1 Precautions: The material being measured is composed of low-micron and/or submicron size agglomerated particles. Precautions must be taken to assure that steady-state conditions have been achieved prior to taking a sample. To prevent material accumulation, the sampling system should never be left in a no-flow condition during test operation. The following procedures are designed to produce consistent and precise results.

4.2 Sampling: Sufficient time (not less than one min) shall be allowed to assure that the system is fully charged with a representative gas sample. The sampling flow rate shall be maintained at 14 ±0.5 litres/min (0.50 ±0.02 cfm). At least three samples shall be taken within the range of 0.012 to 0.021 grams of exhaust gas per sq. millimetre (0.017 to 0.030 lb. per sq. in.) of filter area. Samples shall be taken both above and below 0.0162 grams of exhaust gas per sq. millimetre (0.0230 lb. per sq. in.) of filter area. Instead of taking different samples sizes, an acceptable alternate shall be to take consecutive samples at 0.0162 ± .0007 g/mm^2 (0.0230 ± 0.0010 lb. per sq in.) until at least three samples are obtained which agree within ±3 smoke numbers.

4.3 Temperature Control: The line temperature from the sampling probe entrance to the filter material shall be maintained between 60° C (140° F) and 175° C (347° F), except for the distance required to cool the gas from the engine exhaust temperature down to the line temperature. The line temperature shall be maintained with a stability of ±10° C (±18° F) during the period of measurement.

4.4 Preparation for Each Power Setting: The following shall be done to prepare the system at each power setting:

(a) Set Valve A to "by-pass", close Valve D, set Valve E (if used) to "smoke sample".

(b) Draw exhaust gas for 5 min. minimum, then use Valve C to set flow rate at 14 ±0.5 litres/min (0.50 ±0.02 cfm).

(c) Clamp clean filter material into the holder.

(d) Open Valve D.

(e) Set Valve A to "sample" and use Valve B to again set the flow rate to 14 ±0.5 litres/min (0.50 ±0.02 cfm). This must be done quickly before particulate build-up on the filter causes excessive pressure drop.

(f) Set Valve A to "by-pass" and close Valve D.

(g) Clamp clean filter material into the holder.

4.5 Sampling Procedure: The procedure for smoke sampling at each power setting shall be as follows:

(a) With Valve D closed and Valve A set at the "by-pass" position, charge the lines with exhaust gas for one min. minimum. Re-establish flow rate at 14 ± 0.5 litres/min (0.50 ±0.02 cfm) as required, using Valve C.

(b) Open Valve D.

(c) Set Valve A to "sample", allow the chosen sample volume to pass, then set Valve A to "by-pass".

(d) Close Valve D, unclamp the filter holder and remove the smoke spot. Clamp clean filter material into the holder.

(e) Repeat (b) through (d) for additional samples, as required in 4.2.

4.6 System Maintenance: The need for cleaning or replacement shall be determined by conducting the following cleanliness check prior to each engine test:

(a) Fully open Valves B, C, and D. Set Valve E (if used) to "smoke sample".

(b) Turn on the sample pump and alternately set Valve A to "by-pass" and "sample" to purge the entire system with clean air for at least 5 min.

(c) Set Valve A to "by-pass".

(d) Close Valve D and clamp clean filter material into the holder. Open Valve D.

(e) Set Valve A to "sample", reset back to "by-pass" after 0.044 standard litre of air per sq. millimetre (1.0 standard cubic ft. per sq. in.) of filter area has been passed through the filter material.

If the filter spot exhibits SN' greater than 3, the system lines must be cleaned or replaced. The system shall not be used until this cleanliness requirement has been met.

4.7 Filter System Leak Check: The following procedure shall be used to leak check the filter system before and after each engine test:

(a) Clamp clean filter material into the holder.

(b) Close Valve A. Fully open Valves B, C, and D. Set Valve E (if used) to "smoke sample".

(c) Turn on sample pump and run for at least one min. When the system is stabilized, run the leak check for 5 min.

The system shall be satisfactory if no more than 5.0 standard litres (0.18 standard cubic ft.) pass through the volume meter during the 5 min. period.

4.8 Sample Line Leak Check: Before and after each engine test, a leak check of the sample line shall be made as follows:

(a) Seal off all the probe orifices.

(b) Set Valve A to "by-pass", and Valve E (if used) to "smoke sample". Fully open Valve C. Close Valve D.

(c) Turn on the sample pump and run for at least one minute. When the system is stabilized, run the leak check for 5 min.

The system shall be satisfactory if no more than 2.0 standard litres (0.07 standard cubic ft.) pass through the volume meter in 5 min.

The system shall not be used until the leakage requirements of 4.7 and 4.8 have been met.

5. INFORMATION AND DATA TO BE RECORDED

5.1 Information:

5.1.1 General:

(a) Facility performing test

(b) Date of test

(c) Description of test equipment

(d) Probe location as determined in accordance with 3.5

5.1.2 Aircraft Description (if Applicable):

(a) Manufacturer

(b) Model Number

(c) Serial Number

(d) User or Operator

(e) Engine Installation Position

5.1.3 Engine Description:

(a) Manufacturer

(b) Model Number

(c) Engine configuration/special configuration identification

(d) Time since overhaul and other pertinent maintenance information

5.2 Test Data: At least the following shall be recorded:

(a) Engine power setting and rotor speed(s)

(b) Date, time of day and data point number

(c) Ambient conditions (barometric pressure, temperature, humidity) at beginning and end of test

(d) Fuel flow rate

(e) Fuel type; additives, if used

(f) Leak and cleanliness checks substantiation

(g) Sample temperature

(h) Sample pressure

(i) Actual sample volume at sampling conditions

(j) Actual sample flow rate at sampling conditions

6. DATA REDUCTION AND ANALYSIS

6.1 Determination of Smoke Number (SN): For each smoke sample there is an individual smoke number (SN') determined by the relative reflectance of the spot. Since the reflectance of the spot depends on the amount of sample filtered through the paper, it is necessary to specify a sample mass (W/A) for comparison purposes. A W/A value of 0.0162 grams of exhaust gas per sq. millimetre (0.0230 pounds per sq. in.) of filter area is used for establishing the smoke number (SN) to be reported.

6.2 Determination of SN': Smoke spot analysis shall be made with a reflectometer as specified in 3.9. This instrument shall be calibrated on an absolute basis with secondary standards traceable to the standard for diffuse reflectance of the National Bureau of Standards. The backing material shall be black with a maximum absolute reflectance of 3%. The reflectance reading of each spot shall be used to calculate SN' by:

$$SN' = 100 \quad [1 - R_s/R_w]$$

where R_s = absolute reflectance of the sample spot

R_w = absolute reflectance of clean filter material

6.3 Calculation of W/A: The sample mass per unit filter spot area (W/A) shall be calculated for each sample size taken.

In SI units:

$$\frac{W}{A} = 3.483 \frac{PV}{AT} \text{ grams per sq. millimetre}$$

In English units:

$$\frac{W}{A} = 1.326 \frac{PV}{AT} \text{ lb. per sq. in.}$$

where A = filter spot area, sq. millimetres (sq. in.)

W = sample mass, grams (pounds)

P = sample pressure, kilopascals absolute (in. of Hg absolute)

T = sample temperature, K (°R)

V = measured sample volume, litres (cubic ft.)

6.4 Evaluation of SN at Specified W/A:

6.4.1 Smoke Number from Different (W/A) Values: If smoke samples are taken at different values of W/A, the following procedure shall be used. If a manifolded or multipoint probe is used, plot SN' versus W/A on semi-log coordinates, with W/A as the logarithmic abscissa. A straight line shall be fitted to these points using the method of least squares. The value of smoke number (SN) shall be read from the straight line function at W/A = 0.0162 g/mm^2 (0.0230 lb/sq in.). This is the value to be reported at that power setting.

If individual point samples are taken, a least squares straight line shall be obtained from the SN' readings at each sampling location using the method of 6.4.1. The smoke number (SN) to be reported at that power setting shall be the arithmetic average of the smoke numbers read from the several least squares straight lines at W/A = 0.0162 g/mm^2 (0.0230 lb/sq. in.).

The smoke number (SN) shall be determined as described above for each power setting specified. If the least squares curve fits are performed by computer, it shall not be necessary to physically plot the curves described above. The data shall be tabulated showing the variation of the individual values of SN' from the straight line and the correlation coefficient of the curve fit.

6.4.2 Smoke Number from One (W/A) Value: If smoke samples are taken only at a single W/A value of 0.0162 g/mm^2 (0.0230 lb. sq in.) using the alternate method of 4.2, the smoke number (SN) to be reported at that power setting shall be the arithmetic average of the SN' values of the three samples meeting the criterion of 4.2. The individual SN' values shall be tabulated along with their variation from the mean.

6.4.3 Plot of Smoke Number Versus Power Setting: The final values of smoke number (SN) to be reported shall be presented by plotting the smoke numbers obtained in 6.4.1 or 6.4.2 along the ordinate versus power setting along the abscissa on rectangular coordinates.

7. PRESENTATION OF RESULTS

At least the following shall be reported:

(a) All information and data required by Section 5.

(b) All W/A calculated in accordance with 6.3.

(c) The plots or equations of SN' versus W/A from 6.4.1, if applicable. All other data required in 6.4.1 or 6.4.2, as applicable.

(d) The plot of SN versus Power Setting from 6.4.3.

8. COMMENTS

The purpose for making the smoke measurements described in this specification is to provide a means for controlling visible smoke emission from aircraft gas turbine engines. The measured smoke numbers for mixed flow fan engines will generally be much lower than for other types of engines, due to fan air dilution. These lower smoke numbers do not necessarily result in reduced plume visibility, since plume visibility depends on both smoke number and plume diameter.

PREPARED BY

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AIRCRAFT EXHAUST EMISSION MEASUREMENTS