GUIDELINES ON THE USE OF PROCEDURES IN THE EMISSIONS CERTIFICATION OF AIRCRAFT ENGINES
(for publication on the ICAO website)

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APPENDIX 3: Instrumentation and Measurement Techniques for Gaseous Emissions

NOMENCLATURE [Reserved]

Symbols and Units

Symbols and abbreviations employed in these guidelines are consistent with those contained in Annex 16 – *Environmental Protection*, Volume II – *Aircraft Engine Emissions* (Second Edition, July 1993).

SECTION 1. - INTRODUCTION

1.1 PURPOSE

1.1.1 The aim of this document is to promote uniformity in the implementation of Annex 16 – *Environmental Protection***,** Volume II – *Aircraft Engine Emissions*, by providing guidance to certificating authorities and applicants regarding the intended meaning and stringency of the current Annex 16, Volume II emissions Standards and those specific procedures that are deemed acceptable in demonstrating compliance to these Standards.

1.1.2 This document also provides guidance in the wider application of equivalent procedures that have been accepted as a technical means for demonstrating compliance with the emissions certification requirements of Annex 16, Volume II. Such equivalent procedures are referred to in Annex 16, Volume II, but are not dealt with in the same detail as in the appendices which describe the emissions evaluation methods for compliance with the relevant chapters of Annex 16, Volume II.

1.1.3 Annex 16, Volume II procedures must be used unless an equivalent procedure is approved by the certificating authority. Procedures presented in these guidelines should not be considered as limited only to those described herein, as these guidelines will be expanded as new procedures are developed. Also, their presentation does not infer limitation of their application or commitment by certificating authorities to their further use.

1.1.4 References to Annex 16, Volume II relate to Amendment 5.

1.2 FRAMEWORK

1.2.1 The basic framework of this document is a replication of the Annex 16, Volume II structure in order to ensure easy reference between the annex and these guidelines. References in the table of contents are only made to a part of the requirements when there is associated guidance material, otherwise the relevant paragraph has been "reserved" for future use. There is minimal repetition of the requirement text in order to simplify the ETM content, lower maintenance costs and reduce the danger of inconsistencies between Volume II and the ETM following future revisions.

1.2.2 The first section provides general information while the second section contains guidance material to Annex 16, Volume II. The format of the guidance material includes three types of information described as explanatory information, equivalent procedures and technical procedures. The definitions of these three types of information are as follows:

Explanatory Information

— Explains Annex 16 emissions Standards language.

— States current policies of regulatory authorities regarding compliance with Annex 16 emissions Standards.

— Provides awareness of critical issues for approval of applicants' compliance methodology proposals.

Equivalent Procedures

An equivalent procedure is a test or analysis procedure which, while differing from one specified in Annex 16, Volume II, in the technical judgement of the certificating authority yields effectively the same emissions levels as the specified procedure.

The use of equivalent procedures may be requested by applicants for many reasons, including:

a) to make use of previously acquired certification test data for the engine type; and

b) to minimize the costs of demonstrating compliance with the requirements of Annex 16, Volume II by keeping engine test time, test bed usage, and equipment and personnel costs to a minimum.

Technical Procedures

A technical procedure is a test or analysis procedure not defined in detail in Annex 16 emissions Standards but which certificating authorities have approved as being acceptable for compliance with the general provisions specified in the emissions Standards.

1.3 EMISSIONS COMPLIANCE DEMONSTRATION PLAN

1.3.1 Prior to undertaking an emissions certification demonstration, the applicant is normally required to submit to the certificating authority an emissions compliance demonstration plan. This plan contains the method by which the applicant proposes to show compliance with the emissions requirements. Approval of this plan and the proposed use of any equivalent procedure remains with the certificating authority. The determination of equivalency for any procedure or group of procedures must be based upon the consideration of all pertinent facts relating to the application.

1.3.2 Emissions compliance demonstration plans should include the following types of information:

a) introduction
   - description of the engine emissions certification basis, i.e. the applicable Annex 16, Volume II amendment and chapter;

b) engine description
   - type, model number and specific details of the basic configuration to be certified;

c) engine emissions certification methodology
   - test concepts, equivalent procedures and technical procedures;

d) test description
   - test methods to comply with the emissions Standards;

e) measurement system
   - description of measurement and sampling system components and procedures, including calibration procedures, that are intended to be used to demonstrate compliance with the emissions Standards; and

f) data evaluation procedures
   - emissions evaluation and adjustment procedures (including equivalent and technical procedures such as those provided in these guidelines) to be used in compliance with the provisions of Annex 16, Volume II appropriate to the engine type being certificated.

1.4 EMISSIONS CERTIFICATION REPORTS

1.4.1 Following completion of an emissions certification demonstration test, an applicant is normally required to submit an emissions certification report. This report provides a complete description of the test process and the test results with respect to compliance with the provisions of Annex 16, Volume II.

1.4.2 These reports should include the following types of information:

a) basis for test approval
   - the approved emissions certification compliance plan for the engine type and model being certificated;

b) description of tests
   - actual configurations tested and non-conforming items (with justification that they are not significant to emissions, or if significant, can be dealt with by an approved method), test methodology (including equivalent procedures and technical procedures), tests conducted, test data validity, and data analysis and adjustment procedures used;

c) test results
   - data to demonstrate compliance with the provisions of Annex 16, Volume II regarding maximum emissions levels for the engine type being certificated; and

d) references.

SECTION 2 – GUIDANCE MATERIAL

PART III – EMISSIONS CERTIFICATION

CHAPTER 2. Turbo-jet and turbofan engines intended for propulsion only at subsonic speeds

2.1 General

2.1.1 Applicability

The provisions of this chapter shall also apply to engines designed for applications that otherwise would have been fulfilled by turbo-jet and turbofan engines.

Explanatory Information

This sentence anticipates the introduction of future engine technologies. The emissions Standards in Chapter 2 would also be applicable to future engine types not categorized as a turbo-jet or turbofan but intended for use in international air transport services. The provision above is not applicable to turbo-prop engines.

2.1.2 Emissions involved [Reserved]

2.1.3 Units of measurement

Explanatory Information

Smoke level is determined indirectly, by means of the loss of reflectance of a filter used to trap smoke particles from a prescribed mass of exhaust per unit area of filter. The result is a dimensionless smoke number "SN" which acts as a surrogate for, or indicator of, plume opacity. These smoke sampling and measurement procedures standardized in Annex 16, Appendix 2 are derived from SAE Aerospace Recommended Practice (ARP) 1179, Aircraft Gas Turbine Exhaust Smoke Measurement.

The smoke measurement standard was developed for engines that generated smoke at considerably higher levels than are seen today. This affects the relative accuracy of the method. The measurement is considered (by the SAE E-31 Committee that developed the method) to be no more accurate than ±3 SN. At smoke levels of SN 50-60 this represents an accuracy of 6 to 5 per cent. At regulatory standards of 30 and below, relative accuracy becomes 10 to 20 per cent or more.

2.1.4 Reference conditions

2.1.4.1 Atmospheric conditions

Explanatory Information

The reference atmospheric conditions to which the gaseous emissions (HC, CO and NOx) are to be corrected are the reference day conditions, as follows: Temperature = 15°C, Humidity = 0.00634 kg H_2O/kg of dry air, Pressure = 101.325 kPa.

2.1.4.2 Thrust settings [Reserved]

2.1.4.3 Reference emissions landing and take-off (LTO) cycle

Explanatory Information

The exhaust emissions test is designed to measure hydrocarbons, carbon monoxide, carbon dioxide and oxides of nitrogen concentrations, and to determine mass emissions through calculations during a simulated aircraft landing-takeoff cycle (LTO). The LTO cycle is based on times in mode data during high activity periods at major airports for four modes of engine operation: taxi/idle, takeoff, climbout, and approach. The mass emissions for these modes are combined to yield the reported emissions certification levels.

2.1.4.4 Fuel specifications

Explanatory Information

Aircraft gas turbine engines use a variety of fuels. The specific fuel type and composition can and often do have a significant effect on engine emissions. Hence, it is an important factor when comparing emissions levels from one engine with those from another. It is particularly important in evaluating engine emission levels relative to a regulation that was based, in part, on an assumed fuel specification. The fuel specification defined in Appendix 4 is typical of Jet A aviation fuel. The requirement for emissions certification testing with a fuel that meets a particular specification provides a fixed point of reference for the engine. It provides for some degree of control over the effect of fuel composition on smoke formation and emission. It also helps in the assessment of the effects of changing technology.

2.1.5 Test Conditions [Reserved]

2.2 Smoke

2.2.1 Applicability [Reserved]

2.2.2 Regulatory Smoke Number [Reserved]

2.3 Gaseous Emissions

2.3.1 Applicability [Reserved]

2.3.2 Regulatory levels [Reserved]

2.4 Information Required

2.4.1 General information [Reserved]

2.4.2 Test information [Reserved]

2.4.3 Derived information

Explanatory Information

The “Maximum Smoke Number” is formally defined as the greatest value of SN measured at any of the four thrust levels defined in 2.1.4.2. However, if a higher smoke number is measured at any other test condition between 7 and 100 per cent of rated thrust during emissions certification tests, it is recommended that the higher value be reported as the “Maximum Smoke Number”.

APPENDIX 2. Smoke Emission Evaluation

Explanatory Information

The procedure for evaluating smoke emissions is an indirect measure of smoke plume visibility which is obtained by using a filter to trap smoke particles contained in a predetermined mass of exhaust gas and measuring the loss of reflectance, i.e., degree of staining, of this filter relative to the absolute reflectance of the filter when clean or free of stain. The uncertainty of the smoke emission evaluation is estimated to be within ±3 SN (smoke numbers).

1. Introduction and Definitions [Reserved]
2. Measurement of Smoke Emissions

2.1 Sampling probe for smoke emissions

a) *The probe shall be made of stainless steel or any other non reactive metal. If a probe with multiple sampling orifices is used, all sampling orifices shall be of equal diameter.*

Equivalent Procedures

Stainless steel is the preferred probe material but other non-reacting materials may be more suitable under specific circumstances, e.g. engine exhaust temperatures which exceed the physical specification limits of stainless steel. Inconel 625 and Nimonic 75 alloys have previously been accepted as a non-reactive probe material. Other materials may be suitable but need to be approved by the certificating authority.

b) *The probe design shall be such that at least 80 per cent of the pressure drop through the probe assembly is taken at the orifices.*

Explanatory Information

Smoke particles are submicron in size which, for sampling from gas turbine engines, precludes the need for isokinetic sampling. Nevertheless, good practice would suggest sampling as close to isokinetically as possible. Taking an 80 per cent pressure drop at the probe orifices is a reasonable compromise. Further information on probe design is provided within the section on Appendix 3, paragraph 5.1.1.

c) *The number of locations sampled shall not be less than 12.* [Reserved]

d) *The sampling plane shall be as close to the engine exhaust nozzle exit plane as permitted by considerations of engine performance but in any case shall be within 0.5 nozzle diameters of the exit plane.* [Reserved]

e) *The applicant shall provide evidence to the certificating authority, by means of detailed traverses, that the proposed probe design and position does provide a representative sample for each prescribed power setting.*

Explanatory Information

Smoke measurements can be performed by means of a single point probe which is traversed through the sampling plane in sufficient detail to provide a representative sample. This measurement can also be made using a multi-orifice probe which has been demonstrated to provide a representative sample by comparison with those of the single point traverse. Work sponsored by the SAE E-31 Committee has shown that the best agreement between a detailed traverse, used to establish the mean value of smoke emissions in the sampling plane, and a multi-point sampling probe is achieved when this probes sampling orifices are located on centres of equal area. The most common configuration is that of a cruciform with the individual orifices equally distributed and located on centres of equal area.

2.2 Sampling line for smoke emissions

Explanatory Information

If carbon-loaded grounded polytetrafluoroethylene (PTFE) is used special care must be taken to allow sufficient cooling of the exhaust sample from the probe to the PTFE line to prevent damaging the PTFE line and possibly compromising the sample.

2.3 Smoke analysis system

a) *sample size measurement*: [Reserved]
b) *sample flow rate measurement*: [Reserved]
c) *filter and holder*: [Reserved]
d) *valves*: [Reserved]
e) *vacuum pump*: [Reserved]
f) *temperature control*: [Reserved]
g) 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 (Figure 2-1), to dump excess flow. The dump line shall be as close as possible to probe off-take and shall not affect the ability of the sampling system to maintain the required 80 per cent pressure drop across the probe assembly. The dump flow may also be sent to the CO_2 analyser or complete emissions analysis system.

Explanatory Information

Achieving an 80 per cent pressure drop across the probe assembly can result in an unacceptably high sample flow rate through the filter holder due to the pressure drop taken across the filter. In these instances, a flow splitter may be required.

h) 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.

Explanatory Information

Smoke from gas turbine engines, although consisting of sub-micron particles, can be particularly sensitive to flow splitter design or other flow elements in the sampling stream due to inertial separation at very high flow velocities. This test addresses these concerns and ensures that the splitter design does not adversely impact the smoke emissions evaluation.

i) *leak performance*: [Reserved]
j) *reflectometer*: [Reserved]

2.4 Fuel specifications [Reserved]

2.5 Smoke measurement procedures

2.5.1 Engine operation [Reserved]

2.5.2 Leakage and cleanliness checks

Explanatory Information

Leakage checks are to ensure clean air does not leak into the system thereby diluting the sample and lowering the smoke number. Cleanliness checks ensure that the sampling system is acceptably clean and the collecting filter will not be contaminated. If the probe cannot be removed from the sampling stream during engine start-up, the probe and lines should be back pressured with a suitably clean gas, such as dry nitrogen, to minimize contamination problems.

2.5.3 Smoke measurement

Explanatory Information

It is common practice, while sampling for smoke, to also measure levels of CO_2 as an operational check of the sampling system. The engine fuel-air ratio is calculated from the measured CO_2 and compared to the fuel-air ratio obtained from engine performance data. These should be in agreement within ±10 per cent at engine power above idle and within ±15 per cent at idle.

Paragraphs a) through d) provide for adjusting and setting the sample flow rate through the filter holder. To duplicate the pressure drop through the filter holder during actual sampling conditions a clean filter is clamped into the holder. This filter should be removed and discarded before clamping a clean filter into the holder as described in d).

3. Calculation of Smoke Number from Measured Data

Explanatory Information

The absolute reflectance of each clean filter should be determined as well as that of the stained filter. Work performed by Dieck, et al, "Aircraft Gas Turbine Smoke Measurement Uncertainty Using the SAE/EPA Method", Journal of Aircraft, Vol. 15, No. 4, April 1978, concluded that "The major instrument-related source of error in SAE/EPA smoke measurement is clean-filter reflectance precision. It is a direct result of the variability in filter reflectance about the average value used". The backing material should be flat and provide equal pressure across the surface of the filter.

4. Reporting of Data to the Certificating Authority [Reserved]

APPENDIX 3: Instrumentation and Measurement Techniques for Gaseous Emissions

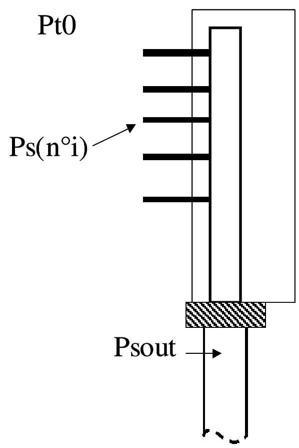
1. Introduction [Reserved]
2. Definitions [Reserved]
3. Data Required [Reserved]
4. General Arrangement of the System [Reserved]
5. Description of Component Parts
    5.1 Sampling system
        5.1.1 Sampling probe

Explanatory Information

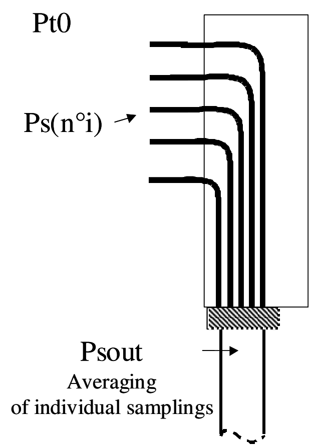
A mixing probe design could include either several sampling orifices leading into a single plenum or several sampling orifices leading into individual sample lines which are mixed external to the probe. The sampling orifices should be equal in size and located on centres of equal area for all mixing probes. If a multi-armed probe is used, then there should be an equal number of orifices on each arm. Considerations for probe design leading to these criteria can be found in "Gas/Turbine Emission Probe Factors", SAE Aerospace Information Report AIR4068A, 1996.

The pressure drop refers to the <u>dynamic head</u> not the total pressure and is needed to ensure that each orifice takes a flow rate that is proportional to the dynamic head present at the sampling orifice. Thus when the samples taken by the individual sampling orifices are mixed together within the probe, the total sample is representative of the mass flux of emissions through the engine exhaust sampling plane.

$$\frac{P_{t0} - p_{s(n^o i)}}{P_{t0} - p_{sout}} \geq 0.8$$



Multi-hole mixing probe
(Mixing in the probe)



Multi-hole non mixing probe
Mixing at the probe exit (before entering the line)

5.1.2 Sampling lines [Reserved]
5.1.3 HC Analyser [Reserved]
5.1.4 CO and CO2 analysers [Reserved]
5.1.5 NOx analysers [Reserved]
5.1.6 Smoke analysis system [Reserved]

6. General Test Procedures
   6.1 Engine operation [Reserved]
   6.2 Major instrument calibration [Reserved]
   6.3 Operation [Reserved]
   6.4 Carbon balance check [Reserved]
7. Calculations
   7.1 Gaseous emissions [Reserved]
      7.1.1 General [Reserved]
      7.1.2 Basic Parameters [Reserved]
      7.1.3 Correction of emissions indices to reference conditions [Reserved]
   7.2 Control parameter functions [Reserved]
   7.3 Exceptions to the proposed procedures [Reserved]

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