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Procedures for the Emissions Certification of Aircraft Engines

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AMENDMENTS

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FOREWORD

ICAO Doc 9501, Volume II, includes material which has been approved by the ICAO Committee on Aviation Environmental Protection (CAEP) Steering Group during their tenth meeting (CAEP/10) in February 2016. This manual is to be periodically revised under the supervision of the CAEP Steering Group and is intended to make the most recent information available to certificating authorities, aircraft engine emissions certification applicants and other interested parties in a timely manner, aiming at achieving the highest degree of harmonisation possible. The technical procedures and equivalent procedures described in this approved revision of the ETM Volume II are consistent with currently accepted techniques and modern instrumentation. This revision and subsequent revisions that may be approved by the CAEP Steering Group will be posted on the ICAO website (http://www.icao.int/) under “publications” until the latest approved revision is submitted to CAEP for formal endorsement and subsequent publication by ICAO.

Comments on this manual, particularly with respect to its application and usefulness, would be appreciated from all States. These comments will be taken into account in the preparation of subsequent editions. Comments concerning this manual should be addressed to:

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NOMENCLATURE

Definitions and symbols

The definitions and symbols employed in this manual are consistent with those contained in Annex 16 — *Environmental Protection*, Volume II — *Aircraft Engine Emissions* (Third Edition, July 2008).

Section 1

INTRODUCTION

1.1 PURPOSE

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

1.1.2 Annex 16, Volume II, procedures must be used unless an equivalent procedure is approved by the certificating authority. This manual 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 the chapters of Annex 16, Volume II, but are not dealt with in the same detail as in the Appendices to the Annex, which describe the emissions evaluation methods for compliance with the relevant chapters.

1.1.3 Procedures presented in this manual should not be considered as exhaustive because this manual 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.

1.2 FRAMEWORK

1.2.1 Section 1 of this manual provides general information and Section 2 provides guidance material concerning the application of the emissions Standards of Annex 16, Volume II. Section 2 replicates the structure of Annex 16, Volume II. For ease of reference the requirements of Annex 16, Volume II, are presented in text boxes, followed by the associated guidance material. Where no guidance material has been provided, the relevant paragraph of Annex 16 has been “Reserved” for future use. The aim of this presentation is to minimize repetition of the Annex 16 text in order to simplify the content of the manual, lower maintenance costs, and reduce the danger of inconsistencies between the Annex and the manual in subsequent revisions.

1.2.2 The guidance material consists of three types of information (explanatory information, equivalent procedure and technical procedure) as follows:

Explanatory information

a) explains the language of the Annex 16 emissions Standards;

b) states current policies of regulatory authorities regarding compliance with Annex 16 emissions Standards;

c) provides information on critical issues for approval of applicants’ compliance methodology proposals.

Equivalent procedure

a) An equivalent procedure is a test or analysis procedure which, while differing from the 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.

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

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

2) 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 procedure

A technical procedure is a test or analysis procedure not defined in detail in the 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 containing the method by which the applicant proposes to show compliance with the emissions requirements. Approval of the compliance demonstration plan and the proposed use of any equivalent procedure remain with the certificating authority. The determination of equivalency for any procedure or group of procedures must be based on 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:* a description of the engine emissions certification basis, i.e. the applicable amendment and chapter of Annex 16, Volume II;

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:* a 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 this manual) to be used in compliance with the provisions of Annex 16, Volume II, appropriate to the engine type being certificated.

1.4 EMISSIONS CERTIFICATION REPORT

1.4.1 Following completion of an emissions certification demonstration test, an applicant is normally required to submit an emissions certification report providing 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 Emissions certification 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 I. DEFINITIONS AND SYMBOLS

CHAPTER 1. DEFINITIONS

***Exhaust nozzle*.** In the exhaust emissions sampling of gas turbine engines where the jet effluxes are not mixed (as in some turbofan engines for example) the nozzle considered is that for the gas generator (core) flow only. Where, however, the jet efflux is mixed the nozzle considered is the total exit nozzle.

Type Certificate. A document issued by a Contracting State to define the design of an aircraft, engine or propeller type and to certify that this design meets the appropriate airworthiness requirements of that State.

Note.— In some Contracting States a document equivalent to a type certificate may be issued for an engine or propeller type.

EXPLANATORY INFORMATION

The definition in Annex 16, Volume II for Type Certificate is the same as Annex 8. In the context of Annex 16, Volume II the Type Certificate refers to the document to approving the appropriate airworthiness and environmental requirements of the engine.

EQUIVALENT PROCEDURE

Defining the exhaust nozzle in this manner, where the fan and core nozzles are not coplanar, is problematic. With imperfect knowledge of the fan flow characteristics when discharged upstream of the core exit nozzle, the effective nozzle size may be ambiguous. This affects the extreme downstream location of the sampling probe or rake and causes problems in terms of a detailed traverse of the total exhaust nozzle. In order to obtain equivalent, but more accurate, gaseous emissions measurements and representative samples, it is considered best practice to arrange the engine configuration in such a way as to separate the fan and core flows, without affecting the engine performance, and sample just the core flow. The above is equally applicable to both gaseous and smoke emissions measurements; however for smoke, the dilution and mixing of bypass air also need to be taken into account and this is covered under Appendix 2, 2.1

CHAPTER 2. SYMBOLS

[Reserved]

PART II. VENTED FUEL

Chapter 1. ADMINISTRATION

Chapter 2. PREVENTION OF INTENTIONAL FUEL VENTING

Aircraft shall be designed and constructed as to prevent the intentional discharge into the atmosphere of liquid fuel from the fuel nozzle manifolds resulting from the process of engine shutdown following normal flight or ground operations.

EXPLANATORY INFORMATION

General:

The process of engine shutdown, following normal flight or ground operations, begins with the cut off of fuel flow from the fuel control unit, and continues until a time when the design features of the engine and/or aircraft stop this flow. The engine and/or aircraft are required to be designed in such a way that this fuel cannot be discharged into the atmosphere.

Administration:

The fuel venting requirement of ICAO Annex 16 – Volume II is written as being applicable to aircraft. Part II, Chapter 1, paragraph 1.1 is further detailing the applicability to turbine engine powered aircraft. ICAO accepts that the showing of compliance with the requirement should either be done as part of the certification of the engine and/or the aircraft. Typically, the fuel venting requirement is reviewed by certificating authorities at engine and aircraft level, due to the fact that fuel venting can be influenced by the engine’s installation effects.

Certification to the Annex 16, Volume II, Part II Chapter 2 requirement has been on the basis of the design and construction of the aircraft’s engine fuel system in order to prevent the intentional discharge into the atmosphere of fuel from the engine’s fuel system resulting from the process of engine shutdown. This section deals with all aspects of stopping fuel from the fuel nozzle manifold from leaving the engine/aircraft during or after engine shutdown. In the past, engines/aircraft designed with any of the systems stated below to address fuel venting have been considered acceptable, and have been approved. None of these systems deliberately cause fuel to be sprayed, vented, or dripped outside of the aircraft or engine after the process of engine shutdown is completed. The engine/aircraft systems’ design and construction for the prevention of intentional fuel venting is subject to review and approval or acceptance by the certificating authority.

<u>Engine Shutdown process</u>:

The process of engine shutdown is described as follows.

The engine shutdown process begins when fuel cut-off is commanded by the pilot. Once fuel flow to the engine is cut-off, a process begins leading to engine shutdown. The amount of time for this process to take place is dependent upon the design features of the engine. As a generic description, this process involves the simultaneous movement of the liquid fuel that resides within the engine (whether from pressure and/or gravitational forces), into the combustion chamber, and/or settling in areas of the engine of lower potential energy (e.g. to a drain tank). The process may also include valves closing to prevent fuel flow into the combustor from the fuel manifold system, as well as trying to prevent residual fuel from vaporizing after engine shutdown. Any residual fuel that drains into the combustion chamber during engine shutdown is expected to be combusted, as the chamber remains at a high enough temperature to combust the fuel. Once the combustor temperature has cooled, any remaining un-combusted fuel is expected to be held (e.g. fuel delivery system, ecology tank, etc.) and not susceptible to release to the atmosphere after engine shutdown.

TECHNICAL PROCEDURE / EQUIVALENT PROCEDURE

The information contained in this section sets forth acceptable means, but not the only means, by which compliance may be shown with the requirement of ICAO Annex 16, Vol. II, Part II Chapter 2.

In order to meet the fuel venting requirement, the following means of compliance have been accepted by the certificating authority:

- Purged forward into the engine combustion chamber as part of the engine shutdown process,
- Retained within the fuel manifolds or within the engine casings[1], or
- Recirculated backwards from the fuel manifolds. These systems inherently use a means of collecting the fuel, either an airframe or engine mounted tank or a movable piston to remove and return manifold fuel.

Any of the above specified systems, or any other system which are intended to be applied to demonstrate compliance, has to be agreed with the certificating authority.

Systems which purge fuel forward on engine shutdown:

These systems rely on a feature which stores compressed gas, usually air, to purge the fuel manifolds on engine shutdown. One or more valves release the gas into the manifold when the engine fuel flow is cut off, causing the fuel from the manifold to rapidly enter the combustor and burn as the engine shuts down. The temperature during this process is considered to be hot enough to burn the fuel as it enters the combustion chamber. In these systems, some parts may be airframe mounted, or the entire system may be considered part of the engine.

Systems which retain fuel within the fuel manifold:

Systems which retain fuel within the fuel manifold have multiple valves in the system (sometimes on every fuel injector). These valves prevent the fuel manifold from draining into the combustor when the engine is shutdown. Consequently no fuel from the manifolds is released to the atmosphere. In some cases, residual fuel (for example within the fuel injectors) may settle in the bottom of fuel manifold due to gravity.

[1] It is noted that the practice of retaining fuel from the fuel manifold within the engine casings after shutdown is not considered good practice as any liquid fuel retained in the casing combustion section may be vaporised during shutdown after the flame is extinguished. As such it may not be considered an acceptable means of compliance in some member states. Existing type certificates which utilize this approach would continue to be considered valid. However, if such an existing/legacy engine model were to be modified in a way that affects the fuel system, a review of the fuel venting requirements may be undertaken as part of the new or amended certification process.

Systems which retain some fuel within engine casings[4]:

Some engines do not use valves so some amount of fuel drains into the engine casings, and is retained in the engine. Fuel which is retained inside the engine in this fashion is re-used during the next start. The amount of fuel which can be retained is severely limited. Care should be taken to design engines to prevent residual fuel from becoming exposed to excessive engine temperatures, as it could lead to a release to the atmosphere and hot end deterioration during subsequent starts. Due to this, some (typically smaller) engine models use case drains which collect residual fuel, and this fuel is directed back to aircraft mounted tanks. The common feature of all these systems is that the designs are such that no liquid fuel leaves the aircraft.

Systems which purge fuel backward from the fuel manifolds:

Some systems are designed to cause the fuel from the manifolds to be purged backwards and drains to a separate tank which either is recycled on subsequent engine runs, or are emptied periodically. Generally in this arrangement, either residual engine air pressure in the combustor, gravity, or a combination of gravity and pressure causes the fuel to be removed from the manifold and fuel injectors (e.g.: ecotank). Other systems may use a moving piston to pull fuel out of the manifold and reuse it to re-fill the manifold on the next start (e.g. ecology valve).

Other/new means of compliance:

The above list of fuel venting prevention systems is not exhaustive, and new technologies may yet be developed that meet the intent of the fuel venting requirement. These new technologies should be presented to the Certification Airworthiness Authorities (CAA) and should include sufficient substantiation material for evaluation during the design review phase of the certification process to determine compliance with the fuel venting standard.

PART III. EMISSIONS CERTIFICATION

CHAPTER 1. ADMINISTRATION

[Reserved]

CHAPTER 2. TURBOJET AND TURBOFAN ENGINES INTENDED FOR PROPULSION ONLY AT SUBSONIC SPEEDS

2.1 GENERAL

2.1.1 Applicability

EXPLANATORY INFORMATION

Part I of Annex 16, Volume II, defines a derivative version[2] in terms of emissions certification, but this definition is referred to in the Annex only in the context of granting exemptions and does not specify how the rule should be applied to modifications of already certificated engine types. Many changes to a certificated engine, which are considered to be major from an airworthiness perspective, require an amendment or supplement to the type certificate (TC). However, these same modifications may have no or very little effect on the emissions characteristics of that engine. If Annex 16 is interpreted literally, these small effects would require a full investigation of compliance with the emissions certification requirements. This may not be necessary in many cases. The following guidelines have been developed to help determine whether a modification can be classified as a "no emissions change" or if it would affect the emissions levels to such an extent that the engine type would need to be re-certificated to Annex 16, Volume II, requirements. Of course manufacturers may elect to re-certify to the latest Annex 16 requirements at any time.

TECHNICAL PROCEDURE

1. No emissions change

The principle of a "no emissions change" is that an engine would not need to be re-certified to the emissions

2. *Derivative version.* An aircraft gas turbine engine of the same generic family as an originally type-certificated engine and having features which retain the basic core engine and combustor design of the original model and for which other factors, as judged by the certificating authority, have not changed.

requirements if the manufacturer can demonstrate that the modification(s) would result in a small cumulative change to the current certified engine emissions levels. Cumulative change could be as a result of more than one change at a given time or multiple changes from more than one derivative version of the same engine being developed. The determination of a "no emissions change" is limited to the following conditions:

a) If all of the characteristic levels prior to any modification are greater than or equal to 95 per cent of the existing ICAO Standard, the manufacturer must provide new engine emissions test data to demonstrate that the resulting characteristic levels after the cumulative changes since original emissions testing will not exceed the existing ICAO exhaust emissions Standard.

b) If all of the characteristic levels are less than 95 per cent of the existing ICAO exhaust emissions Standard, then new or related emissions test data and good engineering judgement based on substantive analysis may be an acceptable means to demonstrate that the resulting emissions levels after the cumulative changes since original emissions testing will not exceed the existing ICAO exhaust emissions Standard.[3] Analyses should consider areas such as cycle changes, combustor and fuel nozzle design, or large changes in combustor inlet velocity profile or turbine cooling flows as discussed in paragraph 5 below.

c) Any new emissions test data and/or engineering/technical analysis under 1 a) and b) must demonstrate that the cumulative changes in absolute emissions levels, as compared to those of the original certification, are within:[4]

NO_x ± 3 g/kN
HC ± 1 g/kN
CO ± 5 g/kN
Smoke ± 2 SN.

With respect to the tracking of cumulative changes, an applicant should maintain formal documentation of the technical basis for all approved "no emissions changes" for an engine model. The tracking list will be reproduced in each emissions certification dossier demonstration.

If a modification is classified as a "no emissions change", the characteristic levels for the derivative version will be considered the same as the parent engine.

2. Changes requiring new emissions levels

A change, or cumulative set of changes, to the type design, which is not considered a "no emissions change" and thus affects the characteristic levels would require new characteristic levels to be determined during the certification programme. The method used to determine new characteristic levels will depend on the scope of design change, and should be discussed in the manufacturer's certification plan and approved by the certification authority. The appropriate approach could include a combination of analysis based on test, component test, or a new emissions certification test. For example:

3. Good engineering judgement means judgement that is consistent with generally accepted scientific and engineering principles and all available relevant information.
4. Absolute emissions level refers to the average of the measured emissions levels corrected to reference conditions. This does not include application of the Appendix 6 statistical factors used to determine characteristic levels.

- Use of calculated emissions values as in paragraph 7.1.3.2. to Appendix 3 from a previous emissions certification test may be appropriate for a cycle change where combustor inlet conditions are within the range of conditions tested previously.
- Use of simple, well documented design correlations may be appropriate for small design changes.
- Use of more complex analysis methods such as computational fluid dynamics may be appropriate if the manufacturer can show that the accuracy of the methods have been validated and approved by the Certificating Authority and are sufficient for the design change being considered.
- A combination of validated analyses supported by combustor rig testing may be acceptable in cases where analysis alone is not sufficient.
- A new emissions certification test is required if the accuracy of other analytical and test methods is insufficient.

3. Existing emissions certification basis retained

If a modified engine remains on the existing type certificate, it may retain the existing certification basis of the parent engine[5] if the modification(s):

a) meets the demonstration criteria of 1 a) or b);

b) results in a decrease in the absolute emissions levels;

c) results in an increase in the absolute emissions levels below those prescribed in 1 c);

d) is necessary for improved safety and continued airworthiness (e.g. Airworthiness Directives).

4. Latest emissions Standards applied

An engine type should demonstrate compliance with the latest applicable emissions Standards when:

a) the engine requires a new TC;

b) the engine modification(s) involves significant technical modifications and where, in the judgement of the certificating authority, the engine would not meet the definition of a derivative engine as defined in Annex 16, Volume II;

c) the engine modification(s) does not meet the demonstration criteria of 1 a) or b);

d) the engine modification(s) results in an increase in any of the absolute emissions levels below those prescribed in 1 c) but which results in an exceedance of the existing ICAO Standard;

e) the engine modification(s) results in an increase in any of the absolute emissions levels in excess of those prescribed in 1 c); or

5. In terms of emissions certification, the parent engine must have demonstrated emissions compliance and is itself not considered to be a derivative of an even earlier Standard.

f) there are significant future environmental impacts.[6]

g) An applicant / engine manufacturer may elect to comply with a new and/or later Standard of this Annex as agreed upon with the certificating authority, provided that the new/later Standard has become applicable ("applicable date" in the foreword of this Annex) and the certificating authority has implemented the new standard.

Certification test data that was approved by the CA to show compliance with an earlier Standard may be used to demonstrate compliance with a new/later standard provided that the test engine build standard and technical details of measurement, sampling, and correction have not changed with the revision of the standard. The formal process of application and approval remain unchanged.

5. Engineering analysis examples

The basic premise in assessing the emissions effects of design changes from an engineering analysis perspective is that emissions are mainly affected by cycle changes, combustor and fuel nozzle design, or large changes in combustor inlet velocity profile or turbine cooling flows. A number of examples are provided below for illustration.

Cycle change

Annex 16, Volume II, requires the measurement of fuel mass flow by direct measurement only to an accuracy of ±2 per cent (Attachment F to Appendix 3, paragraph d)) and thrust to an accuracy of ±1 per cent at take-off power and ±5 per cent at the minimum thrust. It may be that no effect on emissions beyond those prescribed in paragraph 1 c) would be expected unless changes in air fuel ratio result in a specific fuel consumption change of more than 1 per cent.

Regarding combustor inlet temperature (T3), the Annex also states that the combustor inlet parameters shall preferably be measured but may be calculated from ambient conditions by appropriate formulas. Following a comparison of T3 detailed traverses versus typical certification test measurements, it was concluded that measurements are within ±6°F (approximately 3.5°C) of theoretical calculations. It may be that no effect on emissions beyond those prescribed in paragraph 1 c) would be expected if the cycle T3 change is within ±6°F.

Combustor and fuel nozzle

Combustor and fuel nozzle changes include some key design characteristics that can significantly affect emissions (e.g. swirl cup flow, primary hole flow, front-end cooling flow, injector atomization). Changes within or outside of production tolerances or part-to-part variation may indicate when a change would be important for emissions or else considered to be not measurable. No effect on emissions beyond those prescribed in 1 c) would be expected if the changes are within current part-to-part variation or prescribed production tolerances.

Boundary conditions

Similar limitations to that for key design characteristics can be applied to that resulting from changes in boundary

6. The application of an old engine type to a new aircraft design could mean a lifetime of 30 years or more and thereby have a more serious impact on the environment than if the engine was produced for spare only.

conditions. For example, if turbine cooling changes by 2 per cent, one could look at the resulting change in combustor flow distribution, and if the change is of the same order as typical part-to-part variation, it may be acceptable to conclude that no effect on emissions beyond that prescribed in 1 c) would be expected.

2.1.1.1 The provisions of this chapter shall apply to all turbojet and turbofan engines, as further specified in 2.2 and 2.3, intended for propulsion only at subsonic speeds, except when certificating authorities make exemptions for:

a) specific engine types and derivative versions of such engines for which the type certificate of the first basic type was issued or other equivalent prescribed procedure was carried out before 1 January 1965; and

b) a limited number of engines beyond the dates of applicability specified in 2.2 and 2.3 for the manufacture of the individual engine.

2.1.1.2 In such cases, an exemption document shall be issued by the certificating authority, the identification plates on the engines shall be marked "EXEMPT," and the grant of exemption shall be noted in the permanent engine record. …

TECHNICAL PROCEDURE

1. Introduction

1.1 The current edition of Annex 16, Volume II, contains two different references to applicability dates:

a) the "date of manufacture for the first individual production model" which refers to the engine type certification; and

b) the "date of manufacture for the individual engine" which refers to the production date of a specific engine serial number.

1.2 The second reference is used in the application of global engine NO_x production cut-off Standards which specify a date after which all in-production engine models must meet a certain NO_x emissions Standard. For example, all engines manufactured after 31 December 1999 must be compliant with the CAEP/2 NO_x Standard. It should be noted that these requirements are applicable to complete new "engine units" released into service as spares or for new aircraft installations, as discussed below, and not engine components required for maintenance aspects, overhaul, parts, etc.

1.3 It is recognized that there may be circumstances where it is justified to permit manufacturers to continue to produce new non-compliant engine units after a production cut-off date. These take the form of exemptions from the relevant Annex 16, Volume II, provisions.

1.4 In order to promote a harmonized global approach to the granting, implementing and monitoring of these exemptions, this section provides guidelines on the process and criteria for issuing exemptions from an NO_x production cut-off Standard.

2. Exemption process

2.1 *Application*

The applicant should submit to the competent authority[7] a formal application letter for the manufacture of the exempted engines, signed by an appropriate manager, and copied to all other relevant organizations and involved competent authorities. The letter should include the following information in order for the competent authority to be in a position to review the application:

a) Administration

name, address and contact details of the applicant.

b) Scope of application for exemptions

1) engine type (model designation, type certificate (TC) number, TC date, emissions TC basis, ICAO engine emissions databank unique identification (UID) number);

2) number of engine exemptions requested;

3) duration (end date) of continued production of exempted engines;

4) designation of whether the proposed exempted engines are "spares" or "new"[8] and to whom the engines will be originally delivered.

c) Justification for the exemptions. In applying for an exemption, an applicant should, to the extent possible, address the following factors, with quantification, in order to support the merits of the exemption request:

1) technical issues, from an environmental and airworthiness perspective, which may have delayed compliance with a production cut-off;

2) economic impacts on the manufacturer, operator(s) and the aviation industry at large;

3) environmental effects. This should consider the amount of additional NO_x that will be emitted as a result of the exemption, including items such as:

— the amount that the engine model exceeds the Standard, taking into account any other engine models in the engine family covered by the same type certificate and their relation to the Standard;

— the amount of NO_x that would be emitted by an alternative engine for the same application;

— the impact of changes to reduce NO_x on other environmental factors, including community noise and CO_2 emissions;

7. In most cases this will be the certificating authority although it may vary depending on the processes of individual Member States.
8. In the case that engines are "new" (installed on new aircraft) and would thus result in a larger negative environmental impact compared to "spare" engines, more justification may be required.

4) the impact of unforeseen circumstances and hardship due to business circumstances beyond the manufacturer's control (e.g. employee strike, supplier disruption or calamitous event);

5) projected future production volumes and plans for producing a compliant version of the engine model for which exemptions are sought;

6) equity issues in administering the production cut-off among economically competing parties (e.g. provide the rationale for granting an exemption when another manufacturer has a compliant engine and does not need an exemption, taking into account the implications for operator fleet composition, commonality and related issues in the absence of the engine for which exemptions are sought); and

7) any other relevant factors.

2.2 *Evaluation*

The evaluation of an exemption application should be based on the justification provided and the following definitions and criteria:

a) Use of engines

"Spare engines" are defined as complete new engine units which are to be installed on in-service aircraft for maintenance and replacement. It can be presumed that applications associated with engines for this purpose would be granted as long as the emissions are equal to or better than the engines they are replacing. The application should also include the other items described in 2.1 a) and b), but it would not need to include the items specified in paragraph 2.1 c). For spare engines, the evaluation of the exemption application would be conducted for recordkeeping and reporting purposes, but it would not be done for approval of an exemption.

"New engines" are defined as complete new engine units which are to be installed on new aircraft. They can be exempted from an NO_x production cut-off requirement only if they already meet the previous Standard (e.g. exemption from a CAEP/6 NO_x production cut-off is possible only if an engine type already meets the CAEP/4 NO_x Standard). Also, in order to gain approval for this type of exemption, applicants must clearly demonstrate that they meet the criteria for an exemption by including items described in 2.1 a), b) and c). The competent authority may require additional information regarding the appropriateness of the potential exemption.

b) Number of new engine exemptions

Exemptions should be based on the total number of engines and the time period for delivery of these engines, which would be agreed at the time the application is approved and based on the considerations explained in 2.1 c). The number of engines exempted would normally not exceed 75 per engine type certificate, and the duration would not exceed four years from the effective date of the production cut-off. Exemptions would apply only to non-compliant engine models on an engine type certificate.

Exemptions for new engines should be processed and approved by the competent authorities for both the manufacture of the exempted engines and the initial operator of the aircraft to which they are to be fitted. Given the international nature of aviation, civil aviation authorities of Member States should attempt to collaborate and consult on the details of exemptions. In the case where engine type certification is done through a reciprocity agreement between Member States, the States involved should coordinate the processing of exemptions and concur before approval is granted.

As part of the review and approval process for exemptions from any production cut-off requirement associated with the CAEP/6 NO_x Standard, competent authorities may in some cases require a form of NO_x emissions offsetting, as appropriate within the context of aviation and considering an applicant's ability to utilize such measures. However, offsetting measures should be applied only when necessary in view of the number of engines for which exemptions are sought (e.g. greater than 30), duration and/or per cent exceedance described in an application.

c) Exceptions

Unlimited exemptions should be granted for spare engines having emissions equivalent to or better than the engines they replace. Engines for use on State aircraft (e.g. military, customs and police) are not covered by the Chicago Convention and are therefore excluded from these civil aircraft NO_x production cut-off requirements.

2.3 *Review*

The competent authority should review, in a timely manner, the application using the information provided in 2.1 and against the definitions/criteria in 2.2. The analysis and conclusions from the review should be communicated to the applicant in a formal response. If the application is approved, the response should clearly state the scope of the exemptions which have been granted. If the application is rejected, then the response should include a detailed justification.

3. Registration and communication

3.1 Oversight of the granted exemptions should include the following elements:

a) The competent authority should publish details of the exempted engines in an official public register, including engine model, maximum number of permitted exemptions and use of the engine.

b) The applicant should have a quality control process for maintaining oversight of and managing the production of engines which have been granted exemptions against an NO_x emissions production cut-off Standard.

c) Exempted engine plates should be marked "EXEMPT [SPARE] or [NEW]".

d) An exemption should be recorded in the engine release to service document which states conformity with the type certificate (e.g. European Aviation Safety Agency (EASA) Form 1, United States Federal Aviation Administration (FAA) Form 8130-3). Proposed standard text: "[New] or [Spare] engine exempted from NO_x emissions production cut-off requirement".

e) The applicant should provide to the competent authority, on a regular basis and appropriate to the limitation of the approval, details on the actual exempted engines which have been produced (e.g. model, serial number, use of engine, aircraft type and serial number on which new engines are installed).

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

EXPLANATORY INFORMATION

Paragraph 2.1.1.3 anticipates the introduction of future engine technologies. The emissions Standards in Chapter 2 would also be applicable to future engine types not categorized as turbojet or turbofan but intended for use in international air transport services. The provision above is not directly applicable to turboprop engines, for example.

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 Engine 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 E-31 Committee of SAE International that developed the method) to be no more accurate than ±3 SN. At smoke levels of SN 50 to 60 this represents an accuracy of 5 per cent to 6 per cent. At regulatory standards of 30 and below, relative accuracy becomes 10 per cent 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 NO_x) 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 and take-off 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, take-off, climb-out 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 does 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 emissions levels relative to a regulation that was based, in part, on an assumed fuel specification. The ICAO fuel specification defined in Appendix 4 is typical, but tighter, than the general Jet A aviation fuel specification. 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

EXPLANATORY INFORMATION

The date when a Standard in 2.2 and 2.3 becomes applicable within a certification project is related to the "date of manufacture of the first individual production model". Because this date is not always clear, certificating authorities use the date of issue of the engine TC as a surrogate. The date is transparent because it is recorded on the TC and this has therefore proven to be a useful approach in defining the certification basis for an engine type or model.

The Part 1, Chapter 1, definition of "date of manufacture" refers to the date of the document issued to an individual production engine which attests compliance with the type certificate.

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 per cent 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".

CHAPTER 3. TURBOJET AND TURBOFAN ENGINES INTENDED FOR PROPULSION AT SUPERSONIC SPEEDS

EXPLANATORY INFORMATION

As part of the CAEP/7 work programme, CAEP Working Group 3 (WG3) reviewed the historical background on the development of the emissions Standards for turbojet and turbofan engines intended for propulsion at supersonic speeds and discussed general technology aspects of supersonic engines in comparison to those for subsonic applications. The output of this work was reported in the *Report of the Seventh Meeting of the Committee on Aviation Environmental Protection* (Doc 9886), February 2007.

While further work, taking into account aircraft and engine development, was considered to be necessary to give clear recommendations on future changes to Chapter 3, the following preliminary observations and conclusions were agreed:

a) The current supersonic Standard seems to be outdated.

b) The Standard should not be applied to new engine projects.

c) Part III, Chapter 3, of Annex 16, Volume II, needs to be revised.

d) The timescale for updating should take into account the technological development of any new SST engine project and be in line with the work to be undertaken on development of revised noise Standards.

e) Any alleviation compared to the current subsonic Standard would require detailed technical investigation.

f) In order for these conclusions to become recommendations, work needs to be completed on whether the current subsonic LTO regulatory approach can be applied to supersonic.

g) Effects of cruise emissions from a potential fleet of supersonic business jets require more scientific understanding.

WG3 continues to monitor developments within the aviation industry and scientific community on this issue. WG3 has also agreed not to update Chapter 3 until a new SST engine project reaches a sufficiently mature level such that it can inform discussions on potential future revisions.

CHAPTER 4. PARTICULATE MATTER EMISSIONS

4.1 General

4.1.1 Applicability

[Reserved]

4.1.2 Emissions involved

[Reserved]

4.1.3 Units of measurement

[Reserved]

4.1.4 Reference conditions

4.1.4.1 Atmospheric conditions

[Reserved]

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

[Reserved]

4.1.4.3 *Fuel specifications*

[Reserved]

4.1.5 Test conditions

[Reserved]

4.2 Non-Volatile Particulate Matter Emissions

4.2.1 Applicability

[Reserved]

4.2.2 Regulatory Levels

[Reserved]

4.2.3 Reporting Requirement

EXPLANATORY INFORMATION

The manufacturer should report:

a. Characteristic level for the maximum $nvPM_{mass}$ concentration in $\mu g/m^3$ with no decimals.

b. EI_{mass} at each thrust setting of the LTO cycle and maximum EI_{mass} in mg/kg of fuel with three significant figures.

c. EI_{num} at each thrust setting of the LTO cycle and maximum EI_{num} in number of particles/kg of fuel with three significant figures.

4.3 Information required

4.3.1 General information
[Reserved]

4.3.2 Test information
[Reserved]

APPENDIX 1. MEASUREMENT OF REFERENCE PRESSURE RATIO

1. GENERAL

1.1 Pressure ratio shall be established using a representative engine.

1.2 Reference pressure ratio shall be derived by correlating measured pressure ratio with engine thrust corrected to standard day ambient pressure and entering this correlation at the standard day rated take-off thrust.

EXPLANATORY INFORMATION

Engine pressure ratio and corrections to standard day may be based on the validated engine performance model that is used to represent the reference engine.

2.1 Total pressure shall be measured at the last compressor discharge plane and the first compressor front face by positioning at least four probes so as to divide the air flow area into four equal sectors and taking a mean of the four values obtained.

Note.— Compressor discharge total pressure may be obtained from total or static pressure measured at a position as close as possible to the compressor discharge plane. However the certificating authority may approve alternative means of estimating the compressor discharge total pressure if the engine is so designed that the provision of the probes referred to above is impractical for the emission test.

EXPLANATORY INFORMATION

Compressor inlet and discharge total pressures are measured with multiple probes during validation of the engine performance model. As part of the model validation process, engine performance data, along with detailed analyses of the flow field between the compressor and combustor, are also used to develop methods to calculate compressor inlet and discharge total pressures based on static pressure measurements that are used by the engine control system. The static pressure tappings for measurement of compressor discharge pressure are typically located on the engine casing between the compressor discharge and the combustor inlet. During actual emissions certification tests, compressor discharge pressure is normally calculated based on these control-system static pressure measurements.

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 material with which the exhaust emission sample is in contact shall be stainless steel or any other non-reactive material.

b) If a probe with multiple sampling orifices is used, all sampling orifices shall be of equal diameter. …

EQUIVALENT PROCEDURE

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 non-reactive probe material in the context of the regulated species. 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 isokinetic as possible. Taking an 80 per cent pressure drop at the probe orifices is a reasonable compromise. Further information on probe design is provided in 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.

EXPLANATORY INFORMATION

The definition of the engine exhaust nozzle is contained in Part 1, Chapter 1, Definitions.

EQUIVALENT PROCEDURE (for mixed flow engine configurations)

For accurate gaseous emissions measurements and representative samples, it is considered best practice to arrange the engine configuration in such a way as to separate the fan and core flows, without affecting the engine performance, and to sample just the core flow. This is equally applicable to smoke emissions measurements; however for mixed flow engine designs, the dilution and mixing of bypass air also need to be taken into account with respect to the exhaust nozzle location. This means that the measured core SN would need to be corrected analytically for dilution and mixing in order to compare against the original visibility criteria.

Currently, Annex 16, Volume II, does not contain any method or procedure for these corrections which has led to inconsistent application of the requirements. Where no specific engine data are available, Version 3 of the First Order Approximation (FOA) for estimating particulate matter (PM) emissions, which contains correlations between SN and non-volatile PM, is provided as a generic dilution correction in the technical procedure below. If it can be shown that an improved correlation is available for a given engine type, or the FOA is developed further, then the improved correlation shall be used with the approval of the certificating authority. No generic mixing correction procedure has yet been identified, and as such, certificating authorities need to address this issue on a project-by-project basis. Ideally the measured core SN would already meet the SN limit. Where this is not the case, further evidence may be required to inform a technically-based engineering judgement as to whether the plume could still be considered to be invisible. This could include a detailed traverse at the mixed exhaust nozzle plane in order to perform a contour analysis and determine the level of mixing.

TECHNICAL PROCEDURE

The following procedure is provided as guidance material on how to correct core Smoke Numbers for dilution at a mixed flow engine exhaust nozzle:

Step 1. Convert the measured core Smoke Number to equivalent carbon mass concentration (see Figure 2-1)

Based on various research studies, the following FOA carbon correlation equation has been established:

$$CI = 0.0694(SN)^{1.23357} \text{ for } SN < 30$$

Example: From an engine with a maximum measured core Smoke Number of 20, the FOA reference curve provides an equivalent carbon mass concentration of 2.8 mg/m^3 at the core exit plane.

Step 2. Adjust carbon mass concentration for mixed stream equivalent

The carbon concentration can now be corrected for the amount of bypass air using the following formula:

$$\textit{Mixed carbon mass} = \frac{\textit{Core carbon mass}}{1 + \textit{bypass ratio}}$$

Example: Assuming a bypass ratio of 5, the mixed carbon mass concentration is 2.8/(1+5) = 0.47 mg/m^3 at the mixed nozzle exit plane.

Step 3. Convert the mixed stream carbon mass back to a Smoke Number

Using the FOA reference curve, the mixed flow carbon mass (calculated in the previous step) is converted to an equivalent Smoke Number.

Example. The diluted Smoke Number, accounting for the fan air using the FOA reference curve, is 4.8 at the mixed nozzle exit plane.

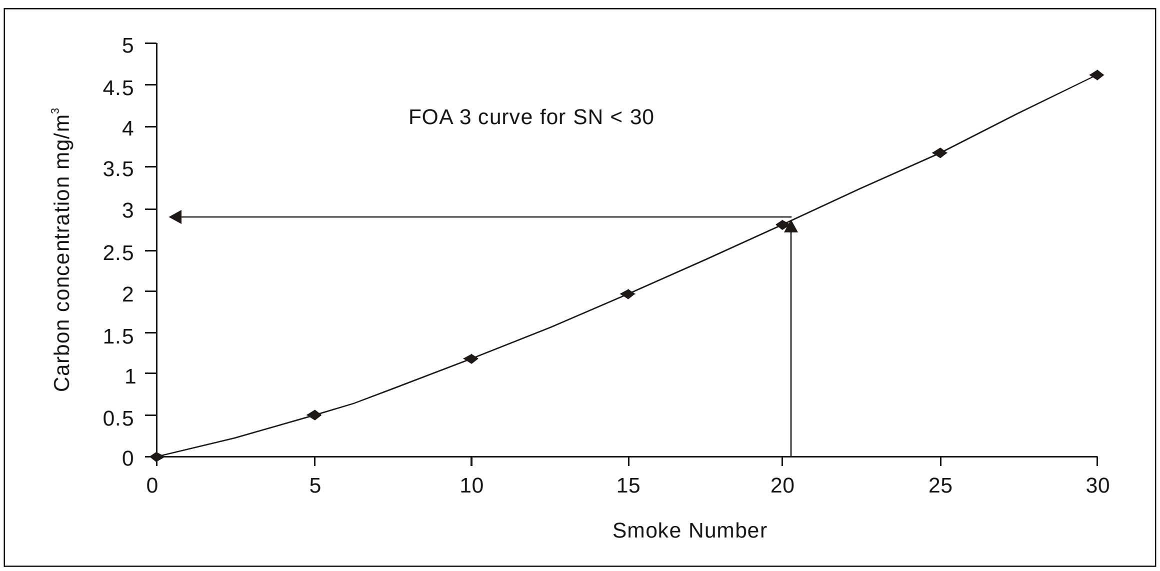


Figure 2-1. SN plotted against carbon concentration

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 thrust 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 E-31 Committee of SAE International 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 probe's 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

2.2.2 *Note.— Stainless steel or carbon-loaded grounded polytetrafluoroethylene (PTFE) meet these requirements.*

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 A2-1), 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*

EQUIVALENT PROCEDURE

ARP 1179 Rev. C requires the use of a green tristimulus filter to adjust for the effect of various light sources from different reflectometer manufacturers. While this is not a requirement in Annex 16, Volume II, it is considered best practice to follow this approach.

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 2.5.3 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 2.5.3 d).

Paragraphs 2.5.3 h) and 3 describe two different options for determining sample size:

Option 1: Sample size is within 12 and 21 kg/m^2 and the values taken are above and below 16.2 kg/m^2. In this case SN' will have to be plotted vs log *W/A*. Using a straight line square fit, SN' at a value of 16.2 kg/m^2 has to be determined which is reported as the SN for this mode.

Option 2: The alternative way is to take consecutive samples at 16.2 kg/m^2. In this case the reported SN would be the arithmetic mean of the three SN' values taken. It is good practice that sample size would be within 16.2 kg/m^2 ± 0.7 kg/m^2 and all three SN' samples would agree with ±3 SN (see also ARP 1179C).

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

EXPLANATORY INFORMATION

The sampling and analysis procedures prescribed in Annex 16, Volume II, Second Edition, 1993, were adopted from SAE ARP 1256, "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines". The calculation procedures were derived from ARP 1533 "Procedure for the Analysis and Evaluation of Gaseous Emissions from Aircraft Engines". ARP 1256 and ARP 1533 were developed and are maintained by the E-31 Committee, Aircraft Exhaust Emissions Measurement, of SAE International.

2. DEFINITIONS

[Reserved]

3. DATA REQUIRED

3.1 Gaseous Emissions

a) Hydrocarbons (HC): a combined estimate of all hydrocarbon compounds present in the exhaust gas.

EXPLANATORY INFORMATION

Gas turbine engine exhaust gases typically contain a variety of hydrocarbon compounds. The specific compounds present and their relative concentrations are usually unknown. Flame ionization detectors (FID), used to measure hydrocarbons, do not respond equally to all hydrocarbon compounds. Although this differential hydrocarbon response is to be held within specific bounds, the resulting measurement is an estimate of the hydrocarbon compounds present in the exhaust gas.

3.2 Other information

[Reserved]

4. GENERAL ARRANGEMENT OF THE SYSTEM

EXPLANATORY INFORMATION

Water is a major product of combustion. Its removal upstream of the measuring instruments is attractive. Removal would minimize possible interference effects where the instrument responds to the water present as well as to the gas or vapour being measured. It would also prevent or minimize water condensing in the instruments which could cause erratic flow and/or contamination. In the worst case, the instrument would be rendered inoperable until thoroughly cleaned. However, devices which remove water are known to remove hydrocarbons and oxides of nitrogen and are therefore permitted only for CO and CO_2 measurements. If the sample is dried, an appropriate dry/semi-dry to wet correction must be made.

For most aircraft gas turbine engines, and most engine running modes, supplemental pumps will be needed to meet the probe system pressure drop requirement (80 per cent at the probe entrance orifices), the sample line residence time and pressure drop, and the need to remove excess flow from the sampling system. Any pump used for the purpose of sample transfer must be heated. Usually, because of the sample gas physical properties and the need to maintain temperature and flow control within the FID used for hydrocarbon analysis, these instruments utilize internal, heated, inert sample transfer pumps. The use of an upstream flow splitter to dump a portion of the sample is also an acceptable procedure to assist in controlling flow to the analytical sampling train.

If loss of hydrocarbons in the sampling system is a concern, the FID, when configured with a heated transfer pump, can be located upstream of the system hot pump as close as physical constraints will allow (e.g. temperature, noise, vibration). The necessity for a dump and/or a hot-sample pump will depend on the ability to meet the sample transfer time and analysis sub-system sample flow rate requirements. This in turn depends on the exhaust sample driving pressure and line losses. Therefore, in general, the size and location of the pumps, and the associated flow control devices, are determined from the particular sampling system configuration.

5. DESCRIPTION OF COMPONENT PARTS

5.1 Sampling system

5.1.1 Sampling probe

EXPLANATORY INFORMATION

Even if active cooling of the probe is employed, care should be taken regarding the minimum sample temperature at the probe (> 145 °C) to avoid temperature gradients when the exhaust sample is transferred to the gas analysers where the line temperature is required to be kept with 160 °C ± 15 °C.

The reason for the minimum temperature is to avoid condensation (of HC primarily, and water). This will help ensure that the gas concentrations are maintained at the same values until they reach the sample point(s).

a) The probe material with which the exhaust emission sample is in contact shall be stainless steel or any other non-reactive material.

b) If a probe with multiple sample orifices is used, all sampling orifices shall be of equal diameter. …

EXPLANATORY INFORMATION

A probe design with multiple orifices (mixing probe) 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, as shown in Figure 2-2. 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 International Aerospace Information Report (AIR) 4068A, 1996. The most common configuration is that of cruciform with individual orifices located on centres of equal area.

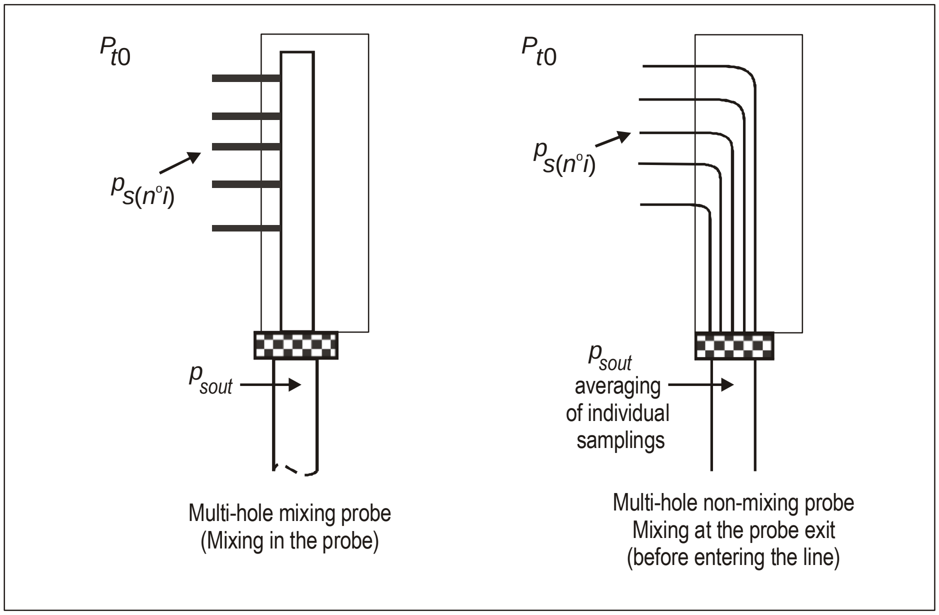


Figure 2-2. Sampling probe designs

EQUIVALENT PROCEDURE

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 non-reactive probe material in the context of the regulated species. 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

The pressure drop is needed to isokinetically sample flows at the different orifices. The orifice is supposed to be the minimum area right at the probe entrance. To achieve the pressure drop criterion, there must be a rapid expansion into the sampling tube.

The pressure drop refers to the dynamic head, 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.

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

c) The number of locations sampled shall not be less than 12.

EXPLANATORY INFORMATION

While 12 orifices is the minimum number for a sampling rake in Annex 16, Volume II, a more appropriate number would be 20 when validated by means of a detailed traverse.

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 diameter of the exit plane.

EXPLANATORY INFORMATION

Further guidance on the issue of “exhaust nozzle” is available under the definitions in Part 1, Chapter 1.

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 thrust setting.

EXPLANATORY INFORMATION

Detailed traverse measurements, although expensive, can be performed with a single-hole probe which measures stabilized concentrations at various positions. These individual measurements can then be used to derive average values and demonstrate representative sampling. The carbon balance check is also derived in the same way. The “80 per cent pressure drop” condition which was introduced in the past to guarantee the sample was representative is no longer justified for the purpose of a single-hole probe.

EQUIVALENT PROCEDURE

When applying this analytical technique, for core flow only, multi-orifice rake designs which have proven most robust seem to have four sampling arms spaced 90 degrees apart with sampling orifices located on centres of equal area. The sampling orifices are equally distributed across the sampling arms, and the contour analysis will determine the minimum number of sampling ports necessary to yield a representative sample.

A detailed traverse is not required for rotating rake designs because they provide, in normal use, as many or more sampling points than the typical single point traverse thus ensuring a representative sample. However, in order to demonstrate that a fixed rake design is orientated in the right position to collect a representative sample, traverse measurements are necessary. The detail (single point, number of rake orientations, number of different power settings) of traverse measurements may depend on the number of sampling orifices on the rake and existing experience of similar engines or derivatives. These rake design requirements are recognized as being complemented by the system check performed in the carbon balance criteria. Where a sample has low emissions indices (EIs) and relatively large "per cent" variations between the detailed traverse and the fixed rake measurements, it can be accepted as representative without having demonstrated NO_x, CO and HC to be within 10 per cent (15 per cent for idle) as long as there is a sufficient large number of orifices and an AFR match within 10 per cent (15 per cent at idle).

All data used in arriving at a probe/rake design should be made available to the certificating authority.

TECHNICAL PROCEDURE

There is no standard definition of a "representative sample" for emissions from aircraft gas turbine engines, nor is there a specification for "detailed traverse". "Representative" and "detailed" are, in this instance, matters of opinion to be negotiated between the manufacturer and the certificating authority. The issue is how much the measured averaged sample can deviate from the true sample mean before it is no longer considered to be representative. The most commonly used definition, arrived at from decades of testing and collaborative analytical exercises by user groups, is 10 per cent for engine modes above idle (i.e. approach, descent, climb and take-off) and ±15 per cent for idle, as per the carbon balance check in 6.4 of Appendix 3. There is a significant difference however. For the carbon balance check a comparison is made between sets of independently related measured values. With knowledge about the combustion process and the hydrogen-to-carbon ratio of the fuel used, an estimate can be made from the measured carbon-containing species, most of which is CO_2, of the engine average fuel-to-air ratio. The actual engine fuel-to-air ratio can be independently arrived at from measured fuel and airflow. These two values can be compared to provide an estimate of how well the exhaust stream was sampled for carbon-containing compounds. However, because CO_2 far outweighs the influence of any other carbon-bearing species in the calculation of fuel-to-air ratios, the spatial variability of CO_2 will determine how many sampling points are required and how these sampling points should be distributed. CO_2 has been found to consistently exhibit the least variability of all the species of interest, which include CO, HC, NO_x and smoke. This suggests that it would be possible to meet the 10 and 15 per cent criteria for carbon balance without having obtained a representative sample, using the same 10 and 15 per cent criteria, of the other species. In other words, obtaining a carbon balance, while a necessary pre-condition for a representative sample, cannot be considered to be a sufficient demonstration of representative sampling on its own.

Historically engine manufacturers, or testing agencies, have addressed this problem in different ways. Recognizing that gas turbine engines are predominately axi-symmetric, one acceptable method (for fixed rake designs) has been to sample the exhaust plume, point by point, with a sufficient number of points to be able to estimate, by statistical means, the true engine average species concentration for each of the species of interest. Engine exhaust species seem almost normally (Gaussian) distributed, thus making simple statistical tools acceptable. Using these sampling points, and the measured concentration values for each of the species of interest, contour plots of constant concentration (isopleths) have been analytically generated at each power setting tested. There are a number of computer programs available for workstations or desktop computers to do this. A probe or rake design is then overlaid on the contour plots in order to estimate the average probe/rake values and compare them to the estimated true average arrived at from the detailed traverse. If the comparisons match the carbon balance criteria, within 10 per cent for engine powers above idle and ±15 per cent at idle, the probe/rake can be considered to provide representative sampling. This process may have to be repeated several times before an acceptable design is found.

5.1.2 Sampling lines
[Reserved]

5.2 HC analyser
[Reserved]

5.3 CO and CO_2 analysers
[Reserved]

5.4 NO_x analyser
[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]

EXPLANATORY INFORMATION

The Annex 16 Vol. II requirement to demonstrate that the air/fuel ratio from the integrated sample total carbon concentration agrees with the estimate based on engine air/fuel ratio (AFR) is the same as the provision of ARP1256 D paragraph 9.k. where the average fuel/air ratio (FAR) calculated from the emission measurements by carbon balance method shall agree with values calculated from fuel and air flow engine data.

It is understood that Annex 16 Vol.II refers to air/fuel ratio and ARP1256D refers to fuel/air ratio and that the two are simply the inverse of each other. For the carbon balance check this makes no difference.

EQUIVALENT PROCEDURE

The carbon balance check in Annex 16 Vol.II requirement has an accuracy tolerance of ±15% for taxi/ground idle mode and of ±10% for all other modes. This tolerance can be slightly different when looking at the invert (FAR) compared to AFR although the ARP1256D requires the same tolerance of 15% at idle and 10% at higher power settings.

Nevertheless, the carbon balance check using FAR as described in ARP1256D has been accepted as being equivalent to carbon balance check based on AFR as described in Annex 16 Vol.II.

Where there are differences from the Annex 16, Vol.II compared to supporting documents such as those provided by SAE E31 then for the purpose of emissions certification those of Annex 16, Vol.II will take precedence.

EXPLANATORY INFORMATION

ARP 1533 provides additional explanation on how to calculate a carbon balance (in para. 7.3) and a FAR balance (in para. 7.4). Both paragraphs claim for a target value of 1.0 ± 0.05 and 5% respectively.

These are target values and quality indicators for the measurement system setup capturing a representative sample, the facility fuel and air flow metering, and for the CO2 gas analyser. These target values are values that the manufacturer should aim for when demonstrating measurement system sampling. While not a requirement, it would be good practice to minimise the FAR balance to within 5%, if possible.

7. CALCULATIONS

TECHNICAL PROCEDURE

This technical procedure provides guidance on the processing of measured data from an emissions certification test in the form of a simplified worked example.
Definitions

Reference engine. For this example, the emissions certification values are calculated based on combustor inlet conditions (T3, P3, and fuel flow) from a validated engine performance model.

Test engine(s). Recommended practice is to use an engine which conforms to the production build Standard. If differences exist, these differences must be documented for approval by the certificating authorities. If any of these non-conformances are predicted to have an impact on engine performance, gaseous emissions or smoke levels, then an explanation and quantification of the impacts will be provided to the certificating authorities for approval. Generally manufacturers will keep deviations from the production standard to a minimum. Measured emissions levels will be corrected to reference engine (production build standard) and standard day conditions.

Detailed traverse. For a new engine type, the next step prior to the actual emissions certification test is to conduct a detailed traverse of the engine exhaust to show that a representative sample is being obtained (see the guidance material on detailed traverse under Appendix 3, 5.1.1).

Emissions tests. Emissions are typically measured at more than the four required thrust levels (typically 8–16 conditions) between ground idle and maximum rated thrust.

Instrument calibration curves for the different analysers may need to be established in order to translate instrument readings to calibrated concentration values. These gas concentrations will be recorded, and emissions indices will be calculated from that using the equations in Appendix 3, 7.1.2, of Annex 16, Volume II. The following simple example shows how to derive EI(CO). Assuming the measured values all on a wet basis:

n/m = H/C = 2;
CO = 500 $ppm(v)_{wet}$ = 0.000 5;
HC = 800 $ppm(v)_{wet}$ = 0.000 8;
CO_2 = 2.25% = 0.022 5;
NO_2 = 20 $ppm(v)_{wet}$ = 0.000 02;
h_{amb} = 0.002 5 vol_{water}/vol_{dryair}
$C_xH_y = CH_4 \rightarrow x = 1, y = 4$

The equation in 7.1.2 for EI(CO) would then read:

$$EI(CO) = (CO/(CO + CO_2 + HC)) \times (10^3 \times 28.011\ g/(12.011\ g + n/m \times 1.008\ g) \times (1 + (0.000\ 3 \times (P_0/m)))$$

Where:
$(P_0/m) = (2 \times Z - n/m) = 2 \times Z - 2$
$Z = \{2 - CO - (2/1 - 4/2 \times 1) \times HC + NO_2\}/\{CO + CO_2 + HC\}$
$= 2 - 0.000\ 5 - 0 \times HC + 0.000\ 02 = 1.999\ 52$
$(P_0/m) = 1.999\ 04$

Hence, from the equation above:

$$\begin{aligned} EI(CO) &= (0.000\ 5/0.022\ 5 + 0.000\ 5 + 0.000\ 8) \times (28.011/(12.011 + 2.016)) \times (1 + (0.000\ 3 \times 1.999\ 04)) \\ &= 0.021\ 008 \times 1\ 996.934\ 483 \times 1.000\ 056 \\ &= 41.98\ g/kg_{fuel} \end{aligned}$$

EI(HC) and EI(NO_x) are calculated in a similar manner using the other two equations in 7.1.2. For EI(NO_x) the NO_2/NO converter efficiency must also be taken into account. EIs are calculated for each measurement point (thrust condition) and engine run.

Attachment E to Appendix 3 contains a comprehensive and precise numerical method which is often used by engine manufacturers' software programs. Further information is contained in SAE ARP 1533 "Procedure for the Analysis and Evaluation of Gaseous Emissions from Aircraft Engines" which contains two fully worked examples of the matrix method solving the combustion chemical equation.

To correct these EIs from measured to reference engine and ambient conditions, a curve fitting technique is recommended. One acceptable alternative method of plotting measured test data is to plot the following:

EI(CO) × P3 v. T3

EI(HC) × P3 v. T3

$EI(NO_x) \times P3^{-0.5} \times e^{19 \times (h_{mass} - 0.006\ 34)}$ v. T3

A best fit of each of the data curves can then be obtained, typically using a polynomial function. In some cases, two curve fit equations are needed, one for low power data and one for high power data. When more than one engine test has been conducted on an engine, data may be plotted for each test run or a single correlation may be used for the multiple runs. However, if multiple engines are tested, a separate set of plots should be made for each test engine.

The procedure for calculating the corrected EI(CO) at values of Fn corresponding to the four LTO operating modes includes the following steps (as shown in Figure 2-3):

a) use validated engine performance model to determine T3ref, P3ref and reference fuel flow;

b) starting with T3ref, determine EI(CO) × P3 from the EI(CO) × P3 v. T3 curve;

c) divide by the corresponding P3ref to get: Corrected EI(CO) = EI(CO) × P3 / P3ref.

Calculation of corrected EI(HC) follows exactly the same process as EI(CO), as does the calculation of corrected EI(NO_x) except step 3 involves multiplying by P3ref $^{-0.5}$ rather than dividing by P3ref.

Once the corrected EI(CO), EI(HC) and EI(NO_x) have been calculated for each operating mode, Dp is calculated using the standard LTO times in mode and corresponding values of reference fuel flow from the validated engine performance model.

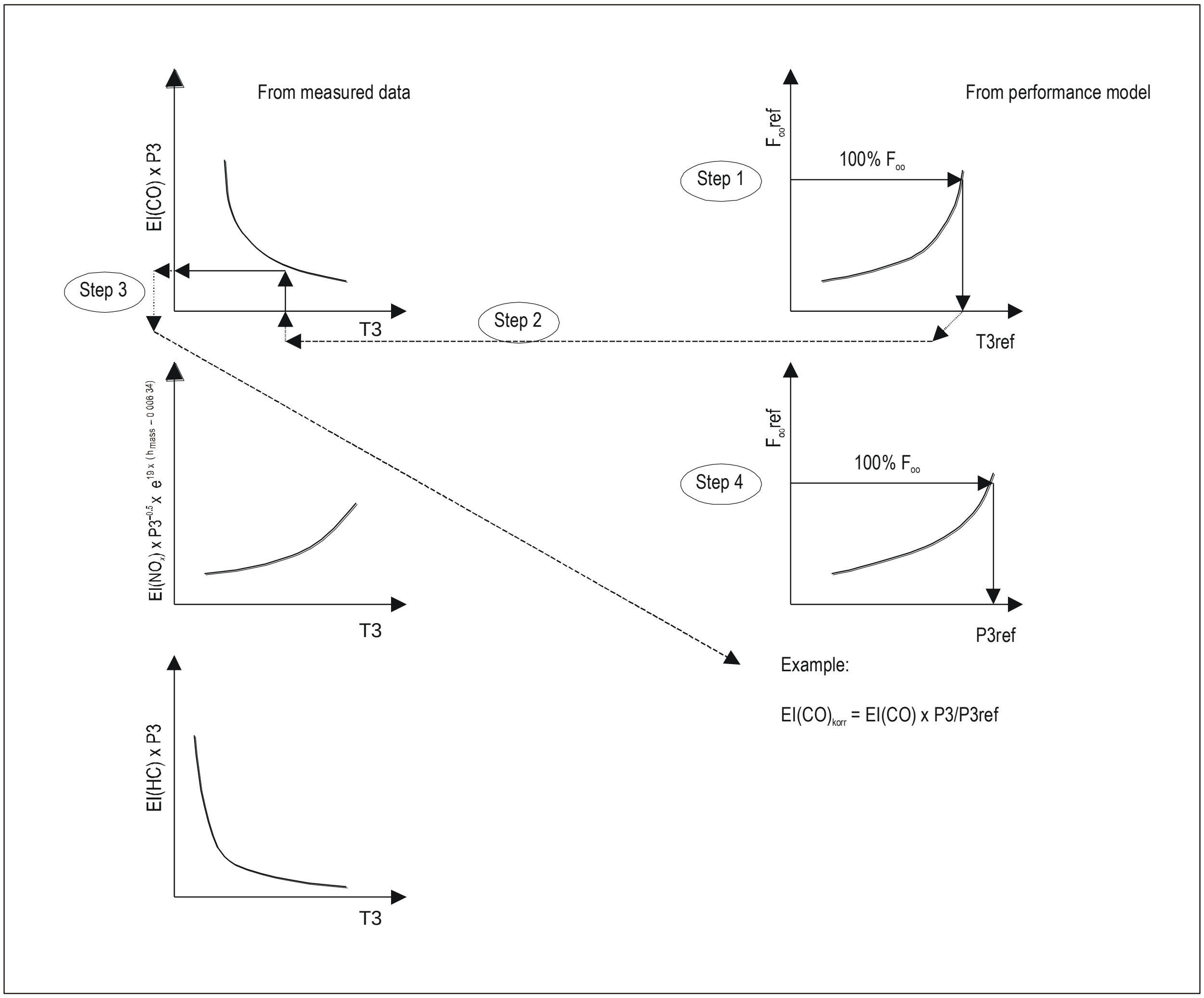


Figure 2-3. Gaseous emissions calculation procedure

7.1 Gaseous emissions
[Reserved]

7.1.1 General
[Reserved]

7.1.2 Basic parameters
[Reserved]

7.1.3 Correction of emission indices to reference conditions

[Reserved]

7.2 Control parameter functions

[Reserved]

7.3 Exceptions to the proposed procedures

[Reserved]

ATTACHMENT A TO APPENDIX 3. SPECIFICATION FOR HC ANALYSER

Note 1.— As outlined in 5.2 of Appendix 3, the measuring element in this analyser is the flame ionization detector (FID) in which the whole or a representative portion of the sample flow is admitted into a hydrogen-fuelled flame. With suitably positioned electrodes an ionization current can be established which is a function of the mass rate of hydrocarbon entering the flame. It is this current which, referred to an appropriate zero, is amplified and ranged to provide the output response as a measure of the hydrocarbon concentration expressed as ppmC equivalent.

Note 2.— See Attachment D for information on calibration and test gases.

Note.— This specification is for analysers that measure the total non speciated hydrocarbon content of the sample by means of a flame ionization detector (FID) as defined in Appendix 3, Section 2 Definitions.

1. GENERAL

***Precautions*:** The performance specifications indicated are generally for analyser full scale. Errors at part scale may be a significantly greater percentage of reading. The relevance and importance of such increases shall be considered when preparing to make measurements. If better performance is necessary, then appropriate precautions shall be taken.

EXPLANATORY INFORMATION

The performance specifications for these analysers, given in terms of full-scale response, can have a significant and adverse impact on part scale measurements. In extreme instances, concentrations of HC at high power, such as take-off, can differ from concentrations at idle by orders of magnitude. In general it is always good practice to use a multi-range instrument and to adjust ranges such as to keep the measurement in the upper 30 per cent of the instrument response range. Calibrations should be performed on each range used as required.

The instrument to be used shall be such as to maintain the temperature of the detector and sample-handling components at a set point temperature not less than 150ºC.

EXPLANATORY INFORMATION

Annex 16, Volume II, previously had (Amendment 6 and before) a set point temperature within the range of 155ºC to 165ºC to a stability of ±2°C. This was adopted from SAE ARP 1256, "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines", 1971. ARP 1256 specified this range to meet the need for minimizing the condensation of hydrocarbons in the instrument, maintain instrument stability and in recognition of the operating characteristics of then commercially available total hydrocarbon analysers (THAs). Since then commercial analysers have evolved, and the ARP has been revised and now recommends that the sample handling components of the total hydrocarbon analysers are housed in a temperature controlled oven housing maintained in the range of 423 to 483 K (159 to 210ºC, 302 to 410ºF). A temperature stability requirement being implicit in the instrument manufacturer's performance specifications is not required explicitly. The stability of the instrument is controlled as long as the operational requirements (hourly checks, checks for span and zero drift as required in Annex 16 as well as the handling instructions of the instrument manufacturer) for the analysers are met. The increase in the set temperature does not affect the emissions.

a) *Total range*: 0 to 5 000 ppmC in appropriate ranges.

EXPLANATORY INFORMATION

A total range of 0 to 5 000 ppmC, while appropriate for the engines in use when Annex 16, Volume II, was published in 1981, is broader than needed for today's engines where concentrations are much lower. Appropriate instruments should be used to ensure best practice measurements in the upper 30 per cent of the range. Thus an instrument with a range upper limit of 5 000 ppmC may not be necessary and may, in fact, negatively affect the ability to ensure suitable range span due to instrument design limitations.

b) *Resolution*:
[Reserved]

c) *Repeatability*:
[Reserved]

d) *Stability*: better than ±2 per cent of full scale of range used or ±l.0 ppmC, whichever is greater, in a period of 1 hour.

EXPLANATORY INFORMATION

Stability, taken to be span stability and sometimes referred to as span drift, is the maximum variation in instrument output over a specified time period and within specified environmental conditions when identical concentration samples, near full-scale deflection, are passed through the instrument and after zero corrections have been made. Stability is the sum of time-dependent drift, i.e. the change in output under invariant laboratory conditions, and changes in output due to other factors such as environmental temperature and/or variations in the FID enclosure temperature.

Stability is highly dependent on how, and under what environmental conditions, the analyser is used. As such it is out of the manufacturers' control and they choose to specify a value for time-dependent drift along with a range of environmental temperatures, i.e. basically under laboratory conditions. Due to improvement of instruments using solid-state electronics the drift specifications from modern THC analysers quote better drift performance (<1 per cent full scale over eight hours in laboratory conditions) than the stability requirements of the standard. Errors associated with this factor are small to negligible. Because measurements are not taken under laboratory conditions and changes in environmental conditions are the norm rather than the exception, operational procedures as described in 6.3.2 d) of Appendix 3 are required.

e) *Zero drift*:
[Reserved]

f) *Noise*: 0.5 Hz and greater, less than ±1 per cent of full scale of range used or ±0.5 ppmC, whichever is greater.

EXPLANATORY INFORMATION

The FID requires fuel and oxidant gases for operation. The fuel gas is typically either a mixture of hydrogen/nitrogen or hydrogen/helium. If the noise specification cannot be met and a hydrogen/nitrogen mixture is being used as the fuel gas, it can be helpful to change to a hydrogen/helium mixture.

g) *Response time*:
[Reserved]

h) *Linearity*:
[Reserved]

2. SYNERGISTIC EFFECTS

Oxygen response: measure the response with two blends of propane, at approximately 500 ppmC concentration known to a relative accuracy of ±1 per cent, as follows:

1) propane in 10 ± 1 per cent O_2, balance N_2

2) propane in 21 ± 1 per cent O_2, balance N_2

If R_1 and R_2 are the respective normalized responses then $(R_1 - R_2)$ shall be less than 3 per cent of R_1.

EXPLANATORY INFORMATION

The typical range of O_2 concentrations in the core exhaust gas is 18 per cent at idle to 15 per cent at take-off. The specification for a response of <3 per cent between samples of 10 per cent and 21 per cent is conservative and effectively limits the differential response to <1 per cent over the range of interest. If needed the O_2 response can be minimized by adjusting the FID burner fuel/air ratio.

Differential hydrocarbon response: measure the response with four blends of different hydrocarbons in air, at concentrations of approximately 500 ppmC, known to a relative accuracy of ±1 per cent, as follows:

a) propane in zero air

b) propylene in zero air

c) toluene in zero air

d) n-hexane in zero air.

If R_a, R_b, R_c and R_d are, respectively, the normalized responses (with respect to propane), then ($R_a - R_b$), ($R_a - R_c$) and ($R_a - R_d$) shall each be less than 5 per cent of R_a.

EXPLANATORY INFORMATION

While the FID response is assumed to respond in a manner proportional to carbon number, it does vary somewhat with the particular hydrocarbon or class of hydrocarbons being measured. For example, three molecules of methane (CH_4) will not necessarily result in the same instrument response as one molecule of propane (C_3H_8). Due to this differential response, it is useful to think of the FID as responding to an "effective" carbon number. It is important that the instrument responses are acceptable for all of the hydrocarbons in the engine exhaust. The group of hydrocarbons (propylene, toluene and n-hexane), with propane as a reference, was chosen to represent, in terms of differential response, the range of hydrocarbons expected in the engine exhaust.

3. OPTIMIZATION OF DETECTOR RESPONSE AND ALIGNMENT

3.1 The manufacturer's instructions for initial setting up procedures and ancillary services and supplies required shall be implemented, and the instrument allowed to stabilize. All setting adjustments shall involve iterative zero checking, and correction as necessary. Using as sample a mixture of approximately 500 ppmC of propane in air, the response characteristics for variations first in fuel flow and then, near an optimum fuel flow, for variations in dilution air flow to select its optimum shall be determined. The oxygen and differential hydrocarbon responses shall then be determined as indicated above.

EXPLANATORY INFORMATION

The FID detector response and alignment can be optimized by adjusting the FID burner fuel and airflow while sampling a mixture containing approximately 500 ppmC propane. Care should be taken when changing fuel flow that the instrument zero does not shift. If it does, the instrument zero should be reset. Response curves illustrating this process are shown in Figures 2-4 and 2-5 and were taken from SAE ARP 1256, "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines".

The objective of this procedure is to select operating flow rates which will give near maximum response with least variation for minor fuel flow variations. It may be necessary to repeat this operation in an iterative fashion:

a) adjust the fuel flow to maximize output;

b) adjust zero if necessary;

c) adjust the airflow to maximize output;

d) readjust the fuel flow, if necessary; and

e) repeat until the burner output is optimized.

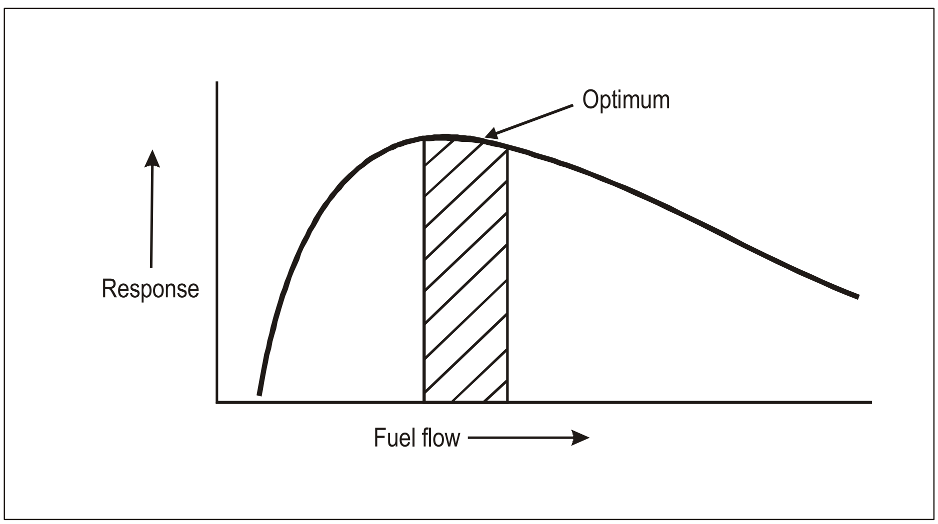


Figure 2-4. Typical fuel flow response curve

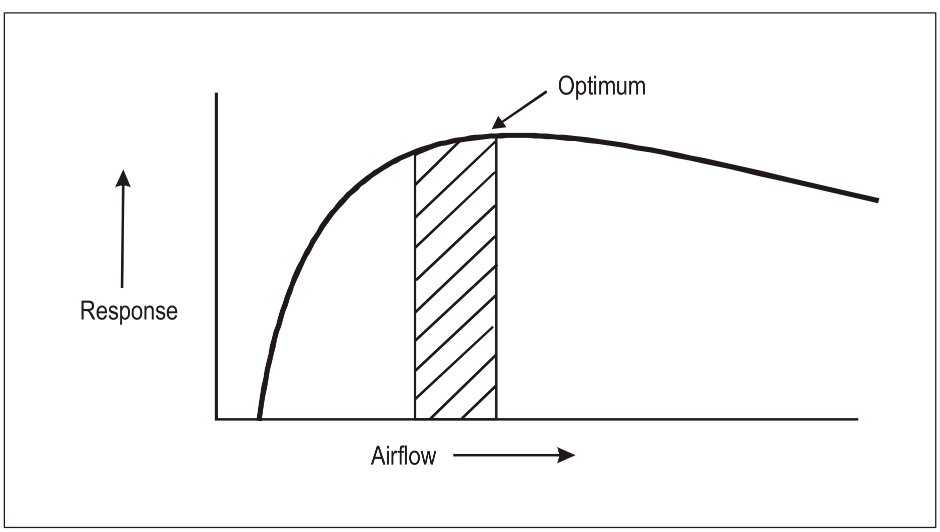


Figure 2-5. Typical airflow response curve

ATTACHMENT B TO APPENDIX 3. SPECIFICATION FOR CO AND CO_2 ANALYSERS

Note 1.— [Reserved]

Note 2.— [Reserved]

Precautions: The performance specifications indicated are generally for analyser full scale. Errors at part scale may be a significantly greater percentage of reading. The relevance and importance of such increases shall be considered when preparing to make measurements. If better performance is necessary, then appropriate precautions shall be taken.

EXPLANATORY INFORMATION

The performance specifications for these analysers, given in terms of full scale response, can have a significant and adverse impact on part scale measurements. This needs to be considered when planning and executing the test and in evaluating the accuracy of the measurements after the test. Concentrations of CO, when going from the idle mode to take-off, can differ by orders of magnitude. In general, where concentrations of species to be measured are known to vary this way, it is always good practice to use a multi-range instrument and to choose ranges such as to keep the measurement in the upper 30 per cent of scale on the range in use, where possible. A measurement made at 20 per cent of full scale could result in an error five times the error specified as a per cent of full scale. This is a general precaution. Some modern instruments with internal electronic ranging and calibration capability can be used over their entire range without penalty. Calibrations should be performed on each range used as required. Relative to the precautions mentioned above, ranges are chosen such that the instrument responds in the upper 30 per cent of scale for the range in use. While this may not always be possible it should be a goal.

The principal performance specification shall be as follows:

CO Analyser

a) *Total range:* [Reserved].

b) *Resolution:* [Reserved].

c) *Repeatability:* [Reserved].

d) *Stability:* [Reserved].

e) *Zero drift:* [Reserved].

f) *Noise:* [Reserved].

g) *Interferences:* to be limited with respect to indicated CO concentration as follows:

1) less than 500 ppm/per cent ethylene concentration.

EXPLANATORY INFORMATION

It is unlikely that high concentrations of ethylene will be found in gas turbine engine exhaust. The highest concentration of hydrocarbons is found at idle, corresponding to the highest concentrations of CO. If all of the hydrocarbons were ethylene, C_2H_4, and the concentration was 100 per cent of the maximum range, 5 000 ppmC — corresponding to 2 500 ppm ethylene — the allowable interference would be less than 125 ppm, or less than 5 per cent of the highest CO range, 2 500 ppm. Since the interference limit is in absolute terms, the relative error will increase for measurements made at less than full scale. If ethylene is present in significant concentrations then corrections to the data are required.

2) less than 2 ppm/per cent CO_2 concentration

3) less than 2 ppm/per cent water vapour.*

EXPLANATORY INFORMATION

These two interferents, CO_2 and water vapour, are additive. Being the major products of combustion they increase and decrease together and are at their highest levels at the highest power. Unfortunately concentrations of CO tend to be at their lowest concentrations at the highest power. This can cause significant problems in the accuracy of the measurement even if the interference limits are met. It is not unusual for tests to be conducted with the sample dried before measurement and the interference due to the remaining interferent, CO_2, compensated for through use of gas or optical filters. It does bear mentioning that the contribution of high power CO concentrations to the total gross CO emission measured over the LTO cycle is relatively small.

CO_2 Analyser

a) Total range: 0 to 10 per cent in appropriate ranges.

*. Need not apply where measurements are on a “dry” basis.

EXPLANATORY INFORMATION

Although the total range specified for CO_2 is 0 to 10 per cent, concentrations most often will vary between 1 per cent and 5 per cent. This range is considerably narrower than that for CO. Nevertheless good practice dictates using ranges that keep the instrument response in the upper 30 per cent of the meter scale, as appropriate.

CO_2 Analyser

b) *Resolution:* [Reserved]

c) *Repeatability:* [Reserved]

d) *Stability:* [Reserved]

e) *Zero drift:* [Reserved]

f) *Noise:* [Reserved]

g) The effect of oxygen (O_2) on the CO_2 analyser response shall be checked. For a change from 0 per cent O_2 to 21 per cent O_2, the response of a given CO_2 concentration shall not change by more than 2 per cent of reading. If this limit cannot be met an appropriate correction factor shall be applied.

Note.— It is recommended, as consistent with good practice, that such correction procedures be adopted in all cases.

EXPLANATORY INFORMATION

Gas turbine engines use a considerable amount of internal cooling air that mixes with the combustion products before exiting the engine. Oxygen rich exhaust samples warrant close attention because of oxygen's effect on the CO_2 measurement.

Annex 16 does not provide any means to address this effect. ARP 1533 however provides all the necessary steps to determine coefficient J for the interference of O_2 on the CO_2 measurement. In order to take into account oxygen interference the P1 (CO_2) term in the basic combustion equation in 2.1 of Attachment E would become:

$$P_1 [CO_2] = [CO_2]_{measured} \times P_T + J \times ([CO_2]_{measured} \times P_3)$$

Where

P_1 = real number of moles of CO_2 in the exhaust sample per mole of fuel
P_3 = real number of moles of O_2 in the exhaust sample per mole of fuel
P_T = total number of moles in the exhaust

J = Oxygen interference coefficient for effect of O_2 on the measurement of CO_2 (concentration factor).

With the "concentration factor" interference effect (or sensitivity effect), the interfering species modifies the slope of the response of the analyser: therefore the effect is proportional to the concentration measured. This is the case for the interference of O on CO. An interference coefficient is required that quantifies the modification of the parts per volume measured.

The same equation can be expressed in concentrations rather than moles:

$[CO_2]_{real} = [CO_2]_{measured}$ x $(1+J$ x $([O_2]_{measured}))$

Case 1:

If the NDIR analyser had been calibrated with CO_2 in zero air (with an O_2/N_2 mixture) where the amount of oxygen was equal to the amount of oxygen in the exhaust measurement, the oxygen effect would become zero.

$[CO_2]_{real} = [CO_2]_{measured}$ x $(1+J$ x $([O_2]_{test} - [O_2]_{cal}))$

Case 2:

In cases where the oxygen concentration in the exhaust is unknown or may vary, the preferred way to calibrate the NDIR analyser would be to use a CO_2 calibration gas balanced with pure nitrogen and adjust for the effect of O_2 interference using the Technical Procedure described below.

TECHNICAL PROCEDURE

Annex 16 does not contain a procedure to correct for oxygen effect.

When a correction is required for the interference of the oxygen on the CO_2 measurement, the correction can be expressed as follows (equivalent to the equations for CO and NO in paragraph 3.3 of Attachment E):

$[CO_2] = [CO_2]_m$ x $(1+J$ x $[O_2])$

Where

$[CO_2]$ = the mean concentration of CO_2 in exhaust sample, vol/vol.
$[CO_2]_m$ = the mean concentration measurement indicated before instrument correction applied, vol/vol.
J = the analyser interference coefficient for interference by O_2.
$[O_2]$ = the mean concentration of O_2 in exhaust sample, vol/vol.

The oxygen modifies the slope of the response of the NDIR. Therefore the effect is proportional to the concentration measured.

A representative value of J is given in ARP 1533B. However this is an arbitrary value and it is recommended that the J coefficient be measured individually for each analyser used. It could be obtained according to the calculations provided in ARP 1533B. It could also be obtained in the laboratory by making a first measurement (m1) with a calibration gas of CO_2 in N_2 ($[O_2]=0$) in the appropriate range of the analyser and a second one (m2) with a test gas of high concentration of O_2. J can be obtained from the following equation:

$J = ([CO_2]m1/[CO2]m2 - 1) / [O_2]$

However, analysers are often calibrated by the instrument manufacturer to automatically correct for O_2 interference. The existence of such corrections should be established before using any correction procedure.

CO and CO_2 Analysers

a) *Response time:* [Reserved]

b) *Sample temperature:* the normal mode of operation is for analysis of the sample in its (untreated) “wet” condition. This requires that the sample cell and all other components in contact with the sample in this subsystem be maintained at a temperature of not less than 50°C, with a stability of ±2°C. The option to measure CO and CO_2 on a dry basis (with suitable water traps) is allowed, in which case unheated analysers are permissible and the interference limits for H_2O vapour removed, and subsequent correction for inlet water vapour and water of combustion is required.

EQUIVALENT PROCEDURE

Stability is defined in terms of a time interval which, because this is a temperature control set point, can be taken as the duration of the test, or one hour to be consistent with the stability limits placed on the detection system.

The temperature quoted for the CO and CO_2 subsystems, 50°C, is on the low end of the sample line specification, 65°C ±15°C. Good practice would suggest that the subsystem temperature be approximately the same as the sample gas temperature. If the samples are dried and the analysers unheated, it would be reasonable to lower the sample temperature to that of the analyser. If water is removed prior to analysis, corrections must be applied to compensate for the loss of water of combustion and inlet water vapour. Correction procedures are detailed in Attachment F to Appendix 3.

c) *Calibration curves:*

i) Analysers with a linear signal output characteristic shall be checked on all working ranges using calibration gases at known concentrations of approximately 0, 30, 60 and 90 per cent of full scale. The maximum response deviation of any of these points from a least squares straight line, fitted to the points and the zero reading, shall not exceed ±2 per cent of the full scale value. If it does then a calibration curve shall be prepared for operational use.

TECHNICAL PROCEDURE

Straight line fits to sets of linear data can be arrived at graphically or analytically. If graphically, the results are subject to interpretation, i.e., best estimate by “eye” by individual. If analytically, there is assurance that each case and all data are handled the same way each time. The most appropriate technique is to perform a linear regression, or “least squares fit” for a line. The calibration gas values are the independent “variables” and are assumed to be correct (to have negligible error) for the purpose of this analysis. The instrument response values are the “dependent” variables and are assumed to have errors and that these errors are normally (Gaussian) distributed about the true line. The equation describing the straight line is:

$$y_i = A + B*x_i$$

true value for response y_i= A (a constant) + B (another constant) * (calibration gas value x_i)
For instruments which have been adjusted such that zero input results in zero output, and where the variance is known to be proportional to the reading, the slope B can be shown to be equal to the ratio of the averages and can be expressed as:

$$\frac{\overline{y}}{\overline{x}}$$

Often A and B are not such simple values for intercept and slope but must be calculated as if the variance were not known to be proportional to the instrument response. Again if we set the instrument to read zero for zero gas input then A = 0 which makes the calculation relatively simple. The generalized expression for B can be found in any elementary statistics or error analysis text and is:

$$B = \frac{N \sum_{i=1}^{N} x_i y_i - \sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i}{N \sum_{i=1}^{N} x_i^2 - \left(\sum_{i=1}^{N} x_i \right)^2}$$

Where x_i is the calibration gas value and y_i is the instrument response and N refers to the number of points used in the analysis.

With N = 4, corresponding to 0, 30, 60 and 90 per cent of full scale, this equation can be rewritten as:

$$B = \frac{4 \sum_{i=1}^{4} x_i y_i - \sum_{i=1}^{4} x_i \sum_{i=1}^{4} y_i}{4 \sum_{i=1}^{4} x_i^2 - \left(\sum_{i=1}^{4} x_i \right)^2}$$

A simple table, for the four sets of values, can be used for organizing the information thereby simplifying the calculation:

Measurement Number i	**X_i cal gas value i**	**Y_i Response i**	**X_i^2**	**X_iY_i**
1				
2				
3				

4				
N=4	$\sum X_i$	$\sum Y_i$	$\sum X_i^2$	$\sum X_i Y_i$

If the instrument is not set to zero-zero (zero response for zero input) then A must be determined. The equation for A (for N = 4) is:

$$A = \frac{\sum_{i=1}^{4} x_i \sum_{i=1}^{4} y_i}{4\sum_{i=1}^{4} x_i^2 - \left(\sum_{i=1}^{4} x_i\right)^2}$$

The table shown earlier can be used to organize the elements of this equation as well.

Usually the next step would be to calculate the uncertainty in y_i about this line. However, instead of controlling uncertainty about the line, ICAO chose to set an absolute limit of ±2 per cent deviation of the full scale value for each point. This should make clear the advantage in using the upper region (top 30 per cent) of the range for all measurements.

ii) Analysers with a non-linear signal output characteristic, and those that do not meet the requirements of linearity given above, shall have calibration curves prepared for all working ranges using calibration gases at known concentrations of approximately 0, 30, 60 and 90 per cent of full scale. Additional mixes shall be used, if necessary, to define the curve shape properly.

TECHNICAL PROCEDURE

For analysers with a non-linear signal output characteristic, calibration curves shall be prepared, again using approximately 0, 30, 60 and 90 per cent of full scale calibration gases. If a curve is substantially non-linear in shape, it is recommended that additional calibration gases be used with values between the ones specified. These calibration curves can be determined analytically using a least squares fit, but in this case the fit would be to a polynomial or exponential. The equations for doing this can be found in any basic text on statistics or error analysis. It should be noted that for exponential fits it is often convenient to work with the logarithm of the expression, which reduces the problem to a least squares fit about a line as is described above. (This technique is used in analysing smoke filters as required in 3.0 of Appendix 2). Although not stated explicitly, the presumption is that the same ±2 per cent of full scale response deviation is true for non-linear as well as linear instruments. The use of a gas divider is an acceptable alternative to acquiring and maintaining additional gas resources.

Table 2-1 summarizes the specifications for CO and CO_2 analysers. These are typical of those analysers offered by major analyser manufacturers.

Table 2-1. NDIR Analyser Performance Specifications

Parameter	*Value*	
	CO_2	*CO*
Total Range	0 to 10% in appropriate ranges	0 to 2 500 ppm in appropriate ranges
Resolution	better than 0.5% fs range used or 100 ppm, whichever greater	better than 0.5% fs range used or 1 ppm, whichever greater
Repeatability	better than ±1% fs range used or ±100 ppm, whichever greater	better than ±1% fs range used or ±2 ppm, whichever greater
Stability	better than ±2% fs range used or ±100 ppm, whichever greater period of 1 hr	better than ±2% fs range used or ±2 ppm, whichever greater period of 1 hr
Zero drift	< ±1% fs range used or ±100 ppm, whichever greater period 1 hr	< ±1% fs range used or ±2 ppm, whichever greater period 1 hr
Noise	> 0.5 Hz, < ±1% fs range used or ±100 ppm, whichever greater	> 0.5 Hz, < ±1% fs range used or ±1 ppm, whichever greater
Interference	≤ 2% of reading for O_2 between 0 and 21%	< 500 ppm/% ethylene < 2 ppm/% CO_2 < 2 ppm/% water vapour
Response time	≤ 10 seconds from instrument inlet to 90% fs	≤ 10 seconds from instrument inlet to 90% fs
Sample temperature	wet samples ≥ 50 °C stability ±2°C	wet samples ≥ 50 °C stability ±2°C

ATTACHMENT C TO APPENDIX 3. SPECIFICATION FOR NOx ANALYSER

Note.— See Attachment D for information on calibration and test gases.

1. [Reserved]

2. [Reserved]

Precautions: The performance specifications indicated are generally for analyser full scale. Errors at part scale may be a significantly greater percentage of reading. The relevance and importance of such increases shall be considered when preparing to make measurements. If better performance is necessary, then appropriate precautions shall be taken.

EXPLANATORY INFORMATION

The performance specifications for these analysers given in terms of full scale response can have a significant and adverse impact on part scale measurements. This needs to be considered when planning and executing the test and in evaluating the accuracy of the measurements after the test. Concentrations of NO_X, when going from the idle mode to take-off, can differ by orders of magnitude. In general, where concentrations of species to be measured are known to vary this way, it is always good practice to use a multi-range instrument, and to choose ranges such as to keep the measurement in the upper 30 per cent of scale on the range in use. A measurement made at 20 per cent of full scale could result in an error five times the error specified as a per cent of full scale. This is a general precaution. Some modern instruments with internal electronic ranging and calibration capability can be used over their entire range without penalty. Calibrations should be performed on each range used as required.

3. The principal performance specification, determined for the instrument operated in an ambient temperature stable to within 2°C, shall be as follows:

   a) *Total range:* 0 to 2 500 ppm in appropriate ranges.

EQUIVALENT PROCEDURE

Taking into account the NO_X emissions concentration of current engines, NO_X analysers with a lower total range, typically 0 – 1 000 ppm, would be acceptable.

b) *Resolution:* [Reserved].

c) *Repeatability:* [Reserved].

d) *Stability:* [Reserved].

e) *Zero drift:* [Reserved].

f) *Noise:* [Reserved].

g) *Interference:* [Reserved].

h) *Response time:* [Reserved].

i) *Linearity:* [Reserved].

j) *Converter:* this shall be designed and operated in such a manner as to reduce NO_2 present in the sample to NO. The converter shall not affect the NO originally in the sample.

The converter efficiency shall not be less than 90 per cent.

This efficiency value shall be used to correct the measured sample NO_2 value (i.e. $[NO_x]_c$ – [NO]) to that which would have been obtained if the efficiency had been 100 per cent.

EQUIVALENT AND TECHNICAL PROCEDURES

When available, follow the NO_X analyser instrument manufacturer's procedures for determining the NO_2 converter efficiency. Alternatively a separate commercially available NO_2 converter tester can be used along with the NO_X analyser being evaluated.

A third alternative, described below, is a procedure that was originally required by the United States Environmental Protection Agency in 40CFR Part 87, "Control of Air Pollution from Aircraft and Aircraft Engines" 1973, and subsequently incorporated into the SAE Aerospace Recommended Practice ARP1256, "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines". The procedure, as described, uses a device requiring acquisition and assembly of the component parts and considerable hands-on operation. However its utility and versatility is implicit when considering the range of applications for which the Environmental Protection Agency either requires it to be used or allows it as an alternative procedure, e.g., land-based vehicles and continuous emissions monitors for stationary sources.

Figure 2-6 schematically depicts such a device. This device is intended for use with the NO_X analyser specified in Attachment C. It depends on the reaction: $NO + O_3 = NO_2 + O_2$.

Starting with a known concentration of NO in N_2, measurements are made through – and bypassing – the chemiluminsecence analyser converter, the inlet to which is shown as "C3" in Figure 2-6. With the NO_X converter ozonator alternately on, reducing the NO concentration by approximately 80 per cent, and off, allowing 100 per cent of the NO to reach the analyser, the analyser's converter efficiency can be determined. This efficiency should be used to correct test data as required.

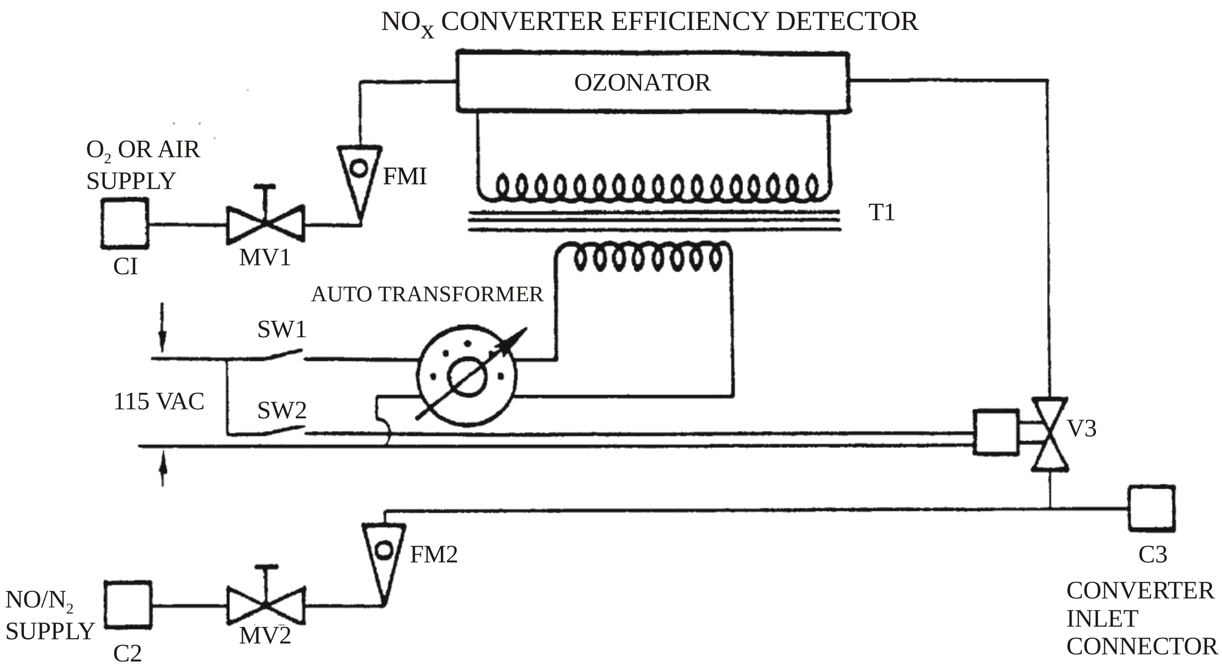


Figure 2-6. NOx converter efficiency detector

The specific instructions for using this device are as follows:

i) Attach the NO/N_2 supply (150-250 ppm.) at "C2", the O_2 supply at "C1", and the analyser inlet connection to the efficiency detector at C3. If lower concentrations of NO are used, air may be used in place of O_2 to facilitate better control of the NO_2 generated during step (iv).

ii) With the efficiency detector autotransformer off, place the NO_X converter in bypass mode and close valve "V3". Open valve "MV2" until sufficient flow and stable readings are obtained at the analyser. Zero and span the analyser output to indicate the value of the NO concentration being used. Record this concentration.

iii) Open valve V3 (on/off flow control solenoid valve for O_2) and adjust valve "MV1" (O_2 supply metering valve) to blend enough O_2 to lower the NO concentration (ii) to about 10 per cent. Record this concentration.

iv) Turn on the ozonator and increase its supply voltage until the NO concentration of (iii) is reduced to about 20 per cent of (ii). NO is now being formed from the NO + O_2 reaction. There must always be at least 10 per cent unreacted NO at this point. Record this concentration.

v) When a stable reading has been obtained from (iv), place the NO_X converter in the convert mode. The analyser will now indicate the total NO_X concentration. Record this concentration.

vi) Turn off the ozonator and allow the analyser reading to stabilize. The mixture NO + O_3 is still passing through the converter. This reading is the total NO_X concentration of the dilute NO span gas used in step (iii). Record this concentration.

vii) Close valve V3. The NO concentration should be equal to or greater than the reading of (ii) indicating whether the NO contains any NO_2.

Calculate the efficiency of the NO_X converter by substituting the concentrations obtained during the test into the following equation:

$$\% \text{ Efficiency} = [(v)-(iv)] / [(vi)-(iv)] \times 100 \%$$

To improve the effectiveness of thermal converters, particularly those with efficiencies of less than 90 per cent, it is sometimes helpful to raise the temperature of the converter.

ATTACHMENT D TO APPENDIX 3. CALIBRATION AND TEST GASES

EXPLANATORY INFORMATION

Calibration and test gases are normally obtained from commercial specialty gas companies and are available with traceability to the appropriate National Metrology Institute (NMI), e.g., NIST in the United States, NPL in the United Kingdom, NMi in the Netherlands or KRISS in the Republic of Korea. These institutes work in collaboration, to ensure and improve the accuracy of primary gas standards.

With few exceptions calibration gases, although traceable to, are not directly available from an NMI.

Traceability is arrived at through adherence to a strict protocol that relates the uncertainty in the concentration of the gas, in high pressure cylinders, provided by the specialty gas company (vendor) to a standard gas being maintained by the NMI.

In the United States, NIST is the designated NMI. NIST generates and maintains standard reference materials (SRMs) as well as employing very high accuracy analytical techniques (≤0.5 per cent) to determine and validate the uncertainty in the gases provided by the vendors. The validation procedure requires the vendor to analyse all of the gas cylinders in a production lot and provide the data to NIST who, after reviewing and accepting the data, chooses, on a random basis, 10 per cent of the cylinders for NIST audit. NIST then certifies the lot based upon the vendor data and NIST audit. Once the cylinders are certified the vendor can either sell these cylinders, as NTRMs (NIST Traceable RMs) or use them to produce other categories of traceable calibration gases. NIST in describing the EPA Protocol Gas Suppliers Audit program summarized the uncertainty of this validation procedure as follows: “If the analytical uncertainty claims of NIST (≤ 0.5%) and the gas vendors (≤1.0%) are valid and there is no bias … then the difference between the NIST analysis and the vendor certified concentrations of the audit mix should ideally be ≤ 1.0% relative and as a worse case, no more than 2% relative”.

In Europe the different National Metrology Institutes use very similar concepts for accurate, nationally-traceable gas calibration Standards. In the United Kingdom, the National Physical Laboratory NPL prepares and maintains the primary standard gas mixtures (PSMs) which are prepared by absolute gravimetric methods and produced through a chain of direct comparisons to the national measurement standards. Reputable vendors provide calibrated gas mixtures at secondary gas standards by comparison with PSM (<0.1 per cent) and primary reference gas mixtures (<0.3 per cent) from the NPL. These secondary gas standards provide a fraction uncertainty of ±0.5 per cent to ±1 per cent (95 per cent level of confidence). These are usually labelled in accordance with ISO 6141 and meet all other appropriate ISO specifications.

Because of the accuracy required and the sophistication of the techniques necessary to produce and analyse gases to the required standards, most if not all engine manufacturers rely on the commercial vendors’ analysis and certification of traceability for concentration and uncertainty and use in-house checks via instrument response for consistency of assay. It is good practice to check all calibration and test gases as they come from the vendor and prior to their use as working gases. This is normally also addressed within existing internal audit procedures for periodic calibration of the different analysers.

In Annex 16 the accuracy specification of the calibration gases is ±2 per cent whereas in the ARP1256D this specification is ±1 per cent. The reason for having a higher value in Annex 16 comes from the difficulty for the engine manufacturers to cross-check the gas vendor certificated value within an accuracy better than 2 per cent.

Annex 16 does not provide information regarding special problems that occur with gas cylinders. Stability can be particularly troublesome with cylinders of very low concentration gases. Even though vendors take considerable care in the manufacture and preparation of cylinders before filling them, there can be defects in the cylinder that result in changes in concentration after the cylinder leaves the vendor. In addition in defect-free cylinders the practice of conditioning the cylinder with high concentrations of the gas of interest at high pressure can result in adsorption of some of this gas which remains after the cylinder is flushed and filled with the low concentration gas. Some of the adsorbed gas can be released as the cylinder pressure drops and if the cylinder temperature increases.

Although not a calibration gas or, strictly speaking, a test gas, the FID combustive gases should also meet a hydrocarbon specification. For hydrogen/nitrogen or hydrogen/helium fuel mixtures, total hydrocarbons present should be <1 ppmC. The oxidant should be hydrocarbon-free grade air, containing <1 ppmC hydrocarbon.

EXPLANATORY INFORMATION

Since NO is what is measured the calibration and test gas for the NOx analyser has to be NO in zero nitrogen although practically there are always traces of NO_2 in the cylinders (generally below few ppm).

Some cylinder vendors indicate the NO concentration as well as the NOx concentration to reflect the presence of NO_2 in small quantities.

Manufacturers, who are using the NOx channel for calibration, could do so if the concentration of NO_2 is known.

EQUIVALENT PROCEDURE

The mixture and composition of calibration and test gases between ARP 1256D and Attachment D of Annex 16 are different. While the Annex specifies zero air as a diluent for CO and CO_2 test gases, the ARP 1256D recommends zero nitrogen (nitrogen as a diluent) as a preferred test gas for spanning the NDIR analyser, thereby eliminating the need for oxygen interference correction when determining or checking the analyser calibration curve.

It should be noted that engine exhaust does contain significant concentrations of O_2, and correcting for O_2 interference when measuring CO_2 is necessary. However, analysers are often calibrated by the instrument manufacturer to automatically correct for O_2 interference. The existence of such corrections should be established before using any correction procedure.

Where zero nitrogen is used as a zero gas, it shall be high purity nitrogen (99.99 per cent nitrogen or better) with less than 1 ppm C, 1 ppm CO, 100 ppm CO_2 and 1 ppm NO_X.

TECHNICAL PROCEDURE

Generally the NOx analyzer should be calibrated by two different approaches depending on the measurement mode being utilized.

For NO only measurement mode:
NO only mode uses an instrument channel with no NO_2 conversion. This mode requires the use of NO in zero nitrogen (NO/N_2) with a certified cylinder value of the NO concentration from the vendor for channel calibration.

For NOx measurement mode:

NOx ($NO+NO_2$) mode uses an instrument channel with NO_2 conversion. This mode requires the use of NO or NOx in zero nitrogen with a certified value of $NO+NO_2$ concentration from the vendor for channel calibration.

Note that, practically speaking, there are always traces of NO_2 in cylinders (generally below a few ppm) even if they are labelled as NO calibration bottles. If the NO_2 cylinder value is not specified by the vendor, to minimize the NOx measurement uncertainty, the vendor cylinder purity specification should limit the NO_2 cylinder concentration to less than 5% of the certified cylinder value of NO concentration.

ATTACHMENT E TO APPENDIX 3. THE CALCULATION OF THE EMISSIONS PARAMETERS — BASIS, MEASUREMENT CORRECTIONS AND ALTERNATIVE NUMERICAL METHOD

1. SYMBOLS

…

L, L' analyser interference coefficient for interference by CO_2

EXPLANATORY INFORMATION

L is the interference effect of CO_2 on the measurement of CO interpreted in terms of a zero shift.
L' is the interference effect of CO_2 on the measurement of NO and NO_x interpreted in terms of a sensitivity change.

Note.— The values of these interference effects are specific to, and must be determined for, the individual analysers.

M, M' analyser interference coefficient for interference by H_2O

EXPLANATORY INFORMATION

M is the interference effect of H_2O on the measurement of CO interpreted in terms of a zero shift.
M' is the interference effect of H_2O on the measurement of NO and NO_x interpreted in terms of a sensitivity change.

Note.— The values of these interference effects are specific to, and must be determined for, the individual analysers.

2. BASIS OF CALCULATION OF EI AND AFR PARAMENTERS

2.1 It is assumed that the balance between the original fuel and air mixture and the resultant state of the exhaust emissions as sampled can be represented by the following equation:

…

$$\text{AFR} = P_0 \left(\frac{M_{AIR}}{mM_{\text{C}} + nM_H} \right)$$

EXPLANATORY INFORMATION

This is a slightly different formulation for AFR than that stated in Appendix 3, 7.1.2, "Basic parameters". In this formulation *m*, the "number of C atoms in characteristic fuel molecule" is placed within the bracket. There is no particular advantage to using one formulation over the other.

2.2 [Reserved]

2.3 [Reserved]

2.4 [Reserved]

2.5 The interference effects are mainly caused by the presence of CO_2 and H_2O in the sample which can affect the CO and NO_x analysers in basically different ways. The CO analyser is prone to a zero-shifting effect and the NO_x analyser to a sensitivity change represented thus:

$$[CO] = [CO]_m + L[CO_2] + M[H_2O]$$
$$\text{and } [NO_x]_c = [NO_x]_{cm}(1 + L'[CO_2] + M'[H_2O])$$

EXPLANATORY INFORMATION

With a zero shift interference effect, the interfering species creates an offset on the measurement, which does not vary with the concentration measured. This is the case for the interference of CO_2 and H_2O on CO.

With a sensitivity change interference effect, the interfering species modifies the slope of the response of the analyser: therefore the effect is proportional to the concentration measured. This is the case for the interference of CO_2 and H_2O on NO.

Note.— The values of these interference effects are specific to, and must be determined for, the individual analysers.

2.6 [Reserved]

3. ANALYTICAL FORMULATIONS
[Reserved]

4. ALTERNATIVE METHODOLOGY — NUMERICAL SOLUTION

EXPLANATORY INFORMATION

Details explaining various calculation procedures can be found in SAE Aerospace Recommended Practice (ARP) 1533B, "Procedure for the Analysis and Evaluation of Gaseous Emissions from Aircraft Engines". ARP 1533B includes, among other things, derivation of equations, the combustion chemical equation, and a matrix method of solving the combustion chemical equation.

ATTACHMENT F TO APPENDIX 3. SPECIFICATION FOR ADDITIONAL DATA

As required in 3.2 of Appendix 3, in addition to the measured sample constituent concentrations, the following data shall also be provided:

a) inlet temperature: [Reserved]

b) inlet humidity (kg water/kg dry air): measured at a point within 50 m of the intake plane ahead of the engine to an accuracy of ±5 per cent of reading or ±0.000317 kg water/kg dry air, whichever is larger.

EXPLANATORY INFORMATION

Originally, Annex 16, Volume II, required humidity measurements within 15 m of the engine intake plane, but the requirement was extended to 50 m based on a study of humidity measurements currently used in engine performance testing. These measurements are completed to measure the representative humidity of the air that will be entering the engine from the upstream airflow, hence the use of the words “ahead of the engine” in the Annex.

Selection of a suitable site for the humidity measurement is based on topography of the test site, prevailing winds and the test bed(s) intake arrangements. A survey of engine manufacturers’ test sites showed the location of performance humidity measurement typically falls within 50 m of the engine inlet, so the required distance between the humidity instrument and engine was increased to allow use of the performance instrumentation.

The requirement for accuracy of the humidity measurement was also changed from “±5 per cent of reading” to “±5 per cent of the measured value or ± 0.000 317 kg water/kg dry air, whichever is larger”. This change was made to enable use of modern humidity instruments that are not capable of meeting ±5 per cent accuracy at very low humidity levels. In practice, engine manufacturers have found the actually attained accuracy in routine operation is just as acceptable with the newer systems as the older systems.

For most operating conditions these instruments have humidity accuracy significantly better than ±5 per cent of reading requirements; however, the accuracy of these instruments can be more than ±5 per cent of reading when relative humidity is very low (little water is in the air). These are the cases, however, where humidity uncertainty has the least impact on the reported emissions.

The lower limit for accuracy was selected to be ±0.000 317 kg water/kg dry air. This corresponds to ±5 per cent at the standard reference humidity of 0.006 34 kg water/kg dry air. When this lower limit for accuracy is used, the accuracy of the humidity correction is within ±0.604 per cent.

APPENDIX 4. SPECIFICATION FOR FUEL TO BE USED IN AIRCRAFT TURBINE ENGINE EMISSION TESTING

The fuel shall meet the specifications of this Appendix 4, unless a deviation and any necessary corrections have been agreed upon by the certificating authority. Additives used for the purpose of smoke suppression (such as organometallic compounds) shall not be present.

EQUIVALENT PROCEDURE

Appropriate evidence should be provided to the certificating authority to substantiate any deviation from the fuel specification of Appendix 4 as early as possible.

A deviation may be accepted when it can be shown that the locally available fuel does not meet the specification. In such a case, use of the available fuel may be acceptable, subject to the substantiation of corrections to compensate for the effect of the deviation on the measured emissions levels. The measured data should then be corrected to reflect the limiting values of the fuel specification of Appendix 4. Corrections will normally be accepted when the magnitude of the correction to the measured data is small in relation to the margin to the certification limits.

The corrections to the declared emission levels resulting from the deviation in test fuel properties should be based upon engine or rig test data which can be related to the specific combustor type, supported by validated analysis where necessary. The corrections would need to be conservative, particularly when test data are not available for the specific combustor type being certificated. Manufacturers should avoid use of fuels that have been heavily hydro-treated or produced using synthetic processes.

The deviations from the fuel specification, and the associated corrections, require the agreement of the certificating authority.

APPENDIX 5. INSTRUMENTATION AND MEASUREMENT TECHNIQUES FOR GASEOUS EMISSIONS FROM AFTERBURNING GAS TURBINE ENGINES

[Reserved]

APPENDIX 6. COMPLIANCE PROCEDURE FOR GASEOUS EMISSIONS AND SMOKE

1. GENERAL

The following general principles shall be followed for compliance with the regulatory levels set forth in Part III, 2.2, 2.3, 3.2 and 3.3:

a) [Reserved]

b) [Reserved]

c) [Reserved]

d) [Reserved]

e) [Reserved]

f) the engines submitted for testing shall have emissions features representative of the engine type for which certification is sought. However, at least one of the engines shall be substantially configured to the production standard of the engine type and have fully representative operating and performance characteristics. One of these engines shall be declared to be the reference standard engine. The methods for correcting to this reference standard engine from any other engines tested shall have the approval of the national certificating authority. The methods for correcting test results for ambient effects shall be those outlined in 7 of Appendix 3 or 7 of Appendix 5, as applicable.

EXPLANATORY INFORMATION

A "reference standard engine" as defined in ICAO Annex 16, Volume II, Appendix 6, section 1 f) is required "to be substantially configured to the production standard of the engine type and have fully representative operating and performance characteristics". The "reference standard engine" performance must be evaluated at ISA SL conditions per section 7 of Appendix 3 (or 5, as appropriate). In ICAO Annex 16, Volume II, Appendix 3, section 7.2.2, it is specifically stipulated that the relationship between Wf and TB, and between Fn and TB can be derived from a validated engine performance model. As such, while standard engine performance may be based on measurements from a "physical engine" or number of "physical engines" configured as above (correcting appropriately for ambient conditions), a "performance model" based on measurements from one or more physical engines may be equivalently used.

A "performance model" (equivalently named as performance deck or cycle deck) is a computer program that provides detailed airflow, fuel flow, temperature, pressure, and shaft speed information for all engine components, conforming to applicable industry practices (e.g. relevant portions of SAE Aerospace Standards AS681). Although other calculation methods are possible, in current practice this computer program solves a mass, energy and momentum balance with specific component performance maps and secondary flow maps. The "performance model" is calibrated to engine test data (speeds, temperatures, pressures) applicable to the specific engine model being considered under various ambient and altitude conditions. The "performance model" is evaluated at ISA Sea Level static conditions with no off-take bleeds and accessory loads other than those necessary for the engine's basic operation.

The performance model may be used to derive the relationship between Wf and TB, between Fn and TB and between PB and TB for the purposes of defining a "reference standard engine".

The "performance model" can be created with data from the engine used for the emissions test. Alternatively, the performance model can be developed with data from a number of engines of similar technology. In this case, it may be shown that the emission relevant parameters (T3, P3, Wf, Fn) of the emissions test engine corrected to the same ambient condition, and taking into account issues such as deterioration, match well enough with the "performance model" parameters.

APPENDIX 7. INSTRUMENTATION AND MEASUREMENT TECHNIQUES FOR NON-VOLATILE PARTICLE EMISSIONS

1. INTRODUCTION

[Reserved]

2. DEFINITIONS, ACRONYMS AND SYMBOLS

2.1 Definitions

[Reserved]

2.2 Acronyms

[Reserved]

2.3 Symbols

[Reserved]

3. DATA REQUIRED

3.1 nvPM Emissions

EXPLANATORY INFORMATION

The nvPM sampling and measurement system is standardised to measure nvPM mass and number engine emissions. In addition, it uses the measurement of the full gaseous emissions as specified in Appendix 3. The measurement of the full gaseous emissions allows a more precise calculation of nvPM mass concentration and nvPM mass and number emission indices, on the basis of wet gaseous concentrations. In this case, the matrix solution described in Appendix 3 Attachment E is typically used to perform necessary corrections to determine gaseous concentrations on a wet basis. For that reason, the CO, HC and NOx concentrations are listed as data required.

An equivalent procedure is described in the ETM section related to paragraph 6.1.2 of Appendix 7 to allow calculation of EI_{mass} and EI_{num} using only nvPM and dry or wet CO_2 measurements. Since the combustion efficiencies of modern turbine engines are greater than 95 per cent. It is reasonable to assume that all of the fuel carbon is converted to CO_2. Thus CO_2-only (undiluted and diluted) measurements could be used to determine nvPM emission factors. In this case, measurements of [HC], [CO] and [NOx] are not required.

3.2 Other information

[Reserved]

4. GENERAL ARRANGEMENT OF THE SAMPLING AND MEASUREMENT SYSTEM

EXPLANATORY INFORMATION

The nvPM sampling and measurement system specified in Appendix 7 addresses the collection, transport and quantification of mass and number of particles emitted from the engine. The measurement environment behind a gas turbine engine places significant constraints on the sampling system used to collect the exhaust sample. The high temperature, high velocity exhaust requires a robust probe at the engine exit and transports the sample to the measurement instruments. The system requirements are compounded by the need to minimise the influence of the sampling system on the exhaust sample. Thus, a sophisticated system is specified. The Transfer Part of the system has been physically standardised to minimise variability between test facilities and operators including the sampling lines. The exhaust sample is diluted and maintained at prescribed temperatures and flow rates to prevent condensation, minimise coagulation of particles to be measured, and to minimise particle transport loss prior to measurement. Once the sampling system has transported the exhaust sample to the measurement instruments, nvPM mass and number concentrations are measured.

The nvPM sampling and measurement methodology is established upon SAE AIR6241 Procedure for the Continuous Sampling and Measurement of Non-Volatile Particle Emissions from Aircraft Turbine Engines.

4.1 nvPM sampling and measurement system

EXPLANATORY INFORMATION

An example of an acceptable sample line connection for use in Sections 2 to 4 is shown in Figure 1.

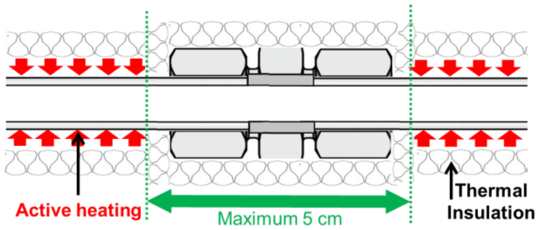


Figure 1. Example of a sampling line connection heating

An example of an acceptable bulkhead connection for use in Sections 2 to 4 is shown in Figure 2.

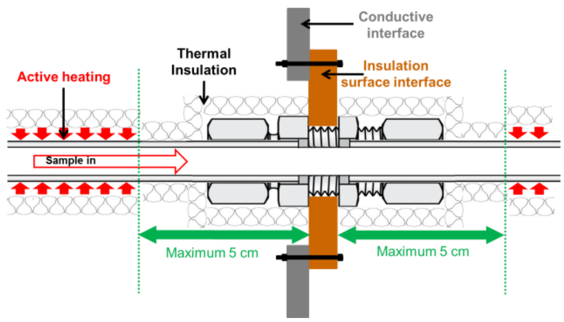


Figure 2. Example of bulkhead union interface heating

4.2 Collection Part
[Reserved]

EXPLANATORY INFORMATION

1. For existing certified engines:

Detailed traverse measurements are time consuming and costly. This should be taken into account by the certificating authority when requiring new traverse measurements for nvPM. Where detailed traverse measurements for gaseous and Smoke emissions testing have been conducted in the past and have been agreed to by the certificating authority, the probe configurations already established may be acceptable for nvPM certification measurements.

2. For new engine types or modifications that invalidate the previous probe configuration for emissions certification:

Where traverse measurements are required in order to demonstrate representative sampling, all emissions certification species should be taken into account for the evaluation of representativeness.

4.3 Transfer Part

[Reserved]

4.4 Measurement Part

4.4.1 nvPM Mass Measurement

EXPLANATORY INFORMATION

Appendix 7 requires nvPMmi to have a certificate showing the instrument has demonstrated conformity to the performance specifications listed in Attachment B to Appendix 7.

Each instrument is delivered with a user manual to provide operating instructions and instrument specific calibration procedures. As standard practice, this manual includes the performance specifications of the instrument. The performance specifications which must be met to demonstrate conformity should normally be contained in this manual.

In the case the manual provides sufficient information to demonstrate conformity, the manual can serve as the instrument's certificate. If this information is not contained in the manual, then an appendix to the manual or another separate document should be provided.

The data that could be expected is:

- Instrument make, model, sub model/version number
- Versions of instrument software and hardware
- The values of the performance specifications with the indication of the determination methods used (e.g. test protocol, numerical results)
- The aerosol source recommended for annual calibration

The instrument certificates are documents required by Appendix 7 and should be provided to the certificating authority during the aircraft engine certification process. In case the certificating authority determines the instrument certificates are not sufficiently detailed, further details can be requested.

As stated in Appendix 7, "each make and model of the nvPMmi shall receive a certificate from the instrument manufacturer or from another competent testing and calibration laboratory confirming that it meets the specifications". It is assumed that the instrument manufacturer has at least the same level of expertise as a competent laboratory as defined in Appendix 7.

4.4.2 nvPM Number Measurement

EXPLANATORY INFORMATION

Appendix 7 requires nvPMni to have certificates showing the VPR and CPC have demonstrated conformity to the performance specifications listed in Attachment C to Appendix 7.

Each instrument is delivered with a user manual to provide operating instructions and instrument specific calibration procedures. As standard practice, this manual includes the performance specifications of the instrument. The performance specifications which must be met to demonstrate conformity should normally be contained in this manual.

In the case the manual provides sufficient information to demonstrate conformity, the manual can serve as the instrument's certificate. If this information is not contained in the manual, then an appendix to the manual or another separate document should be provided.

The data that could be expected is:

- Instrument make, model, sub model/version number
- Versions of instrument software and hardware
- The values of the performance specifications with the indication of the determination methods used (e.g. test protocol, numerical results,)

The instrument certificates are documents that may be required by the certificating authority during the aircraft engine certification process. In case the certificating authority determines the instrument certificates are not sufficiently detailed, further details can be requested.

As stated in Appendix 7 Attachment C, "each make and model of the CPC shall receive a certificate from the instrument manufacturer or from another competent testing and calibration laboratory confirming that it meets the performance specifications listed" in 1.3. It is assumed that the instrument manufacturer has at least the same level of expertise as a competent laboratory as defined in Appendix 7.

4.4.3 Make-up flow

[Reserved]

5.GENERAL TEST PROCEDURE

5.1 Calibration and Maintenance

EXPLANATORY INFORMATION

Once a nvPMmi or a nvPMni has been demonstrated to comply with performance specifications (Table A7-3 of Attachment B to Appendix 7 for nvPMmi, Attachment C to Appendix 7 for nvPMni), its configuration both in hardware and software affecting data acquisition and signal processing has to be maintained. For example, a nvPMmi may relate optical or other physical properties of the engine particles to the particle used in the calibration method performed in a laboratory using signal processing methods. Any changes or improvements to hardware and such processing software or firmware to the nvPMmi or nvPMni may affect the fundamental processing and the measurement of reported quantities, therefore, will require a new demonstration of conformity of the instrument for use in engine certification. This requirement does not include the routine or annual calibration of the instrument. The calibration of the instrument may lead to entering a different calibration factor into the instrument software, but does not change the way measured physical properties are processed.

EQUIVALENT PROCEDURE

All changes to the nvPMmi should be documented sufficiently to allow NAAs to determine if changes affecting data acquisition and processing have been made.

The Equivalent Procedure below will provide guidance for demonstrating conformity to the nvPMmi performance specifications only after hardware or software changes to the nvPMmi which affect data acquisition and processing and not for demonstration of conformity for a new instrument.

An independently calibrated approved nvPMmi and independently calibrated nvPMmi with hardware and software changes should be configured in parallel with the TOT instrument behind the engine source as specified in Appendix 7, Attachment B, paragraph 3.2.

In addition to the four filters acquired to meet the applicability requirement (Appendix 7, Attachment B, paragraph 3.2.2), data points should be obtained with the two nvPMmi (filters not required) at a minimum of 10 mass concentrations at relatively uniform intervals up to the maximum mass concentration measured for demonstration of applicability (as specified in Table 1). A minimum of three or six (at respective relative mass concentrations identified in Table 1) independent data points with a minimum duration of 30 seconds each should be obtained.

Conformity of the updated instrument to the repeatability, zero drift, linearity, rise time and accuracy performance specifications in Table A7-3 should be shown using the measurements from the approved nvPMmi as the reference, for the range of concentrations in Table 1, and with statistics on the repeats at each concentration. This is in addition to the demonstration of applicability as specified in Appendix 7, Attachment B, paragraph 3.2.

Table 1. EC mass loading parameters for demonstration of conformity for an nvPMmi after a hardware or software (HW/SW) change.

Applicability (Appendix 7, Attachment B, paragraph 3.2) **(Reference mass from TOT EC filters)**		**Repeatability, Linearity, and Accuracy** **(Reference mass from approved nvPMmi)**	
Target Concentration **(Relative to Maximum Applicability Concentration – µg/m³)**	**No. of Tests**	**Target Concentration** **(Relative to Maximum Applicability Concentration – µg/m³)**	**No. of Tests**
minimum ≤ 0.67 × middle concentration (< 120 µg/m3)	1 or 2	0.0	6
		0.10 ± 0.05 × maximum	6
		0.20 ± 0.05 × maximum	6
		0.30 ± 0.05 × maximum	3
		0.40 ± 0.05 × maximum	3
middle ≤ 0.67 × maximum	1 or 2	0.50 ± 0.05 × maximum	3
		0.60 ± 0.05 × maximum	3
		0.70 ± 0.05 × maximum	3

maximum (> 120 µg/m3)	1 or 2	0.80 ± 0.05 × maximum	3
		0.90 ± 0.05 × maximum	3
		maximum	6
Total:	4	Total:	45

For demonstrating applicability, a minimum of four filters are required as stated in Appendix 7, Attachment B, paragraph 3.2.

For demonstrating conformity with the repeatability, linearity and accuracy performance specifications, six repeats are necessary at some concentrations to meet requirements as stated in Appendix 7, Attachment B, paragraph 4.2 and the second column of Table A7-5. Note that the concentrations requiring six repeats may not be equal to those in the first column of Table A7-5, but the relative concentrations (0, 10, 20 and 100 per cent of the maximum concentration) are equivalent.

Conformity to the LoD specification (row 4 in Table A7-3) must be demonstrated as stated in Attachment B to Appendix 7, paragraph 4.4 or using the equivalent procedure provided in this guidance document and sampling interval may be demonstrated with a statement from the nvPMmi manufacturer.

5.2 Engine operation
[Reserved]

5.3 Carbon balance

EQUIVALENT PROCEDURE

Since it possible to perform the full gaseous emissions measurement with the nvPM sampling and measurement system, the carbon balance check for nvPM measurements shall be achieved using the Air/fuel ratio formula given in Appendix 3 paragraph 7.1.2:

$$Air/fuel\ ratio = \left(\frac{P_0}{m}\right)\left(\frac{M_{Air}}{M_C + \left(\frac{n}{m}\right)M_H}\right)$$

where P_0 includes all gaseous emissions concentrations.

Since the combustion efficiencies of modern turbine engines are greater than 95 per cent, it is reasonable to assume that all of the fuel carbon is converted to CO_2. Thus, CO_2-only measurements could be used for determination of the air/fuel ratio and the equation could be simplified using a simplified P_0.

$$\frac{P_0}{m} = \frac{1}{[CO_2]_S} + \frac{n}{4m}$$

$[CO_2]_b$ concentration of CO_2 in dry air, by volume = 0.0003

$[CO_2]_S$ mean concentration of CO_2 vol/vol in undiluted exhaust as sampled, semi-dry or dry

M_{AIR} molecular mass of dry air = 28.966 g or, where appropriate,

= (32 $[O_2]_b$ + 28.1564 $[N_2]_b$ + 44.011 $[CO_2]_b$) g

M_C atomic mass of carbon = 12.011 g

M_H atomic mass of hydrogen = 1.008 g$[N_2]_b$ = concentration of N2 + rare gases in dry air, by volume = 0.7902

$[O_2]_b$ concentration of O_2 in dry air, by volume = 0.2095

m number of C atoms in characteristic fuel molecule

n number of H atoms in characteristic fuel molecule

The Air/fuel ratio estimated from the CO_2 measured concentration shall agree with the estimated engine Air/fuel ratio with an accuracy of ±15 per cent for the taxi/ground idle mode and with an accuracy of ±10 per cent for all other modes.

For modern engines, the simplified AFR estimation always predicts a slightly higher AFR than the full gaseous estimation. The estimated bias is:

-less than 1 per cent for high power settings due to the high combustion efficiency, and

-less than 3 per cent for idle conditions.

This impacts the carbon balance accuracy comparison to the estimated engine AFR. It is possible that the simplified carbon balance method could exceed the requirement. Thus care should be taken to take account of the bias.

5.4 Operation of nvPM Sampling and Measurement System

[Reserved]

5. CALCULATIONS

6.1 nvPM mass concentration and nvPM mass and number emission indices equations

6.1.1 nvPM mass concentration

EQUIVALENT PROCEDURE

The nvPM mass concentration has to be corrected for the first stage dilution factor (DF_1). DF_1 is determined using the following equation:

$$DF_1 = \frac{[CO_2]}{[CO_2]_{dil1}}$$

where $[CO_2]$ is calculated using the full gaseous emissions concentrations as specified in Attachment E to Appendix 3 for the wet correction.

Since the combustion efficiencies of modern turbine engines are greater than 95 per cent, it is reasonable to assume that all of the fuel carbon is converted to CO_2, and CO_2-only measurements could be used for determination of nvPM emissions. In this case, the CO_2 concentration cannot be wet-corrected and the first stage dilution factor is calculated using directly the sampled $[CO_2]_S$:

$$DF_{1\_S} = \frac{[CO_2]_S}{[CO_2]_{dil1}}$$

Thus, the nvPM mass concentration could be calculated using the following equation:

$$nvPM_{mass} = DF_{1\_S} \text{ x } nvPM_{mass\_STP} \text{ x } k_{thermo}$$

For modern engines, the uncertainties introduced by using the simplified equation result in an increase of $nvPM_{mass}$ by up to 5 per cent for high power settings. This number decreases towards low power settings.

6.1.2 nvPM mass and number emission indices

EQUIVALENT PROCEDURE

Since the combustion efficiencies of modern turbine engines are greater than 95 per cent, it is reasonable to assume that all of the fuel carbon is converted to CO_2. nvPM and CO_2-only measurements could be used for determination of EI_{mass} and EI_{num} using the following simplified equations:

$$EI_{mass} = \frac{22.4 \times nvPM_{mass\_STP} \times 10^{-3}}{\left([CO_2]_{dil1} - \frac{1}{DF_{1\_S}} \left([CO_2]_b \right) \right) (M_C + \alpha M_H)} \times k_{thermo}$$

$$EI_{num} = \frac{22.4 \times DF_2 \times nvPM_{num\_STP} \times 10^{6}}{\left([CO_2]_{dil1} - \frac{1}{DF_{1\_S}} \left([CO_2]_b \right) \right) (M_C + \alpha M_H)} \times k_{thermo}$$

where

DF_{1_S} First stage dilution factor calculated using directly sampled $[CO_2]_S$:

$$DF_{1\_S} = \frac{[CO_2]_S}{[CO_2]_{dil1}}$$

For modern engines, the uncertainties introduced by using the simplified equations result in an increase of the EI_{mass} and EI_{num} by less than 0.1 per cent for high power settings due to the high combustion efficiency, and by less than 5 per cent for idle conditions.

EXPLANATORY INFORMATION

This explanatory information provides examples of both types of calculation, using the full gaseous emissions concentrations to obtain more precise emission indices and using the simplified method.

In these examples the engine operates at an idle power condition and Jet A1 fuel is used. The engine exhaust plane temperature is 405°C (T_{EGT}) and Diluter1 inlet temperature is 163°C (T_1).

Given parameters:

$[CO_2]_{dry}$	26051 ppm = 0.026051
$[CO]_{dry}$	1012 ppm = 0.001012
$[H_2O]$	0.0244
[HC]	0.000117
$[CO_2]_b$	0.0003
$nvPM_{mass\_STP}$	19 [µg/m^3]
$nvPM_{num\_STP}$	2.18 x10^3 [number/cm^3]
$[CO_2]_{dil1}$	2591 ppm /1000000 = 0.002591
DF_2	100
α	1.92 (typical Jet A1)

1. Full gaseous method nvPM mass and number emission indices and nvPM mass concentration calculation examples

$$k_{thermo} = \left(\frac{T_1+273.15}{T_{EGT}+273.15}\right)^{-0.38}$$

k_{thermo}= 1/(((163+273.15)/(405+273.15))$^{0.38}$) = 1.18

Convert $[CO_2]$ dry to wet basis, $[CO_2] = [CO_2]_{dry}$ (1 - 0.0244) = 0.025415

$DF_1 = [CO_2] / [CO_{2\_dil1}]$ = 0.025415/0.002591 = 9.809

Convert [CO] dry to wet basis, $[CO] = [CO]_{dry}$ (1 - 0.0244) = 0.0009873

- nvPM primary mass concentration

$$nvPM_{mass} = DF_1 \times nvPM_{mass\_STP} \times k_{thermo}$$

$nvPM_{mass}$ = 9.809 x 19 x 1.18

$nvPM_{mass}$ = 220 µg/m^3

- nvPM mass emission index

$$EI_{mass} = \frac{22.4 \times nvPM_{mass\_STP} \times 10^{-3}}{\left([CO_2]_{dil1} + \frac{1}{DF_1}\left([CO] - [CO_2]_b + [HC]\right)\right)(M_C + \alpha M_H)} \times k_{thermo}$$

$$EI_{mass} = \frac{22.4 \times 19 \times 10^{-3}}{\left(0.002591 + \frac{1}{9.81}(0.0009873 - 0.0003 + 0.000117)\right)(12.011 + 1.92 \times 1.008)} \times 1.18$$

$$EI_{mass} = 13.5 \left[\frac{mg}{kg\,fuel}\right]$$

- nvPM number emission index

$$EI_{num} = \frac{22.4 \times DF_2 \times nvPM_{num\_STP} \times 10^{6}}{\left([CO_2]_{dil1} + \frac{1}{DF_1}\left([CO] - [CO_2]_b + [HC]\right)\right)(M_C + \alpha M_H)} \times k_{thermo}$$

$$EI_{num} = \frac{22.4 \times 100 \times 2.18 \times 10^{3} \times 10^{6}}{\left(0.002591 + \frac{1}{9.81}(0.0009873 - 0.0003 + 0.000117)\right)(12.011 + 1.92 \times 1.008)} \times 1.18$$

$$EI_{num} = 1.55\times10^{14}\left[\frac{\text{number}}{\text{kg fuel}}\right]$$

2. Simplified nvPM mass and number emission indices and nvPM mass concentration calculation examples

k_{thermo}= 1/(((163+273.15)/(405+273.15))$^{0.38}$) = 1.18

$DF1_{\_S} = [CO_2]_S / [CO_2]_{dil1}$ = 0.026051/0.002591 = 10.05

- nvPM primary mass concentration

$DF1_{\_S} = [CO_2]_S / [CO_{2\_dil1}]$ = 0.026051/0.002591 = 10.05

$nvPM_{mass}$ = 10.05 x 19 x 1.18

$nvPM_{mass}$ = 225 µg/m^3 (full gaseous method value calculated above: 220 µg/m^3)

- nvPM mass emission index

$$EI_{mass} = \frac{22.4\times nvPM_{mass\_STP}\times10^{-3}}{\left([CO_2]_{dil1} - \frac{1}{DF_{1\_S}}([CO_2]_b)\right)(M_C + \alpha M_H)}\times k_{thermo}$$

$$EI_{mass} = \frac{22.4\times19\times10^{-3}}{\left(0.002591 - \frac{0.0003}{10.05}\right)(12.011+1.92\times1.008)}\times1.18$$

$$EI_{mass} = 14.1\left[\frac{\text{mg}}{\text{kg fuel}}\right]$$ (full gaseous method value calculated above: 13.5 mg/kg fuel)

- nvPM number emission index

$$EI_{num} = \frac{22.4\times DF_2\times nvPM_{num\_STP}\text{ x }10^{6}}{\left([CO_2]_{dil1} - \frac{1}{DF_{1\_S}}([CO_2]_b)\right)(M_C + \alpha M_H)}\times k_{thermo}$$

$$EI_{num} \approx \frac{22.4 \times 100 \times 2.18 \times 10^{3} \times 10^{6}}{\left(0.002591 - \frac{0.0003}{10.05}\right)(12.011 + 1.92 \times 1.008)} \times 1.18$$

$$EI_{num} = 1.61 \times 10^{14} \left[\frac{\text{number}}{\text{kg fuel}}\right]$$ (full gaseous method value calculated above: 1.55×10^{14} number/kg fuel)

6.2 Correction factors for nvPM emissions

6.2.1 Correction for nvPM thermophoretic losses in the Collection Part

[Reserved]

6.3 Control parameter functions

6.3.1 Definitions

[Reserved]

6.3.2 The nvPM mass and number emission indices (EI) shall be obtained for each LTO operating mode at T_B of the reference standard engine. A minimum of three test points shall be required to define the idle mode. For each LTO operating mode, the corresponding fuel flow under ISA conditions shall be obtained. The following relationships shall be determined under ISA reference conditions for nvPM mass and number emission indices:

[Reserved]

6.4 Calculation procedure

[Reserved]

6.5 Exceptions to the proposed procedures

[Reserved]

ATTACHMENT A TO APPENDIX 7
REQUIREMENTS AND RECOMMENDATIONS FOR NON-VOLATILE PARTICLE MEASUREMENT SAMPLING SYSTEM

1. SECTION 1: PROBE IN – SPLITTER1 IN

[Reserved]

2. SECTION 2: SPLITTER1 IN – DILUTER1 OUT

2.1 Requirements

[Reserved]

2.2 Splitter 1

EXPLANATORY INFORMATION

Figures 1 and 2 show examples of splitter geometries and assemblies that meet the requirements and are acceptable for use. Note that there are many other possible geometries and assemblies that could meet the requirements and could be acceptable for use.

The number of Splitter1 flow paths depends on the number of undiluted sample measurement lines and/or the need to relieve large excess sample pressure. Additional emission diagnostic instrumentation may be placed in the Make-up flow path downstream of Splitter2.

Splitter design is not based upon hydraulic flow considerations but on the desire for standardisation between sampling systems. Consideration of splitter design may not be necessary for the measurement of turbine engine nvPM emissions, since theoretically there is no impact on small particles (less than 300 nm diameter).

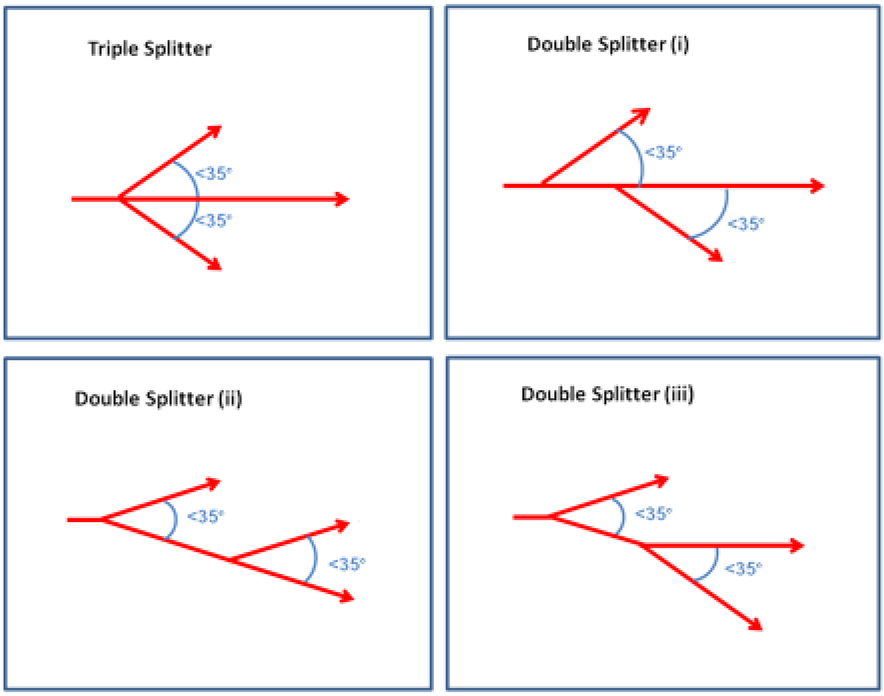
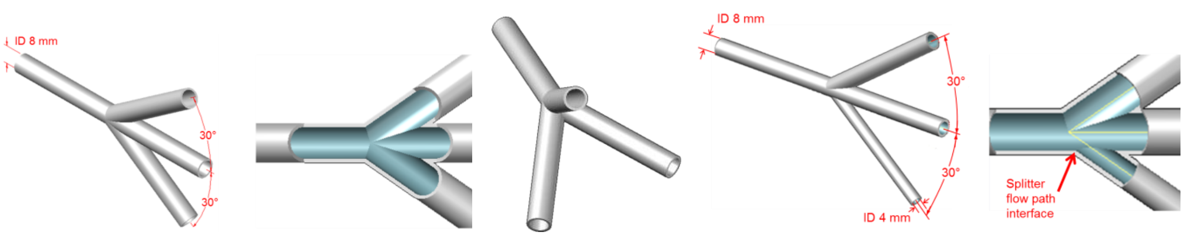


Figure 1. Schematic examples of splitter geometries



(a) (b) (c)

Figure 2. Triple splitter example geometry as (a) single plane; (b) multi-plane; and (c) line diameter change

2.3 Isolation Valve 1

[Reserved]

2.4 Section 2 line

[Reserved]

2.5 Diluter1

[Reserved]

2.6 Gas Line

EQUIVALENT PROCEDURE

While the engine is at a stable operating condition, sequential switching between CO, HC, and NOx measurements and nvPM measurement could be allowed.

EXPLANATORY INFORMATION

Smoke measurements may be obtained using the nvPM sampling system. The Collection Part (section 1) of the nvPM sampling and measurement system meets the specifications in Appendix 2 and the Splitter1 assembly allows the GL, or another heated sampling line, to be used to measure Smoke Number as long as the sampling line requirements in Appendix 2 are met. If Smoke Number measurements are taken, it is recommended to obtain them sequentially with the nvPM measurements.

Installation of the smoke sampling line at Splitter 1 for certification measurements may increase the total sampling line length for smoke measurements by up to 8 m due to the Collection Part. In this case, the requirement in Appendix 2 Paragraph 2.2.1 for a maximum sampling line length of 25 m may be exceeded, up to a maximum combined length of 33m.

A Smoke Number reduction of less than 1 SN has been determined for an additional 8 m sampling line length by FOA3 modeling and direct measurements for Smoke Numbers up to 15. The certificating authority may consider granting an increase of sampling line length for smoke measurements. It is good practice to add 1 SN to the measured data as a conservative approach for determining the Smoke Number in such a case.

2.6 Excess sample line

[Reserved]

3. SECTION 3: DILUTER1 OUT – CYCLONE SEPARATOR IN

3.1 Requirements

[Reserved]

4. SECTION 4: CYCLONE SEPARATOR IN – INSTRUMENT IN

4.1 Cyclone Separator
[Reserved]

4.2 Splitter 2
[Reserved]

4.3 Measurement system interface
[Reserved]

5. SECTION 5: nvPM MEASUREMENT

2.1 Make-up flow

EXPLANATORY INFORMATION

Figure 1 shows a location example of two flow controllers installed in the Make-up flow line to provide Section 3 system flow control. In the figure, Section 3 flowrate of 25 slpm is the sum of the nvPMmi (4 slpm), VPR (4 slpm), Primary Pump Flow Controller (14 slpm) and CO_2 Pump Flow Controller (3 slpm).

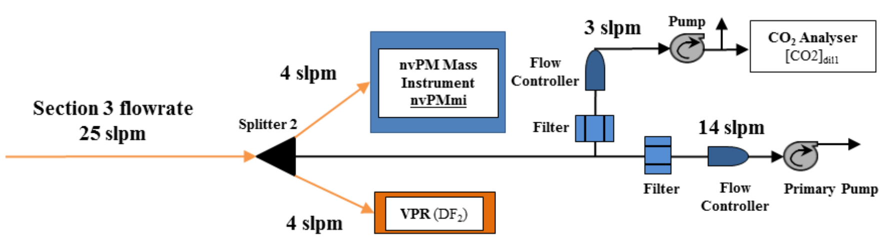


Figure 1. Example of system flow rates that ensure Section 3 flow rate satisfies 25±2 slpm

Figure 2 shows examples of sampling layout options for performing nvPM sampling system flow control and $[CO2]_{dil1}$ measurement for determination of the first stage dilution factor DF_1.

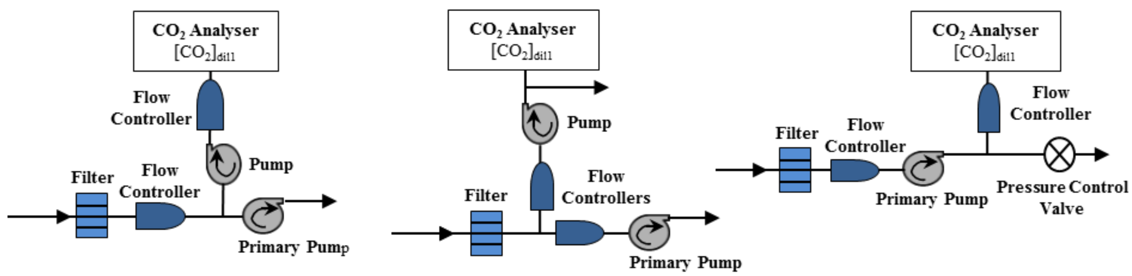


Figure 2. Examples of sampling layout for nvPM sampling system flow control at first stage dilution measurement

The sample gas measured downstream of Diluter1 can be considered ‘dry’ as it will consist of at least 88 per cent dry air or dry nitrogen. The diluted sample water content is negligible and consequently there is no ‘wet’ correction required for the CO_2 measurement downstream of Diluter1.

ATTACHMENT B TO APPENDIX 7
SPECIFICATION FOR NON-VOLATILE PARTICLE MASS INSTRUMENT AND CALIBRATION

EXPLANATORY INFORMATION

Non-volatile PM (nvPM) is defined as those particles present at the aircraft engine exit plane which do not volatilise when heated to a temperature of 350 °C. nvPM consists mainly of nanometer size black carbon with trace amounts of ash and metallic particles emitted by aircraft engines under normal operating conditions. Total nvPM mass cannot be directly measured except by filter sampling and analysis which is expensive and time consuming. Therefore, the on-line measurement of black carbon mass concentration is considered the most appropriate method for representing the nvPM emissions from aircraft engines. For calibration purposes, however, the mass of elemental carbon (EC) determined by thermal-optical analysis is used as a surrogate for black carbon mass since it is the most applicable method at the time the nvPM regulation was established.

The table below provides a clarification of the terms used in Appendix 7 Attachment B.

Term	**Use**
Demonstrate Conformity (for a performance specification)	To show that an nvPMmi meets an individual Appendix 7 Performance Specification
Certificate	Received after an nvPMmi has *demonstrated conformity* to all Performance Specifications
Accuracy	Part of Performance Specifications: Determine nvPMmi agreement with EC Mass concentration determined from TOT method, by way of linear regression
Applicability	Part of Performance Specifications: Validation of Instrument and annual calibration source for nvPM mass measurement of aircraft gas turbine engine exhaust

Annual Calibration	Adjust nvPMmi calibration factor to agree with EC Mass concentration determined from the TOT method (Although in Table A7-5, not part of the nvPMmi certificate)

1. SPECIFICATIONS

[Reserved]

2. THERMAL OPTICAL TRANSMITTANCE (TOT) METHOD

2.1. General

EXPLANATORY INFORMATION

The thermal-optical transmission (TOT) method can speciate elemental carbon (EC) from organic carbon (OC), and is performed by a thermal-optical analyser with timed heating ramps and “cool-down” cycles. While the method measures all carbon species that evolve during the analysis and provides total carbon (TC) loading on the filter, the elemental carbon fraction (EC) is used for calibration. In the laboratory method, all carbon evolving from the filter is oxidised to form carbon dioxide (CO_2), which is then reduced to methane (CH_4), and measured using a flame ionisation detector (FID) as described below.

A red light (wavelength of 670nm) laser and a photocell are used to monitor transmittance of a filter punch of known area, which typically darkens as refractory OC chars during a non-oxidising heat ramp and then lightens as the char burns off during an oxidizing heat ramp. Figure 1 illustrates a typical heat cycle of the TOT method. Note that Figure 1 is provided for illustration purposes and does not reflect the required temperature profile for the TOT method analysis cycle. Instrument software divides TC into OC and EC by evaluating the split time at which the transmittance of the filter returns to its original value from the beginning of the analysis. One should note that since the instrument uses light transmittance through the filter to speciate the carbon types, any artefacts that remain on the filter (due to lack of complete charring etc.) can be determined as elemental carbon rather than organic carbon during analysis. The range for this method is 1 to 105 µgC (micro-grams carbon) per filter punch (usually about 1.5 cm^2). The limit of detection is about 0.2 µgC per cm^2.

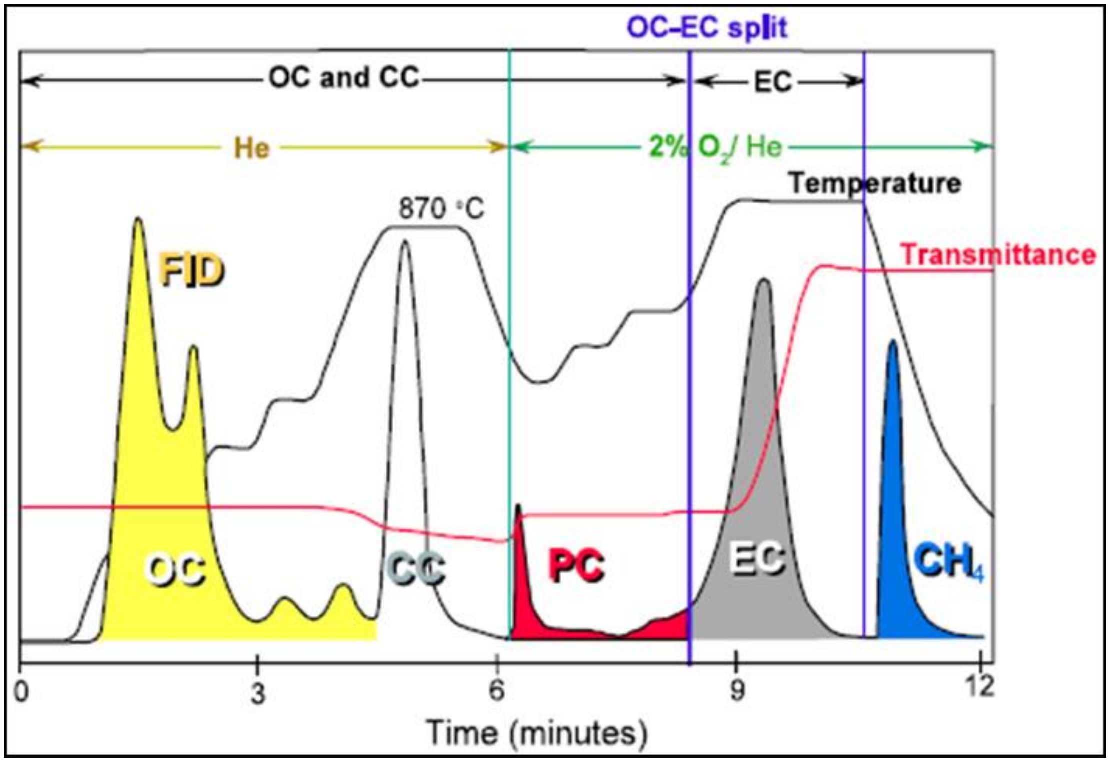


Figure 1. Typical thermogram for filter sample containing organic carbon (OC), carbonate carbon (CC), and elemental carbon (EC). PC is carbon generated by pyrolysis. The curves indicated with the OC, CC, PC, EC, and CH_4 labels are CH_4 concentrations being measured by a flame ionisation detector (FID) for the laboratory TOT carbon analyser. The final peak is the methane calibration peak.

The optical component of the analyser is used to correct for pyrolysis of organic carbon compounds to elemental carbon in order to avoid underestimation of OC and overestimation of EC. In order to ensure a proper OC/EC split, calibration of the internal oven temperature should be conducted according to the manufacturer's specifications. The sample reflectance and transmittance are continuously monitored by a laser and a photo detector throughout the thermal cycle. When pyrolysis takes place, there is an increase in light absorption resulting in a decrease in reflectance and transmittance. Thus, by monitoring the reflectance/transmittance, the portion of the elemental carbon peak corresponding to pyrolysed organic carbon can be correctly assigned to the organic fraction. An example of the laser transmission amplitude (curve denoted with the "Transmittance" label) is shown in Figure 1.

In the semi-continuous TOT analyser, a quartz filter is mounted directly in the instrument and samples are collected for the desired time period. Once the collection is complete, the oven is purged with helium and a stepped-temperature ramp increases the oven temperature to 870°C, thermally desorbing organic compounds and pyrolysis products into a manganese dioxide (MnO_2) oxidizing oven. As the carbon fragments flow through the MnO_2 oven, they are quantitatively converted to CO_2 gas. The CO_2 is swept out of the oxidising oven with the helium stream and measured directly by a self-contained nondispersive infrared (NDIR) detector. A second temperature ramp (oven temperature to 930°C) is then initiated in a He/O_2 gas stream and any elemental carbon is oxidised off the filter and into the oxidising oven and NDIR. The elemental carbon is then detected in the same manner as the organic carbon.

2.2. Reagents and Materials

[Reserved]

2.3. Sample Preparation

[Reserved]

2.4. Calibration and Quality Control

[Reserved]

2.5. Measurement

[Reserved]

2.6. Calculations

[Reserved]

3. PROCEDURE TO DEMONSTRATE CONFORMITY TO PERFORMANCE SPECIFICATIONS

Note. - The procedure described in this paragraph is used to demonstrate the conformity to the performance specifications of each make and model of the nvPMmi.

The performance specifications listed in Table A7-3 shall be demonstrated using the TOT method as described in paragraph 2. The measurements shall be performed using the two following sources: a diffusion flame combustion aerosol source and a gas turbine engine exhaust nvPM source**.**

EXPLANATORY INFORMATION

The nvPM mass instrument (nvPMmi) is required to demonstrate conformity to the performance specifications in Table A7-3 to Attachment B of Appendix 7 using a diffusion flame combustion aerosol source (DFCAS). Specifically for the applicability performance specification, as stated in Appendix 7, an aircraft turbine engine must be used as the combustion aerosol source.

Care should be taken when selecting and operating a DFCAS as the nvPMmi response can potentially change for different soot aerosol sources.

A DFCAS is a device employing diffusion flame combustion using a given fuel that emits airborne particulate matter. A diffusion flame is a mode of combustion in which the fuel and oxidiser (air) are supplied separately to the combustion zone, where mixing by molecular diffusion takes place together with the combustion reactions. Hydrocarbon-fuelled diffusion flames produce soot (a form of non-volatile particulate matter) and organic aerosols (a form of volatile particulate matter). The DFCAS is a combination of the device to produce the flame and the fuel used.

Examples of a DFCAS

- Gaseous fuel – non-premixed methane inverted flame; non-premixed propane soot generator

- Liquid fuel – gas turbine combustor rig; gas turbine engine; diesel direct injection engine

DFCAS types
DFCAS are considered at the type level for the conformity demonstration and annual calibration procedure. The following lists guidance on how to differentiate DFCAS types.

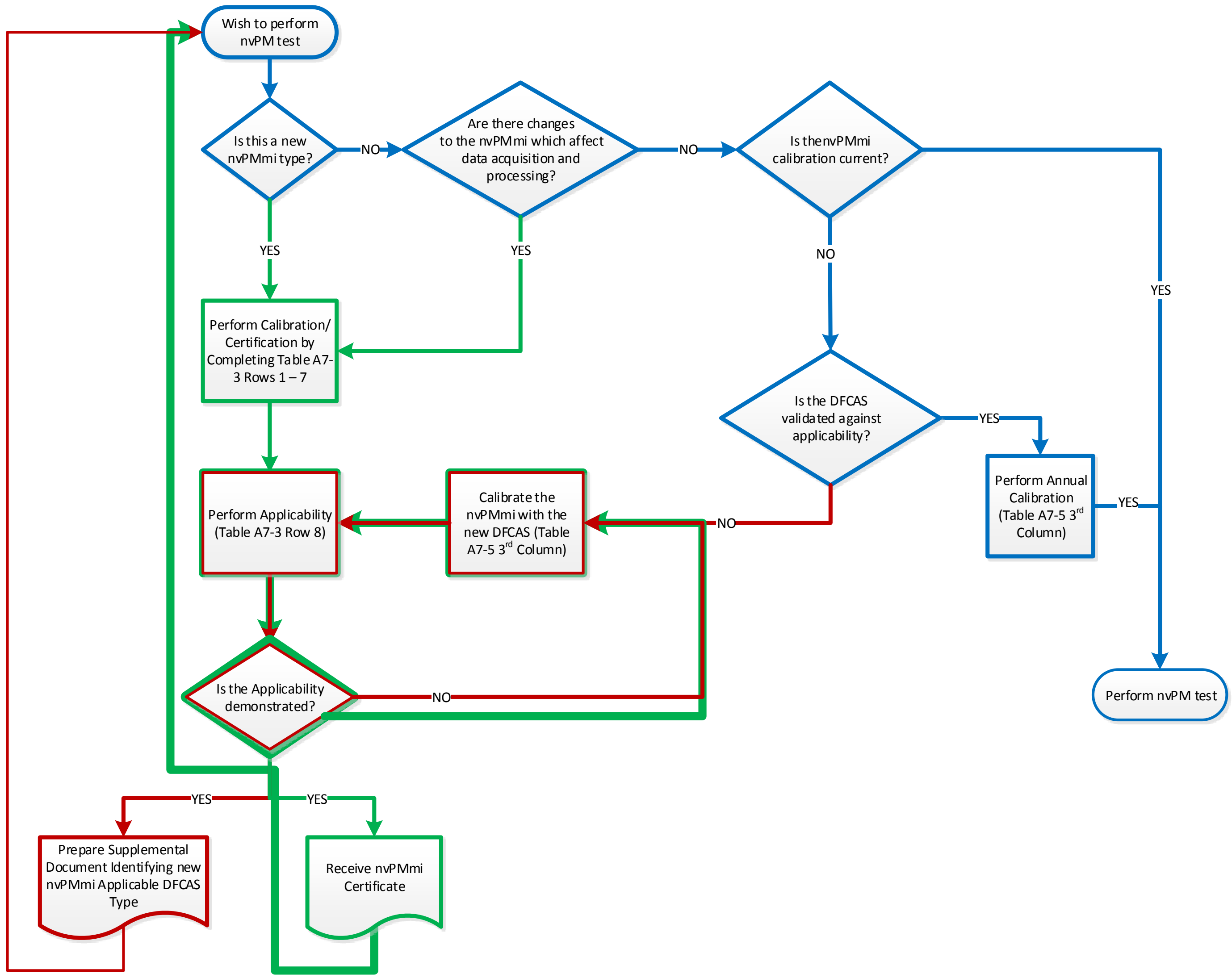
- One laboratory aerosol generator is different from another laboratory aerosol generator of a different design
- One aircraft engine model is different from another aircraft engine model. It may be possible to show that the soot produced from one engine model is sufficiently similar to another engine model that they can be considered the same DFCAS type.
- A laboratory aerosol generator is different from an aircraft engine

A change of operating settings on a DFCAS, which results in significant changes to the nvPMmi response, is considered a change of DFCAS type.

Using the same laboratory aerosol generator design or the same aircraft engine model with a different serial number does not constitute a change of DFCAS type.

TECHNICAL PROCEDURE

The Technical Procedure below provides guidance for demonstrating conformity to nvPMmi performance specifications using a DFCAS.


Wish to perform nvPM test
Is this a new nvPMmi type?
NO
Are there changes to the nvPMmi which affect data acquisition and processing?
NO
Is thenvPMmi calibration current?
YES
YES
YES
NO
Perform Calibration/ Certification by Completing Table A7-3 Rows 1 – 7
Is the DFCAS validated against applicability?
YES
Perform Annual Calibration (Table A7-5 3rd Column)
YES
Perform Applicability (Table A7-3 Row 8)
Calibrate the nvPMmi with the new DFCAS (Table A7-5 3rd Column)
NO
Is the Applicability demonstrated?
NO
Perform nvPM test
YES
YES
Prepare Supplemental Document Identifying new nvPMmi Applicable DFCAS Type
Receive nvPMmi Certificate

This flow chart describes the process that will be followed by an engine manufacturer to perform a nvPM mass concentration measurement and how to treat different DFCAS types.

The flow chart describes 3 processes:

Certificate Process (green)

The flowchart shows the process to get a nvPMmi certificate in demonstrating conformity to the performance specifications in Table A7-3. This process needs to be completed once for each nvPMmi make and model and in the case of a change in hardware or software is made to the nvPMmi which affect data acquisition and processing.

It is recommended that the nvPMmi show conformity to the performance specification repeatability, zero drift, linearity, rise time, and accuracy specifications in Table A7-3 using a single DFCAS. Conformity to the LoD specification (row 4 in Table A7-3) must be demonstrated as stated in Attachment B to Appendix 7, paragraph 4.4 or using the equivalent procedure provided in this guidance document. In this step the Accuracy must be demonstrated as stated in Appendix 7 using the first and second column in Table A7-5 followed by the demonstration of applicability using an aircraft gas turbine engine as a DFCAS.

The DFCAS types used to calibrate and demonstrate Applicability must be different as stated in paragraph 3 of Attachment B to Appendix 7.
If the Applicability is not validated, the instrument will be calibrated with a new DFCAS type using the first and third column Table A7-5. This calibration must meet the Accuracy requirements from Table A7-3 Row 7 as specified in Attachment B to Appendix 7. Then the Applicability has to be demonstrated using an aircraft gas turbine engine.

When the Applicability has been demonstrated, the nvPMmi will receive its certificate as stated in Appendix 7 paragraph 4.4.1.
Testing Process (blue)
This shows the procedure to calibrate the nvPMmi and measure mass concentration.
Calibration with a new DFCAS type (red)

As stated in paragraph 3 of Attachment B to Appendix 7:
- In the case where the calibration is done with a new DFCAS type, for which Applicability has not been validated, then the Applicability must be demonstrated before the nvPMmi can be used for measurement;
- The DFCAS types used to calibrate and demonstrate Applicability must be different.

The data demonstrating that the new DFCAS type is applicable should be recorded in a document.

3.1Measurement using a diffusion flame combustion aerosol source

EXPLANATORY INFORMATION

The calibration system for nvPM measurements should be located in a well-ventilated area and must contain at least a diffusion flame combustion source, an adjustable dilution system, a cyclone or other large particle remover, a splitter, a quartz filter sampler or semi-continuous EC/OC analyser and the nvPM mass measurement instrument. Other diagnostic instruments may also be used. The sampling lines downstream of the splitter should be of matching material (stainless steel or carbon loaded PTFE), same geometry and flow rates to match particle losses in each sample line. An example calibration system is illustrated in Figure 1 and the components identified in Table 1.

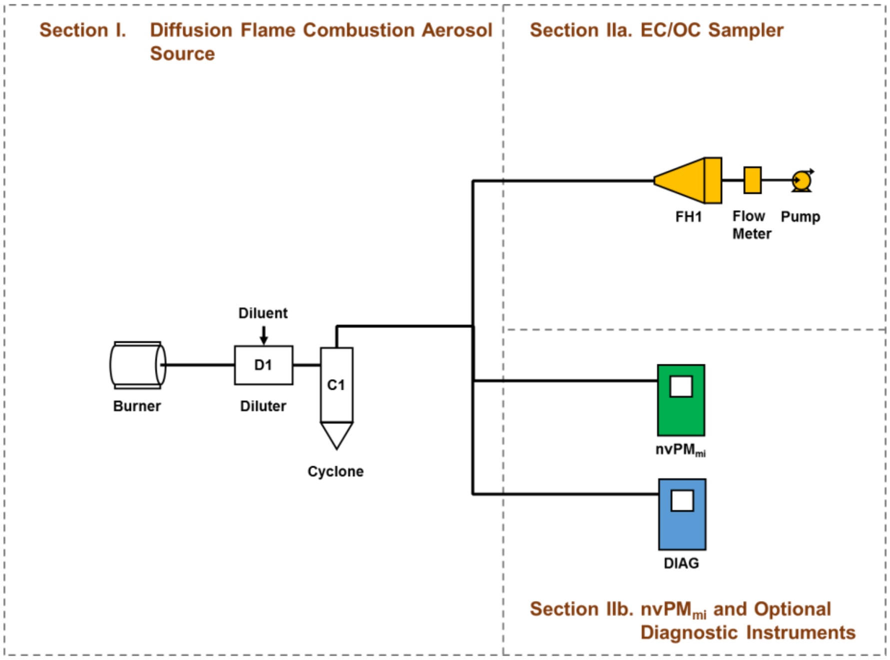


Figure 1. Schematic of an example instrument calibration system

Table 1. Breakdown of sections and major components of calibration system

Section	**I – PM combustion source**	**II – Sample collection**	
Sub-section	I. Diffusion Flame Combustion Source	IIa. EC/OC analysis	IIb. nvPMmi and diagnostic analyser(s)
Major component(s)	Burner : diffusion flame burner C1 : 1 µm cut point stainless steel cyclone D1 : diluter (N_2 or air)	Either: FH1: stainless steel quartz filter holder for EC/OC determination using manual filter preparation and laboratory EC/OC analyser (shown) Or: Semi continuous EC/OC analyser (not shown)	nvPMmi A-DIAG : optional diagnostic particle analyser

In the system shown in Figure 1, soot particles are created in the diffusion flame the characteristics of which will depend on the flow of fuel, air, and diluent provided to the burner. Upon leaving the burner the exhaust stream is diluted as necessary to meet the target soot concentrations. Large particles are then removed in the cyclone and the sample stream is distributed to the various instruments for analysis.

The exact instrumentation set-up should be based on the standard operating procedure for each instrument being calibrated. One example set-up using a splitter is shown in Figure 2. Another suitable system using an ejector, plenum, and manifold is shown in Figure 3.

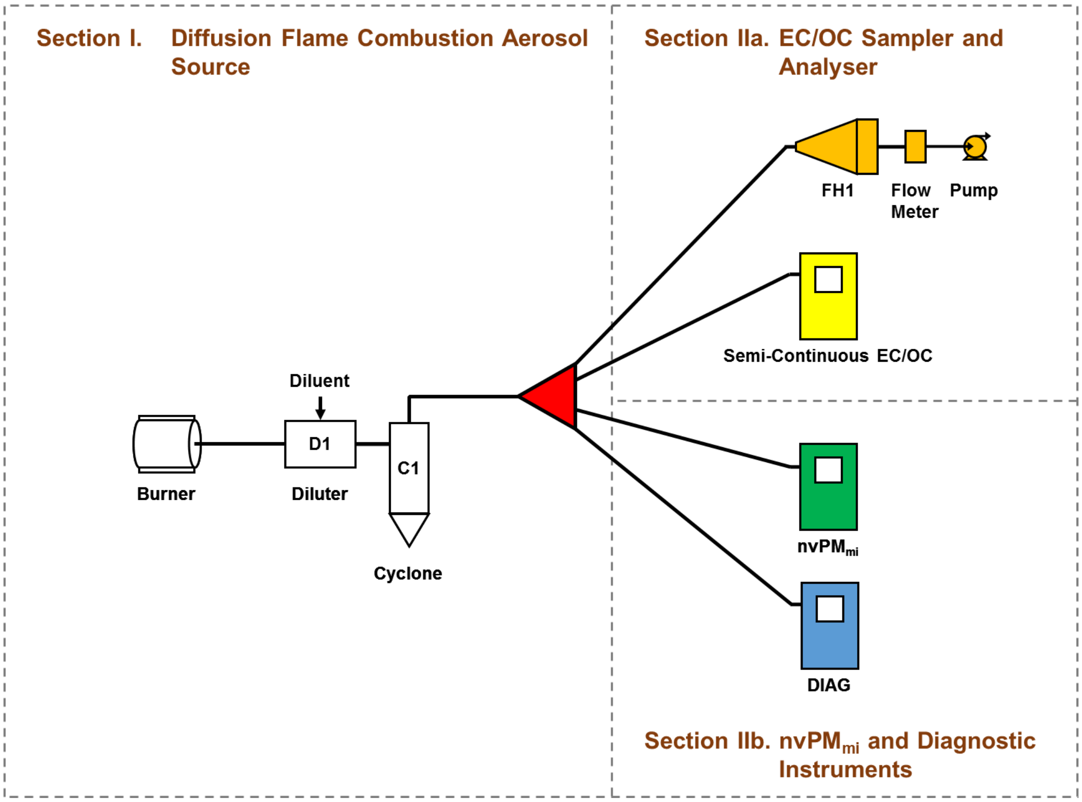


Figure 2. Schematic of an example instrument calibration system using a splitter

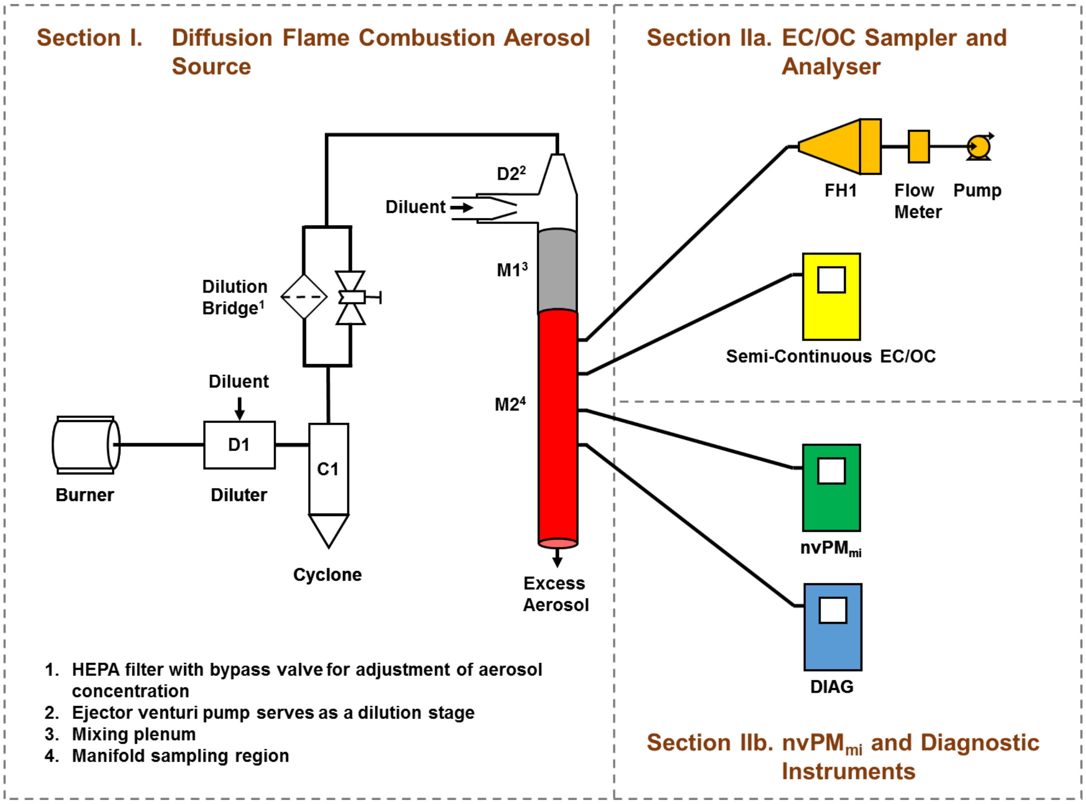


Figure 3. Schematic of an example instrument calibration system with a manifold located behind the cyclone

3.2 Measurement using a gas turbine engine exhaust nvPM source

[Reserved]

4 CALCULATION OF INSTRUMENT PERFORMANCE

4.1 [Reserved]

4.2 [Reserved]

4.3 [Reserved]

4.4 Limit of Detection of the nvPMmi shall be determined as specified in ISO 9169, paragraphs 6.4.5.5. If the instrument does not make a measurement when there are no particles in the sample, then a higher nvPM mass concentration, C_{LOD}, just above zero shall be used such that the instrument produces regular readings. The Limit of Detection in this case shall be determined as:

$$Y_{D,0.95} = \bar{Y}_{LOD} - C_{LOD} + 2 \times t_{v,0.95} \times s_{LOD}$$

where:

$Y_{LOD,0.95}$	= Limit of Detection at 95 per cent confidence interval
Y_{LOD}	= The average of the values $Y_{LOD,j}$
C_{LOD}	= The average of the values $C_{LOD,j}$
$t_{v,0.95}$	= The two sided Student's factor at 95 per cent confidence, degree $v=n-1$
s_{LOD}	= The standard deviation associated with the average Y_{LOD}

EQUIVALENT PROCEDURE

Equivalent methods of determining the limit of detection (LOD) are present in the technical literature and international standards. ISO 11843-1: 1997 Capability of Detection Part 1 Terms and Definitions provides the following:

- **minimum detectable net concentration or amount**
    - true net concentration or amount of the analyte in the material to be analysed which will lead, with probability (1 - β), to the conclusion that the concentration or amount of the analyte in the analysed material is larger than that in the blank material

International Union of Pure and Applied Chemistry (IUPAC) and ISO detection limits (minimum detectable amounts) are based on the theory of hypothesis testing and the probabilities of false positives α, and false negatives β. The limit of detection is given as

$$L_D = K_\alpha \sigma_0 + K_\beta \sigma_D$$

where K_α and α are associated with the one sided tails of the distribution of the blank with standard deviation σ_0 corresponding to probability levels, 1-α. Similarly, K_β and β are associated with the one sided tails of the distribution of the limit of detection with standard deviation σ_D corresponding to probability levels, 1- β. The latter is obtained at a low concentration near the detection limit. Often, it can be assumed that α=β, and σ=constant, such that $K_\alpha = K_\beta$ and $\sigma_D = \sigma_0$. This assumption implies that the LOD varies with twice the critical level, L_C, which is defined as

$$L_C = K_\alpha \sigma_0$$

The values of α and β recommended by IUPAC and ISO documents are 0.05 each. If σ_0 is estimated by s_0, based on ν degrees of freedom, K can be replaced by Student's t, such that

$$L_C = t_{v,0.95}\, s_0$$

and

$$L_D = 2\, t_{v,0.95}\, s_0$$

which contributed to the formulation found in ISO 9169. Based on the assumptions that α=β and σ=constant, such that

$K_\alpha = K_\beta$ and $\sigma_D=\sigma_0$, then by corollary $s_D=s_0$ and

$$L_D = 2\ t_{\nu,0.95}\ s_D.$$

An equivalent procedure for determining the Limit of Detection is:

$$Y_{D,0.95} = 2 \times t_{\nu,0.95} \times s_{LOD}$$

where:

$Y_{LOD,0.95}$ = Limit of Detection at 95 per cent confidence interval

$t_{v,0.95}$ = The one sided Student's factor at 95 per cent confidence, degrees of freedom $v=n-1$ where n is the number of measurements (repeats at a recommended 30 second averaging time)

s_{LOD} = The standard deviation of the measurements $Y_{LOD,j}$ obtained by measuring at a concentration near the limit of detection over the averaging time.

5.CALIBRATION

EXPLANATORY INFORMATION

In the context of instrument calibration, "as found" is the condition in which the instrument was received by the laboratory performing the calibration prior to any alterations or adjustments. The "as found" condition is an indication of the operability of the instrument since its last calibration. Evaluating the instrument in this manner is useful for understanding instrument drift.

TECHNICAL PROCEDURE

For annual calibration, a Diffusion Flame Combustion Aerosol Source (DFCAS) that satisfies all of the specified source requirements in paragraph 3.1 for particle properties and mass concentration may be employed.

The change in nvPMmi annual calibration factor should not exceed the Accuracy performance specification (±10%).

ATTACHMENT C TO APPENDIX 7
SPECIFICATION AND CALIBRATON FOR THE VOLATILE PARTICLE REMOVER AND THE NON-VOLATILE PARTICLE NUMBER INST.RUMENT

1. SPECIFICATIONS

1.1 VPR specifications

[Reserved]

1.2 VPR to CPC interface

[Reserved]

1.3 CPC specifications

[Reserved]

1.4 System requirement

[Reserved]

2. CALIBRATION

2.1 VPR

EXPLANATORY INFORMATION

In the context of instrument calibration, "as found" is the condition in which the instrument was received by the laboratory performing the calibration prior to any alterations or adjustments. A certificate stating the "as found" values should be requested. For the VPR, dilution factors, particle penetration and particle removal efficiency should be reported. The "as found" condition is an indication of the state of operability of the instrument since its last calibration. Evaluating the instrument in this manner is useful for understanding instrument drift.

2.2 CPC calibration

EXPLANATORY INFORMATION

In the context of instrument calibration, "as found" is the condition in which the instrument was received by the laboratory performing the calibration prior to any alterations or adjustments. A certificate stating the "as found" values should be requested. For a CPC these values would include inlet flow, temperatures and pressures, laser and optic checks, zero count test, lower detection and concentration linearity tests. Evaluating the instrument in this manner is useful for understanding instrument drift.

ATTACHMENT D TO APPENDIX 7
SPECIFICATIONS FOR ADDITIONAL DATA
[Reserved]

ATTACHMENT E TO APPENDIX 7
PROCEDURES FOR SYSTEM OPERATION

EXPLANATORY INFORMATION

It may be beneficial to perform additional system checks prior to an engine test to ensure the nvPM sampling and measurement system operates correctly during an engine test, especially if new system components are being utilised, for example a different type of probe.

To check that summation of the flows in Section 5 match that of Section 3 flowrate, an optional flow measurement check may be performed by disconnecting Section 3 from Section 2 and placing a flow meter at Section 3 inlet to verify that the flow is within 25 slpm ± 2 slpm, while ensuring flow rates in each Splitter2 flow path are equal to those to be used during engine test.

To help ensure Diluter1 operability at low power engine conditions, when probe inlet pressure is low, an optional operational check may be performed prior to the engine test using the following recommended procedure:

a) CO_2 calibration gas containing between 3 per cent to 5 per cent of CO_2 should be connected to the sampling probe without over-pressurising the probe tip inlet, such that the calibration gas enters Section 1 near ambient pressure;

b) The nvPM sampling and measurement system should be operated at the flow rates and temperatures used during engine testing;

c) P_1 Pressure Control Valve and the optional shut-off valve on the excess sample flow path should be closed;

d) DF_1 should be calculated. If DF_1 is found to be above 14, then the GL flow rate should be reduced.

Blockage of Diluter1 orifice nozzle may cause DF_1 to increase above 14 indicating that the orifice needs to be cleaned. The flow schematic for the optional Diluter1 operability check is shown in Figure 1.

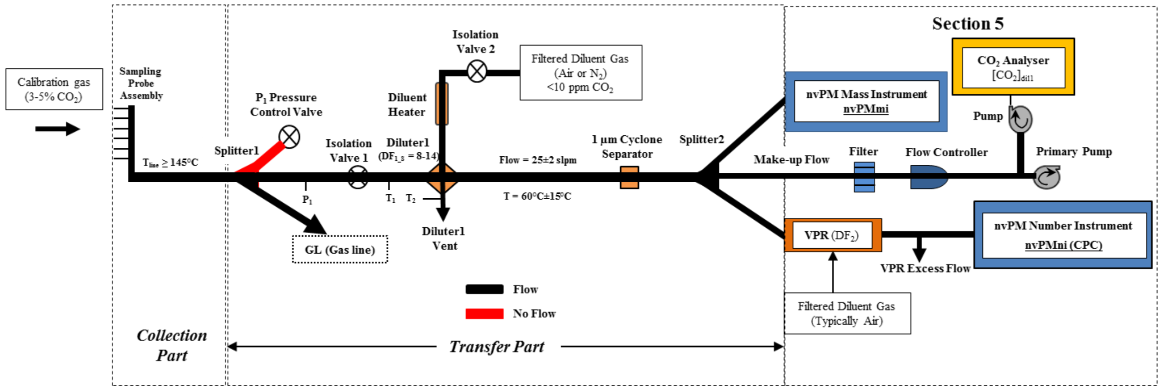


Figure 1. Flow schematic for Diluter1 operability check

1. COLLECTION PART AND GAS LINE LEAKAGE CHECK

[Reserved]

2. COLLECTION PART AND GAS LINE CLEANLINESS CHECK

[Reserved]

3. TRANSFER PART CLEANLINESS/LEAKAGE CHECK

[Reserved]

4. COLLECTION PART BACK-PURGING

[Reserved]

5. AMBIENT nvPM MEASUREMENT

[Reserved]

6. VPR DILUTION FACTOR CALIBRATION CHECK

EXPLANATORY INFORMATION

An alternative to performing the operational VPR dilution checks of the DF_2 values from a Competent Laboratory is using real time measurements of CO_2 at the CPC inlet downstream of the second stage dilution, $[CO_2]_{dil2}$, as shown in Figure 1.

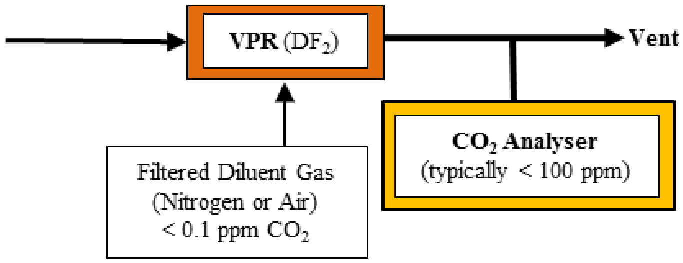


Figure 1. Alternative setup to determine DF$_2$

CO_2 measurement capability for concentration levels as low as 5ppm is needed for this procedure. The suitable range for the CO_2 analyser is typically 30 to 70 ppm FS. Ideally the measured sample gas concentrations should be in the 20 to 95% FS range. If this alternative check is performed, the VPR diluent gas shall contain less than 0.1 ppm of CO_2. The sample does not need to be dried.

During an engine test, DF_2 as calculated below should be used to check if the VPR meets the calibration DF_2 values provided by the Competent Laboratory.

$$DF_2 = \frac{[CO_2]_{dil1}}{[CO_2]_{dil2}}$$

In addition, using this option eliminates the need for dilution factor operational checks pre and post engine test series.

— END —