

International Standards and  
Recommended Practices



**Annex 16**  
to the Convention on  
International Civil Aviation

# Environmental Protection

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**Volume II**  
Aircraft Engine Emissions

This edition incorporates all amendments adopted by the Council prior to 8 March 2008 and supersedes, on 20 November 2008, all previous editions of Annex 16, Volume II.

For information regarding the applicability of the Standards and Recommended Practices, see Foreword.

Third Edition  
July 2008

International Civil Aviation Organization



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**International Civil Aviation Organization**

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# FOREWORD

## Historical background

In 1972 the United Nations Conference on the Human Environment was held in Stockholm. The position of ICAO at this Conference was developed in Assembly Resolution A18-11 which contained the following clause among others:

- “2. in fulfilling this role ICAO is conscious of the adverse environmental impact that may be related to aircraft activity and its responsibility and that of its member States to achieve maximum compatibility between the safe and orderly development of civil aviation and the quality of the human environment;”

The 18th Assembly also adopted Resolution A18-12 relating to the environment which states:

### “THE ASSEMBLY:

1. REQUESTS the Council, with the assistance and co-operation of other bodies of the Organization and other international organizations to continue with vigour the work related to the development of Standards, Recommended Practices and Procedures and/or guidance material dealing with the quality of the human environment;”

This resolution was followed up by the establishment of an ICAO Action Programme Regarding the Environment. As part of this Action Programme a Study Group was established to assist the Secretariat in certain tasks related to aircraft engine emissions. As a result of the work of this Study Group, an ICAO Circular entitled *Control of Aircraft Engine Emissions* (Circular 134) was published in 1977. This Circular contained guidance material in the form of a certification procedure for the control of vented fuel, smoke and certain gaseous emissions for new turbojet and turbofan engines intended for propulsion at subsonic speeds.

It was agreed by the Council that the subject of aircraft engine emissions was not one that was solely confined to objective technical issues but was one that needed consideration by experts in many fields and included the direct views of Member States. A Council committee, known as the Committee on Aircraft Engine Emissions (CAEE) was therefore established in 1977 to pursue a number of aspects of the subject.

At the second meeting of the Committee on Aircraft Engine Emissions, held in May 1980, proposals were made for material to be included in an ICAO Annex. After amendment following the usual consultation with Member States of the Organization, the proposed material was adopted by the Council to form the text of this document. The Council agreed that it was desirable to include all provisions relating to environmental aspects of aviation in one Annex. It therefore renamed Annex 16 as “Environmental Protection”, making the existing text of the Annex into “Volume I — Aircraft Noise”, the material contained in this document becoming “Volume II — Aircraft Engine Emissions”.

## Applicability

Part I of Volume II of Annex 16 contains definitions and symbols and Part II contains Standards relating to vented fuel. Part III contains Standards relating to emissions certification applicable to the classes of aircraft engines specified in the individual chapters of the Part, where such engines are fitted to aircraft engaged in international civil aviation.

### Action by Contracting States

*Notification of differences.* The attention of Contracting States is drawn to the obligation imposed by Article 38 of the Convention by which Contracting States are required to notify the Organization of any differences between their national regulations and practices and the International Standards contained in this Annex and any amendments thereto. Contracting States are invited to extend such notification to any differences from the Recommended Practices contained in this Annex, and any amendments thereto, when the notification of such differences is important for the safety of air navigation. Further, Contracting States are invited to keep the Organization currently informed of any differences which may subsequently occur, or of the withdrawal of any differences previously notified. A specific request for notification of differences will be sent to Contracting States immediately after the adoption of each amendment to this Annex.

The attention of States is also drawn to the provisions of Annex 15 related to the publication of differences between their national regulations and practices and the related ICAO Standards and Recommended Practices through the Aeronautical Information Service, in addition to the obligation of States under Article 38 of the Convention.

*Use of the Annex text in national regulations.* The Council, on 13 April 1948, adopted a resolution inviting the attention of Contracting States to the desirability of using in their own national regulations, as far as is practicable, the precise language of those ICAO Standards that are of a regulatory character and also of indicating departures from the Standards, including any additional national regulations that were important for the safety or regularity of international air navigation. Wherever possible, the provisions of this Annex have been written in such a way as to facilitate incorporation, without major textual changes, into national legislation.

### Status of Annex components

An Annex is made up of the following component parts, not all of which, however, are necessarily found in every Annex; they have the status indicated.

1.— Material comprising the Annex proper:

- a) *Standards and Recommended Practices* adopted by the Council under the provisions of the Convention. They are defined as follows:

*Standard:* Any specification for physical characteristics, configuration, matériel, performance, personnel or procedure, the uniform application of which is recognized as necessary for the safety or regularity of international air navigation and to which Contracting States will conform in accordance with the Convention; in the event of impossibility of compliance, notification to the Council is compulsory under Article 38.

*Recommended Practice:* Any specification for physical characteristics, configuration, matériel, performance, personnel or procedure, the uniform application of which is recognized as desirable in the interest of safety, regularity or efficiency of international air navigation, and to which Contracting States will endeavour to conform in accordance with the Convention.

- b) *Appendices* comprising material grouped separately for convenience but forming part of the Standards and Recommended Practices adopted by the Council.
- c) *Provisions* governing the applicability of the Standards and Recommended Practices.
- d) *Definitions* of terms used in the Standards and Recommended Practices which are not self-explanatory in that they do not have accepted dictionary meanings. A definition does not have an independent status but is an essential part of each Standard and Recommended Practice in which the term is used, since a change in the meaning of the term would affect the specification.

- e) *Tables* and *Figures* which add to or illustrate a Standard or Recommended Practice and which are referred to therein, form part of the associated Standard or Recommended Practice and have the same status.

2.— Material approved by the Council for publication in association with the Standards and Recommended Practices:

- a) *Forewords* comprising historical and explanatory material based on the action of the Council and including an explanation of the obligations of States with regard to the application of the Standards and Recommended Practices ensuing from the Convention and the Resolution of Adoption.
- b) *Introductions* comprising explanatory material introduced at the beginning of parts, chapters or sections of the Annex to assist in the understanding of the application of the text.
- c) *Notes* included in the text, where appropriate, to give factual information or references bearing on the Standards or Recommended Practices in question, but not constituting part of the Standards or Recommended Practices.
- d) *Attachments* comprising material supplementary to the Standards and Recommended Practices, or included as a guide to their application.

#### **Disclaimer regarding patents**

Attention is drawn to the possibility that certain elements of Standards and Recommended Practices in this Annex may be the subject of patents or other intellectual property rights. ICAO shall not be responsible or liable for not identifying any or all such rights. ICAO takes no position regarding the existence, validity, scope or applicability of any claimed patents or other intellectual property rights, and accepts no responsibility or liability therefore or relating thereto.

#### **Selection of language**

This Annex has been adopted in four languages — English, French, Russian and Spanish. Each Contracting State is requested to select one of those texts for the purpose of national implementation and for other effects provided for in the Convention, either through direct use or through translation into its own national language, and to notify the Organization accordingly.

#### **Editorial practices**

The following practice has been adhered to in order to indicate at a glance the status of each statement: *Standards* have been printed in light face roman; *Recommended Practices* have been printed in light face italics, the status being indicated by the prefix Recommendation; *Notes* have been printed in light face italics, the status being indicated by the prefix *Note*.

It is to be noted that in the English text the following practice has been adhered to when writing the specifications: Standards employ the operative verb “shall” while Recommended Practices employ the operative verb “should”.

The units of measurement used in this document are in accordance with the International System of Units (SI) as specified in Annex 5 to the Convention on International Civil Aviation. Where Annex 5 permits the use of non-SI alternative units, these are shown in parentheses following the basic units. Where two sets of units are quoted it must not be assumed that the pairs of values are equal and interchangeable. It may, however, be inferred that an equivalent level of safety is achieved when either set of units is used exclusively.

Any reference to a portion of this document which is identified by a number includes all subdivisions of that portion.

Table A. Amendments to Annex 16

<i>Amendment</i>	<i>Source(s)</i>	<i>Subject(s)</i>	<i>Adopted Effective Applicable</i>
1st Edition	Special Meeting on Aircraft Noise in the Vicinity of Aerodromes (1969)		2 April 1971 2 August 1971 6 January 1972
1	First Meeting of the Committee on Aircraft Noise	Noise certification of future production and derived versions of subsonic jet aeroplanes and updating of terminology used to describe aircraft weight.	6 December 1972 6 April 1973 16 August 1973
2	Third Meeting of the Committee on Aircraft Noise	Noise certification of light propeller-driven aeroplanes and subsonic jet aeroplanes of 5 700 kg and less maximum certificated takeoff weight and guidance on discharge of functions by States in the cases of lease, charter and interchange of aircraft.	3 April 1974 3 August 1974 27 February 1975
3 (2nd Edition)	Fourth Meeting of the Committee on Aircraft Noise	Noise certification standards for future subsonic jet aeroplanes and propeller-driven aeroplanes, other than STOL aeroplanes, and guidelines for noise certification of future supersonic aeroplanes, propeller-driven STOL aeroplanes and installed APU and associated aircraft systems when operating on the ground.	21 June 1976 21 October 1976 6 October 1977
4 (3rd Edition)	Fifth Meeting of the Committee on Aircraft Noise	Introduction of a new parameter, viz. number of engines in the noise certification standards for subsonic jet aeroplanes, improvements in detailed test procedures to ensure that the same level of technology is applied to all types of aircraft, and editorial changes to simplify the language and eliminate inconsistencies.	6 March 1978 6 July 1978 10 August 1978
5 (Annex 16, Volume I — 1st Edition)	Sixth Meeting of the Committee on Aircraft Noise	<ol style="list-style-type: none"> <li>1. Annex retitled <i>Environmental Protection</i> and to be issued in two volumes as follows: Volume I — <i>Aircraft Noise</i> (incorporating provisions in the third edition of Annex 16 as amended by Amendment 5) and Volume II — <i>Aircraft Engine Emissions</i>.</li> <li>2. Introduction in Volume I of noise certification Standards for helicopters and for future production of existing SST aeroplanes, updating of guidelines for noise certification of installed APU and associated aircraft systems and editorial amendments including changes to units of measurement to bring the Annex in line with Annex 5 provisions.</li> </ol>	11 May 1981 11 September 1981 26 November 1981
6 (Annex 16, Volume II — 1st Edition)	Second Meeting of the Committee on Aircraft Engine Emissions	Introduction of Volume II containing Standards relating to the control of fuel venting, smoke and gaseous emissions from newly manufactured turbojet and turbofan engines intended for subsonic and supersonic propulsion.	30 June 1981 30 October 1981 18 February 1982
1	First Meeting of the Committee on Aviation Environmental Protection	Changes in test fuel specifications, Appendix 4.	4 March 1988 31 July 1988 17 November 1988
2 (2nd Edition)	Second Meeting of the Committee on Aviation Environmental Protection	<ol style="list-style-type: none"> <li>a) increased stringency of NOx emissions limits;</li> <li>b) improvements in the smoke and gaseous emissions certification procedure.</li> </ol>	24 March 1993 26 July 1993 11 November 1993

<i>Amendment</i>	<i>Source(s)</i>	<i>Subject(s)</i>	<i>Adopted Effective Applicable</i>
3	Third Meeting of the Committee on Aviation Environmental Protection	Amendment of the criteria on calibration and test gases in Appendices 3 and 5.	20 March 1997 20 March 1997 —
4	Fourth Meeting of the Committee on Aviation Environmental Protection	Increased stringency of NO <sub>x</sub> emissions limits.	26 February 1999 19 July 1999 4 November 1999
5	Sixth Meeting of the Committee on Aviation Environmental Protection	Increase in stringency of the NO <sub>x</sub> emissions Standards.	23 February 2005 11 July 2005 24 November 2005
6 (3rd Edition)	Seventh meeting of the Committee on Aviation Environmental Protection	<ul style="list-style-type: none"> <li>a) clarification of applicable corrections to reference day and reference engine conditions and of the humidity terminology used;</li> <li>b) amendments allowing the use of test fuels outside those specified with certificating authority approval;</li> <li>c) standardization of terminology relating to thrust setting;</li> <li>d) clarification of the appropriate value of fuel flow to be used at each LTO point; and</li> <li>e) amendments to the requirements specifying the materials that may be used in sampling rates.</li> </ul>	7 March 2008 20 July 2008 20 November 2008
7	Eighth meeting of the Committee on Aviation Environmental Protection (CAEP/8).	<ul style="list-style-type: none"> <li>a) increase in stringency of the NO<sub>x</sub> emissions Standards;</li> <li>b) an update to the references to the Environmental Technical Manual (Doc 9501), Volume II — Procedures for the Emissions Certification of Aircraft Engines;</li> <li>c) updates to the text to replace “variations in procedures” by “equivalent procedures”, in order to improve consistency and harmonization within Annex 16, Volume II and with the Environmental Technical Manual (Doc 9501), Volume II — Procedures for the Emissions Certification of Aircraft Engines;</li> <li>d) the format of applicability dates in 2.3.2 made consistent with the convention used in Annex 6 and Annex 16, Volume I;</li> <li>e) improved readability by moving some paragraphs to more appropriate places; and</li> <li>f) minor editorial changes.</li> </ul>	4 March 2011 18 July 2011 17 November 2011





# INTERNATIONAL STANDARDS AND RECOMMENDED PRACTICES

## PART I. DEFINITIONS AND SYMBOLS

### CHAPTER 1. DEFINITIONS

Where the following expressions are used in Volume II of this Annex, they have the meanings ascribed to them below:

**Afterburning.** A mode of engine operation wherein a combustion system fed (in whole or part) by vitiated air is used.

**Approach phase.** The operating phase defined by the time during which the engine is operated in the approach operating mode.

**Climb phase.** The operating phase defined by the time during which the engine is operated in the climb operating mode.

**Date of manufacture.** The date of issue of the document attesting that the individual aircraft or engine as appropriate conforms to the requirements of the type or the date of an analogous document.

**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.

*Note.— Attention is drawn to the difference between the definition of “derived version of an aeroplane” in Volume I of Annex 16 and the definition of “derivative version” in this Volume.*

**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.

**Oxides of nitrogen.** The sum of the amounts of the nitric oxide and nitrogen dioxide contained in a gas sample calculated as if the nitric oxide were in the form of nitrogen dioxide.

**Rated thrust.** For engine emissions purposes, the maximum take-off thrust approved by the certificating authority for use under normal operating conditions at ISA sea level static conditions, and without the use of water injection. Thrust is expressed in kilonewtons.

**Reference pressure ratio.** The ratio of the mean total pressure at the last compressor discharge plane of the compressor to the mean total pressure at the compressor entry plane when the engine is developing take-off thrust rating in ISA sea level static conditions.

*Note.— Methods of measuring reference pressure ratio are given in Appendix 1.*

**Smoke.** The carbonaceous materials in exhaust emissions which obscure the transmission of light.

**Smoke Number.** The dimensionless term quantifying smoke emissions (*see* 3 of Appendix 2).

**Take-off phase.** The operating phase defined by the time during which the engine is operated at the rated thrust.

**Taxi/ground idle.** The operating phases involving taxi and idle between the initial starting of the propulsion engine(s) and the initiation of the take-off roll and between the time of runway turn-off and final shutdown of all propulsion engine(s).

**Unburned hydrocarbons.** The total of hydrocarbon compounds of all classes and molecular weights contained in a gas sample, calculated as if they were in the form of methane.

---

## CHAPTER 2. SYMBOLS

Where the following symbols are used in Volume II of this Annex, they have the meanings ascribed to them below:

CO	Carbon monoxide
$D_p$	The mass of any gaseous pollutant emitted during the reference emissions landing and take-off cycle
$F_n$	Thrust in International Standard Atmosphere (ISA), sea level conditions, for the given operating mode
$F_{oo}$	Rated thrust
$F^*_{oo}$	Rated thrust with afterburning applied
HC	Unburned hydrocarbons ( <i>see</i> definition)
NO	Nitric oxide
NO <sub>2</sub>	Nitrogen dioxide
NO <sub>x</sub>	Oxides of nitrogen ( <i>see</i> definition)
SN	Smoke Number ( <i>see</i> definition)
$\pi_{oo}$	Reference pressure ratio ( <i>see</i> definition)

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## **PART II. VENTED FUEL**

### **CHAPTER 1. ADMINISTRATION**

1.1 The provision of this Part shall apply to all turbine engine powered aircraft intended for operation in international air navigation manufactured after 18 February 1982.

1.2 Certification related to the prevention of intentional fuel venting shall be granted by the certificating authority on the basis of satisfactory evidence that either the aircraft or the aircraft engines comply with requirements of Chapter 2.

*Note.— The document attesting certification relating to fuel venting may take the form of a separate fuel venting certificate or a suitable statement contained in another document approved by the certificating authority.*

1.3 Contracting States shall recognize as valid a certification relating to fuel venting granted by the certificating authority of another Contracting State provided the requirements under which such certification was granted are not less stringent than the provision of Volume II of this Annex.



## **CHAPTER 2. PREVENTION OF INTENTIONAL FUEL VENTING**

Aircraft shall be so 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.

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## PART III. EMISSIONS CERTIFICATION

### CHAPTER 1. ADMINISTRATION

1.1 The provisions of 1.2 to 1.4 shall apply to all engines included in the classifications defined for emission certification purposes in Chapters 2 and 3 where such engines are fitted to aircraft engaged in international air navigation.

1.2 Emissions certification shall be granted by the certifying authority on the basis of satisfactory evidence that the engine complies with requirements which are at least equal to the stringency of the provisions of Volume II of this Annex. Compliance with the emissions levels of Chapters 2 and 3 shall be demonstrated using the procedure described in Appendix 6.

*Note.— The document attesting emissions certification may take the form of a separate emissions certificate or a suitable statement contained in another document approved by the certifying authority.*

1.3 The document attesting emissions certification for each individual engine shall include at least the following information which is applicable to the engine type:

- a) name of certifying authority;
- b) manufacturer's type and model designation;
- c) statement of any additional modifications incorporated for the purpose of compliance with the applicable emissions certification requirements;
- d) rated thrust;
- e) reference pressure ratio;
- f) a statement indicating compliance with Smoke Number requirements;
- g) a statement indicating compliance with gaseous pollutant requirements.

1.4 Contracting States shall recognize as valid emissions certification granted by the certifying authority of another Contracting State provided that the requirements under which such certification was granted are not less stringent than the provisions of Volume II of this Annex.

1.5 Contracting States shall recognize as valid engine exemptions for an engine production cut-off requirement granted by a certifying authority of another Contracting State provided that the exemptions are granted in accordance with the process and criteria defined in the *Environmental Technical Manual* (Doc 9501), Volume II — *Procedures for the Emissions Certification of Aircraft Engines*.



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

### 2.1 General

#### 2.1.1 Applicability

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 over a specific period of time 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 NEW” or “EXEMPT SPARE” and the grant of exemption shall be noted in the permanent engine record. Exemptions shall be reported by engine serial number and made available via an official public register.

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.

*Note.— In considering exemptions, certificating authorities should take into account the probable numbers of such engines that will be produced and their impact on the environment. When such an exemption is granted, the certificating authority should consider imposing a time limit on the production of such engines for installation on new aircraft. Further guidance on issuing exemptions is provided in the Environmental Technical Manual (Doc 9501), Volume II — Procedures for the Emissions Certification of Aircraft Engines.*

#### 2.1.2 Emissions involved

The following emissions shall be controlled for certification of aircraft engines:

Smoke

Gaseous emissions

- Unburned hydrocarbons (HC);
- Carbon monoxide (CO); and
- Oxides of nitrogen (NO<sub>x</sub>).

#### 2.1.3 Units of measurement

2.1.3.1 The smoke emission shall be measured and reported in terms of Smoke Number (SN).

2.1.3.2 The mass ( $D_p$ ) of the gaseous pollutant HC, CO, or NO<sub>x</sub> emitted during the reference emissions landing and take-off (LTO) cycle, defined in 2.1.4.2 and 2.1.4.3, shall be measured and reported in grams.

#### 2.1.4 Reference conditions

##### 2.1.4.1 Atmospheric conditions

The reference atmospheric conditions shall be ISA at sea level except that the reference absolute humidity shall be 0.00634 kg water/kg dry air.

##### 2.1.4.2 Thrust settings

The engine shall be tested at sufficient thrust settings to define the gaseous and smoke emissions of the engine so that mass emission rates and Smoke Numbers can be determined at the following specific percentages of rated thrust as agreed by the certificating authority:

<i>LTO operating mode</i>	<i>Thrust setting</i>
Take-off	100 per cent $F_{oo}$
Climb	85 per cent $F_{oo}$
Approach	30 per cent $F_{oo}$
Taxi/ground idle	7 per cent $F_{oo}$

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

The reference emissions LTO cycle for the calculation and reporting of gaseous emissions shall be represented by the following time in each operating mode.

<i>Phase</i>	<i>Time in operating mode, minutes</i>
Take-off	0.7
Climb	2.2
Approach	4.0
Taxi/ground idle	26.0

##### 2.1.4.4 Fuel specifications

The fuel used during tests shall meet the specifications of Appendix 4.

#### 2.1.5 Test conditions

2.1.5.1 The tests shall be made with the engine on its test bed.

2.1.5.2 The engine shall be representative of the certificated configuration (*see* Appendix 6); off-take bleeds and accessory loads other than those necessary for the engine's basic operation shall not be simulated.

2.1.5.3 When test conditions differ from the reference atmospheric conditions in 2.1.4.1, the gaseous emissions test results shall be corrected to the reference atmospheric conditions by the methods given in Appendix 3.

## 2.2 Smoke

### 2.2.1 Applicability

The provisions of 2.2.2 shall apply to engines whose date of manufacture is on or after 1 January 1983.

### 2.2.2 Regulatory Smoke Number

The Smoke Number at any of the four LTO operating mode thrust settings when measured and computed in accordance with the procedures of Appendix 2, or equivalent procedures as agreed by the certifying authority, and converted to a characteristic level by the procedures of Appendix 6 shall not exceed the level determined from the following formula:

$$\text{Regulatory Smoke Number} = 83.6 (F_{oo})^{-0.274}$$

or a value of 50, whichever is lower

*Note.*— Guidance material on the definition and the use of equivalent procedures is provided in the Environmental Technical Manual (Doc 9501), Volume II — Procedures for the Emissions Certification of Aircraft Engines.

## 2.3 Gaseous emissions

### 2.3.1 Applicability

The provisions of 2.3.2 shall apply to engines whose rated thrust is greater than 26.7 kN and whose date of manufacture is on or after 1 January 1986 and as further specified for oxides of nitrogen.

### 2.3.2 Regulatory levels

Gaseous emission levels when measured and computed in accordance with the procedures of Appendix 3 and converted to characteristic levels by the procedures of Appendix 6, or equivalent procedures as agreed by the certifying authority, shall not exceed the regulatory levels determined from the following formulas:

Hydrocarbons (HC):  $D_p/F_{oo} = 19.6$

Carbon monoxide (CO):  $D_p/F_{oo} = 118$

Oxides of nitrogen (NO<sub>x</sub>):

- a) for engines of a type or model for which the date of manufacture of the first individual production model was before 1 January 1996 and for which the date of manufacture of the individual engine was before 1 January 2000.

$$D_p/F_{oo} = 40 + 2\pi_{oo}$$

- b) for engines of a type or model for which the date of manufacture of the first individual production model was on or after 1 January 1996 or for which the date of manufacture of the individual engine was on or after 1 January 2000.

$$D_p/F_{oo} = 32 + 1.6\pi_{oo}$$

- c) for engines of a type or model for which the date of manufacture of the first individual production model was on or after 1 January 2004:

1) for engines with a pressure ratio of 30 or less:

i) for engines with a maximum rated thrust of more than 89.0 kN:

$$D_p/F_{oo} = 19 + 1.6\pi_{oo}$$

ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$$D_p/F_{oo} = 37.572 + 1.6\pi_{oo} - 0.2087F_{oo}$$

2) for engines with a pressure ratio of more than 30 but less than 62.5:

i) for engines with a maximum rated thrust of more than 89.0 kN:

$$D_p/F_{oo} = 7 + 2.0\pi_{oo}$$

ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$$D_p/F_{oo} = 42.71 + 1.4286\pi_{oo} - 0.4013F_{oo} + 0.00642\pi_{oo} \times F_{oo}$$

3) for engines with a pressure ratio of 62.5 or more:

$$D_p/F_{oo} = 32 + 1.6\pi_{oo}$$

d) for engines of a type or model for which the date of manufacture of the first individual production model was on or after 1 January 2008 or for which the date of manufacture of the individual engine was on or after 1 January 2013:

1) for engines with a pressure ratio of 30 or less:

i) for engines with a maximum rated thrust of more than 89.0 kN:

$$D_p/F_{oo} = 16.72 + 1.4080\pi_{oo}$$

ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$$D_p/F_{oo} = 38.5486 + 1.6823\pi_{oo} - 0.2453F_{oo} - 0.00308\pi_{oo}F_{oo}$$

2) for engines with a pressure ratio of more than 30 but less than 82.6:

i) for engines with a maximum rated thrust of more than 89.0 kN:

$$D_p/F_{oo} = -1.04 + 2.0\pi_{oo}$$

ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$$D_p/F_{oo} = 46.1600 + 1.4286\pi_{oo} - 0.5303F_{oo} + 0.00642\pi_{oo}F_{oo}$$

3) for engines with a pressure ratio of 82.6 or more:

$$D_p/F_{oo} = 32 + 1.6\pi_{oo}$$

e) for engines of a type or model for which the date of manufacture of the first individual production model was on or after 1 January 2014:

1) for engines with a pressure ratio of 30 or less:

i) for engines with a maximum rated thrust of more than 89.0 kN:

$$D_p / F_{oo} = 7.88 + 1.4080\pi_{oo}$$

ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$$D_p / F_{oo} = 40.052 + 1.5681\pi_{oo} - 0.3615F_{oo} - 0.0018\pi_{oo}F_{oo}$$

2) for engines with a pressure ratio of more than 30 but less than 104.7:

i) for engines with a maximum rated thrust of more than 89.0 kN:

$$D_p / F_{oo} = -9.88 + 2.0\pi_{oo}$$

ii) for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN:

$$D_p / F_{oo} = 41.9435 + 1.505\pi_{oo} - 0.5823F_{oo} + 0.005562\pi_{oo} F_{oo}$$

3) for engines with a pressure ratio of 104.7 or more:

$$D_p / F_{oo} = 32 + 1.6\pi_{oo}$$

*Note.*— *Guidance material on the definition and the use of equivalent procedures is provided in the Environmental Technical Manual (Doc 9501), Volume II — Procedures for the Emissions Certification of Aircraft Engines.*

## 2.4 Information required

*Note.*— *The information required is divided into three groups: 1) general information to identify the engine characteristics, the fuel used and the method of data analysis; 2) the data obtained from the engine test(s); and 3) the results derived from the test data.*

### 2.4.1 General information

The following information shall be provided for each engine type for which emissions certification is sought:

- a) engine identification;
- b) rated thrust (in kilonewtons);
- c) reference pressure ratio;
- d) fuel specification reference;
- e) fuel hydrogen/carbon ratio;

- f) the methods of data acquisition;
- g) the method of making corrections for ambient conditions; and
- h) the method of data analysis.

#### 2.4.2 Test information

The following information shall be provided for each engine tested for certification purposes at each of the thrust settings specified in 2.1.4.2. The information shall be provided after correction to the reference ambient conditions where applicable:

- a) fuel flow (kilograms/second);
- b) emission index (grams/kilogram) for each gaseous pollutant; and
- c) measured Smoke Number.

#### 2.4.3 Derived information

2.4.3.1 The following derived information shall be provided for each engine tested for certification purposes:

- a) emission rate, i.e. emission index  $\times$  fuel flow, (grams/second) for each gaseous pollutant;
- b) total gross emission of each gaseous pollutant measured over the LTO cycle (grams);
- c) values of  $D_p/F_{oo}$  for each gaseous pollutant (grams/kilonewton); and
- d) maximum Smoke Number.

2.4.3.2 The characteristic Smoke Number and gaseous pollutant emission levels shall be provided for each engine type for which emissions certification is sought.



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

### 3.1 General

#### 3.1.1 Applicability

The provisions of this chapter shall apply to all turbojet and turbofan engines intended for propulsion at supersonic speeds whose date of manufacture is on or after 18 February 1982.

#### 3.1.2 Emissions involved

The following emissions shall be controlled for certification of aircraft engines:

Smoke

Gaseous emissions

Unburned hydrocarbons (HC);

Carbon monoxide (CO); and

Oxides of nitrogen (NO<sub>x</sub>).

#### 3.1.3 Units of measurement

3.1.3.1 The smoke emission shall be measured and reported in terms of Smoke Number (SN).

3.1.3.2 The mass ( $D_p$ ) of the gaseous pollutants HC, CO, or NO<sub>x</sub> emitted during the reference emissions landing and take-off (LTO) cycle, defined in 3.1.5.2 and 3.1.5.3 shall be measured and reported in grams.

#### 3.1.4 Nomenclature

Throughout this chapter, where the expression  $F_{oo}^*$  is used, it shall be replaced by  $F_{oo}$  for engines which do not employ afterburning. For taxi/ground idle thrust setting,  $F_{oo}$  shall be used in all cases.

#### 3.1.5 Reference conditions

##### 3.1.5.1 Atmospheric conditions

The reference atmospheric conditions shall be ISA at sea level except that the reference absolute humidity shall be 0.00634 kg water/kg dry air.

3.1.5.2 *Thrust settings*

The engine shall be tested at sufficient power settings to define the gaseous and smoke emissions of the engine so that mass emission rates and Smoke Numbers corrected to the reference ambient conditions can be determined at the following specific percentages of rated output as agreed by the certificating authority.

<i>Operating mode</i>	<i>Thrust setting</i>
Take-off	100 per cent $F_{oo}^*$
Climb	65 per cent $F_{oo}^*$
Descent	15 per cent $F_{oo}^*$
Approach	34 per cent $F_{oo}^*$
Taxi/ground idle	5.8 per cent $F_{oo}$

3.1.5.3 *Reference emissions landing and take-off (LTO) cycle*

The reference emissions LTO cycle for the calculation and reporting of gaseous emissions shall be represented by the following time in each operating mode.

<i>Phase</i>	<i>Time in operating mode, minutes</i>
Take-off	1.2
Climb	2.0
Descent	1.2
Approach	2.3
Taxi/ground idle	26.0

3.1.5.4 *Fuel specifications*

The fuel used during tests shall meet the specifications of Appendix 4. Additives used for the purpose of smoke suppression (such as organo-metallic compounds) shall not be present.

## 3.1.6 Test conditions

3.1.6.1 The tests shall be made with the engine on its test bed.

3.1.6.2 The engine shall be representative of the certificated configuration (*see* Appendix 6); off-take bleeds and accessory loads other than those necessary for the engine's basic operation shall not be simulated.

3.1.6.3 Measurements made for determination of emission levels at the thrusts specified in 3.1.5.2 shall be made with the afterburner operating at the level normally used, as applicable.

3.1.7 When test conditions differ from the reference conditions in 3.1.5, the test results shall be corrected to the reference conditions by the methods given in Appendix 5.

## 3.2 Smoke

### 3.2.1 Regulatory Smoke Number

The Smoke Number at any thrust setting when measured and computed in accordance with the procedures of Appendix 2 and converted to a characteristic level by the procedures of Appendix 6 shall not exceed the regulatory level determined from the following formula:

$$\text{Regulatory Smoke Number} = 83.6 (F_{oo}^*)^{-0.274}$$

or a value of 50,  
whichever is lower

*Note.*— *Certificating authorities may alternatively accept values determined using afterburning provided that the validity of these data is adequately demonstrated.*

## 3.3 Gaseous emissions

### 3.3.1 Regulatory levels

Gaseous emission levels when measured and computed in accordance with the procedures of Appendix 3 or Appendix 5, as applicable, and converted to characteristic levels by the procedures of Appendix 6 shall not exceed the regulatory levels determined from the following formulas:

$$\text{Hydrocarbons (HC): } D_p/F_{oo}^* = 140(0.92)^{\pi_{oo}}$$

$$\text{Carbon monoxide (CO): } D_p/F_{oo}^* = 4\,550(\pi_{oo})^{-1.03}$$

$$\text{Oxides of nitrogen (NO}_x\text{): } D_p/F_{oo}^* = 36 + 2.42\pi_{oo}$$

*Note.*— *The characteristic level of the Smoke Number or gaseous pollutant emissions is the mean of the values of all the engines tested, measured and corrected to the reference standard engine and reference ambient conditions, divided by the coefficient corresponding to the number of engines tested, as shown in Appendix 6.*

## 3.4 Information required

*Note.*— *The information required is divided into three groups: 1) general information to identify the engine characteristics, the fuel used and the method of data analysis; 2) the data obtained from the engine test(s); and 3) the results derived from the test data.*

3.4.1 The following information shall be provided for each engine type for which emissions certification is sought:

- a) engine identification;
- b) rated output (in kilonewtons);
- c) rated output with afterburning applied, if applicable (in kilonewtons);

- d) reference pressure ratio;
- e) fuel specification reference;
- f) fuel hydrogen/carbon ratio;
- g) the methods of data acquisition;
- h) the method of making corrections for ambient conditions; and
- i) the method of data analysis.

#### 3.4.2 Test information

The following information shall be provided for each engine tested for certification purposes at each of the thrust settings specified in 3.1.5.2. The information shall be provided after correction to the reference ambient conditions where applicable:

- a) fuel flow (kilograms/second);
- b) emission index (grams/kilogram) for each gaseous pollutant;
- c) percentage of thrust contributed by afterburning; and
- d) measured Smoke Number.

#### 3.4.3 Derived information

3.4.3.1 The following derived information shall be provided for each engine tested for certification purposes:

- a) emission rate, i.e. emission index  $\times$  fuel flow, (grams/second), for each gaseous pollutant;
- b) total gross emission of each gaseous pollutant measured over the LTO cycle (grams);
- c) values of  $D_p/F^*_{oo}$  for each gaseous pollutant (grams/kilonewton); and
- d) maximum Smoke Number.

3.4.3.2 The characteristic Smoke Number and gaseous pollutant emission levels shall be provided for each engine type for which emissions certification is sought.

*Note.— The characteristic level of the Smoke Number or gaseous pollutant emissions is the mean of the values of all the engines tested, measured and corrected to the reference standard engine and reference ambient conditions, divided by the coefficient corresponding to the number of engines tested, as shown in Appendix 6.*

# 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.

## 2. MEASUREMENT

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 emissions test.*

2.2 Necessary correlation factors shall be determined during type certification testing using a minimum of one engine and any associated engine component tests and analysis.

2.3 Procedures shall be acceptable to the certificating authority.



## APPENDIX 2. SMOKE EMISSION EVALUATION

### 1. INTRODUCTION AND DEFINITIONS

*Note.— The procedures specified here are concerned with the acquisition of representative exhaust samples and their transmission to, and analysis by, the emissions measuring system.*

1.1 Any equivalent procedures to those contained in this Appendix shall only be allowed after prior application to and approval by the certificating authority.

1.2 Where the following expressions and symbols are used in this Appendix, they have the meanings ascribed to them below:

**Sampling reference size.** The sample mass,  $16.2 \text{ kg/m}^2$  of stained filter area, which if passed through the filter material results in a change of reflectance which gives a value of the SN parameter.

**Sampling size.** A chosen exhaust sample, the magnitude of whose mass (expressed in kilograms per square metre of stained filter surface area) lies in the range prescribed in 2.5.3 h) of this Appendix which, when passed through the filter material, causes a change in reflectance yielding a value for the SN parameter.

**Sampling volume.** The chosen sample volume (expressed in cubic metres) whose equivalent mass, calculated as indicated in 3 of this Appendix, conforms to the above definition of sampling size.

**SN.** Smoke Number; Dimension less term quantifying smoke emission level based upon the staining of a filter by the reference mass of exhaust gas sample, and rated on a scale of 0 to 100 (*see* 3 of this Appendix).

**SN'.** Smoke Number obtained from an individual smoke sample, not necessarily of the reference size, as defined in 3 of this Appendix.

**W.** Mass of individual exhaust gas smoke sample, in kilograms, calculated from the measurements of sample volume, pressure and temperature (*see* 3 of this Appendix).

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

- 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.

## 2.2 Sampling line for smoke emissions

2.2.1 The sample shall be transferred from the probe to the sample collection system via a line of 4.0 to 8.5 mm inside diameter taking the shortest route practicable which shall in no case be greater than 25 m. The line temperature shall be maintained at a temperature between 60°C and 175°C with a stability of  $\pm 15^\circ\text{C}$ , except for the distance required to cool the gas from the engine exhaust temperature down to the line control temperature.

2.2.2 Sampling lines shall be as “straight through” as possible. Any necessary bends shall have radii which are greater than 10 times the inside diameter of the lines. The material of the lines shall be such as to discourage build-up of particulate matter or static electricity.

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

## 2.3 Smoke analysis system

*Note.*— *The method prescribed herein is based upon the measurement of the reduction in reflectance of a filter when stained by a given mass flow of exhaust sample.*

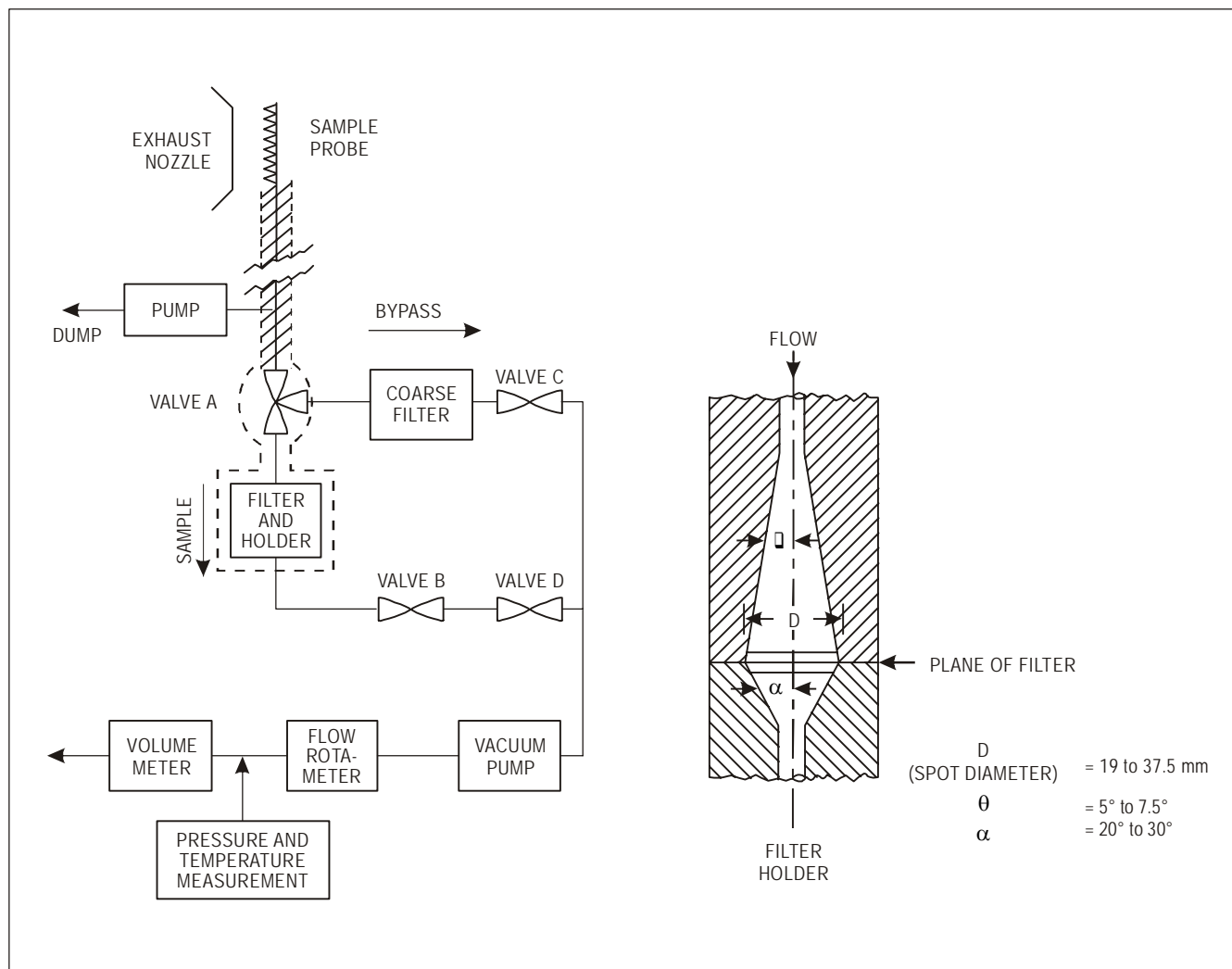
The arrangement of the various components of the system for acquiring the necessary stained filter samples shall be as shown schematically in Figure A2-1. An optional bypass around the volume meter may be installed to facilitate meter reading. The major elements of the system shall meet the following requirements:

- a) *sample size measurement:* a wet or dry positive displacement volume meter shall be used to measure sample volume to an accuracy of  $\pm 2$  per cent. The pressure and temperature at entry to this meter shall also be measured to accuracies of 0.2 per cent and  $\pm 2^\circ\text{C}$  respectively;
- b) *sample flow rate measurement:* the sample flow rate shall be maintained at a value of  $14 \pm 0.5$  L/min and the flowmeter for this purpose shall be able to make this measurement with an accuracy of  $\pm 5$  per cent;
- c) *filter and holder:* the filter holder shall be constructed in corrosion-resistant material and shall have the flow channel configuration shown in Figure A2-1. The filter material shall be Whatman type No. 4, or any equivalent approved by the certificating authority;
- d) *valves:* four valve elements shall be provided as indicated in Figure A2-1:
  - 1) valve A shall be a quick-acting, full-flow, flow diverter enabling the incoming sample to be directed through the measuring filter or around the bypass circuits or shut-off;

*Note.*— *Valve A may, if necessary, consist of two valves interlocked to give the requisite function.*

- 2) valves B and C shall be throttling valves used to establish the system flow rate;
  - 3) valve D shall be a shut-off valve to enable the filter holder to be isolated;
- all valves shall be made of corrosion-resistant material;
- e) *vacuum pump:* this pump shall have a no-flow vacuum capability of  $-75$  kPa with respect to atmospheric pressure; its full-flow rate shall not be less than 28 L/min at normal temperature and pressure;





**Figure A2-1. Smoke analysis system**

- f) *temperature control*: the analyser internal sample line through to the filter holder shall be maintained at a temperature between 60°C and 175°C with a stability of  $\pm 15^\circ\text{C}$ ;

*Note.*— The objective is to prevent water condensation prior to reaching the filter holder and within it.

- 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<sub>2</sub> analyser or complete emissions analysis system.
- 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.
- i) *leak performance*: the subsystem shall meet the requirements of the following test:

- 1) clamp clean filter material into holder,
  - 2) shut off valve A, fully open valves B, C and D.
  - 3) run vacuum pump for one minute to reach equilibrium conditions;
  - 4) continue to pump and measure the volume flow through the meter over a period of five minutes. This volume shall not exceed 5 L (referred to normal temperature and pressure) and the system shall not be used until this standard has been achieved.
- j) *reflectometer*: the measurements of the diffuse reflection density of the filter material shall be by an instrument conforming to the International Organization for Standardization, Standard No. ISO 5-4<sup>1</sup>. The diameter of the reflectometer light beam on the filter paper shall not exceed D/2 nor be less than D/10 where D is the diameter of filter stained spot as defined in Figure A2-1.

## 2.4 Fuel specifications

The fuel shall meet the specifications of Appendix 4.

## 2.5 Smoke measurement procedures

### 2.5.1 Engine operation

2.5.1.1 The engine shall be operated on a static test facility which is suitable and properly equipped for high accuracy performance testing.

2.5.1.2 The tests shall be made at the thrust settings approved by the certificating authority. The engine shall be stabilized at each setting.

### 2.5.2 Leakage and cleanliness checks

No measurements shall be made until all sample transfer lines and valves are warmed up and stable. Prior to a series of tests the system shall be checked for leakage and cleanliness as follows:

- a) *leakage check*: isolate probe and close off end of sample line, perform leakage test as specified in 2.3 h) with the exceptions that valve A is opened and set to “bypass”, valve D is closed and that the leakage limit is 2 L. Restore probe and line interconnection;
- b) cleanliness check:
  - 1) open valves B, C and D

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1. International Organization for Standardization, Standard No. ISO 5-4: 1995 entitled “Photography – Density measurements – Part 4: Geometric conditions for reflection density”.

- 2) run vacuum pump and alternately set valve A to “bypass” and “sample” to purge the entire system with clean air for five minutes;
- 3) set valve A to “bypass”;
- 4) close valve D and clamp clean filter material into holder. Open valve D;
- 5) set valve A to “sample” and reset back to “bypass” after 50 kg of air per square metre of filter has passed through the filter material;
- 6) measure resultant filter spot SN’ as described in paragraph 3 of this Appendix;
- 7) if this SN’ exceeds 3, the system shall be cleaned (or otherwise rectified) until a value lower than 3 is obtained.

The system shall not be used until the requirements of these leakage and cleanliness checks have been met.

### 2.5.3 Smoke measurement

Smoke measurement shall be made independently of other measurements unless the smoke values so measured are significantly below the limiting values, or unless it can be demonstrated that the smoke values from simultaneous smoke and gaseous emissions measurements are valid, in which case smoke measurements may be made simultaneously with gaseous emissions measurements. In all cases the bend radius requirements for sampling lines detailed in 2.2.2 shall be strictly observed. The smoke analysis subsystem shall be set up and conform to the specifications of 2.3. Referring to Figure A2-1, the following shall be the major operations in acquiring the stained filter specimens:

- a) during engine operation with the probe in position, valve A shall not be placed in the no-flow condition, otherwise particulate buildup in the lines might be encouraged;
- b) set valve A to “bypass”, close valve D and clamp clean filter into holder. Continue to draw exhaust sample in the bypass setting for at least five minutes while the engine is at or near to the required operating condition, valve C being set to give a flow rate of  $14 \pm 0.5$  L/min;
- c) open valve D and set valve A to “sample”, use valve B to set flow rate again to value set in b);
- d) set valve A to “bypass” and close valve D, clamp clean filter material into the holder;
- e) when the engine is stabilized on condition, allow one minute of sample flow with settings as at d);
- f) open valve D, set valve A to “sample”, reset flow rate if necessary, and allow chosen sample volume (*see h*) to pass, before setting valve A back to “bypass” and close valve D;
- g) set aside stained filter for analysis, clamp clean filter into holder;
- h) the chosen sample sizes shall be such as to be within the range of 12 kg to 21 kg of exhaust gas per square metre of filter, and shall include samples which are either at the value of 16.2 kg of exhaust gas per square metre of filter or lie above and below that value. The number of samples at each engine operating condition shall not be less than 3 and e) to g) shall be repeated as necessary.

### 3. CALCULATION OF SMOKE NUMBER FROM MEASURED DATA

The stained filter specimens obtained as outlined in 2.5.3 shall be analysed using a reflectometer as specified in 2.3. The backing material used shall be black with an absolute reflectance of less than 3 per cent. The absolute reflectance reading  $R_S$  of each stained filter shall be used to calculate the reduction in reflectance by

$$SN' = 100(1 - R_S/R_W)$$

where  $R_W$  is the absolute reflectance of clean filter material.

The masses of the various samples shall be calculated by

$$W = 0.348 PV/T \times 10^{-2}(\text{kg})$$

where  $P$  and  $T$  are, respectively, the sample pressure in Pascal and the temperature in Kelvin, measured immediately upstream of the volume meter.  $V$  is the measured sample volume in cubic metres.

For each engine condition in the case that the sample sizes range above and below the reference value, the various values of  $SN'$  and  $W$  shall be plotted as  $SN'$  versus  $\log W/A$ , where  $A$  is the filter stain area ( $\text{m}^2$ ). Using a least squares straight line fit, the value of  $SN'$  for  $W/A = 16.2 \text{ kg/m}^2$  shall be estimated and reported as the Smoke Number ( $SN$ ) for that engine mode. Where sampling at the reference size value only is employed, the reported  $SN$  shall be the arithmetic average of the various individual values of  $SN'$ .

### 4. REPORTING OF DATA TO THE CERTIFICATING AUTHORITY

The measured data shall be reported to the certificating authority. In addition the following data shall be reported for each test:

- a) sample temperature;
- b) sample pressure;
- c) actual sample volume at sampling conditions;
- d) actual sample flow rate at sampling conditions; and
- e) leak and cleanliness checks substantiation (*see* 2.5.2).

## APPENDIX 3. INSTRUMENTATION AND MEASUREMENT TECHNIQUES FOR GASEOUS EMISSIONS

### 1. INTRODUCTION

*Note.*— The procedures specified in this appendix are concerned with the acquisition of representative exhaust samples and their transmission to, and analysis by, the emissions measuring system. The procedures do not apply to engines employing afterburning. The methods proposed are representative of the best readily available and most established practice.

Any equivalent procedures to those contained in this appendix shall only be allowed after prior application to and approval by the certifying authority.

### 2. DEFINITIONS

Where the following expressions are used in this appendix, they have the meanings ascribed to them below:

**Accuracy.** The closeness with which a measurement approaches the true value established independently.

**Air/fuel ratio.** The mass rate of airflow through the hot section of the engine divided by the mass rate of fuel flow to the engine.

**Calibration gas.** A high accuracy reference gas to be used for alignment, adjustment and periodic checks of instruments.

**Concentration.** The volume fraction of the component of interest in the gas mixture — expressed as volume percentage or as parts per million.

**Flame ionization detector.** A hydrogen-air diffusion flame detector that produces a signal nominally proportional to the mass-flow rate of hydrocarbons entering the flame per unit of time — generally assumed responsive to the number of carbon atoms entering the flame.

**Interference.** Instrument response due to presence of components other than the gas (or vapour) that is to be measured.

**Noise.** Random variation in instrument output not associated with characteristics of the sample to which the instrument is responding, and distinguishable from its drift characteristics.

**Non-dispersive infrared analyser.** An instrument that by absorption of infrared energy selectively measures specific components.

**Parts per million (ppm).** The unit volume concentration of a gas per million unit volume of the gas mixture of which it is a part.

**Parts per million carbon (ppmC).** The mole fraction of hydrocarbon multiplied by  $10^6$  measured on a methane-equivalence basis. Thus, 1 ppm of methane is indicated as 1 ppmC. To convert ppm concentration of any hydrocarbon to an equivalent ppmC value, multiply ppm concentration by the number of carbon atoms per molecule of the gas. For example, 1 ppm propane translates as 3 ppmC hydrocarbon; 1 ppm hexane as 6 ppmC hydrocarbon.

**Reference gas.** A mixture of gases of specified and known composition used as the basis for interpreting instrument response in terms of the concentration of the gas to which the instrument is responding.

**Repeatability.** The closeness with which a measurement upon a given, invariant sample can be reproduced in short-term repetitions of the measurement with no intervening instrument adjustment.

**Resolution.** The smallest change in a measurement which can be detected.

**Response.** The change in instrument output signal that occurs with change in sample concentration. Also the output signal corresponding to a given sample concentration.

**Stability.** The closeness with which repeated measurements upon a given invariant sample can be maintained over a given period of time.

**Zero drift.** Time-related deviation of instrument output from zero set point when it is operating on gas free of the component to be measured.

**Zero gas.** A gas to be used in establishing the zero, or no-response, adjustment of an instrument.

### 3. DATA REQUIRED

#### 3.1 Gaseous emissions

Concentrations of the following emissions shall be determined:

- a) Hydrocarbons (HC): a combined estimate of all hydrocarbon compounds present in the exhaust gas.
- b) Carbon monoxide (CO).
- c) Carbon dioxide (CO<sub>2</sub>).

*Note.— CO<sub>2</sub> is not a regulated engine emission but its concentration is required for calculation and check purposes.*

- d) Oxides of nitrogen (NO<sub>x</sub>): an estimate of the sum of the two oxides, nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>).
- e) Nitric oxide (NO).

#### 3.2 Other information

In order to normalize the emissions measurement data and to quantify the engine test characteristics, the following additional information shall be provided:

- inlet temperature;
- inlet humidity;

- atmospheric pressure;
- hydrogen/carbon ratio of fuel;
- other required engine parameters (for example, thrust, rotor speeds, turbine temperatures and gas-generator air flow).

This data shall be obtained either by direct measurement or by calculation, as presented in Attachment F to this appendix.

#### 4. GENERAL ARRANGEMENT OF THE SYSTEM

No desiccants, dryers, water traps or related equipment shall be used to treat the exhaust sample flowing to the oxides of nitrogen and the hydrocarbon analysis instrumentation. Requirements for the various component subsystems are given in 5, but the following list gives some qualifications and variations:

- a) it is assumed that each of the various individual subsystems includes the necessary flow control, conditioning and measurement facilities;
- b) the necessity for a dump and/or a hot-sample pump will depend on ability to meet the sample transfer time and analysis subsystem sample flow rate requirements. This in turn depends on the exhaust sample driving pressure and line losses. It is considered that these pumps usually will be necessary at certain engine running conditions; and
- c) the position of the hot pump, relative to the gas analysis subsystems, may be varied as required. (For example, some HC analysers contain hot pumps and so may be judged capable of being used upstream of the system hot pump.)

*Note.— Figure A3-1 is a schematic drawing of the exhaust gas sampling and analytical system and typifies the basic requirements for emissions testing.*

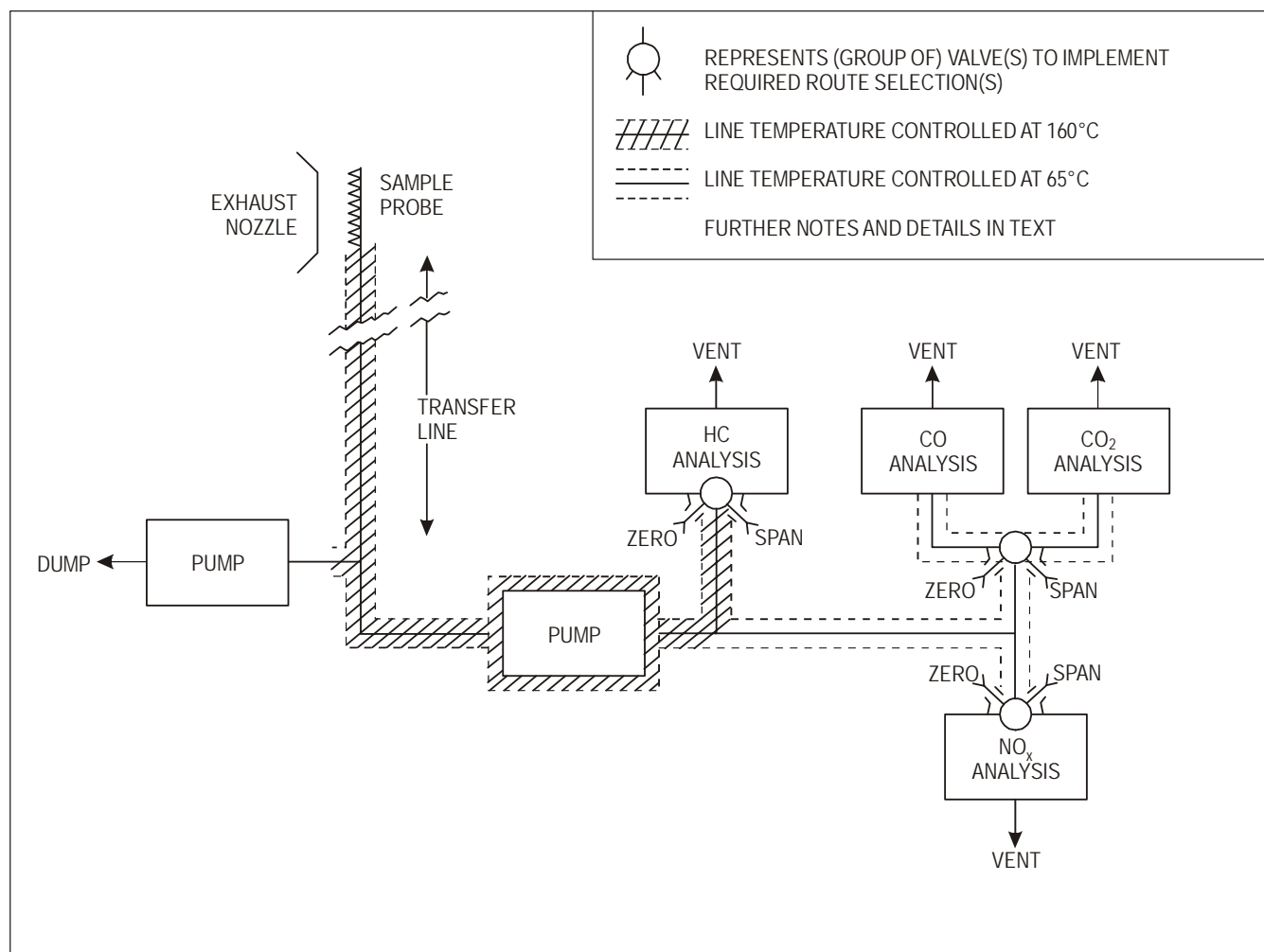
#### 5. DESCRIPTION OF COMPONENT PARTS

*Note.— A general description and specification of the principal elements in the engine exhaust emissions measurement system follows. Greater detail, where necessary, will be found in Attachments A, B and C to this appendix.*

##### 5.1 Sampling system

###### 5.1.1 Sampling probe

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



**Figure A3-1. Sampling and analysis system, schematic**

### 5.1.2 Sampling lines

The sample shall be transferred from the probe to the analysers via a line of 4.0 to 8.5 mm inside diameter, taking the shortest route practicable and using a flow rate such that the transport time is less than 10 seconds. The line shall be maintained at a temperature of  $160^{\circ}\text{C} \pm 15^{\circ}\text{C}$  (with a stability of  $\pm 10^{\circ}\text{C}$ ), except for a) the distance required to cool the gas from the engine exhaust temperature down to the line control temperature, and b) the branch which supplies samples to the CO, CO<sub>2</sub>, and NO<sub>x</sub> analysers. This branch line shall be maintained at a temperature of  $65^{\circ}\text{C} \pm 15^{\circ}\text{C}$  (with a stability of  $\pm 10^{\circ}\text{C}$ ). When sampling to measure HC, CO, CO<sub>2</sub> and NO<sub>x</sub> components the line shall be constructed in stainless steel or carbon-loaded grounded PTFE.

### 5.2 HC analyser

The measurement of total hydrocarbon sample content shall be made by an analyser using the heated flame ionization detector (FID), between the electrodes of which passes an ionization current proportional to the mass rate of hydrocarbon entering a hydrogen flame. The analyser shall be deemed to include components arranged to control temperature and flow rates of sample, sample bypass, fuel and diluent gases, and to enable effective span and zero calibration checks.

*Note.— An overall specification is given in Attachment A to this appendix.*



### 5.3 CO and CO<sub>2</sub> analysers

Non-dispersive infrared analysers shall be used for the measurements of these components, and shall be of the design which utilizes differential energy absorption in parallel reference and sample gas cells, the cell or group of cells for each of these gas constituents being sensitized appropriately. This analysis subsystem shall include all necessary functions for the control and handling of sample, zero and span gas flows. Temperature control shall be that appropriate to whichever basis of measurement, wet or dry, is chosen.

*Note.— An overall specification is given in Attachment B to this appendix.*

### 5.4 NO<sub>x</sub> analyser

The measurement of NO concentration shall be by the chemiluminescent method in which the measure of the radiation intensity emitted during the reaction of the NO in the sample with added O<sub>3</sub> is the measure of the NO concentration. The NO<sub>2</sub> component shall be converted to NO in a converter of the requisite efficiency prior to measurement. The resultant NO<sub>x</sub> measurement system shall include all necessary flow, temperature and other controls and provide for routine zero and span calibration as well as for converter efficiency checks.

*Note.— An overall specification is given in Attachment C to this appendix.*

## 6. GENERAL TEST PROCEDURES

### 6.1 Engine operation

6.1.1 The engine shall be operated on a static test facility which is suitable and properly equipped for high accuracy performance testing.

6.1.2 The emissions tests shall be made at the thrust settings prescribed by the certificating authority. The engine shall be stabilized at each setting.

### 6.2 Major instrument calibration

*Note.— The general objective of this calibration is to confirm stability and linearity.*

6.2.1 The applicant shall satisfy the certificating authority that the calibration of the analytical system is valid at the time of the test.

6.2.2 For the hydrocarbon analyser this calibration shall include checks that the detector oxygen and differential hydrocarbon responses are within the limits specified, as laid down in Attachment A to this appendix. The efficiency of the NO<sub>2</sub>/NO converter shall also be checked and verified to meet the requirements in Attachment C to this appendix.

6.2.3 The procedure for checking the performance of each analyser shall be as follows (using the calibration and test gases as specified in Attachment D to this appendix):

- a) introduce zero gas and adjust instrument zero, recording setting as appropriate;
- b) for each range to be used operationally, introduce calibration gas of (nominally) 90 per cent range full-scale deflection (FSD) concentration; adjust instrument gain accordingly and record its setting;

- c) introduce approximately 30 per cent, 60 per cent, and 90 per cent range FSD concentration and record analyser readings;
- d) fit a least squares straight line to the zero, 30 per cent, 60 per cent and 90 per cent concentration points. For the CO and/or CO<sub>2</sub> analyser used in their basic form without linearization of output, a least squares curve of appropriate mathematical formulation shall be fitted using additional calibration points if judged necessary. If any point deviates by more than 2 per cent of the full scale value (or  $\pm 1$  ppm\*, whichever is greater) then a calibration curve shall be prepared for operational use.

### 6.3 Operation

6.3.1 No measurements shall be made until all instruments and sample transfer lines are warmed up and stable and the following checks have been carried out:

- a) leakage check: prior to a series of tests the system shall be checked for leakage by isolating the probe and the analysers, connecting and operating a vacuum pump of equivalent performance to that used in the smoke measurement system to verify that the system leakage flow rate is less than 0.4 L/min referred to normal temperature and pressure;
- b) cleanliness check: isolate the gas sampling system from the probe and connect the end of the sampling line to a source of zero gas. Warm the system up to the operational temperature needed to perform hydrocarbon measurements. Operate the sample flow pump and set the flow rate to that used during engine emission testing. Record the hydrocarbon analyser reading. The reading shall not exceed 1 per cent of the engine idle emission level or 1 ppm (both expressed as methane), whichever is the greater.

*Note 1.— It is good practice to back-purge the sampling lines during engine running, while the probe is in the engine exhaust but emissions are not being measured, to ensure that no significant contamination occurs.*

*Note 2.— It is also good practice to monitor the inlet air quality at the start and end of testing and at least once per hour during a test. If levels are considered significant, then they should be taken into account.*

6.3.2 The following procedure shall be adopted for operational measurements:

- a) apply appropriate zero gas and make any necessary instrument adjustments;
- b) apply appropriate calibration gas at a nominal 90 per cent FSD concentration for the ranges to be used, adjust and record gain settings accordingly;
- c) when the engine has been stabilized at the required thrust setting, continue to run it and observe pollutant concentrations until a stabilized reading is obtained, which shall be recorded;
- d) recheck zero and calibration points at the end of the test and also at intervals not greater than 1 hour during tests. If either has changed by more than  $\pm 2$  per cent of range FSD, the test shall be repeated after restoration of the instrument to within its specification.

### 6.4 Carbon balance check

Each test shall include a check that the air/fuel ratio as estimated from the integrated sample total carbon concentration exclusive of smoke, agrees with the estimate based on engine air/fuel ratio within  $\pm 15$  per cent for the taxi/ground idle mode, and within 10 per cent for all other modes (*see* 7.1.2).

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\* Except for the CO<sub>2</sub> analyser, for which the value shall be  $\pm 100$  ppm.

## 7. CALCULATIONS

### 7.1 Gaseous emissions

#### 7.1.1 General

The analytical measurements made shall be the concentrations of the various gaseous emissions, as detected at their respective analysers for a range of combustor inlet temperatures ( $T_B$ ) encompassing the four LTO operating modes. Using the calculations of 7.1.2, or the alternative methods defined in Attachment E to this appendix, the measured emissions indices (EI) for each gaseous emission shall be established. To account for deviations from reference atmospheric conditions, the corrections of 7.1.3 shall be applied. Note that these corrections may also be used to account for deviations of the tested engine from the reference standard engine where appropriate (see Appendix 6, paragraph 1 f). Using combustor inlet temperature ( $T_B$ ) as a correlating parameter, the emissions indices and fuel flow corresponding to the operation at the four LTO operating modes of a reference standard engine under reference day conditions shall then be established using the procedures of 7.2.

#### 7.1.2 Basic parameters

$$\text{EI}_p \text{ (emission index for component } p) = \frac{\text{mass of } p \text{ produced in g}}{\text{mass of fuel used in kg}}$$

$$\text{EI}(\text{CO}) = \left( \frac{[\text{CO}]}{[\text{CO}_2] + [\text{CO}] + [\text{HC}]} \right) \left( \frac{10^3 M_{\text{CO}}}{M_{\text{C}} + (n/m)M_{\text{H}}} \right) (1+T(\text{P}_0/m))$$

$$\text{EI}(\text{HC}) = \left( \frac{[\text{HC}]}{[\text{CO}_2] + [\text{CO}] + [\text{HC}]} \right) \left( \frac{10^3 M_{\text{HC}}}{M_{\text{C}} + (n/m)M_{\text{H}}} \right) (1+T(\text{P}_0/m))$$

$$\text{EI}(\text{NO}_x) \text{ (as NO}_2) = \left( \frac{[\text{NO}_x]}{[\text{CO}_2] + [\text{CO}] + [\text{HC}]} \right) \left( \frac{10^3 M_{\text{NO}_2}}{M_{\text{C}} + (n/m)M_{\text{H}}} \right) (1+T(\text{P}_0/m))$$

$$\text{Air/fuel ratio} = (\text{P}_0/m) \left( \frac{M_{\text{AIR}}}{M_{\text{C}} + (n/m)M_{\text{H}}} \right)$$

where

$$\text{P}_0/m = \frac{2Z - n/m}{4(1 + h_{\text{vol}} - [TZ/2])}$$

and

$$Z = \frac{2 - [\text{CO}] - ([2/x] - [y/2x]) [\text{HC}] + [\text{NO}_2]}{[\text{CO}_2] + [\text{CO}] + [\text{HC}]}$$

$M_{\text{AIR}}$  molecular mass of dry air = 28.966 g or, where appropriate, = (32  $R$  + 28.156 4  $S$  + 44.011  $T$ )g

$M_{HC}$	molecular mass of exhaust hydrocarbons, taken as $CH_4 = 16.043$ g
$M_{CO}$	molecular mass of CO = 28.011 g
$M_{NO_2}$	molecular mass of $NO_2 = 46.008$ g
$M_C$	atomic mass of carbon = 12.011 g
$M_H$	atomic mass of hydrogen = 1.008 g
$R$	concentration of $O_2$ in dry air, by volume = 0.209 5 normally
$S$	concentration of $N_2$ + rare gases in dry air, by volume = 0.709 2 normally
$T$	concentration of $CO_2$ in dry air, by volume = 0.000 3 normally
[HC]	mean concentration of exhaust hydrocarbons vol/vol, expressed as carbon
[CO]	mean concentration of CO vol/vol, wet
[ $CO_2$ ]	mean concentration of $CO_2$ vol/vol, wet
[ $NO_x$ ]	mean concentration of $NO_x$ vol/vol, wet = [NO + $NO_2$ ]
[NO]	mean concentration of NO in exhaust sample, vol/vol, wet
[ $NO_2$ ]	mean concentration of $NO_2$ in exhaust sample, vol/vol, wet
	$= \frac{([NO_x]_c - [NO])}{\eta}$
[ $NO_x$ ] <sub>c</sub>	mean concentration of NO in exhaust sample after passing through the $NO_2/NO$ converter, vol/vol, wet
$\eta$	efficiency of $NO_2/NO$ converter
$h_{vol}$	humidity of ambient air, vol water/vol dry air
$m$	number of C atoms in characteristic fuel molecule
$n$	number of H atoms in characteristic fuel molecule
$x$	number of C atoms in characteristic exhaust hydrocarbon molecule
$y$	number of H atoms in characteristic exhaust hydrocarbon molecule

The value of  $n/m$ , the ratio of the atomic hydrogen to atomic carbon of the fuel used, is evaluated by fuel type analysis. The ambient air humidity,  $h_{vol}$  shall be measured at each set condition. In the absence of contrary evidence as to the characterization ( $x,y$ ) of the exhaust hydrocarbons, the values  $x = 1$ ,  $y = 4$  are to be used. If dry or semi-dry CO and  $CO_2$  measurements are to be used then these shall first be converted to the equivalent wet concentration as shown in Attachment E to this appendix, which also contains interference correction formulas for use as required.

## 7.1.3 Correction of emission indices to reference conditions

Corrections shall be made to the measured engine emission indices for all pollutants in all relevant engine modes to account for deviations from the reference atmospheric conditions (ISA at sea level) of the actual test inlet air conditions of temperature and pressure. These corrections may also be used to account for deviations of the tested engine from the reference standard engine where appropriate (see Appendix 6, 1 f)). The reference value for humidity shall be 0.00634 kg water/kg dry air.

Thus, EI corrected =  $K \times$  EI measured,

where the generalized expression for  $K$  is:

$$K = (P_{Bref}/P_B)^a \times (FAR_{ref}/FAR_B)^b \times \exp((T_{Bref} - T_B)/c) \times \exp(d[h_{mass} - 0.00634])$$

$P_B$	Combustor inlet pressure, measured
$T_B$	Combustor inlet temperature, measured
$FAR_B$	Fuel/air ratio in the combustor
$h_{mass}$	Ambient air humidity, kg water/kg dry air
$P_{ref}$	ISA sea level pressure
$T_{ref}$	ISA sea level temperature
$P_{Bref}$	Pressure at the combustor inlet of the engine tested (or the reference engine if the data is corrected to a reference engine) associated with $T_B$ under ISA sea level conditions.
$T_{Bref}$	Temperature at the combustor inlet under ISA sea level conditions for the engine tested (or the reference engine if the data is to be corrected to a reference engine). This temperature is the temperature associated with each thrust level specified for each mode.
$FAR_{ref}$	Fuel/air ratio in the combustor under ISA sea level conditions for the engine tested (or the reference engine if the data is to be corrected to a reference engine).
$a, b, c, d$	Specific constants which may vary for each pollutant and each engine type.

The combustor inlet parameters shall preferably be measured but may be calculated from ambient conditions by appropriate formulas.

7.1.4 Using the recommended curve fitting technique of 7.2 to relate emission indices to combustor inlet temperature effectively eliminates the  $\exp((T_{Bref} - T_B)/c)$  term from the generalized equation and for most cases the  $(FAR_{ref}/FAR_B)$  term may be considered unity. For the emissions indices of CO and HC many testing facilities have determined that the humidity term is sufficiently close to unity to be eliminated from the expression and that the exponent of the  $(P_{Bref}/P_B)$  term is close to unity.

Thus,

$$\text{EI(CO) corrected} = \text{EI derived from } (P_B/P_{Bref}) \cdot \text{EI(CO) v. } T_B \text{ curve}$$

$$\text{EI(HC) corrected} = \text{EI derived from } (P_B/P_{Bref}) \cdot \text{EI(HC) v. } T_B \text{ curve}$$

$$\text{EI(NO}_x\text{) corrected} = \text{EI derived from EI(NO}_x\text{) } (P_{Bref}/P_B)^{0.5} \exp(19 [h_{mass} - 0.00634]) \text{ v. } T_B \text{ curve}$$

If this recommended method for the CO and HC emissions index correction does not provide a satisfactory correlation, an alternative method using parameters derived from component tests may be used.

Any other methods used for making corrections to CO, HC and NO<sub>x</sub> emission indices shall have the approval of the certificating authority.

## 7.2 Control parameter functions

( $D_p$ ,  $F_{oo}$ ,  $\pi$ )

### 7.2.1 Definitions

$D_p$	The mass of any gaseous pollutant emitted during the reference emissions landing and take-off cycle.
$F_{oo}$	Rated thrust (see Part I, Chapter 1, Definitions)
$F_n$	Thrust at LTO operating mode, $n$ , (kN)
$W_f$	Fuel mass flow rate of the reference standard engine under ISA sea level conditions (kg/s).
$W_{f_n}$	Fuel mass flow rate of the reference standard engine under ISA sea level conditions at LTO operating mode, $n$ .
$\pi$	The ratio of the mean total pressure at the last compressor discharge plane of the compressor to the mean total pressure at the compressor entry plane when the engine is developing take-off thrust rating at ISA sea level static conditions.

7.2.2 The emissions indices (EI <sub>$n$</sub> ) for each pollutant, corrected to reference atmospheric conditions and, if necessary, to the reference standard engine, (EI <sub>$n$</sub>  (corrected)), shall be obtained for each LTO operating mode. A minimum of three test points shall be required to define the idle mode. The following relationships shall be determined under reference atmospheric conditions for each gaseous emission:

- between EI (corrected) and  $T_B$ ; and
- between  $W_f$  and  $T_B$ ; and
- between  $F$  and  $T_B$ ;

*Note 1.— These are illustrated, for example, by Figure A3-2 a), b) and c).*

*Note 2.— The relationships b) and c) may be established directly from engine test data, or may be derived from a validated engine performance model.*

A reference engine is defined as an engine substantially configured to the production standard of the engine type and with fully representative operating and performance characteristics.

The manufacturer shall also supply to the certificating authority all of the necessary engine performance data to substantiate these relationships and for ISA sea level ambient conditions:

- rated thrust ( $F_{oo}$ ); and
- engine pressure ratio ( $\pi$ ) at maximum rated thrust.

*Note.— These are illustrated by Figure A3-2 d).*

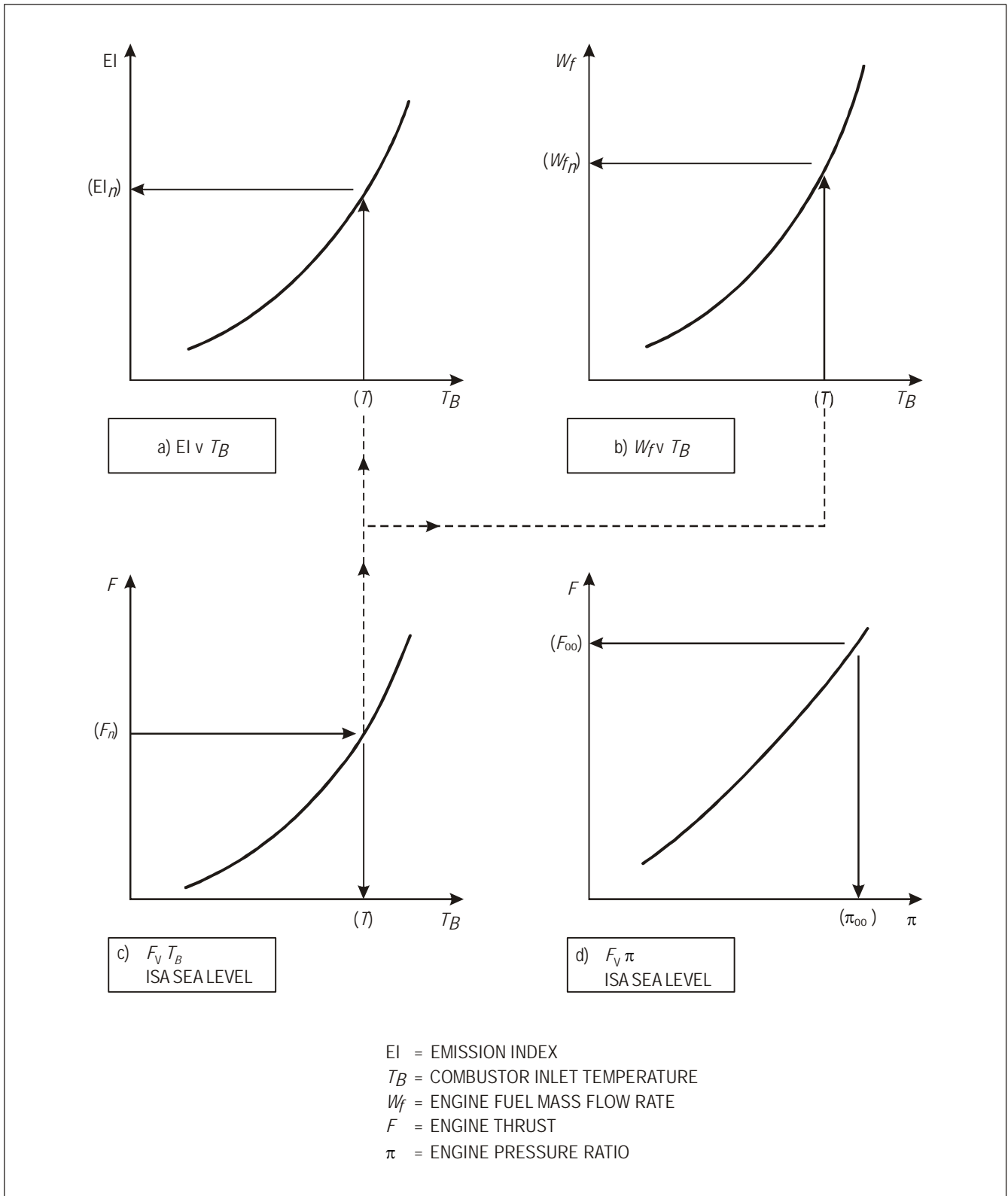


Figure A3-2. Calculation procedure

7.2.3 The estimation of EI (corrected) for each gaseous emission at the four LTO operating modes shall comply with the following general procedure:

- a) determine the combustor inlet temperature ( $T_B$ ) (Figure A3-2 c)) at the values of  $F_n$  corresponding to the four LTO operating modes,  $n$ , under reference atmospheric conditions;
- b) from the EI (corrected)/ $T_B$  characteristic (Figure A3-2 a)), determine the  $EI_n$  value corresponding to  $T_B$ ;
- c) from the  $W_f/T_B$  characteristic (Figure A3-2 b)), determine the  $W_{f_n}$  value corresponding to  $T_B$ ;
- d) note the ISA maximum rated thrust and pressure ratio values. These are  $F_{oo}$  and  $\pi$  respectively (Figure A3-2 d));
- e) calculate, for each pollutant  $D_p = \Sigma (EI_n) (W_{f_n}) (t)$  where:

$t$  time in LTO mode (minutes)

$W_{f_n}$  fuel mass flow rate (kg/min)

$\Sigma$  is the summation for the set of modes comprising the reference LTO cycle.

7.2.4 While the methodology described above is the recommended method, the certifying authority may accept equivalent mathematical procedures which utilize mathematical expressions representing the curves illustrated if the expression have been derived using an accepted curve fitting technique.

### 7.3 Exceptions to the proposed procedures

In those cases where the configuration of the engine or other extenuating conditions exist which would prohibit the use of this procedure, the certifying authority, after receiving satisfactory technical evidence of equivalent results obtained by an alternative procedure, may approve an alternative procedure.



## 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.*

### 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.

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 within the range 155°C to 165°C to a stability of  $\pm 2^\circ\text{C}$ . The leading specification points shall be as follows, the detector response having been optimized and the instrument generally having stabilized:

- a) *Total range:* 0 to 5 000 ppmC in appropriate ranges.
- b) *Resolution:* better than 0.5 per cent of full scale of range used or 0.5 ppmC, whichever is greater.
- c) *Repeatability:* better than  $\pm 1$  per cent of full scale of range used, or  $\pm 0.5$  ppmC, whichever is greater.
- d) *Stability:* better than  $\pm 2$  per cent of full scale of range used or  $\pm 1.0$  ppmC, whichever is greater, in a period of 1 hour.
- e) *Zero drift:* less than  $\pm 1$  per cent of full scale of range used or  $\pm 0.5$  ppmC, whichever is greater, in a period of 1 hour.
- f) *Noise:* 0.5 Hz and greater, less than  $\pm 1$  per cent of full scale of range used or  $\pm 0.5$  ppmC, whichever is greater.
- g) *Response time:* shall not exceed 10 seconds from inlet of the sample to the analysis system, to the achievement of 90 per cent of the final reading.
- h) *Linearity:* response with propane in air shall be linear for each range within  $\pm 2$  per cent of full scale, otherwise calibration corrections shall be used.

### 2. SYNERGISTIC EFFECTS

*Note.— In application there are two aspects of performance which can affect the accuracy of measurement:*

- a) *the oxygen effect (whereby differing proportions of oxygen present in the sample give differing indicated hydrocarbon concentration for constant actual HC concentrations); and*

- b) the relative hydrocarbon response (whereby there is a different response to the same sample hydrocarbon concentrations expressed as equivalent ppmC, dependent on the class or admixture of classes of hydrocarbon compounds).

The magnitude of the effects noted above shall be determined as follows and limited accordingly.

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

- 1) propane in  $10 \pm 1$  per cent O<sub>2</sub>, balance N<sub>2</sub>
- 2) propane in  $21 \pm 1$  per cent O<sub>2</sub>, balance N<sub>2</sub>

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

*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  $\pm 1$  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  $R_a$ .

### 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.

3.2 The linearity of each analyser range shall be checked by applying propane in air samples at concentrations of approximately 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 zero) shall not exceed  $\pm 2$  per cent of full scale value. If it does, a calibration curve shall be prepared for operational use.

## ATTACHMENT B TO APPENDIX 3. SPECIFICATION FOR CO AND CO<sub>2</sub> ANALYSERS

*Note 1.— Paragraph 5.3 of Appendix 3 summarizes the characteristics of the analysis subsystem to be employed for the individual measurements of CO and CO<sub>2</sub> concentrations in the exhaust gas sample. The instruments are based on the principle of non-dispersive absorption of infrared radiation in parallel reference and sample gas cells. The required ranges of sensitivity are obtained by use of stacked sample cells or changes in electronic circuitry or both. Interferences from gases with overlapping absorption bands may be minimized by gas absorption filters and/or optical filters, preferably the latter.*

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

**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.

The principal performance specification shall be as follows:

### CO Analyser

- a) *Total range:* 0 to 2 500 ppm in appropriate ranges.
- b) *Resolution:* better than 0.5 per cent of full scale of range used or 1 ppm, whichever is greater.
- c) *Repeatability:* better than  $\pm 1$  per cent of full scale of range used, or  $\pm 2$  ppm, whichever is greater.
- d) *Stability:* better than  $\pm 2$  per cent of full scale of range used or  $\pm 2$  ppm, whichever is greater, in a period of 1 hour.
- e) *Zero drift:* less than  $\pm 1$  per cent of full scale of range used or  $\pm 2$  ppm, whichever is greater, in a period of 1 hour.
- f) *Noise:* 0.5 Hz and greater, less than  $\pm 1$  per cent of full scale of range used or  $\pm 1$  ppm, whichever is greater.
- g) *Interferences:* to be limited with respect to indicated CO concentration as follows:
  - 1) less than 500 ppm/per cent ethylene concentration
  - 2) less than 2 ppm/per cent CO<sub>2</sub> concentration
  - 3) less than 2 ppm/per cent water vapour.\*

If the interference limitation(s) for CO<sub>2</sub> and/or water vapour cannot be met, appropriate correction factors shall be determined, reported and applied.

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

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\* Need not apply where measurements are on a "dry" basis.

*CO<sub>2</sub> Analyser*

- a) *Total range*: 0 to 10 per cent in appropriate ranges.
- b) *Resolution*: better than 0.5 per cent of full scale of range used or 100 ppm, whichever is greater.
- c) *Repeatability*: better than  $\pm 1$  per cent of full scale of range used or  $\pm 100$  ppm, whichever is greater.
- d) *Stability*: better than  $\pm 2$  per cent of full scale of range used or  $\pm 100$  ppm, whichever is greater, in a period of 1 hour.
- e) *Zero drift*: less than  $\pm 1$  per cent of full scale of range used or  $\pm 100$  ppm, whichever is greater, in a period of 1 hour.
- f) *Noise*: 0.5 Hz and greater, less than  $\pm 1$  per cent of full scale of range used or  $\pm 100$  ppm, whichever is greater.
- g) The effect of oxygen (O<sub>2</sub>) on the CO<sub>2</sub> analyser response shall be checked. For a change from 0 per cent O<sub>2</sub> to 21 per cent O<sub>2</sub>, the response of a given CO<sub>2</sub> 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.*

*CO and CO<sub>2</sub> Analysers*

- a) *Response time*: shall not exceed 10 seconds from inlet of the sample to the analysis system, to the achievement of 90 per cent of the final reading.
- 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  $\pm 2^\circ\text{C}$ . The option to measure CO and CO<sub>2</sub> on a dry basis (with suitable water traps) is allowed, in which case unheated analysers are permissible and the interference limits for H<sub>2</sub>O vapour removed, and subsequent correction for inlet water vapour and water of combustion is required.
- 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  $\pm 2$  per cent of the full scale value. If it does then a calibration curve shall be prepared for operational use.
  - 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.

## ATTACHMENT C TO APPENDIX 3. SPECIFICATION FOR NO<sub>x</sub> ANALYSER

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

1. As indicated in 5.4 of Appendix 3, the measurement of the oxides of nitrogen concentration shall be by the chemiluminescent technique in which radiation emitted by the reaction of NO and O<sub>3</sub> is measured. This method is not sensitive to NO<sub>2</sub> and therefore the sample shall be passed through a converter in which NO<sub>2</sub> is converted to NO before the measurement of total NO<sub>x</sub> is made. Both the original NO and the total NO<sub>x</sub> concentrations shall be recorded. Thus by difference, a measure of the NO<sub>2</sub> concentration shall be obtained.

2. The instrument to be used shall be complete with all necessary flow control components, such as regulators, valves, flowmeters, etc. Materials in contact with the sample gas shall be restricted to those which are resistant to attack by oxides of nitrogen, such as stainless steel, glass, etc. The temperature of the sample shall everywhere be maintained at values, consistent with the local pressures, which avoid condensation of water.

**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.

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.
- b) *Resolution:* better than 0.5 per cent of full scale of range used or 1 ppm, whichever is greater.
- c) *Repeatability:* better than ±1 per cent of full scale of range used, or ±1 ppm, whichever is greater.
- d) *Stability:* better than ±2 per cent of full scale of range used or ±1 ppm, whichever is greater, in a period of 1 hour.
- e) *Zero drift:* less than ±1 per cent of full scale of range used or ±1 ppm, whichever is greater, in a period of 1 hour.
- f) *Noise:* 0.5 Hz and greater, less than ±1.0 per cent of full scale of range used or ±1 ppm, whichever is greater, in a period of 2 hours.
- g) *Interference:* suppression for samples containing CO<sub>2</sub> and water vapour, shall be limited as follows:
  - less than 0.05 per cent reading/per cent CO<sub>2</sub> concentration;
  - less than 0.1 per cent reading/per cent water vapour concentration.

If the interference limitation(s) for CO<sub>2</sub> and/or water vapour cannot be met, appropriate correction factors shall be determined, reported and applied.

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

- h) *Response time:* shall not exceed 10 seconds from inlet of the sample to the analysis system to the achievement of 90 per cent of the final reading.

- i) *Linearity*: better than  $\pm 2$  per cent of full scale of range used or  $\pm 2$  ppm, whichever is greater.
- j) *Converter*: this shall be designed and operated in such a manner as to reduce  $\text{NO}_2$  present in the sample to  $\text{NO}$ . The converter shall not affect the  $\text{NO}$  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  $\text{NO}_2$  value (i.e.  $[\text{NO}_x]_c - [\text{NO}]$ ) to that which would have been obtained if the efficiency had not been 100 per cent.

## ATTACHMENT D TO APPENDIX 3. CALIBRATION AND TEST GASES

**Table of calibration gases**

<i>Analyser</i>	<i>Gas</i>	<i>Accuracy*</i>
HC	propane in zero air	±2 per cent or ±0.05 ppm**
CO <sub>2</sub>	CO <sub>2</sub> in zero air	±2 per cent or ±100 ppm**
CO	CO in zero air	±2 per cent or ±2 ppm**
NO <sub>x</sub>	NO <sub>x</sub> in zero nitrogen	±2 per cent or ±1 ppm**

\* Taken over the 95 per cent confidence interval.

\*\* Whichever is greater.

The above gases are required to carry out the routine calibration of analysers during normal operational use.

**Table of test gases**

<i>Analyser</i>	<i>Gas</i>	<i>Accuracy*</i>
HC	propane in 10 ±1 per cent O <sub>2</sub> balance zero nitrogen	±1 per cent
HC	propane in 21 ±1 per cent O <sub>2</sub> balance zero nitrogen	±1 per cent
HC	propylene in zero air	±1 per cent
HC	toluene in zero air	±1 per cent
HC	n-hexane in zero air	±1 per cent
HC	propane in zero air	±1 per cent
CO <sub>2</sub>	CO <sub>2</sub> in zero air	±1 per cent
CO <sub>2</sub>	CO <sub>2</sub> in zero nitrogen	±1 per cent
CO	CO in zero air	±1 per cent
NO <sub>x</sub>	NO in zero nitrogen	±1 per cent

\* Taken over the 95 per cent confidence interval.

The above gases are required to carry out the tests of Attachments A, B and C.

Carbon monoxide and carbon dioxide calibration gases may be blended singly or as dual component mixtures. Three component mixtures of carbon monoxide, carbon dioxide and propane in zero air may be used, provided the stability of the mixture is assured.

Zero gas as specified for the CO, CO<sub>2</sub> and HC analysers shall be zero air (which includes “artificial” air with 20 to 22 per cent O<sub>2</sub> blended with N<sub>2</sub>). For the NO<sub>x</sub> analyser zero nitrogen shall be used as the zero gas. Impurities in both kinds of zero gas shall be restricted to be less than the following concentrations:

- 1 ppm C
- 1 ppm CO
- 100 ppm CO<sub>2</sub>
- 1 ppm NO<sub>x</sub>

The applicant shall ensure that commercial gases, as supplied, do in fact meet this specification, or are so specified by the vendor.

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

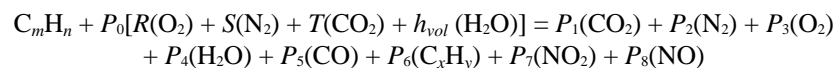
**1. SYMBOLS**

<i>AFR</i>	air/fuel ratio, the ratio of the mass flow rate of dry air to that of the fuel
<i>EI</i>	emission index; $10^3 \times$ mass flow rate of gaseous emission product in exhaust per unit mass flow rate of fuel
<i>K</i>	ratio of concentration measured wet to that measured dry (after cold trap)
<i>L, L'</i>	analyser interference coefficient for interference by CO <sub>2</sub>
<i>M, M'</i>	analyser interference coefficient for interference by H <sub>2</sub> O
<i>M<sub>AIR</sub></i>	molecular mass of dry air = 28.966 g or, where appropriate, = (32 <i>R</i> + 28.156 4 <i>S</i> + 44.011 <i>T</i> ) g
<i>M<sub>CO</sub></i>	molecular mass of CO = 28.011 g
<i>M<sub>HC</sub></i>	molecular mass of exhaust hydrocarbon, taken as CH <sub>4</sub> = 16.043 g
<i>M<sub>NO<sub>2</sub></sub></i>	molecular mass of NO <sub>2</sub> = 46.008 g
<i>M<sub>C</sub></i>	atomic mass of carbon = 12.011 g
<i>M<sub>H</sub></i>	atomic mass of hydrogen = 1.008 g
<i>P<sub>1</sub></i>	number of moles of CO <sub>2</sub> in the exhaust sample per mole of fuel
<i>P<sub>2</sub></i>	number of moles of N <sub>2</sub> in the exhaust sample per mole of fuel
<i>P<sub>3</sub></i>	number of moles of O <sub>2</sub> in the exhaust sample per mole of fuel
<i>P<sub>4</sub></i>	number of moles of H <sub>2</sub> O in the exhaust sample per mole of fuel
<i>P<sub>5</sub></i>	number of moles of CO in the exhaust sample per mole of fuel
<i>P<sub>6</sub></i>	number of moles of C <sub><i>x</i></sub> H <sub><i>y</i></sub> in the exhaust sample per mole of fuel
<i>P<sub>7</sub></i>	number of moles of NO <sub>2</sub> in the exhaust sample per mole of fuel
<i>P<sub>8</sub></i>	number of moles of NO in the exhaust sample per mole of fuel
<i>P<sub>T</sub></i>	$P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8$
<i>R</i>	concentration of O <sub>2</sub> in dry air, by volume = 0.2095 normally

$S$	concentration of $N_2$ + rare gases in dry air, by volume = 0.7902 normally
$T$	concentration of $CO_2$ in dry air, by volume = 0.0003 normally
$P_0$	number of moles of air per mole of fuel in initial air/fuel mixture
$Z$	symbol used and defined in 3.4
$[CO_2]$	mean concentration of $CO_2$ in exhaust sample, vol/vol
$[CO]$	mean concentration of $CO$ in exhaust sample, vol/vol
$[HC]$	mean concentration of $HC$ in exhaust sample, vol C/vol
$[NO]$	mean concentration of $NO$ in exhaust sample, vol/vol
$[NO_2]$	mean concentration of $NO_2$ in exhaust sample, vol/vol
$[NO_x]$	mean concentration of $NO$ and $NO_2$ in exhaust sample, vol/vol
$[NO_x]_c$	mean concentration of $NO$ in exhaust sample, after passing through the $NO_2/NO$ converter, vol/vol
$[NO_2]$	mean = $\frac{([NO_x]_c - [NO])}{\eta}$
$[ ]_d$	mean concentration in exhaust sample after cold trap, vol/vol
$[ ]_m$	mean concentration measurement indicated before instrument correction applied, vol/vol
$h_{vol}$	humidity of ambient air, vol water/vol dry air
$h_d$	humidity of exhaust sample leaving “drier” or “cold trap”, vol water/vol dry sample
$m$	number of C atoms in characteristic fuel molecule
$n$	number of H atoms in characteristic fuel molecule
$x$	number of C atoms in characteristic exhaust hydrocarbon molecule
$y$	number of H atoms in characteristic exhaust hydrocarbon molecule
$\eta$	efficiency of $NO_2/NO$ converter

## 2. BASIS OF CALCULATION OF EI AND AFR PARAMETERS

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:



from which the required parameters can, by definition, be expressed as

$$EI(\text{CO}) = P_5 \left( \frac{10^3 M_{\text{CO}}}{mM_{\text{C}} + nM_{\text{H}}} \right)$$

$$EI(\text{HC}) = xP_6 \left( \frac{10^3 M_{\text{HC}}}{mM_{\text{C}} + nM_{\text{H}}} \right) \text{ expressed as methane equivalent}$$

$$EI(\text{NO}_x) = (P_7 + P_8) \left( \frac{10^3 M_{\text{NO}_2}}{mM_{\text{C}} + nM_{\text{H}}} \right) \text{ expressed as NO}_2 \text{ equivalent}$$

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

2.2 Values for fuel hydrocarbon composition ( $m$ ,  $n$ ) are assigned by fuel specification or analysis. If only the ratio  $n/m$  is so determined, the value  $m = 12$  may be assigned. The mole fractions of the dry air constituents ( $R$ ,  $S$ ,  $T$ ) are normally taken to be the recommended standard values but alternative values may be assigned, subject to the restriction  $R + S + T = 1$  and the approval of the certifying authority.

2.3 The ambient air humidity,  $h_{\text{vol}}$ , is as measured at each test condition. It is recommended that, in the absence of contrary evidence as to the characterization ( $x$ ,  $y$ ) of the exhaust hydrocarbon, values of  $x = 1$  and  $y = 4$  are assigned.

2.4 Determination of the remaining unknowns requires the solution of the following set of linear simultaneous equations, where (1) to (4) derive from the fundamental atomic conservation relationships and (5) to (9) represent the gaseous product concentration relationships.

$$m + TP_0 = P_1 + P_5 + xP_6 \dots\dots\dots (1)$$

$$n + 2h_{\text{vol}}P_0 = 2P_4 + yP_6 \dots\dots\dots (2)$$

$$(2R + 2T + h_{\text{vol}})P_0 = 2P_1 + 2P_3 + P_4 + P_5 + 2P_7 + P_8 \dots\dots\dots (3)$$

$$2SP_0 = 2P_2 + P_7 + P_8 \dots\dots\dots (4)$$

$$[\text{CO}_2] P_{\text{T}} = P_1 \dots\dots\dots (5)$$

$$[\text{CO}] P_{\text{T}} = P_5 \dots\dots\dots (6)$$

$$[\text{HC}] P_{\text{T}} = xP_6 \dots\dots\dots (7)$$

$$[\text{NO}_x] P_{\text{T}} = \eta P_7 + P_8 \dots\dots\dots (8)$$

$$[\text{NO}] P_{\text{T}} = P_8 \dots\dots\dots (9)$$

$$P_{\text{T}} = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 \dots\dots\dots (10)$$

The above set of conditional equations is for the case where all measured concentrations are true, that is, not subject to interference effects or to the need to correct for sample drying. In practice, interference effects are usually present to a significant degree in the CO, and NO measurements, and the option to measure CO<sub>2</sub> and CO on a dry or partially dry basis is often used. The necessary modifications to the relevant equations are described in 2.5 and 2.6.

2.5 The interference effects are mainly caused by the presence of CO<sub>2</sub> and H<sub>2</sub>O in the sample which can affect the CO and the NO<sub>x</sub> analysers in basically different ways. The CO analyser is prone to a zero-shifting effect and the NO<sub>x</sub> analyser to a sensitivity change, represented thus:

$$[\text{CO}] = [\text{CO}]_m + L[\text{CO}_2] + M[\text{H}_2\text{O}]$$

$$\text{and } [\text{NO}_x]_c = [\text{NO}_x]_{cm} (1 + L'[\text{CO}_2] + M'[\text{H}_2\text{O}])$$

which transform into the following alternative equations to (6), (8) and (9), when interference effects require to be corrected,

$$[\text{CO}]_m P_T + LP_1 + MP_4 = P_5 \dots\dots\dots (6A)$$

$$[\text{NO}_x]_{cm} (P_T + L'P_1 + M'P_4) = \eta P_7 + P_8 \dots\dots\dots (8A)$$

$$[\text{NO}]_m (P_T + L'P_1 + M'P_4) = P_8 \dots\dots\dots (9A)$$

2.6 The option to measure CO<sub>2</sub> and CO concentrations on a dry or partially dry sample basis, that is, with a sample humidity reduced to  $h_d$ , requires the use of modified conditional equations as follows:

$$[\text{CO}_2]_d (P_T - P_4) (1 + h_d) = P_1 \dots\dots\dots (5A)$$

and

$$[\text{CO}]_d (P_T - P_4) (1 + h_d) = P_5$$

However, the CO analyser may also be subject to interference effects as described in 2.5 and so the complete alternative CO measurement concentration equation becomes

$$[\text{CO}]_{md} (P_T - P_4) (1 + h_d) + LP_1 + Mh_d (P_T - P_4) = P_5 \dots\dots\dots (6B)$$

### 3. ANALYTICAL FORMULATIONS

#### 3.1 General

Equations (1) to (10) can be reduced to yield the analytical formulations for the EI and AFR parameters, as given in 7.1 to this appendix. This reduction is a process of progressive elimination of the roots  $P_0$ ,  $P_1$  through  $P_8$ ,  $P_T$ , making the assumptions that all concentration measurements are of the “wet” sample and do not require interference corrections or the like. In practice, the option is often chosen to make the CO<sub>2</sub> and CO concentration measurements on a “dry” or “semi-dry” basis; also it is often found necessary to make interference corrections. Formulations for use in these various circumstances are given in 3.2, 3.3 and 3.4.

#### 3.2 Equation for conversion of dry concentration measurements to wet basis

Concentration wet =  $K \times$  concentration dry; that is,

$$[ ] = K [ ]_d$$

The following expression for  $K$  applies when CO and CO<sub>2</sub> are determined on a “dry” basis:

$$K = \frac{\{4 + (n/m) T + ([n/m]T - 2h_{vol}) ([NO_2] - (2[HC]/x)) + (2 + h_{vol}) ([y/x] - [n/m]) [HC]\} (1 + h_d)}{(2 + h) \{2 + (n/m) (1 + h_d) ([CO_2]_d + [CO]_d)\} - ([n/m] T - 2h) (1 - [1 + h_d] [CO]_d)}$$

### 3.3 Interference corrections

The measurements of CO and/or NO<sub>x</sub> and NO may require corrections for interference by the sample CO<sub>2</sub> and water concentrations before use in the above analytical equations. Such corrections can normally be expressed in the following general ways:

$$[CO] = [CO]_m + L[CO_2] + M[H_2O]$$

$$[CO]_d = [CO]_{md} + L[CO_2]_d + M \left( \frac{h_d}{1 + h_d} \right)$$

$$[NO] = [NO]_m (1 + L'[CO_2] + M'[H_2O])$$

$$\eta[NO_2] = ([NO_x]_{cm} - [NO]_m) (1 + L'[CO_2] + M'[H_2O])$$

### 3.4 Equation for estimation of sample water content

Water concentration in sample

$$[H_2O] = \frac{([n/2m] + h_{vol} [P_0/m]) ([CO_2] + [CO] + [HC])}{1 + T(P_0/m)} - (y/2x) [HC]$$

where

$$P_0/m = \frac{2Z - n/m}{4(1 + h_{vol} - [TZ/2])}$$

and

$$Z = \frac{2 - [CO] - ([2/x] - [y/2x])[HC] + [NO_2]}{[CO_2] + [CO] + [HC]}$$

It should be noted that this estimate is a function of the various analyses concentration readings, which may themselves require water interference correction. For better accuracy an iterative procedure is required in these cases with successive recalculation of the water concentration until the requisite stability is obtained. The use of the alternative, numerical solution methodology (4) avoids this difficulty.

#### **4. ALTERNATIVE METHODOLOGY — NUMERICAL SOLUTION**

4.1 As an alternative to the analytical procedures summarized in 3, it is possible to obtain readily the emissions indices, fuel/air ratio, corrected wet concentrations, etc., by a numerical solution of equations (1) to (10) for each set of measurements, using a digital computer.

4.2 In the equation set (1) to (10) the actual concentration measurements are substituted using whichever of the alternative equations (5A), (6A), etc. applies for the particular measuring system, to take account of interference corrections and/or dried sample measurements.

4.3 Suitable simple two-dimensional array equation-solving computer programmes are widely available and their use for this purpose is convenient and flexible, allowing ready incorporation and identification of any sample drying options and interference or other corrections.

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## ATTACHMENT F TO APPENDIX 3. SPECIFICATIONS 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: measured as the total temperature at a point within one diameter of the engine intake plane to an accuracy of  $\pm 0.5^{\circ}\text{C}$ ;
- b) inlet humidity (kg water/kg dry air): measured at a point within 15 m of the intake plane ahead of the engine to an accuracy of  $\pm 5$  per cent of reading;
- c) atmospheric pressure: measured within 1 km of the engine test location and corrected as necessary to the test stand altitude to an accuracy of  $\pm 100$  Pa;
- d) fuel mass flow: by direct measurement to an accuracy of  $\pm 2$  per cent;
- e) fuel H/C ratio: defined as  $n/m$ , where  $C_mH_n$  is the equivalent hydrocarbon representation of the fuel used in the test and evaluated by reference to the engine fuel type analysis;
- f) engine parameters:
  - 1) thrust: by direct measurement to an accuracy of  $\pm 1$  per cent at take-off power and  $\pm 5$  per cent at the minimum thrust used in the certification test, with linear variation between these points;
  - 2) rotation speed(s): by direct measurement to an accuracy of at least  $\pm 0.5$  per cent;
  - 3) gas generator airflow: determined to an accuracy of  $\pm 2$  per cent by reference to engine performance calibration.

The parameters a), b), d) and f) shall be determined at each engine emissions test setting, while c) shall be determined at intervals of not less than 1 hour over a period encompassing that of the emissions tests.





## 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 certifying authority. Additives used for the purpose of smoke suppression (such as organometallic compounds) shall not be present.

<i>Property</i>	<i>Allowable range of values</i>
Density kg/m <sup>3</sup> at 15°C	780 – 820
Distillation temperature, °C	
10% boiling point	155 – 201
Final boiling point	235 – 285
Net heat of combustion, MJ/kg	42.86 – 43.50
Aromatics, volume %	15 – 23
Naphthalenes, volume %	1.0 – 3.5
Smoke point, mm	20 – 28
Hydrogen, mass %	13.4 – 14.3
Sulphur, mass %	less than 0.3%
Kinematic viscosity at –20°C, mm <sup>2</sup> /s	2.5 – 6.5



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

## 1. INTRODUCTION

*Note.*— The procedures specified in this appendix are concerned with the acquisition of representative exhaust samples and their transmission to, and analysis by, the emissions measuring system. These procedures only apply when afterburning is employed. The methods proposed are representative of the best readily available and most established modern practice. The need to correct for ambient conditions is recognized and a method will be specified when one becomes available. Meanwhile any correction methods used when afterburning is employed should be approved by the certificating authority.

Variations in the procedure contained in this appendix shall only be allowed after prior application to and approval by the certificating authority.

## 2. DEFINITIONS

Where the following expressions are used without further explanation in this appendix, they have the meanings ascribed to them below:

**Accuracy.** The closeness with which a measurement approaches the true value established independently.

**Calibration gas.** A high accuracy reference gas to be used for alignment, adjustment and periodic checks of instruments.

**Concentration.** The volume fraction of the component of interest in the gas mixture — expressed as volume percentage or as parts per million.

**Flame ionization detector.** A hydrogen-air diffusion flame detector that produces a signal nominally proportional to the mass-flow rate of hydrocarbons entering the flame per unit of time — generally assumed responsive to the number of carbon atoms entering the flame.

**Interference.** Instrument response due to presence of components other than the gas (or vapour) that is to be measured.

**Noise.** Random variation in instrument output not associated with characteristics of the sample to which the instrument is responding, and distinguishable from its drift characteristics.

**Non-dispersive infrared analyser.** An instrument that by absorption of infrared energy selectively measures specific components.

**Parts per million (ppm).** The unit volume concentration of a gas per million unit volume of the gas mixture of which it is a part.

**Parts per million carbon (ppmC).** The mole fraction of hydrocarbon multiplied by  $10^6$  measured on a methane-equivalence basis. Thus, 1 ppm of methane is indicated as 1 ppmC. To convert ppm concentration of any hydrocarbon to an equivalent ppmC value, multiply ppm concentration by the number of carbon atoms per molecule of the gas. For example, 1 ppm propane translates as 3 ppmC hydrocarbon; 1 ppm hexane as 6 ppmC hydrocarbon.

**Plume.** Total external engine exhaust flow, including any ambient air with which the exhaust mixes.

**Reference gas.** A mixture of gases of specified and known composition used as the basis for interpreting instrument response in terms of the concentration of the gas to which the instrument is responding.

**Repeatability.** The closeness with which a measurement upon a given, invariant sample can be reproduced in short-term repetitions of the measurement with no intervening instrument adjustment.

**Resolution.** The smallest change in a measurement which can be detected.

**Response.** The change in instrument output signal that occurs with change in sample concentration. Also the output signal corresponding to a given sample concentration.

**Stability.** The closeness with which repeated measurements upon a given invariant sample can be maintained over a given period of time.

**Zero drift.** Time-related deviation of instrument output from zero set point when it is operating on gas free of the component to be measured.

**Zero gas.** A gas to be used in establishing the zero, or no response, adjustment of an instrument.

### 3. DATA REQUIRED

#### 3.1 Gaseous emissions

Concentrations of the following emissions shall be determined:

- a) Hydrocarbons (HC): a combined estimate of all hydrocarbon compounds present in the exhaust gas.
- b) Carbon monoxide (CO).
- c) Carbon dioxide (CO<sub>2</sub>).

*Note.— CO<sub>2</sub> is not considered a pollutant but its concentration is required for calculation and check purposes.*

- d) Oxides of nitrogen (NO<sub>x</sub>): an estimate of the sum of the two oxides, nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>).
- e) Nitric oxide (NO).

#### 3.2 Other information

In order to normalize the emissions measurement data and to quantify the engine test characteristics, other information in addition to the requirements of Chapter 3, 3.4 shall be provided as follows:

- inlet temperature;
- inlet humidity;
- atmospheric pressure;

- wind vectors relative to engine exhaust axis;
- hydrogen/carbon ratio of fuel;
- engine installation details;
- other required engine parameters (for example, thrust, rotor speeds, turbine temperatures);
- pollutant concentration data and statistical validation parameters.

This data shall be obtained either by direct measurement or by calculation, as presented in Attachment F to this appendix.

#### 4. GENERAL ARRANGEMENT OF THE SYSTEM

Owing to the reactive nature of the exhaust plume from engines using afterburning, it is necessary to ensure that the measured emissions do in fact correspond to those actually emitted into the surrounding atmosphere. This is achieved by sampling the plume sufficiently far downstream from the engine that the exhaust gases have cooled to a temperature where reactions have ceased. No desiccants, dryers, water traps or related equipment shall be used to treat the exhaust sample flowing to the oxides of nitrogen and the hydrocarbon analysis instrumentation. Requirements for the various component subsystems are given in 5, but the following list gives some qualifications and variations:

- a) it is assumed that each of the various individual subsystems includes the necessary flow control, conditioning and measurement facilities;
- b) the necessity for a dump and/or a hot-sample pump will depend on the ability to meet the sample transfer time and analysis subsystem sample flow rate requirements. This in turn depends on the exhaust sample-driving pressure and line losses. It is considered that these pumps usually will be necessary at certain engine running conditions; and
- c) the position of the hot pump, relative to the gas analysis subsystems, may be varied as required. (For example, some HC analysers contain hot pumps and so may be judged capable of being used upstream of the system hot pump.)

*Note.— Figures A5-1 and A5-2 are schematic drawings of the exhaust gas sampling and analytical system and typify the basic requirements for emissions testing.*

#### 5. DESCRIPTION OF COMPONENT PARTS

*Note.— A general description and specification of the principal elements in the engine exhaust emissions measurement system follows. Greater detail, where necessary, will be found in Attachments A, B and C to this appendix.*

##### 5.1 Sampling system

###### 5.1.1 Sampling probe

- a) The probe shall be constructed so that individual samples can be withdrawn at various locations across a diameter of the plume. Mixed samples shall not be permitted.
- b) The material with which the sample is in contact shall be stainless steel and its temperature shall be maintained at a value not less than 60°C.

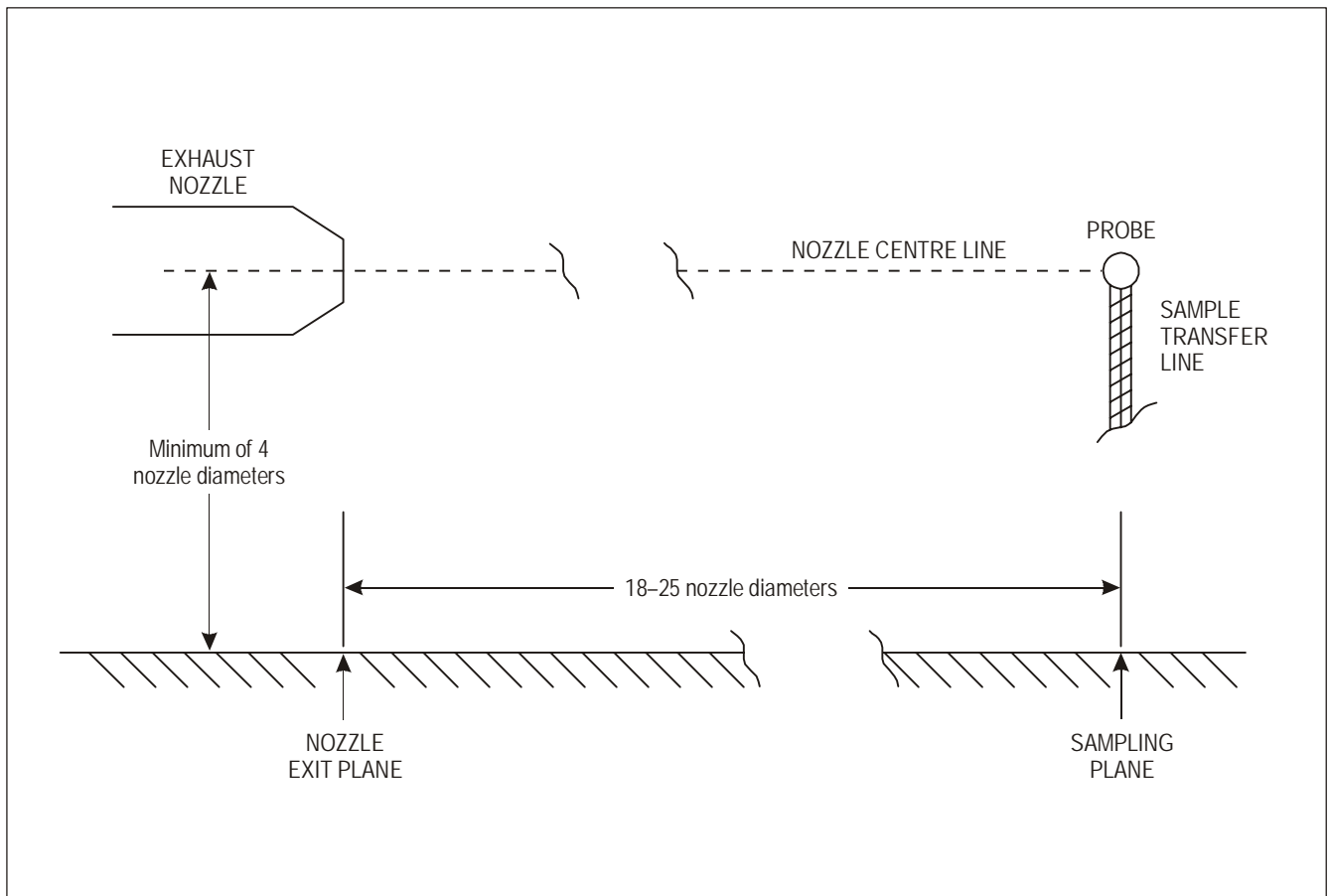
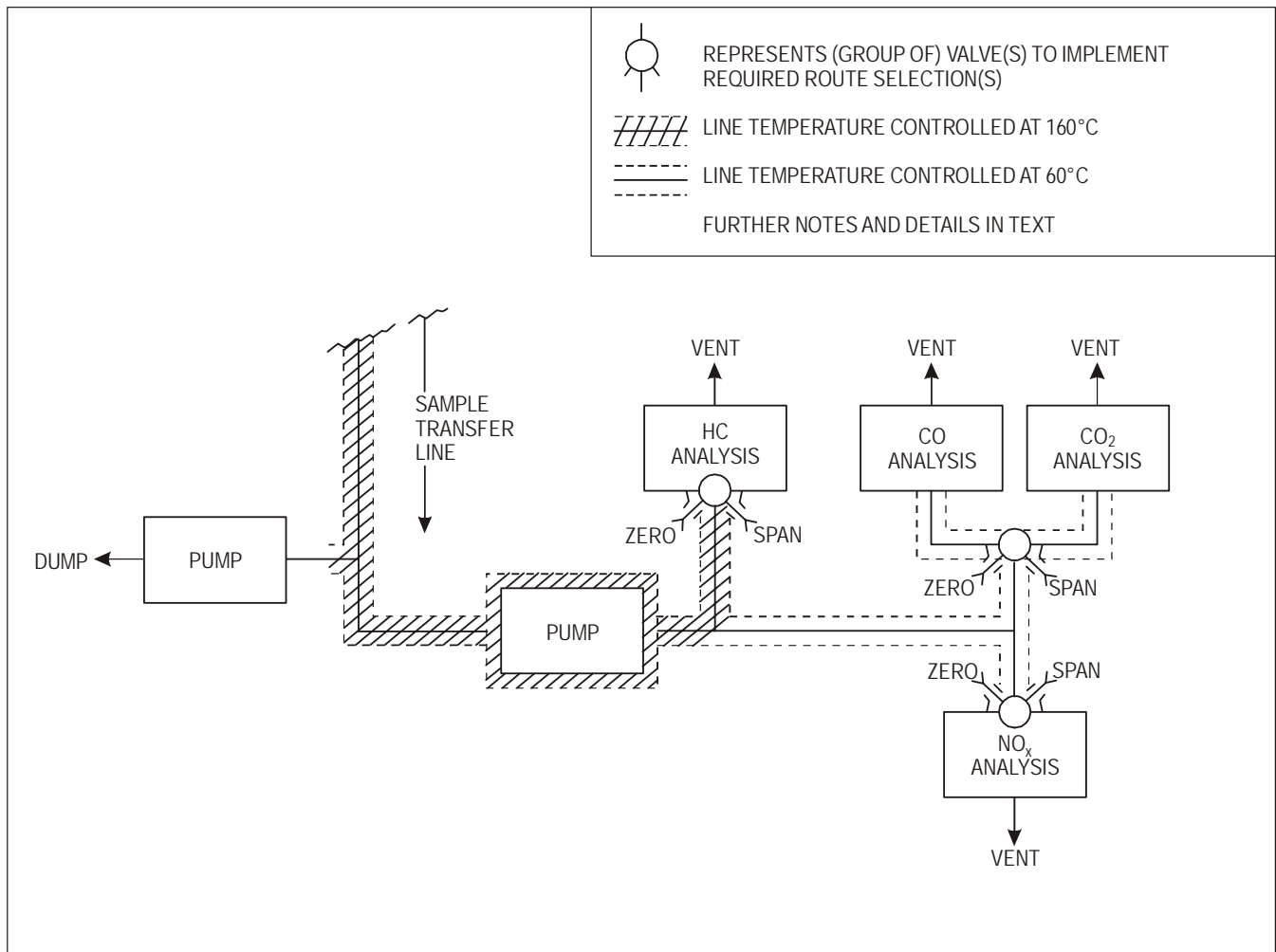


Figure A5-1. Exhaust gas sampling system, schematic



**Figure A5-2. Sample transfer and analysis system, schematic**

- c) The sampling plane shall be perpendicular to the projected engine nozzle centre line, and shall be situated as close as possible to a position 18 nozzle diameters from the nozzle exit plane, consistent with 7.1.2, but in no case greater than 25 nozzle diameters. The nozzle exit diameter shall be for the maximum engine power condition. Between and including exit and sampling planes there shall be an unobstructed region of at least 4 nozzle exit diameters in radial distance about the project engine nozzle centre line.
- d) The minimum number of sampling points shall be equal to 11. The measurement plane, located at a distance  $X$  from the engine shall be divided into three sections demarcated by circles centred around the exhaust stream axis with radii
- $$R1 = 0.05X$$
- $$R2 = 0.09X$$

and a minimum of 3 samples shall be taken from each section. The difference between the number of samples in each section must be less than 3. The sample taken at the most remote distance from the axis shall be from a point located at a radius of between  $0.11X$  and  $0.16X$ .

### 5.1.2 Sampling lines

The sample shall be transferred from the probe to the analysers via a line of 4.0 to 8.5 mm inside diameter, taking the shortest route practicable and using a flow rate such that the transport time is less than 10 seconds. The line shall be maintained at a temperature of  $160^{\circ}\text{C} \pm 15^{\circ}\text{C}$  (with a stability of  $\pm 10^{\circ}\text{C}$ ). When sampling to measure HC, CO,  $\text{CO}_2$  and  $\text{NO}_x$  components, the line shall be constructed in stainless steel or carbon-loaded grounded PTFE.

## 5.2 HC analyser

The measurement of total hydrocarbon sample content shall be made by an analyser using the heated flame ionization detector (FID), between the electrodes of which passes an ionization current proportional to the mass rate of hydrocarbon entering a hydrogen flame. The analyser shall be deemed to include components arranged to control temperature and flow rates of sample, sample bypass, fuel and diluent gases, and to enable effective span and zero calibration checks.

*Note.*— An overall specification is given in Attachment A to this appendix.

## 5.3 CO and $\text{CO}_2$ analysers

Non-dispersive infrared analysers shall be used for the measurement of these components, and shall be of the design which utilizes differential energy absorption in parallel reference and sample gas cells, the cell or group of cells for each of these gas constituents being sensitized appropriately. This analysis subsystem shall include all necessary functions for the control and handling of sample, zero and span gas flows. Temperature control shall be that appropriate to whichever basis of measurement, wet or dry, is chosen.

*Note.*— An overall specification is given in Attachment B to this appendix.

## 5.4 $\text{NO}_x$ analyser

The measurement of NO concentration shall be by the chemiluminescent method in which the measure of the radiation intensity emitted during the reaction of the NO in the sample with added  $\text{O}_3$  is the measure of the NO concentration. The  $\text{NO}_2$  component shall be converted to NO in a converter of the requisite efficiency prior to measurement. The resultant  $\text{NO}_x$  measurement system shall include all necessary flow, temperature and other controls and provide for routine zero and span calibration as well as for converter efficiency checks.

*Note.*— An overall specification is given in Attachment C to this appendix.

# 6. GENERAL TEST PROCEDURES

## 6.1 Engine operation

The engine shall be operated on an open air static test facility which is suitable and properly equipped for high accuracy performance testing, and which conforms to the requirements for sampling probe installation as specified in 5.1. The emissions tests shall be made at the power settings prescribed by the certificating authority. The engine shall be stabilized at each setting.



## 6.2 Ambient air conditions

6.2.1 A check shall be made on the ambient concentrations of CO, HC, CO<sub>2</sub> and NO<sub>x</sub>, with the engine under test running at the test condition. Unusually high concentrations indicate abnormal conditions such as exhaust gas recirculation, fuel spillage or some other source of unwanted emissions in the test area and such situations shall be rectified or avoided as appropriate.

*Note.*— For guidance, the normal ambient concentration of CO<sub>2</sub> is 0.03 per cent, and ambient concentration levels for CO and HC of 5 ppm and NO<sub>x</sub> of 0.5 ppm are unlikely to be exceeded under normal conditions.

6.2.2 Extreme climatic conditions, such as those involving precipitation or excessive wind speed shall also be avoided.

## 6.3 Major instrument calibration

*Note.*— The general objective of this calibration is to confirm stability and linearity.

6.3.1 The applicant shall satisfy the certificating authority that the calibration of the analytical system is valid at the time of the test.

6.3.2 For the hydrocarbon analyser this calibration shall include checks that the detector oxygen and differential hydrocarbon responses are within the limits specified in Attachment A to this appendix. The efficiency of the NO<sub>2</sub>/NO converter shall also be checked and verified to meet the requirements in Attachment C to this appendix.

6.3.3 The procedure for checking the performance of each analyser shall be as follows (using the calibration and test gases as specified in Attachment D to this appendix):

- a) introduce zero gas and adjust instrument zero, recording setting as appropriate;
- b) for each range to be used operationally, introduce calibration gas of (nominally) 90 per cent range full-scale deflection (FSD) concentration; adjust instrument gain accordingly and record its setting;
- c) introduce approximately 30, 60 and 90 per cent range FSD concentrations and record analyser readings;
- d) fit a least squares straight line to the zero, 30, 60 and 90 per cent concentration points. For the CO and/or CO<sub>2</sub> analyser used in its basic form without linearization of output, a least squares curve of appropriate mathematical formulation shall be fitted using additional calibration points if judged necessary. If any point deviates by more than 2 per cent of the full scale value (or  $\pm 1$  ppm\*, whichever is greater) then a calibration curve shall be prepared for operational use.

## 6.4 Operation

6.4.1 No measurements shall be made until all instruments and sample transfer lines are warmed up and stable and the following checks have been carried out:

- a) leakage check: prior to a series of tests the system shall be checked for leakage by isolating the probe and the analysers, connecting and operating a vacuum pump of equivalent performance to that used in the smoke measurement system to verify that the system leakage flow rate is less than 0.4 L/min referred to normal temperature and pressure;

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\* Except for the CO<sub>2</sub> analyser, for which the value shall be  $\pm 100$  ppm.

- b) cleanliness check: isolate the gas sampling system from the probe and connect the end of the sampling line to a source of zero gas. Warm the system up to the operational temperature needed to perform hydrocarbon measurements. Operate the sample flow pump and set the flow rate to that used during engine emission testing. Record the hydrocarbon analyser reading. The reading shall not exceed 1 per cent of the engine idle emission level or 1 ppm (both expressed as methane), whichever is the greater.

*Note 1.— It is good practice to back-purge the sampling lines during engine running, while the probe is in the engine exhaust but emissions are not being measured, to ensure that no significant contamination occurs.*

*Note 2.— It is also good practice to monitor the inlet air quality at the start and end of testing and at least once per hour during a test. If levels are considered significant, then they should be taken into account.*

6.4.2 The following procedure shall be adopted for operational measurements:

- a) apply appropriate zero gas and make any necessary instrument adjustments;
- b) apply appropriate calibration gas at a nominal 90 per cent FSD concentration for the ranges to be used, adjust and record gain settings accordingly;
- c) when the engine has been stabilized at the requisite operating conditions and sampling location, continue to run it and observe pollutant concentrations until a stabilized reading is obtained, which shall be recorded. At the same engine operating condition repeat the measurement procedure for each of the remaining sampling locations;
- d) recheck zero and calibration points at the end of the test and also at intervals not greater than 1 hour during tests. If either has changed by more than  $\pm 2$  per cent of full scale of range, the test shall be repeated after restoration of the instrument to within its specification.

## 7. CALCULATIONS

### 7.1 Gaseous emissions

#### 7.1.1 General

The analytical measurements made shall be the concentrations of the various classes of pollutant, at the relevant afterburning mode(s) of the engine, at the various locations in the sampling plane. In addition to the recording of these basic parameters, other parameters shall be computed and reported, as follows.

#### 7.1.2 Analysis and validation of measurements

- a) At each engine setting, the concentrations measured at different probe sampling positions must be averaged as follows:

$$C_{i \text{ moy}} = \sum_{j=1}^n C_{i \text{ j}}$$

where

$\sum_{j=1}^n$  Summation of the total number  $n$  of sampling positions used.

$C_{ij}$  Concentration of species  $i$  measured at the  $j$ th sampling position.

$C_{i\text{ moy}}$  average or mean concentration of species  $i$ .

All dry concentration measurements shall be converted into real wet concentrations. (See Attachment E to this appendix).

- b) The quality of the measurements for each pollutant will be determined through a comparison with measurements of  $\text{CO}_2$  using the correlation coefficient:

$$r_i = \frac{n \sum_{j=1}^n C_{ij} \text{CO}_{2j} - \sum_{j=1}^n C_{ij} \sum_{j=1}^n \text{CO}_{2j}}{\sqrt{\left\{ n \sum_{j=1}^n (\text{CO}_{2j})^2 - \left( \sum_{j=1}^n \text{CO}_{2j} \right)^2 \right\} \left\{ n \sum_{j=1}^n C_{ij}^2 - \left( \sum_{j=1}^n C_{ij} \right)^2 \right\}}}$$

Values of  $r_i$  which are near to 1 indicate that measurements taken over the entire sampling period are sufficiently stable and that the curves are Gaussian. In the event that  $r_i$  is less than 0.95, measurements must be repeated in a sampling plane located at a more remote distance from the aircraft engine. The measurement process, per se, is then followed by the same calculations and the same demonstration as previously.

### 7.1.3 Basic parameters

For the measurements at each engine operating mode the average concentration for each gaseous species is estimated as shown in 7.1.2, any necessary corrections for dry sample measurement and/or interferences having been made as indicated in Attachment E to this appendix. These average concentrations are used to compute the following basic parameters:

$$\text{EI}_p \text{ (emission index for component } p) = \frac{\text{mass of } p \text{ produced in g}}{\text{mass of fuel used in kg}}$$

$$\text{EI}(\text{CO}) = \left( \frac{[\text{CO}]}{[\text{CO}_2] + [\text{CO}] + [\text{HC}]} \right) \left( \frac{10^3 M_{\text{CO}}}{M_{\text{C}} + (n/m)M_{\text{H}}} \right) (1+T(\text{P}_0/m))$$

$$\text{EI}(\text{HC}) = \left( \frac{[\text{HC}]}{[\text{CO}_2] + [\text{CO}] + [\text{HC}]} \right) \left( \frac{10^3 M_{\text{HC}}}{M_{\text{C}} + (n/m)M_{\text{H}}} \right) (1+T(\text{P}_0/m))$$

$$\text{EI}(\text{NO}_x) \text{ (as NO}_2) = \left( \frac{[\text{NO}_x]}{[\text{CO}_2] + [\text{CO}] + [\text{HC}]} \right) \left( \frac{10^3 M_{\text{NO}_2}}{M_{\text{C}} + (n/m)M_{\text{H}}} \right) (1+T(\text{P}_0/m))$$

$$\text{Air/fuel ratio} = (\text{P}_0/m) \left( \frac{M_{\text{AIR}}}{M_{\text{C}} + (n/m)M_{\text{H}}} \right)$$

where

$$P_0 / m = \frac{2Z - (n/m)}{4(1 + h_{vol} - [TZ / 2])}$$

and

$$Z = \frac{2 - [\text{CO}] - ([2/x] - [y/2x])[HC] + [\text{NO}_2]}{[\text{CO}_2] + [\text{CO}] + [HC]}$$

$M_{\text{AIR}}$  molecular mass of dry air = 28.966 g or, where appropriate, = (32  $R$  + 28.156 4  $S$  + 44.011  $T$ ) g

$M_{\text{HC}}$  molecular mass of exhaust hydrocarbons, taken as  $\text{CH}_4$  = 16.043 g

$M_{\text{CO}}$  molecular mass of CO = 28.011 g

$M_{\text{NO}_2}$  molecular mass of  $\text{NO}_2$  = 46.088 g

$M_{\text{C}}$  atomic mass of carbon = 12.011 g

$M_{\text{H}}$  atomic mass of hydrogen = 1.008 g

$R$  concentration of  $\text{O}_2$  in dry air, by volume = 0.209 5 normally

$S$  concentration of  $\text{N}_2$  + rare gases in dry air, by volume = 0.709 2 normally

$T$  concentration of  $\text{CO}_2$  in dry air, by volume = 0.000 3 normally

[HC] mean concentration of exhaust hydrocarbons vol/vol, wet, expressed as carbon

[CO] mean concentration of CO vol/vol, wet

[ $\text{CO}_2$ ] mean concentration of  $\text{CO}_2$  vol/vol, wet

[ $\text{NO}_x$ ] mean concentration of  $\text{NO}_x$  vol/vol, wet = [NO +  $\text{NO}_2$ ]

[NO] mean concentration of NO in exhaust sample, vol/vol, wet

[ $\text{NO}_2$ ] mean concentration of  $\text{NO}_2$  in exhaust sample, vol/vol, wet

$$= \frac{([\text{NO}_x]_c - [\text{NO}])}{\eta}$$

[ $\text{NO}_x$ ]<sub>c</sub> mean concentration of NO in exhaust sample after passing through the  $\text{NO}_2/\text{NO}$  converter, vol/vol, wet

$\eta$  efficiency of  $\text{NO}_2/\text{NO}$  converter

$h_{vol}$  humidity of ambient air, vol water/vol dry air

$m$  number of C atoms in characteristic fuel molecule

$n$	number of H atoms in characteristic fuel molecule
$x$	number of C atoms in characteristic exhaust hydrocarbon molecule
$y$	number of H atoms in characteristic exhaust hydrocarbon molecule

The value of  $n/m$ , the ratio of the atomic hydrogen to atomic carbon of fuel used, is evaluated by fuel type analysis. The ambient air humidity,  $h$ , shall be measured at each set condition. In the absence of contrary evidence as to the characterization ( $x, y$ ) of the exhaust hydrocarbons, the values  $x = 1$ ,  $y = 4$  are to be used. If dry or semi-dry CO and CO<sub>2</sub> measurements are to be used then these shall first be converted to the equivalent wet concentrations as shown in Attachment E to this appendix, which also contains interference correction formulas for use as required.

*Note.— The procedure given in 7.1.4 and 7.2 is only applicable to tests made when afterburning is not used. For tests when afterburning is used, a similar procedure could be used after approval by the certifying authority.*

#### 7.1.4 Correction of emission indices to reference conditions

Corrections shall be made to the measured engine emission indices for all pollutants in all relevant engine operating modes to account for deviations from the reference conditions (ISA at sea level) of the actual test inlet air conditions of temperature and pressure. The reference value for humidity shall be 0.00634 kg water/kg dry air.

Thus, EI corrected =  $K \times$  EI measured,

where the generalized expression for  $K$  is:

$$K = (P_{Bref}/P_B)^a \times (FAR_{ref}/FAR_B)^b \times \exp([T_{Bref} - T_B]/c) \times \exp(d[h_{vol} - 0.00634])$$

$P_B$	Combustor inlet pressure, measured
$T_B$	Combustor inlet temperature, measured
$FAR_B$	Fuel/air ratio in the combustor
$h_{vol}$	Ambient air humidity, vol water/vol dry air
$P_{ref}$	ISA sea level pressure
$T_{ref}$	ISA sea level temperature
$P_{Bref}$	Pressure at the combustor inlet of the engine tested (or the reference engine if the data is corrected to a reference engine) associated with $T_B$ under ISA sea level conditions.
$T_{Bref}$	Temperature at the combustor inlet under ISA sea level conditions for the engine tested (or the reference engine if the data is to be corrected to a reference engine). This temperature is the temperature associated with each thrust level specified for each mode.
$FAR_{ref}$	Fuel/air ratio in the combustor under ISA sea level conditions for the engine tested (or the reference engine if the data is to be corrected to a reference engine).
$a, b, c, d$	Specific constants which may vary for each pollutant and each engine type.

The combustor inlet parameters shall preferably be measured but may be calculated from ambient conditions by appropriate formulas.

7.1.5 Using the recommended curve fitting technique to relate emission indices to combustor inlet temperature effectively eliminates the  $\exp((T_{Bref} - T_B)/c)$  term from the generalized equation and for most cases the  $(FAR_{ref}/FAR_B)$  term may be considered unity. For the emissions indices of CO and HC many testing facilities have determined that the humidity term is sufficiently close to unity to be eliminated from the expression and that the exponent of the  $(P_{Bref}/P_B)$  term is close to unity.

Thus,

EI(CO) corrected = EI derived from  $(P_B/P_{Bref}) \cdot EI(\text{CO})$  v.  $T_B$  curve

EI(HC) corrected = EI derived from  $(P_B/P_{Bref}) \cdot EI(\text{HC})$  v.  $T_B$  curve

EI( $\text{NO}_x$ ) corrected = EI derived from  $EI(\text{NO}_x) (P_{Bref}/P_B)^{0.5 \exp(19[I_{vol} - 0.00634])}$  v.  $T_B$  curve

If this recommended method for the CO and HC emissions index correction does not provide a satisfactory correlation, an alternative method using parameters derived from component tests may be used.

Any other methods used for making corrections to CO, HC and  $\text{NO}_x$  emissions indices shall have the approval of the certificating authority.

## 7.2 Control parameter functions

$(D_p, F_{oo}, \pi)$

### 7.2.1 Definitions

- $D_p$  The mass of any gaseous pollutant emitted during the reference emissions landing and take-off cycle.
- $F_{oo}$  The maximum thrust available for take-off under normal operating conditions at ISA sea level static conditions, without the use of water injection, as approved by the applicable certificating authority.
- $\pi$  The ratio of the mean total pressure at the last compressor discharge plane of the compressor to the mean total pressure at the compressor entry plane when the engine is developing take-off thrust rating at ISA sea level static conditions.

7.2.2 The emission indices (EI) for each pollutant, corrected for pressure and humidity (as appropriate) to the reference ambient atmospheric conditions as indicated in 7.1.4 and if necessary to the reference engine, shall be obtained for the required LTO engine operating mode settings ( $n$ ) of idle, approach, climb-out and take-off, at each of the equivalent corrected thrust conditions. A minimum of three test points shall be required to define the idle mode. The following relationships shall be determined for each pollutant:

- between EI and  $T_B$ ; and
- between  $W_f$  (engine fuel mass flow rate) and  $T_B$ ; and
- between  $F_n$  (corrected to ISA sea level conditions) and  $T_B$  (corrected to ISA sea level conditions);

*Note.— These are illustrated, for example, by Figure A5-3 a), b) and c).*

When the engine being tested is not a “reference” engine, the data may be corrected to “reference” engine conditions using the relationships b) and c) obtained from a reference engine. A reference engine is defined as an engine substantially configured

to the description of the engine to be certificated and accepted by the certificating authority to be representative of the engine type for which certification is sought.

The manufacturer shall also supply to the certificating authority all of the necessary engine performance data to substantiate these relationships and for ISA sea level ambient conditions:

- d) maximum rated thrust ( $F_{oo}$ ); and
- e) engine pressure ratio ( $\pi$ ) at maximum rated thrust.

*Note.*— *These are illustrated by Figure A5-3 d).*

7.2.3 The estimation of EI for each pollutant at each of the required engine mode settings, corrected to the reference ambient conditions, shall comply with the following general procedure:

- a) at each mode ISA thrust condition  $F_n$ , determine the equivalent combustor inlet temperature ( $T_B$ ) (Figure A5-3 c));
- b) from the EI/ $T_B$  characteristic (Figure A5-3 a)), determine the EI<sub>*n*</sub> value corresponding to  $T_B$ ;
- c) from the  $W_f/T_B$  characteristics (Figure A5-3 b)), determine the  $W_{f_n}$  value corresponding to  $T_B$ ;
- d) note the ISA maximum rated thrust and pressure ratio values. These are  $F_{oo}$  and  $\pi$  respectively (Figure A5-3 d));
- e) calculate, for each pollutant  $Dp = \Sigma (EI_n) (W_{f_n}) (t)$  where:

$t$  time in LTO mode (minutes)

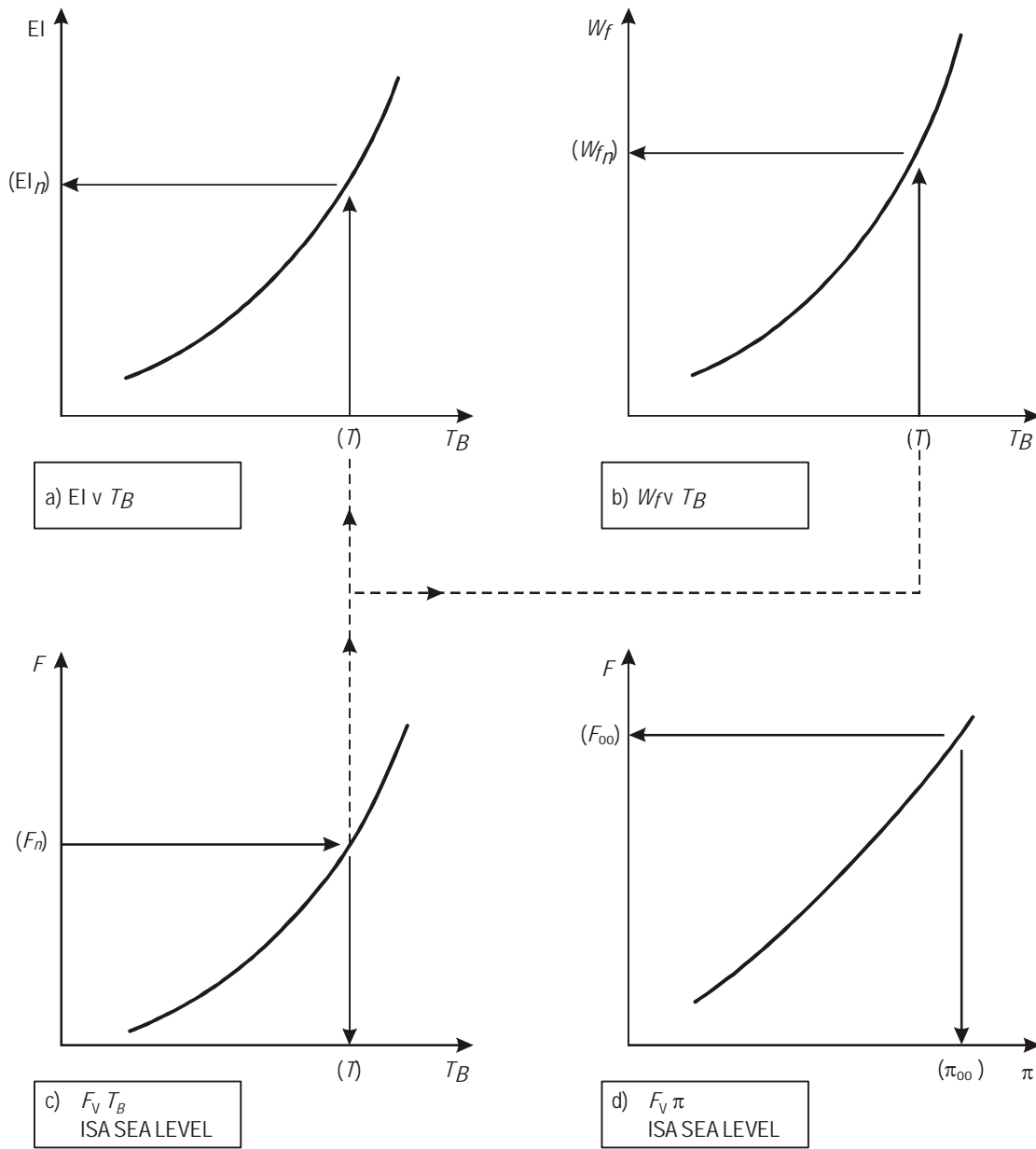
$W_{f_n}$  fuel mass flow rate (kg/min)

$\Sigma$  is the summation for the set of modes comprising the reference LTO cycle.

7.2.4 While the methodology described above is the recommended method, the certificating authority may accept equivalent mathematical procedures which utilize mathematical expressions representing the curves illustrated if the expressions have been derived using an accepted curve fitting technique.

### 7.3 Exceptions to the proposed procedures

In those cases where the configuration of the engine or other extenuating conditions exist which would prohibit the use of this procedure, the certificating authority, after receiving satisfactory technical evidence of equivalent results obtained by an alternative procedure, may approve an alternative procedure.



EI = EMISSION INDEX  
 $T_B$  = COMBUSTOR INLET TEMPERATURE  
 $W_f$  = ENGINE FUEL MASS FLOW RATE  
 $F$  = ENGINE THRUST  
 $\pi$  = ENGINE PRESSURE RATIO

Figure A5-3. Calculation procedure



## ATTACHMENT A TO APPENDIX 5. SPECIFICATION FOR HC ANALYSER

*Note 1.— As outlined in 5.2 of Appendix 5, 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.*

### 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.

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 within the range 155°C to 165°C to a stability of  $\pm 2^\circ\text{C}$ . The leading specification points shall be as follows, the detector response having been optimized and the instrument generally having stabilized:

- a) *Total range:* 0 to 500 ppmC in appropriate ranges.
- b) *Resolution:* better than 0.5 per cent of full scale of range used or 0.5 ppmC, whichever is greater.
- c) *Repeatability:* better than  $\pm 1$  per cent of full scale of range used, or  $\pm 0.5$  ppmC, whichever is greater.
- d) *Stability:* better than  $\pm 2$  per cent of full scale of range used or  $\pm 1$  ppmC, whichever is greater, in a period of 1 hour.
- e) *Zero drift:* less than  $\pm 1$  per cent of full scale of range used or  $\pm 0.5$  ppmC, whichever is greater, in a period of 1 hour.
- f) *Noise:* 0.5 Hz and greater, less than  $\pm 1$  per cent of full scale of range used or  $\pm 0.5$  ppmC, whichever is greater.
- g) *Response time:* shall not exceed 10 seconds from inlet of the sample to the analysis system, to the achievement of 90 per cent of the final reading.
- h) *Linearity:* response with propane in air shall be linear for each range within  $\pm 2$  per cent of full scale, otherwise calibration corrections shall be used.

### 2. SYNERGISTIC EFFECTS

*Note.— In application there are two aspects of performance which can affect the accuracy of measurement:*

- a) *the oxygen effect (whereby differing proportions of oxygen present in the sample give differing indicated hydrocarbon concentration for constant actual HC concentrations); and*

- b) the relative hydrocarbon response (whereby there is a different response to the same sample hydrocarbon concentrations expressed as equivalent ppmC, dependent on the class or admixture of classes of hydrocarbon compounds).

The magnitude of the effects noted above shall be determined as follows and limited accordingly.

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

- 1) propane in  $10 \pm 1$  per cent O<sub>2</sub>, balance N<sub>2</sub>
- 2) propane in  $21 \pm 1$  per cent O<sub>2</sub>, balance N<sub>2</sub>

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

*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  $\pm 1$  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  $R_a$ .

### 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.

3.2 The linearity of each analyser range shall be checked by applying propane in air samples at concentrations of approximately 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 zero) shall not exceed  $\pm 2$  per cent of full scale value. If it does, a calibration curve shall be prepared for operational use.

## ATTACHMENT B TO APPENDIX 5. SPECIFICATION FOR CO AND CO<sub>2</sub> ANALYSERS

*Note 1.— Paragraph 5.3 of Appendix 5 summarizes the characteristics of the analysis subsystem to be employed for the individual measurements of CO and CO<sub>2</sub> concentrations in the exhaust gas sample. The instruments are based on the principle of non-dispersive absorption of infrared radiation in parallel reference and sample gas cells. The required ranges of sensitivity are obtained by use of stacked sample cells or changes in electronic circuitry or both. Interferences from gases with overlapping absorption bands may be minimized by gas absorption filters and/or optical filters, preferably the latter.*

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

**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.

The principal performance specification shall be as follows:

### CO Analyser

- a) *Total range:* 0 to 2 500 ppm in appropriate ranges.
- b) *Resolution:* better than 0.5 per cent of full scale of range used or 1 ppm, whichever is greater.
- c) *Repeatability:* better than  $\pm 1$  per cent of full scale of range used, or  $\pm 2$  ppm, whichever is greater.
- d) *Stability:* better than  $\pm 2$  per cent of full scale of range used or  $\pm 2$  ppm, whichever is greater, in a period of 1 hour.
- e) *Zero drift:* less than  $\pm 1$  per cent of full scale of range used or  $\pm 2$  ppm, whichever is greater, in a period of 1 hour.
- f) *Noise:* 0.5 Hz and greater, less than  $\pm 1$  per cent of full scale of range used or  $\pm 1$  ppm, whichever is greater.
- g) *Interferences:* to be limited with respect to indicated CO concentration as follows:
  - 1) less than 500 ppm/per cent ethylene concentration
  - 2) less than 2 ppm/per cent CO<sub>2</sub> concentration
  - 3) less than 2 ppm/per cent water vapour.\*

If the interference limitation(s) for CO<sub>2</sub> and/or water vapour cannot be met, appropriate correction factors shall be determined, reported and applied.

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

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

*CO<sub>2</sub> Analyser*

- a) *Total range*: 0 to 10 per cent in appropriate ranges.
- b) *Resolution*: better than 0.5 per cent of full scale of range used or 100 ppm, whichever is greater.
- c) *Repeatability*: better than  $\pm 1$  per cent of full scale of range used or  $\pm 100$  ppm, whichever is greater.
- d) *Stability*: better than  $\pm 2$  per cent of full scale of range used or  $\pm 100$  ppm, whichever is greater, in a period of 1 hour.
- e) *Zero drift*: less than  $\pm 1$  per cent of full scale of range used or  $\pm 100$  ppm, whichever is greater, in a period of 1 hour.
- f) *Noise*: 0.5 Hz and greater, less than  $\pm 1$  per cent of full scale of range used or  $\pm 100$  ppm, whichever is greater.
- g) The effect of oxygen (O<sub>2</sub>) on the CO<sub>2</sub> analyser response shall be checked. For a change from 0 per cent O<sub>2</sub> to 21 per cent O<sub>2</sub> the response of a given CO<sub>2</sub> 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.

*CO and CO<sub>2</sub> Analysers*

- a) *Response time*: shall not exceed 10 seconds from inlet of the sample to the analysis system, to the achievement of 90 per cent of the final reading.
- 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  $\pm 2^\circ\text{C}$ . The option to measure CO and CO<sub>2</sub> on a dry basis (with suitable water traps) is allowed, in which case unheated analysers are permissible and the interference limits for H<sub>2</sub>O vapour removed, and subsequent correction for inlet water vapour and water of combustion is required.
- 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  $\pm 2$  per cent of the full scale value. If it does then a calibration curve shall be prepared for operational use.
  - 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.

## ATTACHMENT C TO APPENDIX 5. SPECIFICATION FOR NO<sub>x</sub> ANALYSER

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

1. As indicated in 5.4 of Appendix 5, the measurement of the oxides of nitrogen concentration shall be by the chemiluminescent technique in which radiation emitted by the reaction of NO and O<sub>3</sub> is measured. This method is not sensitive to NO<sub>2</sub> and therefore the sample shall be passed through a converter in which NO<sub>2</sub> is converted to NO before the measurement of total NO<sub>x</sub> is made. Both the original NO and the total NO<sub>x</sub> concentrations shall be recorded. Thus by difference, a measure of the NO<sub>2</sub> concentration shall be obtained.

2. The instrument to be used shall be complete with all necessary flow control components, such as regulators, valves, flowmeters, etc. Materials in contact with the sample gas shall be restricted to those which are resistant to attack by oxides of nitrogen, such as stainless steel, glass, etc. The temperature of the sample shall everywhere be maintained at values, consistent with the local pressures, which avoid condensation of water.

**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.

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.
- b) *Resolution:* better than 0.5 per cent of full scale of range used or 1 ppm, whichever is greater.
- c) *Repeatability:* better than ±1 per cent of full scale of range used, or ±1 ppm, whichever is greater.
- d) *Stability:* better than ±2 per cent of full scale of range used or ±1 ppm, whichever is greater, in a period of 1 hour.
- e) *Zero drift:* less than ±1 per cent of full scale of range used or ±1 ppm, whichever is greater, in a period of 1 hour.
- f) *Noise:* 0.5 Hz and greater, less than ±1.0 per cent of full scale of range used or ±1 ppm, whichever is greater, in a period of 2 hours.
- g) *Interference:* suppression for samples containing CO<sub>2</sub> and water vapour, shall be limited as follows:
  - less than 0.05 per cent reading/per cent CO<sub>2</sub> concentration;
  - less than 0.1 per cent reading/per cent water vapour concentration.

If the interference limitation(s) for CO<sub>2</sub> and/or water vapour cannot be met, appropriate correction factors shall be determined, reported and applied.

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

- h) *Response time*: shall not exceed 10 seconds from inlet of the sample to the analysis system to the achievement of 90 per cent of the final reading.
- i) *Linearity*: better than  $\pm 2$  per cent of full scale of range used or  $\pm 2$  ppm, whichever is greater.
- j) *Converter*: this shall be designed and operated in such a matter as to reduce  $\text{NO}_2$  present in the sample to  $\text{NO}$ . The converter shall not affect the  $\text{NO}$  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  $\text{NO}_2$  value (i.e.  $[\text{NO}_{x,c}] - [\text{NO}]$ ) to that which would have been obtained if the efficiency had not been 100 per cent.

## ATTACHMENT D TO APPENDIX 5. CALIBRATION AND TEST GASES

**Table of calibration gases**

<i>Analyser</i>	<i>Gas</i>	<i>Accuracy*</i>
HC	propane in zero air	±2 per cent or ±0.05 ppm**
CO <sub>2</sub>	CO <sub>2</sub> in zero air	±2 per cent or ±100 ppm**
CO	CO in zero air	±2 per cent or ±2 ppm**
NO <sub>x</sub>	NO <sub>x</sub> in zero nitrogen	±2 per cent or ±1 ppm**

\* Taken over the 95 per cent confidence interval.  
 \*\* Whichever is greater.

The above gases are required to carry out the routine calibration of analysers during normal operational use.

**Table of test gases**

<i>Analyser</i>	<i>Gas</i>	<i>Accuracy*</i>
HC	propane in 10 ±1 per cent O <sub>2</sub> balance zero nitrogen	±1 per cent
HC	propane in 21 ±1 per cent O <sub>2</sub> balance zero nitrogen	±1 per cent
HC	propylene in zero air	±1 per cent
HC	toluene in zero air	±1 per cent
HC	n-hexane in zero air	±1 per cent
HC	propane in zero air	±1 per cent
CO <sub>2</sub>	CO <sub>2</sub> in zero air	±1 per cent
CO <sub>2</sub>	CO <sub>2</sub> in zero nitrogen	±1 per cent
CO	CO in zero air	±1 per cent
NO <sub>x</sub>	NO in zero nitrogen	±1 per cent

\* Taken over the 95 per cent confidence interval.

The above gases are required to carry out the tests of Attachments A, B and C.

Carbon monoxide and carbon dioxide calibration gases may be blended singly or as dual component mixtures. Three component mixtures of carbon monoxide, carbon dioxide and propane in zero air may be used, provided the stability of the mixture is assured.

Zero gas as specified for the CO, CO<sub>2</sub> and HC analysers shall be zero air (which includes “artificial” air with 20 to 22 per cent O<sub>2</sub> blended with N<sub>2</sub>). For the NO<sub>x</sub> analyser zero nitrogen shall be used as the zero gas. Impurities in both kinds of zero gas shall be restricted to be less than the following concentrations:

- 1 ppm C
- 1 ppm CO
- 100 ppm CO<sub>2</sub>
- 1 ppm NO<sub>x</sub>

The applicant shall ensure that commercial gases, as supplied, do in fact meet this specification, or are so specified by the vendor.



**ATTACHMENT E TO APPENDIX 5. THE CALCULATION OF THE  
EMISSIONS PARAMETERS — BASIS, MEASUREMENT  
CORRECTIONS AND ALTERNATIVE NUMERICAL METHOD**

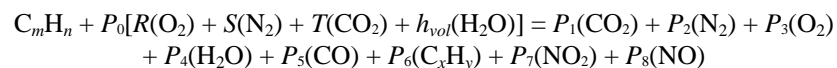
**1. SYMBOLS**

$AFR$	air/fuel ratio; the ratio of the mass flow rate of dry air to that of the fuel
$EI$	emission index; $10^3 \times$ mass flow rate of gaseous emission product in exhaust per unit mass flow rate of fuel
$K$	ratio of concentration measured wet to that measured dry (after cold trap)
$L, L'$	analyser interference coefficient for interference by $CO_2$
$M, M'$	analyser interference coefficient for interference by $H_2O$
$M_{AIR}$	molecular mass of dry air = 28.966 g or, where appropriate, = $(32 R + 28.156 4 S + 44.011 T)$ g
$M_{CO}$	molecular mass of CO = 28.011 g
$M_{HC}$	molecular mass of exhaust hydrocarbon, taken as $CH_4$ = 16.043 g
$M_{NO_2}$	molecular mass of $NO_2$ = 46.008 g
$M_C$	atomic mass of carbon = 12.011 g
$M_H$	atomic mass of hydrogen = 1.008 g
$P_1$	number of moles of $CO_2$ in the exhaust sample per mole of fuel
$P_2$	number of moles of $N_2$ in the exhaust sample per mole of fuel
$P_3$	number of moles of $O_2$ in the exhaust sample per mole of fuel
$P_4$	number of moles of $H_2O$ in the exhaust sample per mole of fuel
$P_5$	number of moles of CO in the exhaust sample per mole of fuel
$P_6$	number of moles of $C_xH_y$ in the exhaust sample per mole of fuel
$P_7$	number of moles of $NO_2$ in the exhaust sample per mole of fuel
$P_8$	number of moles of NO in the exhaust sample per mole of fuel
$P_T$	$P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8$
$R$	concentration of $O_2$ in dry air, by volume = 0.2095 normally

$S$	concentration of $N_2$ + rare gases in dry air, by volume = 0.7902 normally
$T$	concentration of $CO_2$ in dry air, by volume = 0.0003 normally
$P_0$	number of moles of air per mole of fuel in initial air/fuel mixture
$Z$	symbol used and defined in 3.4
$[CO_2]$	mean concentration of $CO_2$ in exhaust sample, vol/vol
$[CO]$	mean concentration of $CO$ in exhaust sample, vol/vol
$[HC]$	mean concentration of $HC$ in exhaust sample, vol/vol
$[NO]$	mean concentration of $NO$ in exhaust sample, vol/vol
$[NO_2]$	mean concentration of $NO_2$ in exhaust sample, vol/vol
$[NO_x]$	mean concentration of $NO$ and $NO_2$ in exhaust sample, vol/vol
$[NO_x]_c$	mean concentration of $NO$ in exhaust sample, after passing through the $NO_2/NO$ converter, vol/vol
$[NO_2]$	mean = $\frac{([NO_x]_c - [NO])}{\eta}$
$[ ]_d$	mean concentration in exhaust sample after cold trap, vol/vol
$[ ]_m$	mean concentration measurement indicated before instrument correction applied, vol/vol
$h_{vol}$	humidity of ambient air, vol water/vol dry air
$h_d$	humidity of exhaust sample leaving “drier” or “cold trap”, vol water/vol dry sample
$m$	number of C atoms in characteristic fuel molecule
$n$	number of H atoms in characteristic fuel molecule
$x$	number of C atoms in characteristic exhaust hydrocarbon molecule
$y$	number of H atoms in characteristic exhaust hydrocarbon molecule
$\eta$	efficiency of $NO_2/NO$ converter

## 2. BASIS OF CALCULATION OF EI AND AFR PARAMETERS

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:



from which the required parameters can, by definition, be expressed as

$$EI(\text{CO}) = P_5 \left( \frac{10^3 M_{\text{CO}}}{mM_{\text{C}} + nM_{\text{H}}} \right)$$

$$EI(\text{HC}) = xP_6 \left( \frac{10^3 M_{\text{HC}}}{mM_{\text{C}} + nM_{\text{H}}} \right) \text{ expressed as methane equivalent}$$

$$EI(\text{NO}_x) = (P_7 + P_8) \left( \frac{10^3 M_{\text{NO}_2}}{mM_{\text{C}} + nM_{\text{H}}} \right) \text{ expressed as NO}_2 \text{ equivalent}$$

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

2.2 Values for fuel hydrocarbon composition ( $m$ ,  $n$ ) are assigned by fuel specification or analysis. If only the ratio  $n/m$  is so determined, the value  $m = 12$  may be assigned. The mole fractions of the dry air constituents ( $R$ ,  $S$ ,  $T$ ) are normally taken to be the recommended standard values but alternative values may be assigned, subject to the restriction  $R + S + T = 1$  and the approval of the certifying authority.

2.3 The ambient air humidity,  $h_{\text{vol}}$ , is as measured at each test condition. It is recommended that, in the absence of contrary evidence as to the characterization ( $x$ ,  $y$ ) of the exhaust hydrocarbon, values of  $x = 1$  and  $y = 4$  are assigned.

2.4 Determination of the remaining unknowns requires the solution of the following set of linear simultaneous equations, where (1) to (4) derive from the fundamental atomic conservation relationships and (5) to (9) represent the gaseous product concentration relationships.

$$m + TP_0 = P_1 + P_5 + xP_6 \dots\dots\dots (1)$$

$$n + 2hP_0 = 2P_4 + yP_6 \dots\dots\dots (2)$$

$$(2R + 2T + h_{\text{vol}})P_0 = 2P_1 + 2P_3 + P_4 + P_5 + 2P_7 + P_8 \dots\dots\dots (3)$$

$$2SP_0 = 2P_2 + P_7 + P_8 \dots\dots\dots (4)$$

$$[\text{CO}_2] P_{\text{T}} = P_1 \dots\dots\dots (5)$$

$$[\text{CO}] P_{\text{T}} = P_5 \dots\dots\dots (6)$$

$$[\text{HC}] P_{\text{T}} = xP_6 \dots\dots\dots (7)$$

$$[\text{NO}_x] P_{\text{T}} = \eta P_7 + P_8 \dots\dots\dots (8)$$

$$[\text{NO}] P_{\text{T}} = P_8 \dots\dots\dots (9)$$

$$P_{\text{T}} = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 \dots\dots\dots (10)$$

The above set of conditional equations is for the case where all measured concentrations are true ones, that is, not subject to interference effects or to the need to correct for sample drying. In practice, interference effects are usually present to a significant degree in the CO, NO<sub>x</sub> and NO measurements, and the option to measure CO<sub>2</sub> and CO on a dry or partially dry basis is often used. The necessary modifications to the relevant equations are described in 2.5 and 2.6.

2.5 The interference effects are mainly caused by the presence of CO<sub>2</sub> and H<sub>2</sub>O in the sample which can affect the CO and NO<sub>x</sub> analysers in basically different ways. The CO analyser is prone to a zero-shifting effect and the NO<sub>x</sub> analyser to a sensitivity change, represented thus:

$$[\text{CO}] = [\text{CP}]_m + L[\text{CO}_2] + M[\text{H}_2\text{O}]$$

and

$$[\text{NO}_x]_c = [\text{NO}_x]_{cm} (1 + L'[\text{CO}_2] + M'[\text{H}_2\text{O}])$$

which transform into the following alternative equations to (6), (8) and (9), when interference effects require to be corrected,

$$[\text{CO}]_m P_T + LP_1 + MP_4 = P_5 \dots\dots\dots (6A)$$

$$[\text{NO}_x]_{cm} (P_T + L'P_1 + M'P_4) = \eta P_7 + P_8 \dots\dots\dots (8A)$$

$$[\text{NO}]_m (P_T + L'P_1 + M'P_4) = P_8 \dots\dots\dots (9A)$$

2.6 The option to measure CO<sub>2</sub> and CO concentrations on a dry or partially dry sample basis, that is, with a sample humidity reduced to  $h_d$ , requires the use of modified conditional equations as follows:

$$[\text{CO}_2]_d (P_T - P_4) (1 + h_d) = P_1 \dots\dots\dots (5A)$$

and

$$[\text{CO}]_d (P_T - P_4) (1 + h_d) = P_5$$

However, the CO analyser may also be subject to interference effects as described in 2.5 and so the complete alternative CO measurement concentration equation becomes

$$[\text{CO}]_{md} (P_T - P_4) (1 + h_d) + LP_1 + Mh_d (P_T - P_4) = P_5 \dots\dots\dots (6B)$$

### 3. ANALYTICAL FORMULATIONS

#### 3.1 General

Equations (1) to (10) can be reduced to yield the analytical formulations for the EI and AFR parameters, as given in 7.1 to this appendix. This reduction is a process of progressive elimination of the roots  $P_0$ ,  $P_1$  through  $P_8$ ,  $P_T$ , making the assumptions that all concentration measurements are of the “wet” sample and do not require interference corrections or the like. In practice the option is often chosen to make the CO<sub>2</sub> and CO concentration measurements on a “dry” or “semi-dry” basis; also it is often found necessary to make interference corrections. Formulations for use in these various circumstances are given in 3.2, 3.3 and 3.4.

#### 3.2 Equation for conversion of dry concentration measurements to wet basis

Concentration wet =  $K \times$  concentration dry; that is,

$$[ ] = K [ ]_d$$

The following expression for  $K$  applies when CO and CO<sub>2</sub> are determined on a “dry” basis:

$$K = \frac{\{4 + (n/m)T + ([n/m]T - 2h_{vol})([NO_2] - (2[HC]/x)) + (2 + h_{vol})([y/x] - [n/m])[HC]\}(1 + h_d)}{(2 + h_{vol})\{2 + (n/m)(1 + h_d)([CO_2]_d + [CO]_d)\} - ([n/m]T - 2h_{vol})(1 - [1 + h_d])[CO]_d)}$$

### 3.3 Interference corrections

The measurements of CO and/or NO<sub>x</sub> and NO may require corrections for interference by the sample CO<sub>2</sub> and water concentrations before use in the above analytical equations. Such corrections can normally be expressed in the following general ways:

$$[CO] = [CO]_m + L[CO_2] + M[H_2O]$$

$$[CO]_d = [CO]_{md} + L[CO_2]_d + M \left( \frac{h_d}{1 + h_d} \right)$$

$$[NO] = [NO]_m (1 + L'[CO_2] + M'[H_2O])$$

$$\eta[NO_2] = ([NO_x]_{cm} - [NO]_m) (1 + L'[CO_2] + M'[H_2O])$$

### 3.4 Equation for estimation of sample water content

Water concentration in sample

$$[H_2O] = \frac{([n/2m] + h_{vol}[P_0/m]) ([CO_2] + [CO] + [HC]) - (y/2x) [HC]}{1 + T(P_0/m)}$$

where

$$P_0/m = \frac{2Z - (n/m)}{4(1 + h_{vol} - [TZ/2])}$$

and

$$Z = \frac{2 - [CO] - ([2/x] - [y/2x]) [HC] + [NO_2]}{[CO_2] + [CO] + [HC]}$$

It should be noted that this estimate is a function of the various analyses concentration readings, which may themselves require water interference correction. For better accuracy an iterative procedure is required in these cases with successive recalculation of the water concentration until the requisite stability is obtained. The use of the alternative, numerical solution methodology (4) avoids this difficulty.

## 4. ALTERNATIVE METHODOLOGY — NUMERICAL SOLUTION

4.1 As an alternative to the analytical procedures summarized in 3 above, it is possible to obtain readily the emissions indices, fuel/air ratio, corrected wet concentrations, etc., by a numerical solution of equations (1) to (10) for each set of measurements, using a digital computer.

4.2 In the equation set (1) to (10) the actual concentration measurements are substituted using whichever of the alternative equations (5A), (6A), etc. applies for the particular measuring system, to take account of interference corrections and/or dried sample measurements.

4.3 Suitable simple two-dimensional array equation-solving computer programmes are widely available and their use for this purpose is convenient and flexible, allowing ready incorporation and identification of any sample drying options and interference or other corrections.

## ATTACHMENT F TO APPENDIX 5. SPECIFICATIONS FOR ADDITIONAL DATA

As required in 3.2 of Appendix 5, in addition to the measured sample constituent concentrations, the following data shall also be provided:

- a) inlet temperature: measured as the total temperature at a point within one diameter of the engine intake plane to an accuracy of  $\pm 0.5^{\circ}\text{C}$ ;
- b) inlet humidity (kg water/kg dry air): measured at a point within 15 m of the intake plane ahead of the engine to an accuracy of  $\pm 5$  per cent of reading;
- c) atmospheric pressure: measured within 1 km of the engine test location and corrected as necessary to the test stand altitude to an accuracy of  $\pm 100$  Pa;
- d) fuel mass flow: by direct measurement to an accuracy of  $\pm 2$  per cent;
- e) fuel H/C ratio: defined as  $n/m$ , where  $C_mH_n$  is the equivalent hydrocarbon representation of the fuel used in the test and evaluated by reference to the engine fuel type analysis;
- f) engine parameters:
  - 1) thrust: by direct measurement to an accuracy of  $\pm 1$  per cent at take-off power and  $\pm 5$  per cent at the minimum thrust used in the certification test, with linear variation between these points;
  - 2) rotation speed(s): by direct measurement to an accuracy of at least  $\pm 0.5$  per cent;
  - 3) gas generator airflow: determined to an accuracy of  $\pm 2$  per cent by reference to engine performance calibration.

The parameters a), b), d) and f) shall be determined at each engine emissions test setting, while c) shall be determined at intervals of not less than 1 hour over a period encompassing that of the emissions tests.

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## 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) the manufacturer shall be allowed to select for certification testing any number of engines, including a single engine if so desired;
- b) all the results obtained during the certification tests shall be taken into account by the certification authority;
- c) a total of at least 3 engine tests shall be conducted, so that if a single engine is presented for certification it must be tested at least 3 times;
- d) if a given engine is tested several times, the arithmetic mean value of the tests shall be considered to be the mean value for that engine. The certification result ( $X$ ) is then the mean of the values ( $X_i$ ) obtained for each engine tested;
- e) the manufacturer shall provide to the certifying authority, the information specified in Part III, 2.4 or 3.4 as appropriate;
- 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 certifying 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.

### 2. COMPLIANCE PROCEDURES

The certifying authority shall award a certificate of compliance if the mean of the values measured and corrected (to the reference standard engine and reference atmospheric conditions) for all the engines tested, when converted to a characteristic level using the appropriate factor which is determined by the number of engines tested ( $i$ ) as shown in the table below, does not exceed the regulatory level.

*Note.— The characteristic level of the Smoke Number or gaseous emissions is the mean of the values of all the engines tested, and, for gaseous emissions only, appropriately corrected to the reference standard engine and reference atmospheric conditions, divided by the coefficient corresponding to the number of engines tested, as shown in Table A6-1.*

**Table A6-1. Characteristic level of the Smoke Number or gaseous emissions**

Number of engines tested ( <i>i</i> )	CO	HC	NO <sub>x</sub>	SN
1	0.814 7	0.649 3	0.862 7	0.776 9
2	0.877 7	0.768 5	0.909 4	0.852 7
3	0.924 6	0.857 2	0.944 1	0.909 1
4	0.934 7	0.876 4	0.951 6	0.921 3
5	0.941 6	0.889 4	0.956 7	0.929 6
6	0.946 7	0.899 0	0.960 5	0.935 8
7	0.950 6	0.906 5	0.963 4	0.940 5
8	0.953 8	0.912 6	0.965 8	0.944 4
9	0.956 5	0.917 6	0.967 7	0.947 6
10	0.958 7	0.921 8	0.969 4	0.950 2
more than 10	$\frac{1 - 0.130\ 59}{\sqrt{i}}$	$\frac{1 - 0.247\ 24}{\sqrt{i}}$	$\frac{1 - 0.096\ 78}{\sqrt{i}}$	$\frac{1 - 0.157\ 36}{\sqrt{i}}$

### 3. PROCEDURE IN THE CASE OF FAILURE

*Note.*— When a certification test fails, it does not necessarily mean that the engine type does not comply with the requirements, but it may mean that the confidence given to the certifying authority in compliance is not sufficiently high, i.e. less than 90 per cent. Consequently, the manufacturer should be allowed to present additional evidence of engine type compliance.

3.1 If an engine type fails a certification test, the certifying authority shall permit the manufacturer, if he/she so wishes, to conduct additional tests on the certification engines. If the total results available still show that the engine type fails the certification requirements, the manufacturer shall be allowed to test as many additional engines as desired. The resulting test results shall then be considered with all previous data.

3.2 If the result is still failure, the manufacturer shall be allowed to select one or more engines for modification. The results of the tests already made on the selected engine(s) while unmodified shall be inspected, and further testing shall be done so that at least three tests are available. The mean of these tests shall be determined for each engine and described as the “unmodified mean”.

3.3 The engine(s) may then be modified, and at least three tests shall be conducted on the modified engine(s), the mean of which shall be described as the “modified mean” in each case. This “modified mean” shall be compared to the “unmodified mean” to give a proportional improvement which shall then be applied to the previous certification test result to determine if compliance has been achieved. It shall be determined before testing of any modified engine is begun that the modification(s) comply with the appropriate airworthiness requirements.

3.4 This procedure shall be repeated until compliance has been demonstrated or the engine type application is withdrawn.

— END —



