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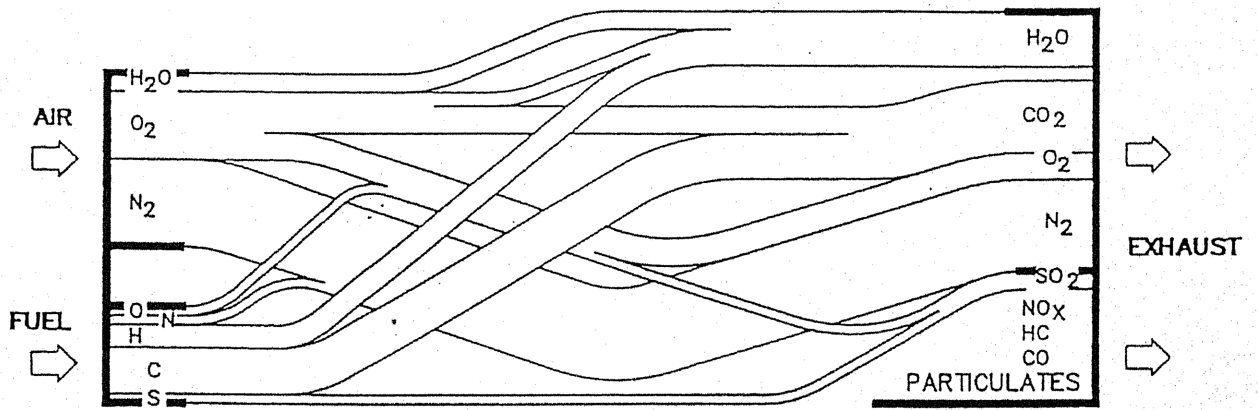

EXHAUST EMISSIONS MEASUREMENT

Recommendations for
reciprocating engines
and gas turbines

Mesures relatives aux polluants dans le gaz d'échapppement

Recommandations pour
moteurs à mouvement
alternatifs et turbines à
gaz

CIMAC

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CONSEIL INTERNATIONAL
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INTERNATIONAL COUNCIL
ON COMBUSTION ENGINES

CIMAC is an international organisation, founded in 1950 by a French initiative to promote technical and scientific knowledge in the field of internal combustion engines (piston engines and gas turbines). This is achieved by the organisation of congresses and working groups.

It is supported by engine manufacturers, engine users, technical universities, research institutes, component suppliers, fuel and lubricating oil suppliers and several other interested parties.

The National Member Associations and previous CIMAC Recommendations are listed in the back of this publication.

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RECOMMENDATIONS REGARDING

EXHAUST EMISSIONS MEASUREMENT

For reciprocating engines
and gas turbines

RECOMMANDATIONS CONCERNANT MESURES RELATIVES AUX POLLUANTS DANS LE GAZ D'ECHAPPEMENT

Pour moteurs à mouvement
alternatifs et turbines à gaz

This document has been prepared by the Working Group Pollution from IC Engines and approved by the Permanent Committee on 24 April 1991

CIMAC Working Group Members

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SUMMARY

CIMAC is an international organisation which represents Engine Manufacturers and Users. This document contains the recommendations for exhaust emissions measurement as made by a Working Group which was set up by CIMAC.

The document covers gas turbines and reciprocating engines, which run on liquid or gaseous fuels. The recommendations are largely aimed at stationary, locomotive and marine engines. It is not intended that road vehicle engines such as for cars, trucks and buses etc. should be included, since they are adequately covered elsewhere.

CIMAC does not intend that these recommendations should conflict with requirements which are already well established in some Countries. The recommendations are intended for use where no established emissions measuring technique is applicable or agreed and, if followed, the results obtained should be reliable and accurate.

The document includes recommendations for engine running conditions, the emissions sampling and analysis system as well as correction methods. At the end of the document is a proposed format which may be used for the presentation of test results. Gaseous emissions, particulates and visible smoke are included.

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1. INTRODUCTION

1.1 Background

At the request of the CIMAC Permanent Committee the Pollution from Internal Combustion Engines Working Group was reformed in January 1986 to make recommendations with regard to exhaust emissions from IC engines. These were to cover reciprocating engines and gas turbines operated on liquid and gaseous fuel.

From the start the new Working Group realised that to agree recommendations on exhaust emission levels and regulations would be a difficult and lengthy task. It would also be a meaningless task unless agreement had first been reached on a generally acceptable method of measuring emissions. Since then, the Group has been working to produce the recommendations which are contained in this document.

1.2 Scope

The recommendations are intended for use with all types of internal combustion engines, reciprocating and gas turbine, which run on diesel, gas or other fuels. The term engines in this text refers to both reciprocating and gas turbines. It is not intended that the recommendations should be used on road vehicle engines such as for cars, trucks and buses etc, since they are adequately covered elsewhere [1]*.

Recommendations are made for all engines but in places it has been necessary to make separate recommendations for reciprocating engines and gas turbines. This has been done to allow for their different operating conditions but also to follow as much as possible what is current and accepted practice.

The recommendations are suitable for use with engines which exhaust to atmosphere. They may also be used with engines exhausting into additional power turbines, process plants, after treatment devices and the like, but in these cases care must be taken to ensure that the results are meaningful. For example it would be necessary to determine ammonia (NH_3) concentration if engines are equipped with a dry-denitration plant using NH_3 as the reagent.

It is intended that these recommendations should be for procedures which are clear, concise and well defined. This is to provide a standard which will define the emissions levels quoted and will enable comparisons between engines to be made. At the same time, it is intended that the recommendations should not be too complicated or expensive to adopt.

Some examples of national standards are mentioned in the references. It can be seen that there are many national and local regulations and these recommendations cannot cover measurement techniques to comply with them all. It is hoped that there will eventually be an ISO standard. These recommendations provide guidance, advice and further background information.

* Numbers in brackets [] indicate references given at the end of the text.

The selection of measurements as well as constituents to be measured should be agreed prior to the test.

People who measure exhaust emissions need to be competent to avoid serious errors being made to distort the readings. No matter how detailed the recommendations they cannot replace the skill and experience of the operator. For example one should look initially at all measurements and compare them with manufacturers recommendations. Measurements may be made intermittently or continuously. If continuously special care is needed when selecting equipment.

It is recognised that some installations will make it impossible or impractical to follow a single recommendation so the text contains some alternatives.

Use of these alternatives shall be declared with the result of the test and a recommended format is included in this document. Deviations from the recommendations should be declared along with the results.

It is assumed that the intake air to the engine contains an insignificant amount of pollution.

Wherever practical, existing recognised standards or procedures have been used and their source indicated in the text.

1.3 Origin of Emissions

The present recommendation concerns measurement methods for certain components of the exhaust gas from internal combustion engines. The interest in measuring these components and their origin is briefly discussed in the following. A more complete discussion is available [10].

Oxides of Nitrogen (NOx) is the general designation for NO plus NO_2. While NO itself is considered relatively harmless, it is oxidized in the atmosphere to NO_2 which is toxic and participates in the formation of photochemical smog. NO_2 is furthermore harmful to plants both directly and in the form of acid rain. Most of the NOx is NO (normally 85-98%) which is the stable compound at high temperature, while NO_2 is mainly formed when the hot combustion products cool down and, later on, in the atmosphere. If the fuel itself contains nitrogen in other forms than N_2, this will usually increase the level of NOx in the exhaust gases.

Carbon Monoxide (CO) replaces oxygen in human blood and exposure to larger concentrations over prolonged periods of time may lead to unconsciousness or even death. CO is formed as an intermediate product in the combustion of all fuels containing carbon and its existence in exhaust gas is a sign of incomplete combustion, due to incomplete mixing of fuel and air, insufficient air for combustion and/or flame quenching.

Carbon Dioxide (CO2) is not toxic, but it has recently attracted much attention due to possible effects on the global temperature level (the so-called "greenhouse" effect). CO_2 is the result of complete combustion of carbon, and the CO_2 measurement is only used to calculate the air: fuel ratio.

Oxides of Sulphur(SOx) is harmful to the lungs especially in combination with particles where a synergistic effect is found. In the atmosphere, SOx combines with water to form acid rain which is harmful to plants and life in lakes. SOx is the result of complete combustion the of fuel's sulphur content which is nearly 100% converted into SO_2. A small amount of SO_3 may also be formed.

Hydrocarbons (HC) is not a specific chemical compound, but a general designation of a large group of compounds which contain carbon and hydrogen, but have very different environmental characteristics. Methane (CH_4) is almost harmless to health. Some hydrocarbons take part in the formation of photochemical smog, but are otherwise not toxic; certain others are carcinogenic. HC in the exhaust gases is a sign of incomplete combustion, due to factors such as incomplete mixing of fuel and air, flame quenching, fuel nozzle malfunction, misfiring etc.

Aldehydes are a product of incomplete combustion of hydrocarbon fuels, especially partly oxygenated fuels such as methanol and ethanol. They are irritating to the pulmary system and in some cases have an unpleasant smell.

Oxygen (02) is not a pollutant and is only measured in order to allow corrections of measured emissions to reference conditions and/or to calculate air:fuel ratio.

Particulate emissions are solid or fluid particles in the exhaust gas. The chemical composition is strongly dependent on fuel characteristics and (for piston engines) on lube oil type and consumption. The main constituents are usually carbon , sulphur components with absorbed water and hydrocarbons from the fuel and lube oil. For health effects, see the above discussion regarding HC and SOx.

Smoke Emissions is the general designation for the visibility of the exhaust gas which may be caused by the content of particles, condensed water vapour and/or NO_2 (which is a yellow/brown gas).

Other pollutants Certain exhaust gas aftertreatment methods, like ammonia-injection/selective catalytic reduction of NOx, may introduce new compounds in the exhaust gas stream. In the case mentioned, unreacted ammonia may be present, together with ammonia sulphate and worn-off particles from the catalyst itself.

The interest in exhaust emissions is that some of them can be irritating, toxic or harmful to the environment. The reason for measuring them is to monitor their concentration and to control them if necessary. Care is necessary because these pollutants have a mutual relationship. By controlling combustion air for example NOx may be reduced while CO and particulates are increased.

1.4 General Approach

The general approach of this document is to provide recommendations for good practice when measuring exhaust emissions. Considerable knowledge, skill and experience are still needed to obtain accurate results. Specific and detailed recommendations cannot be made since they would contradict well established and good practice which varies from country to country. This document does not attempt to impose a single universal method since it is not felt that this is practical at the present time. The document does, however, attempt to provide a useful guide and ready reference for those involved in measuring exhaust emissions.

Another goal of this document is to provide a bridge between engine specialists and emission specialists. Mutual understanding is necessary but often lacking. Throughout the text background information on advantages, disadvantages, dangers, physical meanings etc. is provided.

It is intended that this document will be re-issued from time to time as contributions are received from member countries and current practice and equipment available changes.

1.5 Units and Terms

The units used are generally those of the International System of Units (SI Units) described in ISO 1000, [16].

The general engine terms used are as defined in ISO 2710 [20] for reciprocating engines and Item 4 of ISO 3977 for gas turbines [7].

Alternative units are shown where they are common practice and conversions are given in Appendix 9.

2. ENGINE RUNNING CONDITIONS

2.1 Standard Reference Conditions

For the purpose of determining the power and fuel consumption of engines, the ISO standard reference conditions [21] should be used ie. temperatures, pressure and humidity. See Appendix 2.

If other reference conditions are chosen, these should be stated.

2.2 Test Procedure

2.2.1 Engine Installation

The engine may be tested on a test bed or in its intended installation. It is essential that there is a suitable means of applying and measuring the required engine loadings, see Appendix 4. The test engine shall be fitted with all dependent and essential auxiliaries or corrections should be made, Appendix 4. All auxiliaries shall be listed and described in the documentation supporting the test results.

2.2.2 Lubricants - (Reciprocating)

Lubricating oil used shall conform with the engine manufacturer's recommendation. The grade used should be recorded. Special lubricants to reduce emissions during the test only should not be used.

2.2.3 Fuel

To make emissions measurements relevant the engine should be tested whenever possible using the site fuel and information on the fuel specified in Appendix 3 should be recorded with the test results.

It is recommended that in every case a fuel sample should be retained. Where continuous emissions are measured any changes in fuel must be monitored.

It is not considered practical to specify the use of a reference fuel when recommending a test procedure for marine and industrial engines.

2.2.4 Exhaust Back Pressure

Where practical, for reciprocating engines only, the engine should be fitted with the actual exhaust system for the required application. However, if this is not possible, an exhaust system capable of providing the equivalent restriction should be fitted. Where this is not practical the back pressure should be measured and necessary corrections should be made for any difference between the actual and the expected back pressure. A description of the exhaust system and back pressures recorded must be provided with the test results.

For gas turbines back pressure is covered in ISO 3977 [7].

2.2.5 Inlet Air

Temperature, pressure and humidity of the inlet air to the engine should be measured in the engine inlet air stream or in a representative position close to the air cleaner. Temperature sensors should be shielded from radiant heat sources.

The air flow should be stated. Where emissions are to be stated in mass units eg. g/kW.h, the air flow rate should (where practical) be measured and recorded or the flow rate calculated. The methods used to measure the flow rate must be declared. Where this is not practical the air flow should be calculated from the exhaust gas analysis results and the fuel flow. Appendix 9 gives details of methods.

For reciprocating engines the air temperature before and after charge cooler (if fitted) and the temperature and pressure in the inlet manifold (after turbocharger if no cooler fitted) should be measured and recorded.

When the air flow is measured before the air enters the engine, the mass of any water condensed from the air should be subtracted from the exhaust gas mass flow when calculating emissions levels. Emissions levels should be reported on a dry sample basis.

If air, gas or other fluids such as water, steam or ammonia are injected at any point prior to the sampling position this should be stated and their mass flows added to the total air mass flow. The fuel mass must be added to this to calculate the exhaust mass flow. Compressor or turbine characteristics may provide a useful check on air flow.

2.2.6 Fuel Flow

Fuel flow rate, taking account of leakage, should be measured preferably to within plus or minus 1% and recorded along with the temperature of the fuel. The accuracy of the fuel consumption measurement should be estimated and stated.

2.2.7 Exhaust

The exhaust gas temperature and pressure should be measured and recorded at the emissions sampling point.

2.2.8 Power Output

The power output of the engine should be calculated from the torque and the engine speed or from the generator. It should be expressed either in kW or bhp or in percent of the rated nominal power where precise power output is needed to express emissions levels. For definitions and measurement of power see Appendix 4.

2.3 Engine Condition and Running

2.3.1 Engine specification

If the engine is new, or if the manufacturer elects, then the engine should be run-in according to the manufacturer's set procedure.

Before commencing the actual testing, the operator may make any final adjustments to the engine and its auxiliaries, such as injection timing or burner configuration which could influence emissions. The build should be such that it would achieve all the manufacturer's claims with regard to power, speed, fuel consumption, oil consumption and durability/reliability. Following the commencement of the test all further adjustments/modifications to the engine's build must be noted and included with the test results.

2.3.2 Pre-conditioning

Before commencing the emission tests the engine should be run at rated power until the operating temperatures have stabilised at the recommended levels.

2.4 Test Cycle

Emissions should be measured under steady state conditions because the load varies slowly for most of the engines considered by this document. At least three measurements of gaseous emissions should be made at each measuring condition and the linear average of these should be recorded. Test time for particulate measurement should be extended as required to provide acceptable accuracy.

The operating condition may be determined by regulations in which case they should be followed. Otherwise the following is recommended:

Depending upon the engine's application the engine should be considered to fall in one of the following categories. Exhaust emissions should then be measured at the corresponding operating points.

CIMAC A Engine operating at constant speed and variable load

100% Rated speed - 100% 75% 50% rated power

CIMAC B Engine operating over or close to the propeller law

100% rated speed - 100% rated power
90.9% rated speed - 75% rated power
79.4% rated speed - 50% rated power.

CIMAC C Engine operating at other conditions

Speed and power values to be negotiated and specified. These will generally be three in number.

3. GAS SAMPLING SYSTEM

3.1 Aim

It is the purpose of the gas sampling system to extract a sample of the exhaust gas which is representative of the mean composition of that gas and to transfer the sample without change or with a known change in composition to the measuring instruments for NO_x, CO, CO_2, O_2, HC and SO_2. For obvious reasons, the physical properties of the sample gas must be acceptable to the measuring instruments. Therefore, the sample gas must be conditioned by removing dust and, if necessary, removing or maintaining the moisture content. However the H,C, O_2 and SO_2 mass balance in the sample gas stream must not be changed.

3.2 General System Description

The gas sampling system is based upon References 4, 5 and 6. An example of the sequence and details of these units are described in Appendix 5, but a short description of their main particulars is given in the following.

- The sampling site should be selected as close as practical to the exhaust of the engine but not less than three pipe diameters from the exit to the exhaust. In the case of a gas turbine plant without any waste heat recovery system, de-NOx system etc. it shall be before any subsequent fired system or introduction of dilutants. In the case of a gas turbine plant such as a combined cycle or cogeneration plant with waste heat recovery system or de-NOx system etc. it should be as close as possible to the exhaust of the overall system.

  In any case, it should be such as to include the total exhaust gas stream.

- The sampling probe should be designed such as to provide a representative sample, consequently it should be long enough to span the width of the exhaust pipe, its gas passage should be made of a non-reactive material and it must be non-leaking.

- The coarse filter should be placed close to the sampling probe in order to protect the main part of the sampling system from deposits. The coarse filter should be non-leaking and made of a non-reactive material. It should be heated to 190 ± 20 °C.

- The fine filter should be made of a non-reactive material, and should be kept at the same temperature as the line in which it is fitted.

- The sample pump should be a diaphragm pump as a rule and should not contaminate the sample. Those parts in contact with the sample gas should be made of non-reactive materials. The capacity of the pump should be sufficient to transport the sample to the instruments within 10 seconds.

- The dehumidifier, which should be used if the measuring instruments require a dried sample, should reduce the moisture content to such a low level that condensation cannot take place in the unheated lines leading to the instruments and in the instruments themselves. The dehumidifier's gas-passages should be made of non-reactive material and its volume should be as small as possible in order to reduce the influence of the condensate on gas composition as much as possible. Some unheated analysers need a very dry sample then an electronic cooler, eg. Peltier effect device, can be used, see Appendix 6.

- The sampling line should be as short as possible and be heated to 190 ± 20 °C. It should not leak and should be made of a non-reactive material.

- The valves used for calibration-gas inlet, change-over and throttling should be non-leaking and those parts in contact with the sample gas should be made of a non-reactive material.

- The flowmeter used should be a float type area flowmeter as a rule and those parts in contact with the sample gas should be made of a non-reactive material.

The analyser system is the installation which is used to measure the exhaust gas components. The gas sample to be analysed is conducted through the sampling system continuously to the gas analyser system, which is located at a place where external influences such as vibration, weather, electromagnetic induction or the like can be kept as small as possible. The components are to be found in the exhaust gas as volume fractions in the order of magnitude of percent (%) or parts per million (ppm). When measuring the concentration of an exhaust gas component gas analysers make a comparison between the exhaust gas and known reference gases. They do not record absolute values. With known fuel and air flows of the engine and the chemical analysis of the fuel, calculations can be made to obtain values for oxygen, carbon dioxide and sulphur dioxide in the exhaust to cross check the measurements by providing calculated mass balances. (See Appendix 9).

4. GAS ANALYSERS

This section lists the types of gas analysers which are recommended for the measurement of the concentrations of the exhaust gas constituents.

Appendix 6 contains descriptions of the recommended gas analyser types, suggested performance standards, methods of checking the performance, emission measurement procedures and analyser instruction manual requirements.

4.1 Recommended Gas Analysers

Exhaust gas	Recommended Analyser Type	App
Oxides of Nitrogen	Chemiluminescence or: Non-dispersive infra-red or: Non-dispersive ultraviolet	A.6.1 A.6.2 A.6.5
Carbon dioxide Carbon monoxide	Non-dispersive infra-red	A.6.2
Sulphur dioxide	Non-dispersive ultraviolet or: Non-dispersive infra-red or: Pulsed UV fluorescence	A.6.5 A.6.2 A.6.5
Oxygen	Paramagnetic or: Zirconia detector or: Electrochemical cell	A.6.4 A.6.4 A.6.4
Hydrocarbons - Total Hydrocarbons - Non Methane Hydrocarbons	 Flame ionisation GC and FID	 A.6.3
Aldehydes	High performance liquid chromatography Absorption photometry	A.6.3 A.6.3
Ammonia	Chemiluminescence (after oxidising ammonia) Spectrographic (indophenol method)	A.6.1

4.2 Emission Measurement Procedures

The measurement should be carried out, taking sufficient care to get accurate results, following the analyser manufacturers instructions. Appendix 6.8 gives advice and recommendations on the following aspects of emissions measurement:

- Installation of analyser systems
- Preparation of calibration gases
- Preparation of analyser systems
- Preparatory performance check of analyser systems:
    - Calibration and linearity check
    - NOx converter efficiency check
    - Interference response check
    - Response time check
- Daily performance check of analyser systems

5. PARTICULATE SAMPLING SYSTEM

5.1 Definition

Exhaust gas particulates are defined as any material in the exhaust gas stream, which is either solid or condensible at the conditions of the method of collection. This means that different collection methods will record different masses of particulate. There is a tendency to consider this kind of pollution from the point of view of the surroundings of the installation.

It is the purpose of the particulate sampling system to extract a sample of the exhaust gas which is representative of the mean composition of that gas and to transfer the sample to the measuring system.

5.2 Measuring Methods

There are three basic groups of widely used systems for measuring particulates:

- The hot filter out-of-stack: EPA Method 5 [8, 15]
- The hot filter in-stack: EPA Method 17 [18]
- The dilution tunnel [9]

All three of these methods have their limitations but no better method is yet available.

CIMAC recommends the use of a dilution method as detailed in Appendix 7. However, CIMAC recognises that use of the EPA methods has been well established in the USA, particularly with gas turbines, and if used carefully these methods can produce reliable results and are acceptable. CIMAC's preference for a dilution method is based upon its convenience and its almost universal acceptance for automotive engines. It is also likely that a dilution method will be proposed for a new ISO standard.

Dilution methods rely upon taking a hot sample of exhaust, diluting it with air and passing the mixture through a filter at between 49 and 52°C (120-125°F). The filter is weighed before and after the test to establish the quantity of particulate collected.

Further details are given in Appendix 7.

5.3 Need for more practical methods

All the above methods are described in detail in the references. Some of the methods take a considerable time to collect a sample which is large enough to record. This is particularly so when the exhaust is clean or has a high air/fuel ratio (as with a gas turbine). The requirements are that the engine must be run under controlled stable load, and that repeated tests should be run to enhance the accuracy.

The general feeling of the CIMAC Working Group of these pollution recommendations is that particulate measurement needs, in the future, a quicker and easier method than is available today, characterised by a direct reading of the results.

Several alternatives may become possible eg. a tapered filter method measuring the natural frequency vibration modification due to filter deposits, or beta rays emission after radiation of the filter. Such instruments are readily available, but the limits of these systems have to be known exactly and eventually accepted before they can be generally recommended. A consistency comparison with the methods in 5.2 on an engine of about equal size and working performance is needed if other methods are to be used.

6. VISIBLE SMOKE

6.1 Definition

The term exhaust smoke is generally used to designate the visibility of the exhaust gases. While gaseous emissions are reasonably well defined and can be measured objectively, the same is not the case for smoke which may be divided into three main groups:

- white or white/blue smoke which may have its colour from condensed water vapour, unburned, condensed fuel or small droplets of unburned lube oil.
- brown/yellow smoke which has its colour mainly from the NO_2 and soot particulates present in the exhaust gas.
- black smoke which has its colour from the soot particle content.

The darkness of the exhaust smoke depends also on the soot and droplet sizes and density. Also of course, on the exhaust gas mixing rate at the stack outlet as well as the physical dimensions of the outlet and the size of the exhaust plume.

6.2 Sampling and Measuring Methods

There are several measuring methods for smoke in use. They can be divided into the following groups:

- Smoke spot methods

  A certain volume of exhaust gas is sucked through a filter paper and the reduction in reflectance of the used filter due to the soot captured on it is measured or evaluated.

  Examples are Bosch Smoke Number, SAE Smoke Number, Bacharach (ASTM) Smoke Number

- Opacity methods

  The percentage reduction of light passing through the exhaust gas is determined. This may be measured in the exhaust pipe (in-line methods, Celesco C107), on a sample stream of exhaust gas (Hartridge) or at the exhaust exit (end-of-line methods, P.H.S., and EPA-QO).

  (Hartridge, Celesco C107, and Public Health Service smoke meter opacity are objective methods, EPA - Qualified Observer - method is a subjective method);

Both types have scales: 0 (clean) - 100 (complete extinction) for the opacity meters

and 0 (clean) - 100 (completely black, no reflection)

or 0-9 or 0-10 (no reflection) for the filtering meters.

The following equation governs light transmission through smoke:

$$I = Io\ e^{-kL}$$

Where Io is the initial light intensity
I is the intensity after passage through a distance L of smoke
k is the light absorption coefficient of the smoke.

Thus the opacity reading of the light extinction types depends on the path length of the instrument and is therefore influenced by exhaust stack or plume diameter. The smoke number derived from the filtering meters depends on the ratio of sample volume to filter area.

The filtering smoke meters do show some similarity to the light extinction types in that the trapped soot particles obscure vision of the filter paper, and prevent reflection from it, in an analogous way to the obscuration produced in the sample column of the opacimeter. Nevertheless the mode of retention of the particles, in the pores of the air filter rather than on a perfectly flat surface, prevents an exact theoretical relationship.

For small reciprocating engines the Bosch method is largely used. Larger engines generally have lower smoke levels. Under these conditions the Bosch method is not as effective since it is only accurate to ±0.3 Bosch units. For smoke levels below 1.0 Bosch a filtration method which passes a larger volume of exhaust gas through the filter is recommended. When transient smoke readings are required an in-stack opacity meter is recommended.

Conversion between these measurement methods of smoke and particulate content is generally difficult and uncertain, except for those methods which share a common datum. Conversion is not recommended by CIMAC, although in principle there is some correlation between the methods. [11, 12, 13].

For gas turbines the Bacharach or SAE smoke spot method are sometimes used to monitor the dry carbon particulate concentration since some correlation has been shown.

The measuring method recommended by CIMAC for gas turbines is the ASTM Smoke Number method. [14].

The visual inspection of the smoke, day by day, is useful in order to detect deterioration of the fuel injection system.

7. CORRECTIONS

7.1 Introduction

All engine data and test results are dependant not only on the tuning and fuel, but also on the ambient conditions. Thus, to compare measured data from different engines, they must be corrected to standard reference conditions to avoid taking into account influences which are not related to the engine. The type of fuel used has an influence on emissions, and thus cannot be simply neglected.

7.2 Corrections to Standard Conditions

These corrections mean transformation of measured engine emissions to standard conditions.

These standard conditions might include ambient conditions of temperature, pressure and humidity. A correction for the nitrogen content of the fuel may also be included.

For the above corrections, only the emission concerned has to be corrected, since not all the emissions will be influenced in the same manner by variation of ambient conditions.

Details of recommended corrections are given in Appendix 8.1 for reciprocating engines and Appendix 8.2 for gas turbines.

8. PRESENTATION OF RESULTS

Recommendations for the presentation of results of emissions measurements are given in Appendix 10. An example of the recommended calculation technique is given in Appendix 9. Recommended formats for the presentation of results are given in Appendix 10.

Results should be presented clearly and should include all information which is needed. This includes information on corrections made and assumptions or estimates made in the process. An assessment of accuracy should be included.

A record should be made of the measuring equipment which has been used, the ambient conditions, the engine performance and the fuel used as described in the text of this document.

The units of the results will vary because requirements are different in various countries. It is hoped that sometime in the future an international standard will be agreed. Meanwhile CIMAC's preferred units are indicated in Appendix 9 and conversions are also given in Appendix 9.

9. CONCLUSION

This document is intended to be used as a guide to the measurement of exhaust emissions from stationary, marine and locomotive engines. Recommendations are given for techniques and equipment to be used to achieve reliable results. Corrections and conversions are included as are examples of calculation techniques and a recommended format for expressing the results.

Where possible common recommendations are given for both reciprocating engines and gas turbines but where this is not considered possible they are divided into two sections. Common recommendations are given regardless of the type of fuel being used.

These recommendations are intended for use by anyone measuring emissions but they are not intended to contradict or replace existing standards which may be required by some regulatory bodies.

This document by CIMAC gathers together the experience of its members to make recommendations for measurement of exhaust emissions. It is hoped that this will be a live document and that it will be re-issued to incorporate modifications and improvements as they are proposed in the future by national committees.

Recommendations of this nature, no matter how detailed, can only ensure that reliable results will be produced if they are followed by operators with knowledge, skill and experience. This document should provide a useful guide and reference to those working in this field.

10. ACKNOWLEDGEMENTS

A considerable effort has been put into this document by both past and present members of the Working Group and their contributions are much appreciated. There has also been considerable support from the organisations which the Working Group represent and many other people.

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(in-stack filtration method)

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Manuelle Staubessung in strömenden Gasen

20. ISO 2710

21. ISO 2533 "Normathosphäre"

22. JIS 0901

23. VDI 3862, Blatt 2
"Measurement of Aliphatic and Aromatic Aldehydes and Ketones. DNPH Method" (in preparation)

24. VDI 3862, Blatt 1
"Measurement of Aliphatic Aldehydes (C_1 to C_3). MTBH Method"

25. JIS K 0089ISO 3977 Items 5 & 7

26. Calculation method from FVV

APPENDIX 1

Definitions and Terminology used

Air/Fuel Ratio: Is the ratio of dry intake air flow to fuel flow, both on a mass basis (Kg/Kg).

Air Excess Ratio: Is the ratio between the actual air/fuel ratio and the stoichiometric air/fuel ratio. Values larger than one mean more air than is necessary for complete combustion.

Analytical Column: A column from which components of interest elute from a gas chromatograph.

Analyser: An instrument which senses the concentration of the component to be measured and converts it into an electrical signal which can be amplified for display on a meter or chart recorder and which may also be fed directly to data acquisition unit.

Calibration Gas: A mixture of gases of specified and known composition used for calibration of the analyser system such as zero gas, span gas etc.

Chemiluminescence Analyser: A method of measuring NOx utilising the principle that NO reacts with ozone (O_3) to give nitrogen dioxide (NO_2) and Oxygen (O_2) with an associated light emission.

Concentration: A measure of the amount of a substance in a gas mixture. Concentrations can be expressed in various units such as % and ppm on either a mass or volume basis or in mg/m^3. In the present text the term concentration will refer to mg/m^3.

Continuous Sampling: The presentation of a flowing sample to the analyser system so as to obtain continuous measurement of the concentrations of the component of interest.

Detector: A device which senses changes in concentration of the component to be measured and converts this into an electrical signal.

Equivalence Ratio: Is the inverse of air excess ratio. Values smaller than one mean more air than is necessary for complete combustion.

Flame Ionization Detection Method: The detection method for organic compounds utilising ionization phenomenon in a hydrogen flame.

Full Scale Deflection (FSD): FSD is the concentration which gives the rated output from a gas analyser, for example, 1 volt at the gain setting in use. It is the same as the range only if the span gain control is set appropriately.

Gaseous Emissions: Substances emitted in the form of gas downstream of the combustion chamber and limited to carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), sulphur trioxide (SO_3) non-methane and total hydrocarbons (NMHC, THC) oxygen (O_2), water (H_2O), ammonia (NH_3) and nitrogen (N_2).

Humidity: A measure of the amount of water vapour present in a gas mixture. Absolute humidity or specific humidity is the mass of vapour per unit mass of gas generally expressed as mass of vapour per mass of dry air. Relative humidity is the ratio of the water vapour pressure to its saturation pressure at that temperature.

Interference: Analyser system response due to the presence in the sample of components other than the gas (or water vapour) that is to be measured.

Interference Component: The coexisting component interfering with the measurement.

Isokinetic: Equal velocity. Isokinetic sampling is when the sample is drawn at the probe at the same gas velocity as the gas stream from which it is drawn.

Linearity: The degree of deviation from linear dependency between the input concentration and the output signal.

Mass Fraction: % or ppm on a mass basis.

Measuring Range: Range of concentration which can be measured by an analyser system. Analysers frequently have the capability of more than one range.

NDIR: Non-Dispersive Infra-red - a measurement principle based on the absorption of Infra-red light by a gas sample at a fixed frequency band of the spectrum.

NDUV: Non-Dispersive Ultraviolet - a measurement principle based on the absorption of ultraviolet light in a gas sample at a fixed frequency band of the spectrum.

Noise: Noise is the random fluctuation of a signal output from an analyser occurring with a period of seconds or less.

Non-Methane Hydrocarbon: Hydrocarbon compounds excluding methane from the total.

Oxides of Nitrogen (NOx): The total concentration of nitric oxide (NO) and nitrogen dioxide (NO_2).

Particulates: Exhaust gas particulates are defined as any material in the exhaust gas stream, which is either solid or condensible at the conditions of the method of collection.

Power: A measure of work done in unit time usually expressed in kW or bhp. The engine power is defined as that which can be taken from the output shaft. Any shaft or electric power which is obtained from the engine waste heat e.g. by an exhaust gas power turbine, may be added to the engine power. The power equivalent of any other waste heat may not be included regardless of whether it is used for process heat or some other purpose.

ppm: Parts per million

ppm C: The volume ppm value as determined by a flame ionisation detector expressed by taking the number of carbon atoms as reference. For example, 100 ppm C_3H_8 equals 3 x 100 = 300 ppm C.

Reading: Indication of concentration of component output from an analyser.

Repeatability: A measure of the similarity between repeated readings when recorded under the same operating conditions. This can apply both to the analytical system and to the gas source.

Response: The relationship between the output signal and the input into an analyser system.

Response Time: The time required for a gas analyser, operating under continuous sampling conditions, to indicate a specified value (for example 90%) of the final indication following a step change in sample gas concentration.

Sample Gas: A flue gas introduced into an analyser after being pretreated through, for example, a coarse filter, or dehumidifier.

Set Flow Rate: The flow rate of sampling gas or calibration gas specified for the analyser system.

Smoke: A measure of the visibility of the exhaust gas, normally expressed as the opacity of the gas, or as a number on a scale which refers to the darkening of a filter paper through which has passed a fixed volume of exhaust gas.

Span Drift: The change in analyser reading from a span gas sample over a specified time period, after subtraction of zero drift.

Span Gas: A gas used for calibration of the analyser system in the expected measuring range.

Stability: The degree to which the characteristics of an analyser or its components remain unaltered with time and changes in the ambient operating conditions.

Stoichiometric Air/Fuel Ratio: The theoretical amount of dry air needed for complete combustion of the fuel, on a mass basis (Kg/Kg).

Total Hydrocarbons: The general term for organic compounds measured by the flame ionization detection method.

Volume Fraction: % or ppm on a volume basis.

Wander: The fluctuation of a signal output from an analyser with a period of minutes.

Zero Drift: The change of the reading for the minimum scale value of an analyser over a specified period of time.

Zero Gas: A gas used for calibration of the minimum scale value of the analyser system.

APPENDIX 2

Standard Reference Conditions

For the purpose of determining the power and fuel consumption of engines, the ISO standard reference conditions should be used [2 & 7]. Currently these are:

	Reciprocating Engines	Gas Turbines
Barometric pressure:	$P_r = 100$ kPa	$P_r = 101.3$ kPa
Air temperature:	$T_r = 298$ K (25°C) (1)	$T_r = 288.15$ K (15°C)
Relative humidity:	$\phi_r = 60\%$ (absolute humidity 10.34 g/kg mass)	$\phi_r = 60\%$
Charge air coolant temperature:	$T_{cr} = 298$K (25°C)	

If other reference conditions are chosen, these should be stated.

(1) For a period of time 27°C may still be used.

APPENDIX 3

Fuel Analysis

Information on the fuel used which should be provided with the test results.

Description and type of fuel

Details of any additives used

For Gaseous Fuels	For Liquid Fuels
Gas analysis, including percentage of methane, ethane, propane, butane, H_2, CO and other combustible gases. Also percentages of CO_2, O_2, N_2, H_2S	Chemical composition including S, O, N, H, C, H_2O, Ash, Va, Na etc
Higher heating (calorific) value	Higher heating (calorific) value
Lower heating (calorific) value	Lower heating (calorific) value
Density	Density
	Viscosity cSt
	Conradson carbon

In every case a fuel sample taken after the fuel cleaning device should be retained.

APPENDIX 4

Engine Power Output

Gas Turbines

Power measurements for gas turbines shall be performed in compliance with ISO 2314 "Gas Turbines - Acceptance Tests"[17].

Reciprocating Engines

The torque produced by the engine shall be measured preferably to within plus or minus 1% and recorded using a dynamometer, generator or other load absorption equipment capable of handling the full power output of the engine. [2]

Where it is not practical for a dynamometer to be used then the engine torque shall be calculated from other measurements such as voltage, current, rack position, propeller speed, etc. A careful assessment of the accuracy of the measured or calculated torque shall be made and declared together with the assumptions which have been used. The torque should be expressed as brake mean effective pressure or Newton metres(Nm).

The speed of the engine shall be recorded to within plus or minus 1%. The speed is the mean rotational speed of the crankshaft or crankshafts in revolutions per minute. If the speed of the crankshaft cannot be measured directly then the rotational speed of some other component (e.g. camshaft, fuel pump drive) may be measured provided its speed ratio to the crankshaft is known and that the ratio is constant over the engine's speed range.

The power output of the engine shall be calculated from the torque and the engine speed and should be expressed as kW or bhp.

Consideration must be given to the power required to drive auxiliaries.

Items of equipment fitted to the engine and without which the engine could not in any circumstance operate at its declared power rating are considered to be engine components and are not, therefore, classed as auxiliaries (e.g. fuel injection pump, exhaust turbocharger and charge air cooler).

Dependent auxiliary:	Item of equipment, the presence or absence of which affects the final shaft output of the engine.
Independent auxiliary:	Item of equipment which uses power supplied from a source other than the engine.
Essential auxiliary:	Item of equipment which is essential for the continued or repeated operation of the engine.
Non-essential auxiliary:	Item of equipment which is not essential for the continued or repeated operation of the engine.

The power to drive auxiliaries need not be subtracted from the engine power.

Any shaft or electric power which is obtained from the engine waste heat eg. by an exhaust gas power turbine, may be added to the engine power. The power equivalent of any other waste heat may not be included regardless of whether it is used for process heat or some other purpose.

APPENDIX 5

Sequence and Details of Gas Sampling System

The preferred sequence of components for gas analysis is shown in the schematic flow diagram, Figure A5.1. The reason for this sequence is described below:

The sampling tube and the coarse filter are in the exhaust pipe and thus heated. The heated pipe will be heated to approximately 190°C. From the fine filter onwards, the system is heated again, and the fine filter is located before the pump to avoid plugging. There is a minimum of fittings before the pump to avoid leakages as much as possible, and a minimum of apparatus is located in inaccessible places. All the other items are located in the pressurised part of the system where the problem of leakages is no longer important because if some of the sample gas leaks to atmosphere it will not cause measurement errors. The span gas valve is not located on the sampling tube inlet for reasons of convenience. It is easier to handle this valve at the measuring location. The dehumidifiers are only located there when they are necessary. Thus, the corresponding span gas goes through the same route and dry readings can be obtained.

For components with high solubility in the condensed water, such as SO_2, a permea pure dryer may be used as a dehumidifier.

The dryer consists of one or more tubes of organic material with a particular high permeation rate for water vapour. While the permeated water vapour is conducted on the outside of the tubes by dry air, the components to be measured are not influenced. A schematic diagram is shown in Fig. A.5.2.

An alternative sequence of components for gas analysis is shown in Figure 5.3. Here the sample pump is located near the analyser so that the sample is drawn through the line. This method may be more convenient but the pressure in the sample line may fall below atmospheric pressure. The risk of air leaking into the sample line is therefore higher and this would cause measurement errors. If this method is used, greater care must be taken to detect and prevent leaks and for this reason the pressurised system shown in Fig. A.5.1 is generally preferred.

In cases where ammonia (NH_3) is present in the flue gas, for instance from NH_3 sources in SCR units, the NO_2 to NO converter should be made of carbon and not of metallic materials.

The metallic converters which are normally used have a working temperature of approximately 700°C. At that temperature NH_3 would completely oxidise to NO according to the reaction:

$$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$$

which would lead to incorrect NO_x results.

A carbon converter on the contrary has a working temperature of only approximately 300°C, at which temperature NH_3 is not oxidised.

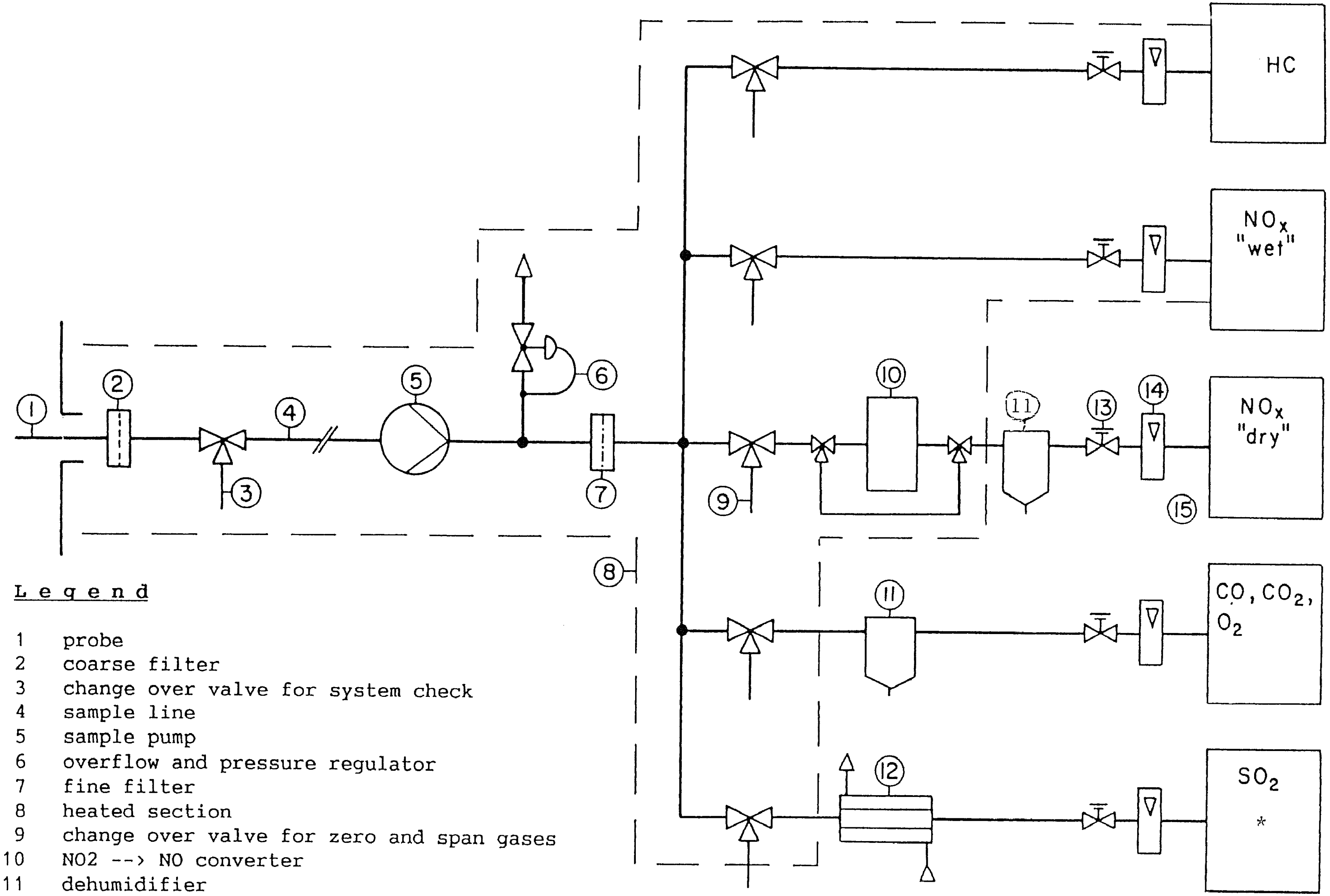
The conversion from NO_2 to NO takes place according to the following reaction:

$$NO_2 + C \rightarrow NO + CO$$

The different behaviour of the metallic and the carbon converter can be used in the determination of the NH_3 content, see Section 4.1 and Figure A5.4.

The design of a suitable sampling probe is shown in Figures A5.5. If an alternative is used details should be given.

FIG. A 5.1



Legend

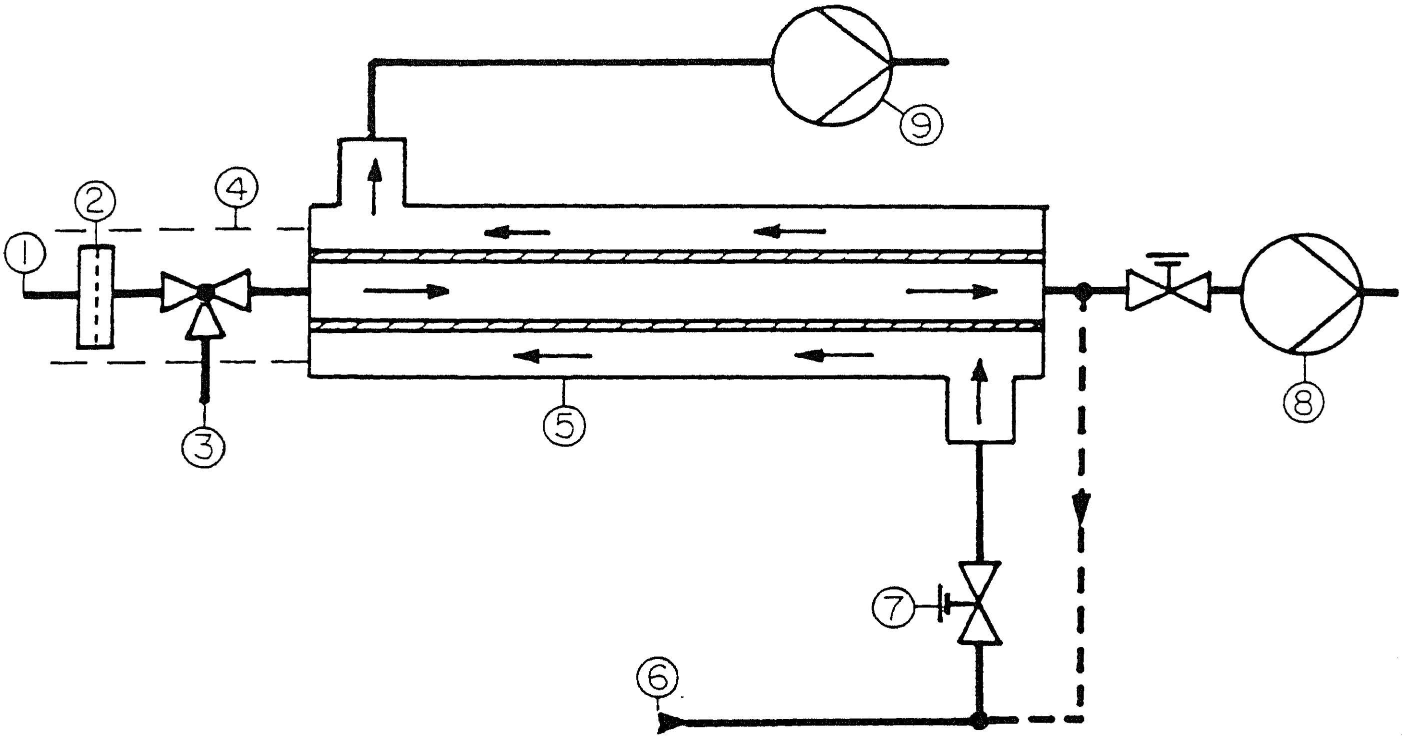
1	probe
2	coarse filter
3	change over valve for system check
4	sample line
5	sample pump
6	overflow and pressure regulator
7	fine filter
8	heated section
9	change over valve for zero and span gases
10	NO2 --> NO converter
11	dehumidifier
12	permea pure dryer
13	flow regulating valve
14	flow meter
15	analyzer

* When using NDUV it can be in the heated section without the permea tube dryer

SCHEMATIC DIAGRAM OF MEASUREMENT SYSTEM

Figure A 5.2

SCHEMATIC DIAGRAM OF PERMEA TUBE DRYER

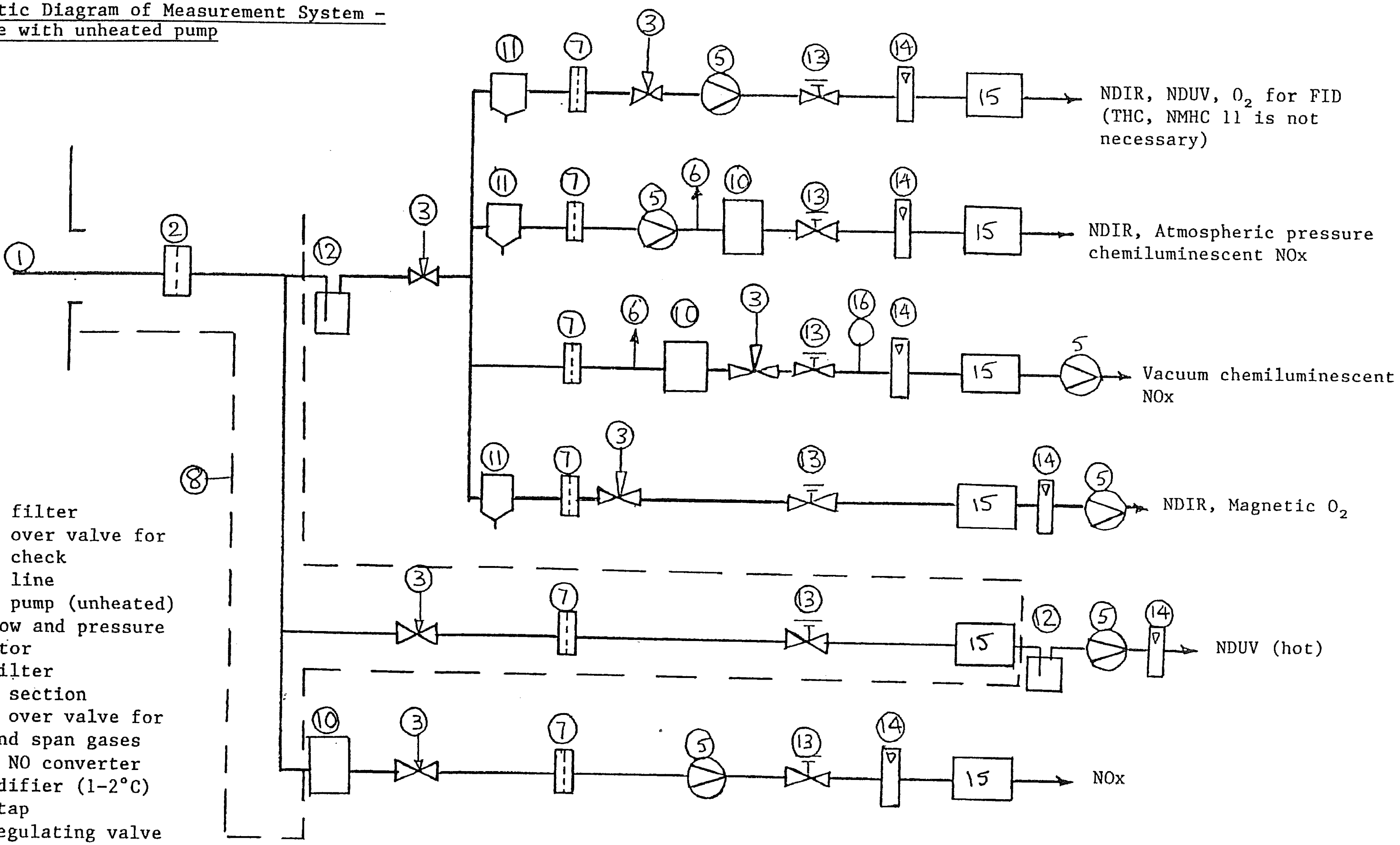


Legend

①	wet sample gas inlet
②	fine filter
③	change-over valve for sample gas / calibration gas
④	heated section
⑤	permea tube dryer
⑥	drying air inlet
⑦	flow regulating valve
⑧	sample pump
⑨	vacuum pump

Figure A.5.3

Schematic Diagram of Measurement System - for use with unheated pump



LEGEND

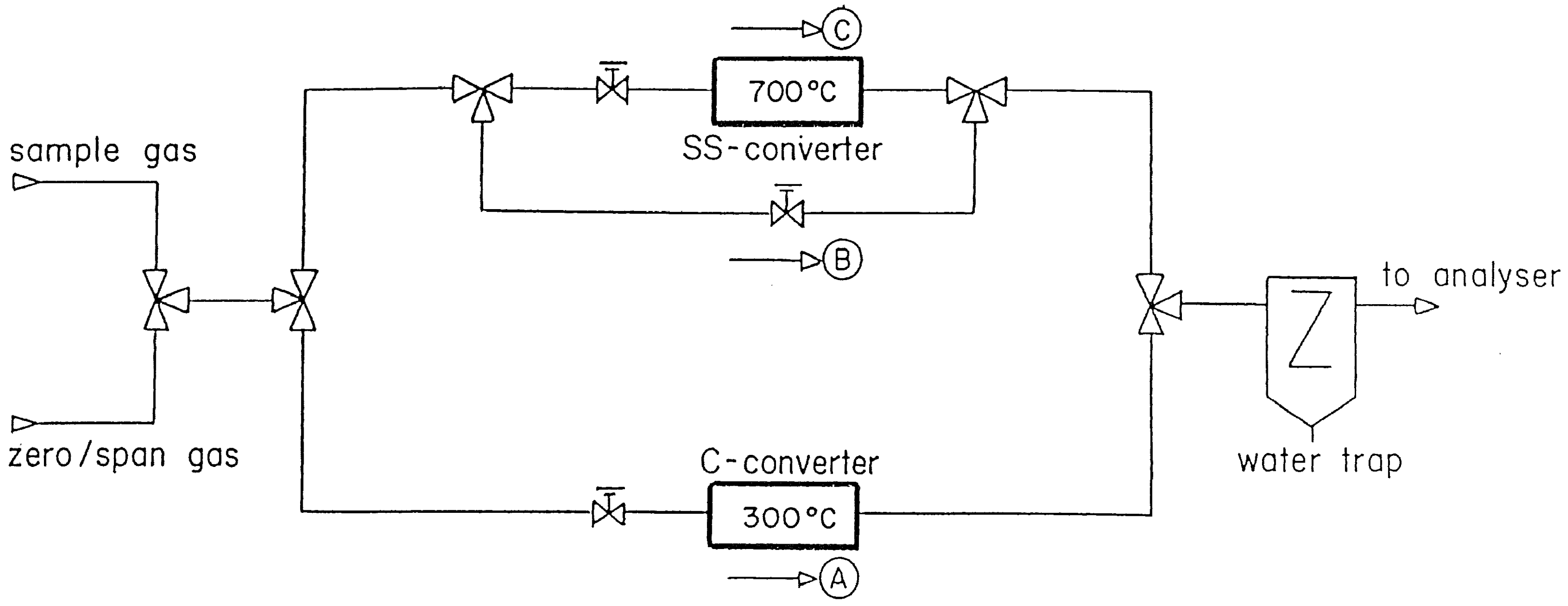
1. Probe
2. Coarse filter
3. Change over valve for system check
4. Sample line
5. Sample pump (unheated)
6. Overflow and pressure regulator
7. Fine filter
8. Heated section
9. Change over valve for zero and span gases
10. NO_2 to NO converter
11. Dehumidifier (1-2°C)
12. Drain tap
13. Flow regulating valve
14. Flow meter
15. Analyser
16. Pressure gauge

NOTES

In this system it is not necessary to heat the pump, fine filter and valves except with the hot NDUV analyser.

Leakage checks must be done by fitting the gas meter to the end of the system, plugging the gas inlet and starting to pump. The meter should record zero flow after a few minutes.

FIGURE A5.4



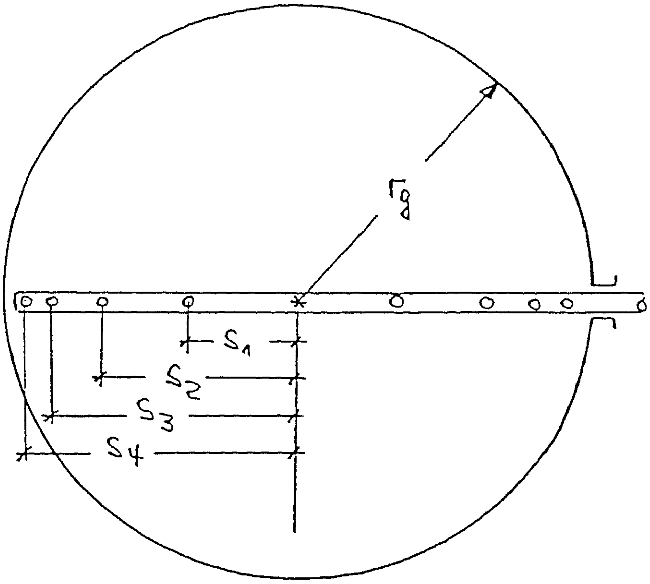
Ⓐ	NO_x - measurement	Ⓐ - Ⓑ	NO_2 - content
Ⓑ	NO - measurement	Ⓒ - Ⓐ	NH_3 - content
Ⓒ	$NO_x + NH_3$ - measurement		

Flow diagram of a converter system for NO_x/NH_3-measurements

FIGURE A5.5

Sampling Probe Design

(multi hole probe)



$$s_i = r_g \sqrt{\frac{2\ (i-1)}{n}}$$

s_i = Distance from centre of the stack (duct) to the hole considered (i)

r_g = Radius of the stack (duct)

n = total number of holes

i = 1 to n/2

APPENDIX 6

Gas Analysers - Reciprocating Engines and Gas Turbines

A.6.1 CHEMILUMINESCENCE NOx ANALYSER

A chemiluminescence NOx analyser with an NO_2 converter can be used for continuous measurement of either nitric oxide (NO) or total oxides of nitrogen (NO_x). It can also analyse ammonia if it is first oxidised to NO.

A.6.1.1 Measuring Principle

The chemiluminescence method utilises the reaction of NO with ozone to give nitrogen dioxide and oxygen. The transition of excited NO_2 to the ground state yields a light emission which is measured utilising a photomultiplier tube and associated electronics.

The method also utilises the principle that NO_2 decomposes to NO according to the catalysed thermal reaction ($2NO_2 \rightarrow 2NO + O_2$). A converter unit designed to provide essentially complete conversion of NO_2 to NO in the sample gas is included as a part of the chemiluminescence analyser package. If a sample gas is passed through the converter prior to entering the reaction chamber a NOx indication is obtained. If the NO_2 converter is bypassed, only the NO portion is measured.

Interference is caused mainly by tri-atomic molecules and may be caused especially by water vapour and carbon dioxide which quench the light emission. If necessary, the concentrations of water vapour and carbon dioxide must be determined and compensated for by correction factors (App.6.7.6).

The temperature of the sample gas passages in the analyser system should be maintained high enough to avoid condensation of water.

A.6.2 NON-DISPERSIVE INFRA RED (NDIR) ANALYSER

A non-dispersive infra red analyser can be used for continuous measurement of nitric oxide, carbon monoxide, carbon dioxide and sulphur dioxide. It may also be used to measure total oxides of nitrogen after appropriate conversion of NO_2 to NO. The NDIR can be used for the determination of ammonia but it suffers from interference from other compounds. The use of NDIR for hydrocarbons is possible if comparative values are required for combustion efficiency, or if only one hydrocarbon is present, eg. methane.

A.6.2.1 Measuring Principle

Gas whose molecules consist of dissimilar atoms absorb infra-red radiation at characteristic wavelengths, and by comparison with the amount transmitted by a non-absorbing reference gas the concentration may be determined.

Various techniques are used to obtain a modulated signal from a detector. This is then converted electronically to a DC voltage proportional to the concentration of the absorbing gas. The most sensitive technique uses a Luft detector which is a cell filled with the pure gas to be measured. The IR radiation is passed alternately through two analysis tubes containing a reference gas and the sample. The detector cell responds to the difference in IR levels reaching it from the two tubes.

The main disadvantage of this detector is its sensitivity to vibration as it is microphonic in design. As with all NDIR instruments, other gases, having similar absorption bands, interfere with the measurements requiring corrections to be made (App.6.7.6).

A design which is slightly less sensitive but is more selective and unaffected by vibration uses a rotating filter after the IR source. The filter has two (or more) cells in it, one of which contains the gas to be measured and one which contains an inert gas. Only the one analysis tube containing the sample gas is then needed, the modulated signal resulting from the difference which the detector sees between the radiation which has had the measuring band removed at source and the unfiltered radiation.

Another two-tube design uses a heated filament detector which is also unaffected by vibration.

NDIR is the recommended method for CO_2 and CO.

A.6.3 HYDROCARBON ANALYSERS

Organic residues from unburnt or partially burnt fuel are required to be analysed in varying degrees of detail as follows:

Total hydrocarbons (THC)
Non-methane hydrocarbons (NMHC)
Specified constituents such as aldehydes.

The techniques adopted to suit the requirements rely on gas chromatography (GC) and the flame ionisation detector (FID) plus a limited use of NDIR (App.6.2).

A.6.3.1 Measuring Principles

In the gas chromatograph a small measured volume of the sample is injected onto an analytical column through which it is swept by an inert carrier gas. Absorption or partitioning agents in the column retard the various components of the sample by varying degrees so that they emerge from the column at different times. They then pass though a detector which gives an electrical signal that depends on their concentration. This is not a continuous analysis technique.

The most sensitive detector is the flame ionisation detector (FID) which also gives a response which is linear with concentration over a wide range, and approximately proportional to the carbon number in the compound.

A polarising voltage between the jet and collector electrode is maintained across a small flame of hydrogen or hydrogen helium mixture burning in air. Only a small number of ions are produced and a very low standing current flows. When hydrocarbons are introduced into the flame the formation of charged carbon atom aggregates takes place and the current is greatly increased.

The FID response varies with the oxygen content of the sample.

A.6.3.2 Total Hydrocarbon (THC) analyser

This uses a FID without a GC to separate the constituents. The output is proportional to the total concentration of organic molecules, but the response varies slightly with the nature of the compounds, oxygenated compounds, for example, having a lower response than plain hydrocarbons. Calibration is carried out with a single standard gas and the concentration is expressed in terms of, say, methane or propane equivalent.

The THC is widely used and is recommended for its reliability and simplicity where regulations permit or for the measurement of combustion efficiency.

A.6.3.3 Non-methane hydrocarbon (NMHC) analysers

There are two types: direct NMHC and subtraction NMHC analysers.

A.6.3.3.1 Direct NMHC analysers

These consist of an automated gas chromatograph with a FID detector. The sample is separated and the air and methane are detected. The higher hydrocarbons are retained in the column. The column is then backflushed so all the non-methane hydrocarbons may be detected. Since the methane and NMHC are separated from the air, no oxygen synergism occurs. Two columns may be used with suitable flow switching to improve the separation and speed up the analysis.

This type is recommended where methane and NMHC are required.

A.6.3.3.2 Subtraction NMHC analysers

If the above method is not available the following may be used but it includes the same errors as the THC meter. This method uses two systems simultaneously: a GC for the analysis of methane and a THC for total hydrocarbons. NMHC is obtained by subtraction of the methane from the THC.

A.6.3.4 Aldehydes and other specified compounds

Aldehydes may be measured using high performance liquid chromatography (HPLC) or by a gas chromatograph with a flame ionisation detector, after the sample has been converted to some derivative. Absorption photometry may also be used.

The analysis for specific organic species is best done by the use of a GC with FID. In this case the separation is continued until all the required constituents have been eluted from the column. Calibration is by standards of each constituent for which the concentration is required.

For the analysis of aldehydes, the following methods are recommended:

- DNPH method [23]

  2.4-Dinithrodiphenylhydrazine (DNPH) reacts with carbonyl radical rapidly and selectively at room temperature to hydrazone derivatives.

  The yellow products are soluble in organic solvents. Using a high performance liquid chromatograph equipped with a spectrophotometric detector or a gas chromatograph with a flame ionisation detector, the composition of aldehydes is determined.

- MBTH method[24]

  Absorption spectrophotometric method for the determination of total concentration of aliphatic C_1 - to C_3 - aldehydes.

  This method is not applicable if the SO_2 concentration present in the sample gas exceeds 30 mg/m^3.

Other selective methods

- Acetylacetone method

  Absorption photometric method for formaldehyde.

- 4-Hexylresorcinol [25]

  Absorption photometric method for acrolein.

A.6.4 OXYGEN ANALYSER

Accurate analysis of oxygen is important because of its use in correcting emissions to a standard exhaust oxygen content. The closer this standard, n%, is to 20.95%, the greater is the effect of oxygen measurement inaccuracy, since the emissions are multiplied by a factor:

$$F = \frac{20.95 - n}{20.95 - O_2}$$

Oxygen analysers fall into three groups: electrochemical cells, zirconia detector and paramagnetic analysers.

Paramagnetic analysers are the recommended instrument where the highest accuracy is required with zirconia detectors as an alternative where a more robust instrument is required. The electrochemical cell is acceptable to some authorities.

Electrochemical cells have the advantages of low cost, portability and insensitivity to vibration.

Zirconia detectors and paramagnetic analysers are more accurate, more stable and need less maintenance.

A.6.4.1 Measuring Principles

A.6.4.1.1 Magnetic Wind analyser

This type of paramagnetic analyser utilises the reduction in the paramagnetism of oxygen with rise in temperature. The sample gas flows through a cell which contains a heated element in a strong magnetic field. When oxygen is present the gas is attracted into the magnetic field. Its magnetism decreases as it is heated and it is displaced by more strongly attracted cold gas. The "magnetic wind" thus set up - which gives its name to this type of instrument - causes a measurable temperature change in a sensitive element which is proportional to the oxygen concentration.

A.6.4.1.2 Susceptibility measurement analyser

This analyser measures directly paramagnetic susceptibility. It is also called the dumb-bell type.

Two diamagnetic spheres of glass filled with nitrogen are mounted on a thin bar forming a dumb-bell. This is supported in a horizontal position by a vertical torsion wire through the centre. Both spheres are in a strong magnetic field acting on each sphere in opposite directions.

When sample gas containing oxygen surrounds the spheres they are repelled by the the magnetic field and this repulsion is counterbalanced by a torsional force from the twisted suspension. An electrically controlled restoring force is applied to hold the dumb-bell stationary in a null balance system, and the magnitude of the electric current is proportional to the susceptibility and hence the oxygen concentration, of the sample gas.

Other gases, notably CO_2, interfere and corrections can be made for the highest accuracy.

A.6.4.1.3 Electrochemical cell

Electrolysis of aqueous electrolytes results in evolution of oxygen at the anode or dissolution of the anode and evolution of hydrogen or base metal at the cathode. In a suitable cell this will be reversible so that applying an oxygen concentration to the cathode will generate a current through the cell which may be measured and related to the oxygen concentration. Various constructions have been devised to limit the dissolution of the anode, prevent evaporation of the electrolyte and reduce attack of the cathode.

A.6.4.1.4 Zirconia detector analyser

A solid electrolytic cell consisting of platinum electrodes and zirconium oxide electrolyte, operated in the temperature range, 750-900°C gives an output which is proportional to the difference in oxygen partial pressure at the electrodes.

The detector is specific to oxygen and has a fast response. As there is no interference by water vapour, the sample need not be dried before analysis. Unburnt hydrocarbons will be oxidised in the cell, which will result in the oxygen measured being the value for 100% combustion efficiency.

A.6.5 SULPHUR DIOXIDE ANALYSER

The recommended method is non-dispersive ultraviolet which suffers least from interferences. This may be heated and used without a dehumidifier as is a FID. NDIR and pulsed UV fluorescence are alternatives, but for these a complete system should be obtained in which some method of compensating for water, hydrocarbons, oxygen and CO_2 interference is included.

A suggested procedure is to pass the sample through a cooler at 0°C to remove most of the water, and then through a catalytic tube furnace to oxidise the hydrocarbons. Final removal of water can then be achieved with a drying agent or permeation tube.

A.6.5.1 Measuring Principles

A.6.5.1.1 Non-dispersive ultraviolet

This type is similar to NDIR instruments but using UV illumination. Interference can occur from water and hydrocarbons.

A.6.5.1.2 Pulsed UV fluorescence

The gas sample in a cell is irradiated, via a monochromatic filter, with pulsed UV illumination. SO_2 molecules absorb this radiation and fluoresce, i.e. they emit radiation at a different wavelength. A window in the cell allows this radiation to pass, via a narrow band filter which excludes the source wavelength, to a photomultiplier tube.

The emitted light is proportional to the SO_2 concentration. Quenching of the emission occurs due to water vapour, oxygen and carbon dioxide together with cross-sensitivity to aromatic hydrocarbons. The sample may be reduced a hudredfold to reduce the effects of cross-sensitivity.

A.6.6 ANALYSER DESIGN PERFORMANCE CHARACTERISTICS

The performance of a gas analysis instrument is designed into it by the manufacturer and tested by him. This information is then published in his technical literature. The properties listed in this section are primarily design related and should not alter much, if at all with age and wear of the instrument. They may be verified at the time of purchase and at rare intervals subsequently if suspected of having changed.

The characteristics most frequently found in specifications are described briefly and typical values to be expected given where these can be generalised.

A.6.6.1 Ambient temperature and sample temperature

Many instruments have their sample cell thermostatted to within ±1° and also the detector and electronics. This considerably reduces any effect which would otherwise be gas law related i.e. about 0.3% per degree C.

A.6.6.2 Ambient pressure and sample pressure

Most instruments are pressure sensitive since it affects the mass of gas in the fixed cell volume or flowing through a capillary.

An NDIR cell is usually vented to atmosphere and, if the sample pressure is not excessive, the effect will be gas law related at about 0.1% per millibar. This can result in a variation of up to 2% in a day but this effect is removed if vented to atmosphere and frequently calibrated.

A FID depends on the sample pressure to the capillary controlling the flow to the flame, and this usually consists of a pressure regulator and bypass flow regulator.

A.6.6.3 Ambient humidity

Instruments should not be affected by ambient humidity unless condensation can occur.

A.6.6.4 Power supply stability

Instruments which are sensitive to voltage fluctuations usually have voltage regulation built in.

Specifications sometimes ignore the effect of voltage variation while others specify values such as ±10%. Care must be taken to verify whether this tolerance means that the instrument will work satisfactorily at any steady voltage within that range, or whether it means that it is unaffected by variation within that range during use. This is easily tested by using a variable voltage source and measuring the effect. Frequency variation is much smaller usually being specified at ±0.5%, and this is usually met by mains electricity supplies. If there is variability, as in an establishment with its own power generation system, the best solution is to purchase the DC power supply version of the instrument if this is available.

A.6.6.5 Operational readiness time

The time from switching on to full operational stability, also referred to as warm-up time, is often as much as 1 to 3 hours. Manufacturers will sometimes quote warm-up times in one of two ways e.g. usable in 5 minutes, fully stable in 1 hour. The user must be aware that if an instrument is used before full stability is reached, calibrations should be carried out immediately before and after a test point and interpolation between the two zero values and span values done to avoid error.

A.6.6.6 Tilt and vibration

This can occur on board ship or in a mobile test laboratory. Susceptible instruments are likely to be the paramagnetic oxygen analyser and some NDIR analysers. Appropriate shock absorbing or suspension mounting of the instrument can reduce the problem, but it is better if instrument sensitivity to tilt or vibration is considered at the time of purchase and avoided.

A.6.6.7 Discrimination and minimum detectable limit

Discrimination is the smallest change in sample composition that can be detected. This is usually defined as the change in concentration giving a signal change to noise ratio of 2. A reasonable value to expect for discrimination, minimum detectable limit or analytical resolution is 0.4% FSD derived from a noise level of 0.2%. Many instruments perform better than this but manufacturers often specify a resolution of only 1%.

A.6.7 ANALYSER OPERATING PERFORMANCE - CHARACTERISTICS AND EVALUATION

The performance of a gas analyser may deteriorate with time and although some of the characteristics in 6.6 come into this category they will usually be apparent during operation and are not the most vital to the accuracy of the results. The operating characteristics which can deteriorate and affect performance more severely are listed and described in this section, together with brief outlines of the methods of checking which should be carried out at regular intervals.

It is recommended that performance checking of the items in this section should be part of a regular formal Quality Audit programme. Six-month intervals are suggested for instruments in regular use. For equipment which is used only rarely it is better to audit before the instruments are brought back into use. Formal records should be maintained and computer programs updated with new values for correction factors.

A.6.7.1 Calibration gases

The composition of the gases need only be known to an accuracy of ±2% in most of the tests in this section. The exception is A.6.7.7, FID response, where measurement of the small differences in response for the various hydrocarbons depends on the accuracy with which their concentrations are known.

It is assumed that a gas divider is available for these tests, and also a chart recorder. Gas dividers are instruments which, when supplied with two different gases, A and B, can be switched to give 100% of A to 100% of B in steps - usually 10%. A calibration certificate of the exact blends is issued with the instrument. If a gas divider is not used, calibration gases will be required of high accuracy for the linearity test.

A.6.7.2 Zero drift, wander and noise

This measures the variation in the instrument zero reading over a long period with zero gas flowing. The gas used is usually nitrogen, but any gas which gives no response from the analyser under test may be used if preferred.

Instrument manufacturers give values of around 1% of FSD per 24 hours or 3% of FSD per week. If the chart recorder for the zero drift test is set to record 1-10% instrument reading to be shown as 0-100% on the chart recorder, this test will measure instrument drift, wander and noise accurately, since 1% on the chart recorder represents 0.1% FSD on the instrument.

Drift is a long term change or reading over a period of hours, caused by thermal changes within the instrument electronics, ageing of components and environmental changes. Wander is change of reading over a period of minutes. If cyclic, this is probably due to a rather wide thermostat setting; if random, it may be from, say, movement of a filament.

Noise is variation over a period of seconds, and, if very rapid, may only be seen as a widening of the recorder pen trace. Measurement of the noise, say 0.15% of FSD, indicates the discrimination of the instrument and, in this example, would be 0.3% FSD.

A.6.7.3 Span stability and repeatability

Span stability or drift is the maximum error in reading over a specified period when identical samples of span gas are passed through the instrument and suitable corrections are made for zero drift. Manufacturers are seen to quote values of <1% of FSD per week so this excludes known ambient effects (see A.6.6.1 and A.6.6.2).

If span gas is introduced at, say, hourly intervals during a zero drift test, this will give a measure of the span stability.

If span gas is introduced at, say, 4 minute intervals for a period of 2 minutes, a number of times the maximum error in reading gives a measure of the repeatability. A value better than 0.5% is to be expected.

A.6.7.4 Response time

The overall response time for a step change in concentration of the sample gas is made up of the response time of the sensor and electronics and the time to flush out the analyser cell and pipework at the specified flowrate. Response time may be specified as time to 100% of reading but this is almost impossible to measure. The most frequent specification is the time to 90% of reading.

Times vary from as little as a few seconds for some THC and NOx analysers, through several seconds for NDIR's and longer for O_2 meters up to a minute or more for electrochemical cells and much longer for GC's. The ultimate criterion is the use to which the analyser is to be put. If a performance test of an engine involves remaining at a steady condition for half an hour, response time is of little importance; if an exhaust traverse is being performed with 10 second stops at each of, say, 72 points, short response times are vital.

A.6.7.5 Linearity

Most analysers are basically non-linear, and include linearising circuits to enable straight line interpolation between zero and span gas readings to calculate the concentration. The method used has been to pull the output voltage back to the straight line at the mid-point or at several points along the scale. Latterly, circuits have been used which store, say, a thousand interpolations or the actual response which have been derived from a curve fit analysis. The raw output is then input to this circuit and the appropriate interpolation output to the recorder, analogue meter or data logger. 10 times enlargement of the output on a chart recorder will show the step changes from such a lineariser.

Where an analyser is a multi-range instrument it is necessary to check the linearity on each range, whereas the previous tests are usually carried out on the most sensitive range.

The test is performed by passing zero to 100% span gas in whatever steps are available through the analyser and then back in reverse to zero gas to verify that span stability and zero drift have not altered the readings during the test. The values for each point should repeat within the discrimination of the instrument.

The results can be plotted on a graph but are better expressed as a percent deviation of the output from the expected output derived from linear interpolation between the 0 and 100% of span outputs.

Example:

Zero	2 divisions
100% span	92 divisions
10% span	10.1 divisions
Linear value for 10%	11.0 divisions

% deviation = 100 x (8.1-9)/9 = -10%

Sometimes specifications will state linearity as % of FSD, in which case, in the example above the value becomes:

100 x (8.1-9)/90 = -1%

It is considered that this is an unacceptably high level of inaccuracy and users are warned to beware of measurements in the bottom 20% of a scale range.

If a more sensitive range is not available and the higher range must be used, a calibration should be carried out in the part of the range which is to be used, and for the highest accuracy, a multi-point calibration within this range. The values obtained are used for interpolation rather than the straight line method.

A.6.7.6 Cross sensitivity or interference

Gases present in the exhaust other than the one being analysed can interfere with the reading in several ways.

Positive interference or cross-sensitivity occurs in NDIR, NDUV and paramagnetic instruments where the interfering gas gives the same effect as the gas being measured but to a lesser degree. Negative interference occurs in NDIR instruments by the interfering gas broadening the absorption band of the measured gas thus reducing its amplitude. Negative interference occurs in paramagnetic instruments where the interfering gas gives the opposite effect to that of oxygen, and it occurs in chemiluminescence and UV fluorescence analysers where the interfering gas reacts with the emitting molecule thus quenching the radiation. Interference occurs in a FID by oxygen synergism and the fuel/air mix has to be optimised to reduce this interference to possibly ±1% for 0-20% oxygen in the sample.

A.6.7.6.1 Method of test

The methods of measurement will be illustrated using the interference of CO_2 on a CO NDIR and on a NOx analyser. The principle is to substitute a non-interfering gas by the interfering gas, and to observe the change of reading.

(a) Use the most sensitive range of the CO analyser and let the maximum CO_2 in the exhaust be 5%. Calibrate the range with a CO in N_2 gas. Pass a gas containing B% CO_2 in N_2 (B is approx 5%).

Measure the apparent CO produced, A vppm. The interference is A/B vppm CO per % CO_2. In dimensionless form (eg. % CO per % CO_2) this becomes 10^{-4} x A/B.

(b) Let the maximum CO_2 in the exhaust be 5%. Use an NO in N_2 calibration gas appropriate to the analyser range. Using a divider pass 50% of this gas and 50% of N_2 through the instrument to give a reading of A vppm NO. Switch the 50% of N_2 to a gas containing B % CO_2 (B is approx 10% CO_2) in nitrogen and record the reading of C vppm NO. The interference in this case is usually expressed as a percent reduction of the NO reading: 100 (A-C)/(A x B/2) % of reading per % CO_2. This can be verified with other concentrations of NO.

A.6.7.6.2 Interfering gases

The most important gases are tabulated below:

	Analyser			Interfering Gas		
Gas	Type	CO_2	H_2O	O_2	CO	Hydrocarbons
CO_2	NDIR		X	X	X	
CO	NDIR	X	X			X
SO_2	NDIR	X	X			X
SO_2	Pulsed UV	X	X	X		X
SO_2	NDUV					X
NO	CL	X	X			
O_2	Paramagnetic	X	X			X
HC	FID			X		

A.6.7.7 Flame Ionisation Detector Response

The difference in the analysis of unburnt hydrocarbons from that of other constituents in the exhaust is that a whole group of different compounds are being detected as one.

This makes calibration difficult since different compounds respond differently in the FID.

Where individual constituents, such as methane, formaldehyde etc. are separated out by a gas chromatograph before detection in the FID, normal GC techniques are applicable. The retention time and response factor for each compound is established by calibration and the response factor used to calculate the amount present in the exhaust sample.

In THC and NMHC one factor is used for all the compounds in the mixture, based on calibration with methane, propane or hexane, and the result expressed as, say vppm propane equivalent. Fortunately the FID has been developed to give a very similar response to many hydrocarbons species to meet the requirements of regulatory authorities, and manufacturers claim, for example, relative hydrocarbon response for calibration on propane of ±2% for propylene, toluene and hexane.

The response factor for methane can be 10% higher than that of propane, so if THC is the method of analysis and the engine fuel is natural gas, methane should be used for calibration.

A.6.7.7.1 Method of test

The method for checking response factors uses separate calibration gases each containing a similar carbon equivalent concentration of one of the gases whose response factor is to be checked, with air as the diluent. Since the response factors are expected to be within ±2%, the accuracy of the certificate value for the gas must be very high.

A recommended method of avoiding dependence on the gas suppliers certificate of recommendation and which also checks whether the values have changed or not is as follows:

- The calibration gas, say 300 vppm propane in air, followed in turn by the gases whose response is to be checked, is passed through a two way tap into either a tube furnace at 900°C containing platinised alumina catalyst, or directly to a carbon dioxide analyser of the appropriate range, say 0-1000 vppm CO_2.
- When going directly to the CO_2 meter the gas acts as its own zero gas, thus eliminating any error due to CO_2 in it. When going via the furnace the hydrocarbon is converted to CO_2 which is then measured in the CO_2 analyser.
- If the analyser has been calibrated with an accurate CO_2 in air mixture, the value obtained from the propane in air calibration gas checks its certificate value. However, since it is the relative

response that is being measured, the propane in air can be used as the span gas and set to any appropriate value, say 900 vppm, not necessarily its exact carbon equivalent.

- The same procedure is carried out with the response test gases and the results obtained used to derive concentrations which compare accurately with the propane calibration gas. When values have been assigned to the test gases, they can be used to measure the response of the FID by passing each of them through it in turn, ensuring that the conditions of pressure and flow are identical for each.

- The relative response factors can then be calculated, and if required, expressed as a percent variation from the propane. Example:

Using the CO_2 analyser:

300 vppm propane set to 900 vppm CO_2 (zeroed on the same gas passed direct to the analyser).

130 vppm toluene (certificate value) gave 875 vppm CO_2.
Toluene = 875/7 = 125 vppm based on the propane standard.

Using the FID:

300 vppm propane in FID set to 300 vppm (air as zero) 125 vppm toluene in FID gave 295 vppm propane equivalent.

- A 300 vppm propane equivalent toluene gas would give 900 vppm CO_2 and, on the FID would have given 295 x 900/875 vppm propane equivalent, = 303.43 vppm.

- The response factor is 303.43/300 = 1.0114 compared with propane. In percent terms the response factor is +1.14% compared with propane.

A.6.7.8 NOx Converter Efficiency

An NO_2 to NO converter should be capable of operating at 95% efficiency or better. If it is below 90% it should be investigated and remedial action taken.

The method of testing the converter is to use an NO in nitrogen calibration gas in the concentration range expected in the exhaust. This is partly oxidised to NO_2 with ozone and then used to test the ability of the converter to return it to NO.

The apparatus is shown in Figure A6.1. It is available commercially as a complete package. The test procedure, which results in a chart recorder output as in Figure A6.2 is the following:

A. Take reading of calibration gas in NO mode.
B. Add oxygen to reduce reading by about 10%.
C. Switch on ozone generator and adjust power until the reading is about 10% to 20% of its original value.
D. Switch to NOx mode and take reading.
E. Switch off ozone generator and await steady reading.
F. Stop oxygen flow.

If the calibration gas contains some NO_2 then E will be greater than B and F greater than A. The only way of verifying whether the calibration gas contains some NO_2 is to pass it through a converter before entering the NOx analyser. However, even if it does contain some NO_2 and the instrument is set up for A and F to be equal, the error in the efficiency calculation will be extremely small.

The calculation method is shown in Figure A6.2.

A.6.8 EMISSION MEASUREMENT TEST PROCEDURES

A.6.8.1 Siting Analyser Systems

The site for operation of the analyser systems should be provided with the following conditions:

1. A low vibration level.

2. An atmosphere free of corrosive gases and dust, and not more than 80% relative humidity.

3. The temperature should be steady and not more than 35°C. The system should not be exposed to sunlight or heat radiation.

4. Fluctuations of power source voltage and frequency should be small.

5. There should be no adjacent equipment which gives electromagnetic interference.

6. The sampling gas line should be as short as possible.

A.6.8.2 Calibration Gases

For each analyser system to be used, zero and calibration gases should be provided.

The concentration values of these calibration gases must be certified by the authorities or the gas supplier to stated accuracy within ±2%. Since changes in the gas mixture may occur over a period of time after mixing, the emission measurement test should be completed within the guarantee period of the gas supplier. The certifications of calibration gases should be referred to in the results of emission measurement test.

Master bottles of high accuracy calibration gases in aluminium bottles should be held against which working standards can be compared for any change.

Note: Gas suppliers now supply gases in suitable bottles where deterioration is not expected. CO and NO mixtures in steel bottles are most suspect.

A.6.8.3 Preparation of Analyser Systems

Each of the analyser systems should be assembled following the manufacturer's instructions. The handling instructions of each analyser should cover the items shown in Appendix 6.9.

All the equipment to be used should have had the necessary performance checks listed in App.6.7 carried out within the time specified in the Quality Audit Procedure.

A.6.8.4 Daily Performance Check of Analyser Systems

Perform the following checks for each of the analyser systems:

1. If the power of analyser system is not left on continuously, allow the appropriate warm-up time. If daily use is anticipated, it is recommended that the analyser systems be left on continuously.

2. Clean or replace filters following the manufacturer's maintenance and checking manuals.

3. Check measurement system for leaks.

4. Check temperature of measurement systems, and ascertain that all flows in the systems are correct.

5. Zero the analyser system using the zero gas. If there is a significant change in setting of zero control from the previous value, determine the cause and correct.

6. Using span gas, check the response of the analyser system on each range using the gain setting from the previous use. If the indication differs from the previous value by more than ±3%, a problem may be indicated. Check and correct as necessary.

   If the indication of analyser system is within ±3% of the previous value, adjust the gain control to produce proper analyser system output.

7. Recheck zero and repeat step (6) if necessary. Record the gain setting and the zero setting after the final adjustment.

8. During the emission measurement testing sequence, recheck the zero and span of each analyser system at intervals not grater than two hours. If either has changed by more than 2% but less than 10%, the values can be corrected by linear interpolation. Changes of more than 10% require that portion of the test to be re-run.

9. Readings should be taken using the appropriate range after the engine and measurement system have stabilised.

A.6.9 ANALYSER INSTRUCTION MANUAL

Each analyser system should have an instruction manual which covers at least the following items:

1. Installation instructions.

2. Instrument specification.

3. Sample conditioning requirements.

4. Piping and wiring diagrams.

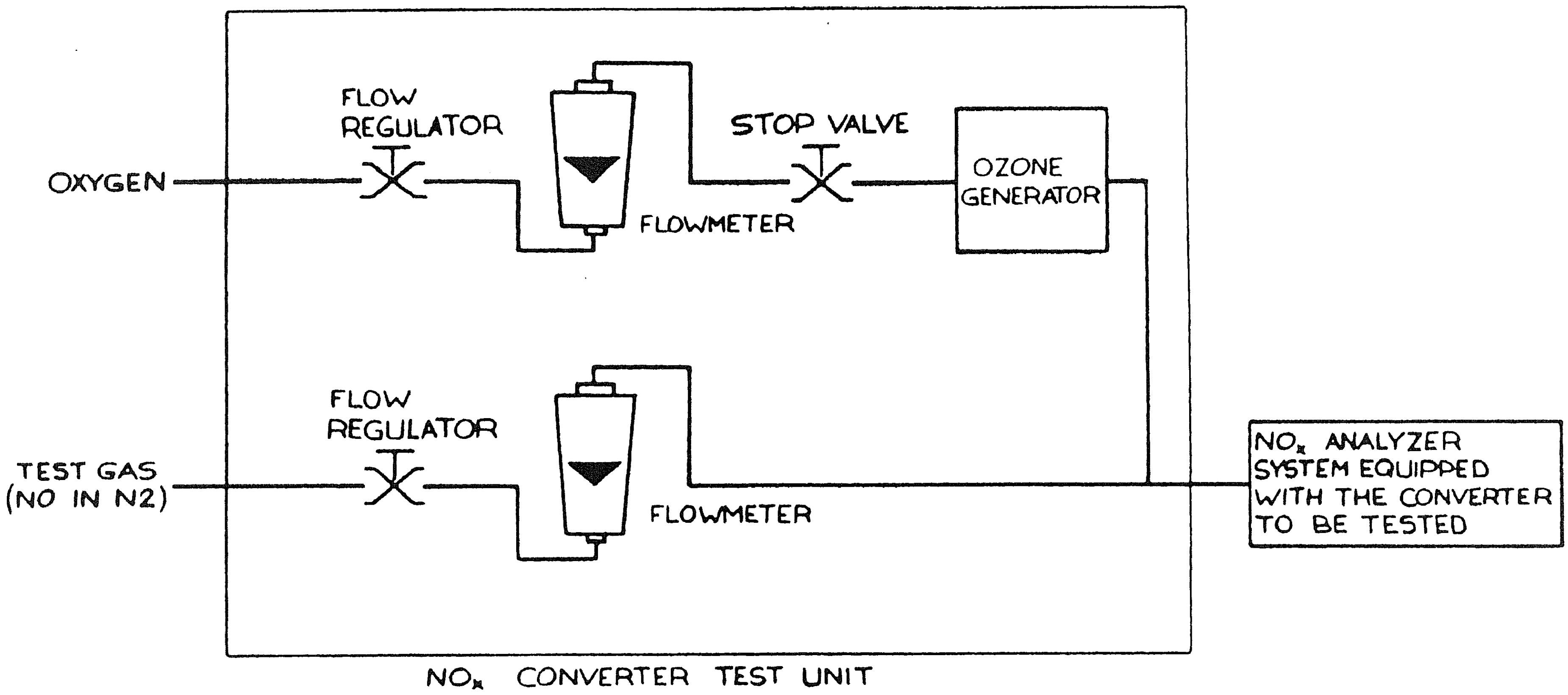
5. Operation instructions:

   (a) Preparation for measurement and calibration
   (b) Calibration
   (c) Measurement
   (d) Shut-down procedure.

6. Maintenance and checking:

   (a) Daily checking procedure
   (b) Periodical checking procedure
   (c) Fault finding guide

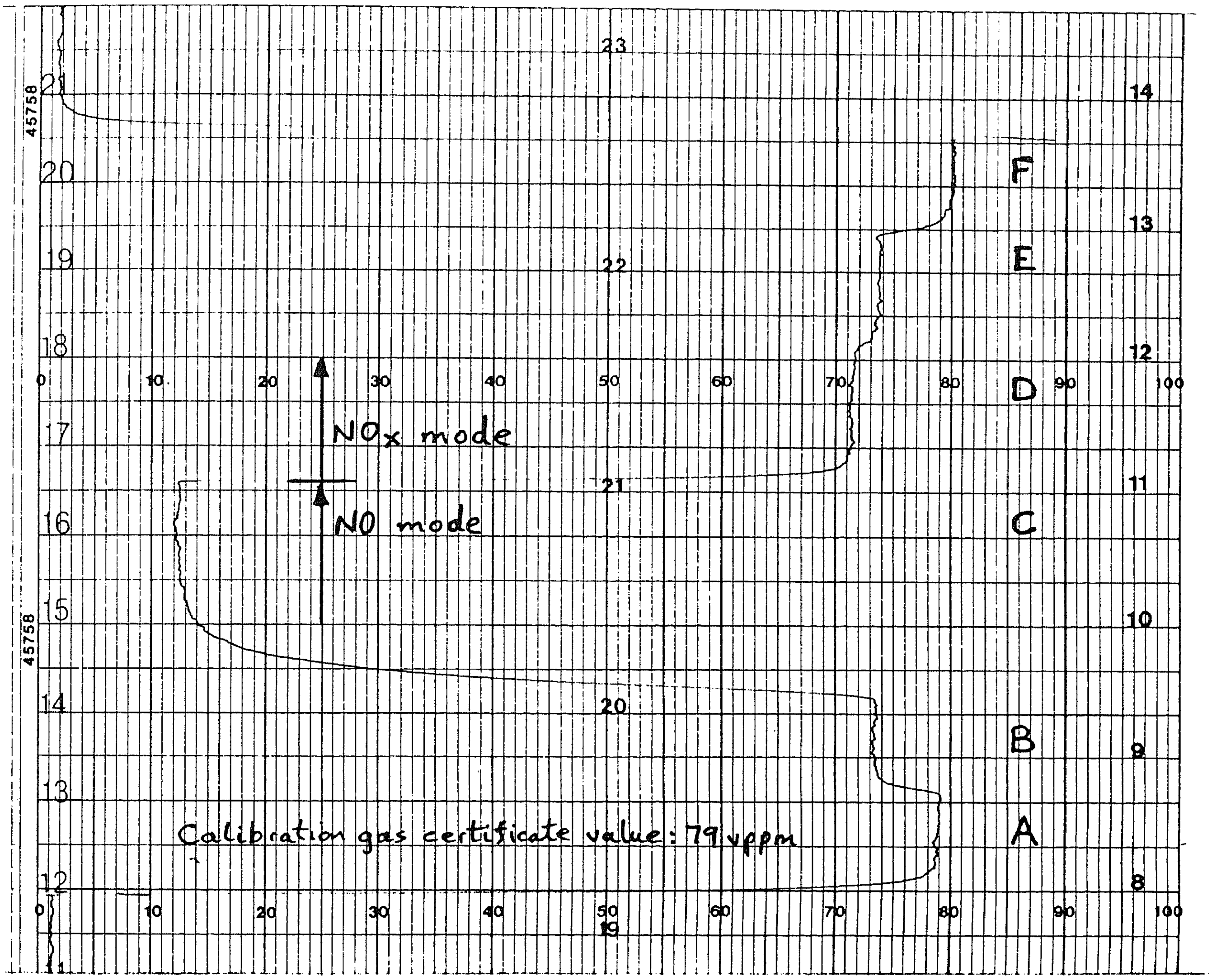
APPARATUS FOR NO_x CONVERTER EFFICIENCY TEST



NOTE:- OZONE GENERATOR MUST HAVE A VARIABLE POWER SUPPLY TO GIVE THE REQUIRED AMOUNT OF OZONE

FIGURE A6.2

RECORD OF MEASUREMENT OF CONVERTER EFFICIENCY



Copy of chart recorder trace for converter efficiency test, showing higher values for F and E than A and B due to NO2 in calibration gas. The same effect is produced if the NOx analyser is not set up correctly.

$$\text{Converter efficiency} = \left(1 - \frac{E - D}{B - C}\right) \times 100\%$$

$$= \left(1 - \frac{2.2}{61.0}\right) \times 100\%$$

$$= \underline{96.4\%}$$

APPENDIX 7

Particulate Sampling Systems

For the determination of particulates, different methods are employed depending on the application and local regulations. Different methods will give different results because the amount of particulates and condensate collected depends upon the measurement temperature. It is therefore important to include in the reports a description of the method applied (see also Appendix 10).

Isokinetic sampling may be required depending on the particle size but there is not proof that it is necessary and it is therefore not considered to be essential. Some regulations however require extraction of exhaust gas at isokinetic conditions. The sampling probe position shall respect requirements concerning distance from pipe bends, contractions, etc., as well as suitable positions covering the cross section of the exhaust pipe.

The ash content of the fuel will affect the particulate level, for example V_2O_5 during the combustion, the particulate level will increase considerably (0.1% of ash or 600 ppm vanadium in the fuel supplied to the engine both mean an input of 1g particulate per 1 kg fuel).

There are several accepted measuring systems, other methods have been proposed but not yet accepted. The measuring method should be identified when the measurement results are reported.

A.7.1 Hot filter out-of-stack : EPA Method 5 [8]

This method is described in considerable detail in Reference 8 so no attempt has been made to reproduce it here. A diagram showing the apparatus is included here as Figure 7.1.

A sample of the exhaust gas is taken and drawn through a hot filter and then passed through condensers. The filter is maintained at 120°C so that it removes solid material and the condensers remove any liquids which will condense at lower temperatures. Both retained particulate quantities are measured. The gas quantity passing through the system is measured also, enabling a calculation of the total particulate presence in the total exhaust gas flow. The filter needs to be weighed before and after the test in dry conditions.

This method is also recommended by the US Diesel Engine Manufacturers Association [3] and a similar method is used in Japan [15] but there is growing resistance to its use for reciprocating engines in the USA and in Europe. It is often applied particularly to gas turbines which have few condensates when they operate on gas or distillate fuel. Then the condensation system is sometimes omitted because it is complicated. This means that some of the particulates would be ignored.

A.7.2 Hot filter in-stack : EPA Method 17 [18]

The difference between this and the out-of-stack method is the location, and therefore, the temperature of the filter.

This method is described in great detail in Reference 18 so it has not been reproduced here. The method does ensure that the filter is maintained at the same temperature as the exhaust gas but there is a complex procedure needed to ensure that errors are not introduced. This means that the filter may have to be weighed at high temperatures under controlled conditions.

The method is complicated and is more suitable for large ducts and for exhaust gas streams which remain at the same temperature for long periods of time and for exhaust gases which contain few condensates and heavy hydrocarbons. The method was originally developed for furnace stacks in industrial plant. It has been used for gas turbines, to which it has subsequently bee applied, but it is far less suitable for diesel engines, especially when they are running on residual fuels.

See also VDI 2066 [19] and Figure A7.2 which has the same filter location but no condensed matter measurement is made.

A.7.3 Dilution tunnel [9]

A.7.3.1 Introduction

This method has practical advantages. The lower filter temperature and the fact that the equipment can usually be located at ground level makes it easier to handle during the tests. If a choice of test method is possible, this one is preferred. It is accepted by authorities, such as US EPA, for certification of engines for road vehicles of all types.

The simplest solution, dilution of the total amount of exhaust gas, is only possible for small engines (less than 500 bhp) and details of this method as applied to road vehicles are given in Reference 9. For larger engines, it is quite acceptable for only a part of the exhaust gas to be drawn into the dilution tunnel to be mixed with fresh air. By doing this it is possible to reduce the size of the dilution tunnel which can then be applied to engines of all sizes. An example of a dilution system is shown in Figure A7.3. An alternative system is shown in Figure A7.4. Recommendations for a suitable system and its use are given below.

A sample of exhaust gas is drawn from the stack into a tunnel. Fresh air is also drawn into the tunnel to dilute the exhaust sample and to reduce its temperature, hence the name dilution tunnel. Some or all of the diluted mixture is then passed through a filter medium which is weighed before and after the test under controlled conditions. The particulate level is calculated from the difference between these two weighings.

The system needs an exact regulation of the temperature after dilution which has to be maintained at a fixed level, below 52°C (125°F). Regulation between 49°C (120°F) and 52°C (125°F) is possible and is recommended for more accurate results.

The dilution rate can easily be calculated from measurements in the stack and in the dilution tunnel of NO_x, CO_2 or another gas component within the concentration limits necessary for precise measurement. Attention has to be given to the fresh air supply concerning the gas components used for establishing the dilution rate. The flow in the dilution tunnel has to be turbulent (Reynolds Number >4000).

There are essentially two methods of installing the filter(s):

(a) Directly at the end of the dilution tunnel, so that all the diluted exhaust gas passes through the filter.

(b) Taking a part of the diluted exhaust gas only for passing through the filters.

In both cases, the diluted gas quantity passing through the filters has to be measured.

The dilution method in which only some of the diluted gas passes through the filters is preferred because it can give more consistent results and it is often easier to control. The following paragraphs therefore give more detailed recommendations and they refer to Figure A7.3.

A.7.3.2 Exhaust Sampling and Transfer Tube

Referring to Figure A7.3 it is recommended that the exhaust is sampled using a separate transfer tube but situated close to the position of the gaseous emissions measuring probe. The exhaust should be sampled using a single tube facing upstream and placed at the centre of the exhaust pipe from the engine. This is quite adequate for the smaller exhaust pipes of less than about 0.5 m^2, but where considerably larger pipes are being sampled or where there is doubt that the particulates are evenly distributed in the exhaust duct, then multiple sampling points should be used and a recommendation for these is shown in Figure A7.5 for circular and Figure A7.6 for rectangular ducts.

The sampling point should be more than 3 duct diameters or 0.5 m, whichever is the greater, from the position where the exhaust stack enters the atmosphere.

The transfer tube should be manufactured from stainless steel or a non-corrosive electrically conducting material with a smooth internal surface so as to discourage particulates adhering to the tube wall. For the same reason, the tube should contain the minimum of bends and these should be gentle rather than sharp and flexible sections should be avoided if possible.

A recommended diameter for the tube is 25 mm, but diameters between 12 and 50 mm have been found to be quite acceptable. The tube should be as short as possible and not more than 5 m in length if it can be avoided. The tube should be lagged for thermal insulation.

A gate valve should be installed in the transfer tube as close to the exhaust duct as possible and used to control the flow of exhaust gas.

The transfer tube should terminate in the centre of the dilution tunnel facing downstream.

A.7.3.3 Tunnel Design

It is recommended that the tunnel diameter should be between about 100 and 200 mm and it should be long enough for complete mixing between the exhaust and the intake air. A length of approximately 10 tunnel diameters between the point where the transfer tube enters the tunnel and the point where the diluted exhaust is sampled from the tunnel is considered sufficient.

The tunnel should be manufactured from stainless steel or other smooth, non-corrosive and electrically conducting material.

The air entering the tunnel should be filtered to remove background particulates from the surrounding air. The efficiency of this filter may be checked by taking particulate samples with no exhaust gas flow. Downstream of the filter there should be an orifice or other suitable device which may be varied in size to control the pressure within the tunnel.

Downstream of the sampling position an extractor fan or pump should be installed of a design such that it will not cause pressure pulsations within the tunnel. The speed of this fan may be controlled or a valve may be fitted to its outlet prior to the diluted exhaust being passed to the atmosphere.

An inlet air heater may be fitted to the dilution tunnel. The object of this is to maintain the temperature at the diluted gas sampling point between the desired limits when the temperature of the exhaust gas being sampled from the duct is very low and therefore insufficient to maintain a high enough temperature in the tunnel without very low dilution ratios being selected. Typically this problem arises when measurements are being taken at low engine loads and it has been found that a close control of gas temperature within the duct makes a significant contribution to increased accuracy.

The tunnel and the extractor fan or pump should be designed to ensure that the flow within the tunnel is turbulent, i.e. with a Reynolds number of >4000.

A.7.3.4 Sampling Circuit and Filter Design

It is recommended that the smooth bore sampling tube should be between 12 and 25 mm in diameter and should be manufactured from stainless steel. It should face upstream and be positioned in the centre of the dilution tunnel and any exposed sections of it should be lagged for thermal insulation. The distance between the entrance to the sampling tube and the filter holder should be as short as possible and less than 1.0 m is recommended.

The stainless filter holder should be designed to accept a filter and a backup filter which are not in contact with each other, but are within 100 mm of each other in series in the sampled diluted exhaust gas stream. A minimum filter diameter of 90 mm is recommended for increased accuracy but with care smaller filters can produce good results.

The filter should be manufactured from fluorocarbon coated glass fibre or it should be a fluorocarbon based membrane filter. It should have a 0.3 μm di-octyl phthalate (DOP) collection efficiency of at least 95%.

Downstream of the filter holder should be installed a sample pump which, depending on its design, may require a plenum or damping chamber to be installed either side of it to reduce pulsations through the filters. A bypass around the pump containing a backpressure valve may be installed to assist with control and a further needle valve should be installed in the line to the flow meter which is used to record the sampling flow rate prior to the diluted sample being exhausted to atmosphere.

A.7.3.5 Tunnel Operating Procedure

The engine should be started and set at, say, 75% load to allow it to warm up. With the dilution tunnel fan or pump (4) operating the gate valve (1) should now be opened to allow the gas to enter the tunnel and warm it. The gate valve (1) or the pump (4) or the throttle (5) should then be adjusted to allow sufficient exhaust through the tunnel to raise the diluted gas temperature in the tunnel to 55-60°C in order to condition the tunnel. Two filters should then be placed in the filter holder (7), after which the sample valve (6) should be opened to allow a sample to be drawn through the filters by the pump (8). The flow rate through the filters should be adjusted using the backpressure valve (9) so that the gas velocity through the filter lies at a set point between 0.2 and 0.4 m/s and this rate should be maintained within ±0.5 m/s.

The tunnel should be run for about 10 minutes during this conditioning process. At some stage during this time the tunnel should be vibrated or tapped with, for example, a short length of plastic hose at various points along its length to dislodge any loose particulates in the tunnel. After the conditioning period the sample valve (6) may be closed, the sample pump may be switched off and the filters may be discarded. The tunnel is then conditioned and ready for testing.

To undertake a test the engine should be set up at the desired test condition with the tunnel fan switched on. The valve (1) and the fan (4) should be adjusted to draw sufficient exhaust into the tunnel to maintain a temperature at the sampling point between 49 and 52°C. The tunnel should be allowed to stabilise for 10 minutes before sampling begins.

The sample valve (6) should then be opened to allow the sample to pass through an unused pre-weighed filter and backup filter in the holder (7) with the sample pump (8) and the backpressure valve (9) set to draw the correct quantity of gas through the filters.

This condition should be held for a sampling time, which would generally be between 5 and 20 minutes but must be for more than 60 seconds. With experience this sampling time should be set to ensure that sufficient particulates are collected for accurate weighing yet not cause too heavy a filter loading which could result from particulates dropping off the filter and a decrease in flow rate as the filter became clogged. A minimum filter loading of 0.5 mg/1000 mm^2 of stain area is recommended and a target filter loading of 1.0 to 3.0 mg/1000 mm^2 is recommended.

When the engine is running at light load with a low exhaust temperature it may be necessary to restrict the air entering the dilution tunnel using an orifice (3) or similar device in order to maintain the temperature at the sampling point between the required limits and to induce sufficient exhaust to provide an adequate filter loading. At very low ambient temperatures it may also be necessary to heat the inlet air using the heater (2). It has been established that particulate levels are sensitive to the temperature in the dilution tunnel so a temperature between 49 and 52°C should be maintained. On some systems this is not possible but the temperature should then always be maintained above 25°C to prevent water condensation.

During the test the temperatures and pressures in the system should be monitored and the NOx, CO_2 or other convenient trace gas should be monitored in the exhaust duct and in the diluted stream of the dilution tunnel close to the sampling point. This measurement can then be used to calculate the dilution ratio.

After the test the filters should be removed and reweighed.

After testing is complete it is recommended that the tunnel and sampling system should be purged with fresh air with a clean filter inserted in the filter holder for a period of 15 to 20 minutes. This should remove any noxious or corrosive gases and dry out any condensation.

Filter weighing should be done under controlled conditions in order to remove errors caused by moisture absorption or evaporation of hydrocarbons.

Unused filters should be stored in a temperature and humidity controlled environment at a temperature set point between 20 and 30°C $\pm$6°C and at a relative humidity set point between 30 and 70% $\pm$10%.

The filters should be conditioned for two hours prior to weighing on an analytical balance which will record to five significant figures. Reference filters should be weighed at the same time under the same conditions.

Weighed filters should be used within 1 hour of weighing or within 8 hours if kept in a sealed container.

Following sampling the filters should be conditioned again in the same environment in an open petri-type dish prior to reweighing. This post-conditioning has a profound effect on the volatile content of the particulates and is important. This conditioning process should be for a period between 2 and 80 hours, but a consistent time period should be selected and maintained if at all possible throughout all the tests. Leaving them overnight is a suitable compromise.

The final weight of the filter and backup filter should be recorded and the difference between these and the initial weights indicate the amount of particulates collected. The reference filters should be weighed again at the end of the tests and these should not have changed in weight by more than ±6% of the recommended minimum filter loading.

A.7.3.6 Calculation of Results

The total quantity of particulates produced by the engine may be calculated from the following formula:

$$\text{Particulates} = \frac{\text{mass collected}}{\text{sampling time}} \times \frac{\text{exhaust flow rate}}{\text{sampling flow rate}} \times \text{dilution ratio}$$

This would give a result in mass of particulate/unit time but it may be expressed at g/bhph, g/kWh or Mg/m^3 as required.

A.7.3.7 General

The above is a general recommendation only for good practice. There are many systems currently available which will give similar results but not all of which will conform to these recommendations in detail. The technique described has been selected as convenient system for a large range of engine sizes but other systems may be quite acceptable. Provided care is taken and good practices observed the difference between the methods should be one of convenience rather than in the test results.

There is currently no internationally recommended standard for measuring particulates from non-automotive sources but the ISO TC 70/SC 5/WG 2 is currently working on a draft standard DP8178.

FIGURE A7.1

Particulate Sample Train

Hot filter out-of-stack [8]

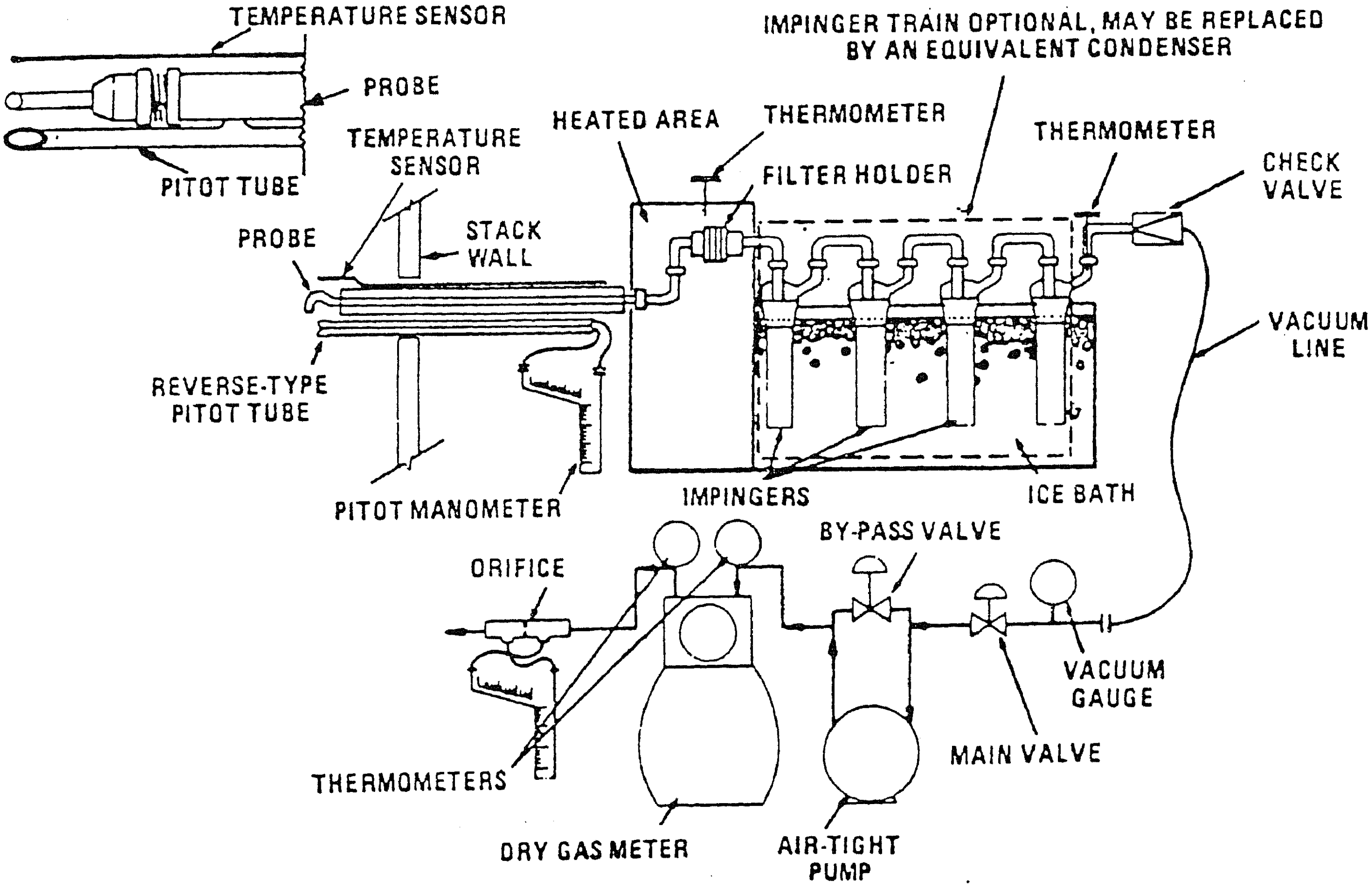
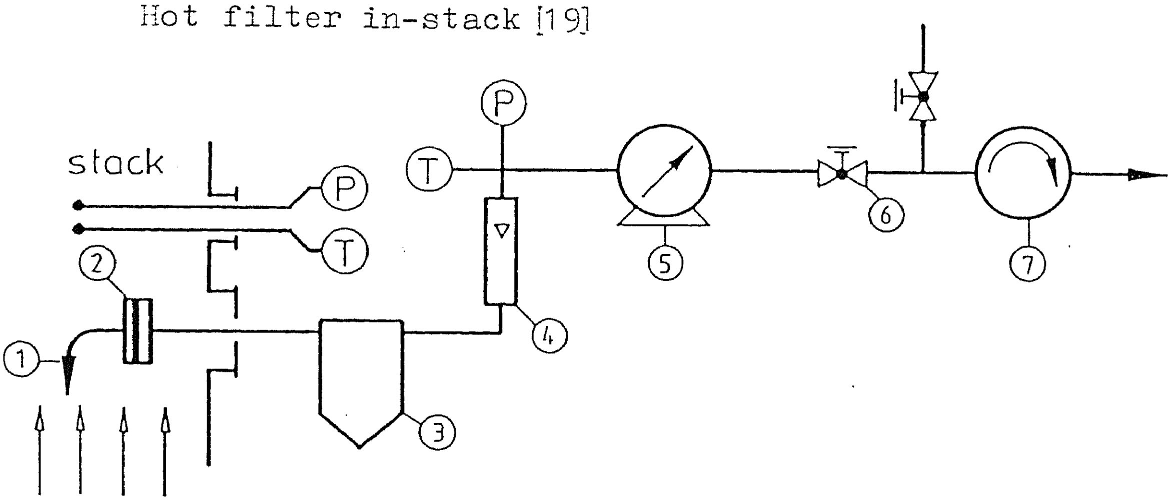


FIGURE A.7.2

Measurement system design - Particle emissions

Hot filter in-stack [19]



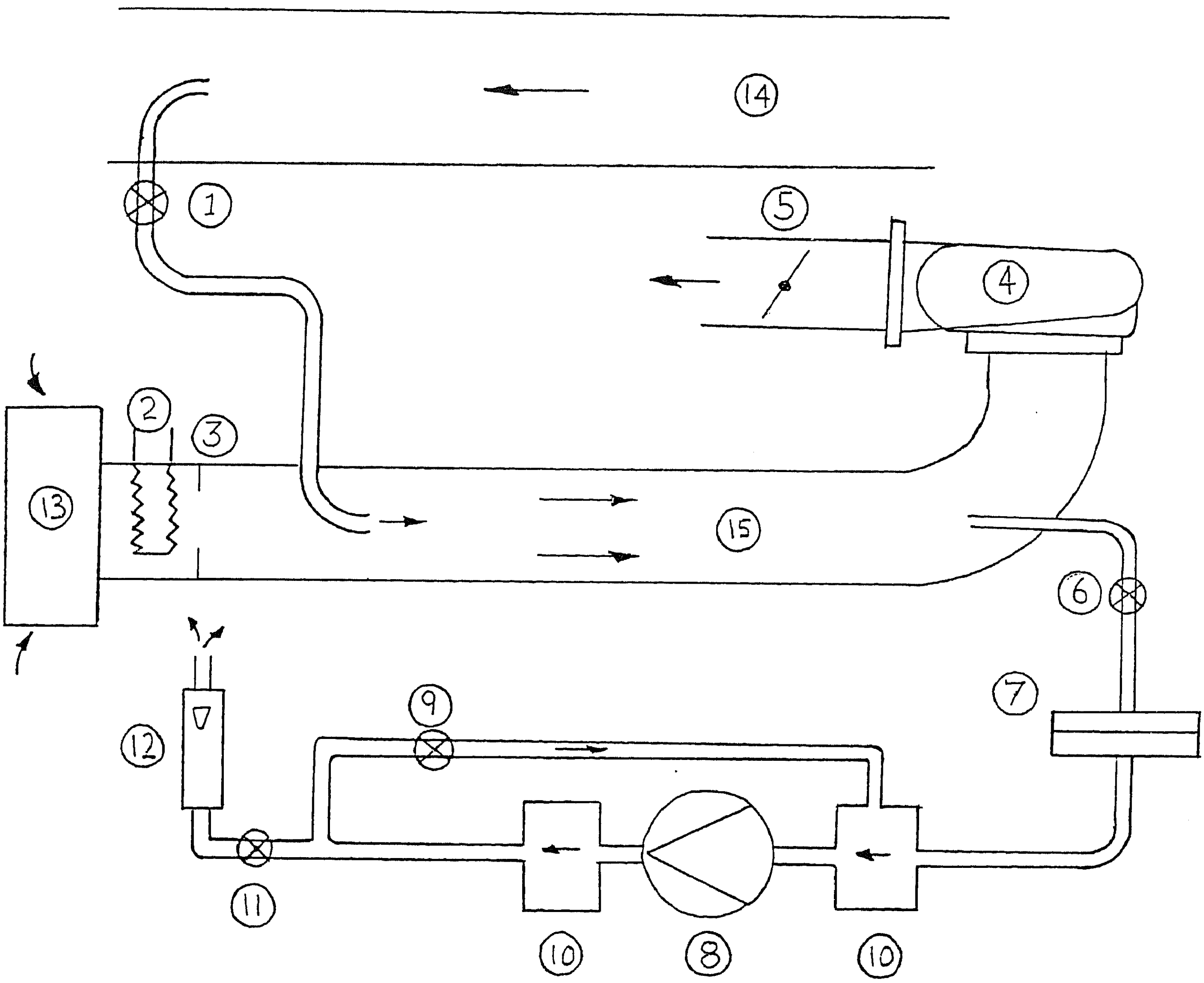
Legend

① nozzle (for isokinetic sampling)
② filter
③ water trap (0°C)
④ flowmeter
⑤ gasmeter

⑥ gasflow regulating valve
⑦ sample pump

Ⓟ pressure
Ⓣ temperature

Figure A.7.3 Example of Particulate Dilution Tunnel



LEGEND

1. Transfer tube gate valve
2. Heater (optional)
3. Restrictor (adjustable)
4. Extractor pump or fan
5. Throttle
6. Sample tube gate valve
7. Filter holder
8. Sample pump
9. Back pressure control valve
10. Damping volumes (optional)
11. Control valve
12. Sample flow meter
13. Dilution air filter
14. Exhaust duct
15. Dilution tunnel

Figure A.7.4 Further Example of a Particulate Dilution Tunnel (ECE R49)

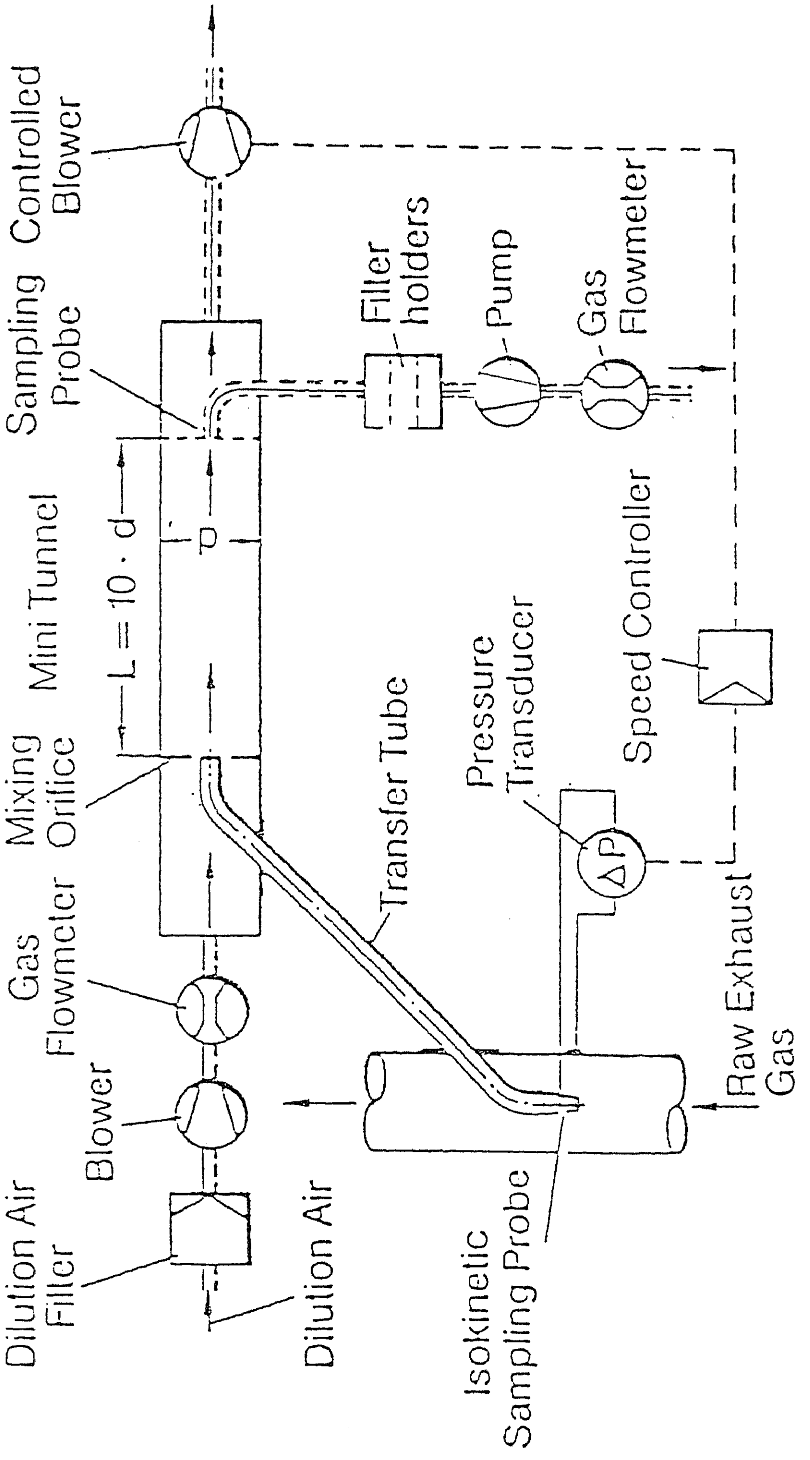
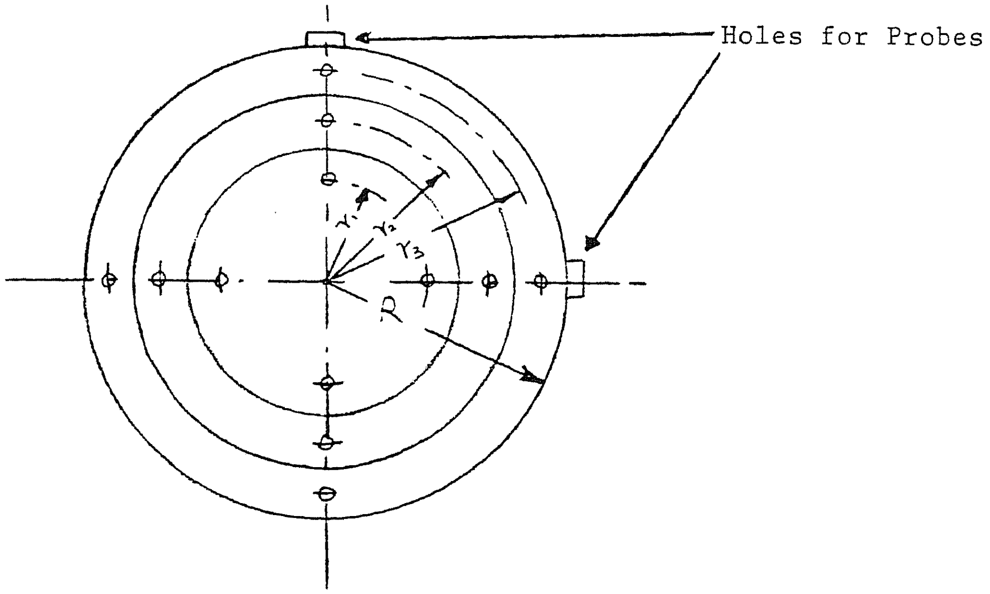
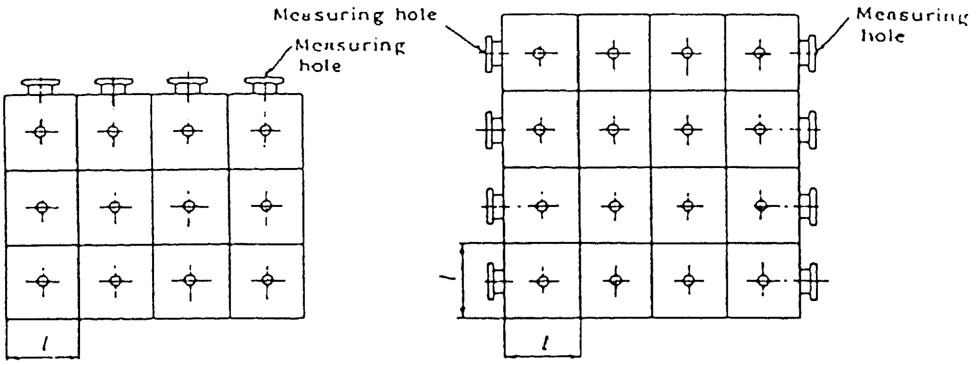


Figure A.7.5 Multiple Point Particulate Sampling - for circular ducts above 0.5m^2 and for ducts with uneven particulate distribution



Duct Diameter (m)	Annular Divisions	No. of Measuring Points	Distance of Measuring Point from Centre of Duct (m)				
<1	1	4	0.707R	-	-	-	-
1-2	2	8	0.500R	0.866R	-	-	-
2-4	3	12	0.408R	0.707R	0.913R	-	-
4-4.5	4	16	0.354R	0.612R	0.791R	0.935R	-
>4.5	5	20	0.316R	0.548R	0.707R	0.837R	0.949R

Figure A.7.6 Multiple Point Particulate Sampling - for non circular ducts



Rectangular Section Square section

Duct Area (m^2)	Length of Division ℓ (m)
<1	$\ell < 0.5$
1-4	$\ell < 0.67$
4-20	$\ell < 1.0$

APPENDIX 8

Corrections

A.8.1 RECIPROCATING ENGINES

A.8.1.1 Introduction

Since engine data are dependent on ambient conditions which are not related to the engine tuning, they shall be corrected to standard reference conditions. This shall be done to avoid taking into account engine independent factors which may influence the measuring results. The type of fuel also used has an influence on emissions, and thus cannot be simply neglected. Specific legislation may however call for limits to be met at the actual conditions and fuel without allowing such corrections.

A.8.1.2 Corrections

These corrections mean transformation of measured engine emissions to standard reference sample conditions, to standard reference ambient atmospheric conditions (temperature, humidity, pressure) and to reference conditions of fuel.

For every correction, only the emissions concerned have to be corrected, since not all the emissions will be influenced in the same manner by a certain variation of ambient conditions.

A.8.1.3 Corrections for sample conditions

If the emissions are to be expressed on concentrations or in volume fractions, they should be given on a dry base and corrected to a standard reference oxygen content. 5%, 13% 15% are typical values used in some regulations.

A.8.1.4 Corrections for ambient conditions

The emissions depend on the temperature and the humidity of the air supplied to the cylinder. The influence of the barometric pressure for turbocharged and charge cooled engines is much less and can thus be neglected. For naturally aspirated engines, this influence may be bigger. The proposed formulae are preferred, but if an engine manufacturer has his own substantiated formula, the use of this correction shall be allowed if its use is declared.

For charge air cooled engines, an additional reference condition for the scavenge air temperature has to be defined. The reference scavenge air temperature should be the temperature obtained when using the engine manufacturers standard charge air cooler and a coolant inlet temperature as defined by ISO.

The following table lists the corrections to be made.

Corrections for Temperature	
naturally aspirated engines:	ambient temperature
turbocharged engines:	ambient temperature scavenge air temperature ie. temperature after charge air cooler
Correction for Humidity	
naturally aspirated engines:	ambient humidity
turbocharged engines:	ambient humidity, but if a water separator device is present, only the humidity before the cylinder should be considered.
Correction for Barometric Pressure	
naturally aspirated engines:	as per maximum pressure
turbocharged engines:	none

(a) Correction of the NOx emission for humidity and temperature

A recommended formula for NOx is as follows:

$$NOx_{corr} = NOx_{meas} \frac{1}{1 + a*(H-10.34) + b*(T_{A}-25) + c*(T_{aCaC}-25)}$$

The proposed coefficients are:

$a = -0.0120$
$b = -0.00275$
$c = 0.00285$

When no charge air cooler is fitted the factor 'c' shall become zero ($C = 0.0$) and b shall become 0.00285 ($b = 0.00285$).

The coefficients in this formula have been derived from results from two and four stroke diesel engines above about 350 mm bore and fitted with charge air coolers. They have not been found to be suitable for all engines, particularly smaller engines.

Other substantiated coefficients may be used if enough data are presented by the engine manufacturer and if the use is declared.

Origin of the numbers in the formula:

10.34 = absolute humidity g/kg mass i.e. 60%
25 = ref. temp. °C
H = abs humidity (g/kg dry air)
T = temperature (deg C)

Indices of the formula:

corr = corrected
meas = measured
A = ambient
aCaC = after charge air cooler

(b) Other emissions

The other emissions such as CO, and HC may be corrected by the engine manufacturers formula if enough data are available to substantiate the formula.

A.8.1.5 Corrections for fuel characteristics

Fuel characteristics such as sulphur content, nitrogen content, CCR and others, influence the emissions of an engine. A correction for the influence of the fuel characteristics should thus be foreseen, in order to avoid relating these influences to the engine tuning. This is generally accepted for the sulphur content, but should also be extended to other fuel components as far as these influences can be certified (e.g. increase of NOx due to fuel bound nitrogen, increase of particles due to ash and CCR).

(a) Fuel bound nitrogen

engine efficiency	conversion rate (of fuel bound nitrogen to NOx)
less than 30%	0.0%
30% to 40%	linear from 0% to 100% as a function of engine efficiency.
more than 40%	100.0%

Note: Engine efficiency is the brake thermal efficiency.

(b) Other characteristics

Other characteristics such as ash content and CCR may be corrected by the engine manufacturers formula if enough data are available to substantiate the formulae.

A.8.2 GAS TURBINES

Emissions regulations have been formulated with different objectives. Some are concerned about the concentration of a pollutant in the exhaust, some about the total mass emitted in a given time and others about the mass emitted for a given fuel consumption or power output.

Although legislative limits for emissions vary widely from one Country to another, there are two main types of regulations.

A.8.2.1. The first type specifies that the emission levels must be lower than the regulation values whatever the test conditions of ambient temperature, pressure and humidity.

In this case the only corrections that may be called for are those referred to in Appendix 9 for the reduction of data to reference conditions of exhaust oxygen content, and to the 'dry' condition (i.e. the concentrations which would exist in the exhaust if the water were removed).

Since it is assumed that sulphur in the fuel is burnt completely to sulphur dioxide, regulations often allow the sulphur dioxide to be calculated from the fuel content.

A.8.2.2 The second type of regulation states that the emission levels must be lower than the regulation value when measured at specified ambient conditions - usually ISO.

This is the usual type for oxides of nitrogen because their formation during combustion is so dependent on the temperature, pressure and water content of the air.

The regulation refer to NOx on a 'dry' basis and at a specified oxygen content in the exhaust. It then instructs that the values be corrected from the test conditions to the specified ambient conditions by a formula such as the one used by the EPA: [5]

$$NOx_r = NOx_m * \left[\frac{288}{Tm}\right]^{1.53} * \left[\frac{101.3}{Pm}\right]^{0.5} * e^{(19[H-0.00633])}$$

where: NOx_r = NOx at specified ambient conditions
NOx_m = NOx at test conditions
T_m = Ambient temperature at test conditions in Kelvin
P_m = Ambient pressure at test conditions in kilopascals
H_m = Specific humidity of the air at test conditions in mass of water per unit mass of air.

Gas turbine manufacturers may disagree with the applicability of this formula to their engines, and an alternative relationship is usually acceptable to the regulatory authority if evidence can be shown of tests which have been carried out to establish their own formula.

The formula may be of the same form or different from the one above.

Some manufacturers have preferred relationships including

$$\left[\frac{T_r}{T_m}\right]^a \text{ and } \left[\frac{P_r}{P_m}\right]^b$$

where these are at combustor inlet conditions instead of ambient values. This involves establishing values for T_r and P_r at the specified ambient conditions as well as obtaining the values for the exponents a and b.

Emissions regulations sometimes allow two other corrections to be made.

The first is for fuel-bound nitrogen in liquid fuels which contributes to the NOx emissions. A typical allowance (EPA) [5] is given in the following table:

Fuel-bound Nitrogen percent by mass	Allowance vol. ppm of NOx
N<0.015	0
0.015<N<0.1	400*N
0.1<N<0.25	40+67*(N-0.1)
N>0.25	50

This value is subtracted from the corrected value, NOx_r, obtained from the earlier formula, expressed in vppm units.

These regulations do not make allowance so far for similar corrections to be made for ammonia in gaseous fuels.

The second correction gives an allowance of NOx which rewards gas turbines which have a higher thermal efficiency than a datum value - typically 30%.

Recommendations

CIMAC recommends that in the absence of any particular regulation, results are reported in vppm or milligrams per normal cubic meter on a 'dry' basis and corrected to 15% oxygen. Ambient conditions should also be reported to enable results to be compared with values which have been corrected by some formula.

APPENDIX 9

Calculations, Conversions, Units and Methods of Deriving Air Flow

CONTENT:

A.9.1 INTRODUCTION

In the following sections procedures for emission calculations are provided.

The extent of the calculations depends on the kind of measurements made and on the way of expressing the pollution.

The main points are:

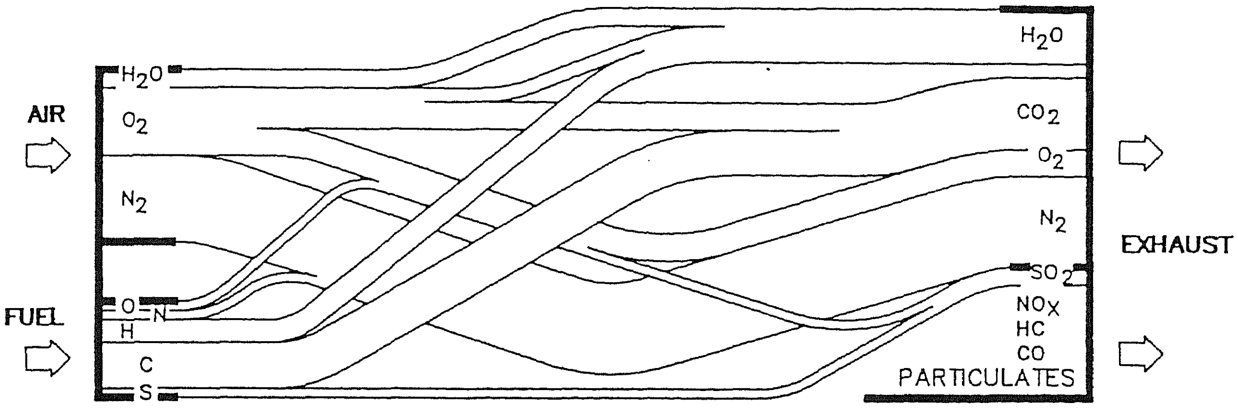
(a) whether the pollution has been measured in wet, dry or eventually in partly dried exhaust gas (volume fraction or concentration) and

(b) whether the results have to be given (in any unit) with respect to dry exhaust or wet.

Cross checking of calculation and measurements, if possible, is recommended.

Before doing these calculations, as on the following pages, corrections for cross sensitivity should also be carried out.

A9.1 INDRODUCTION - cont.



From (measured or calc.)	To (calculated)	Needed for calculation
ppm in dry exh.gas	ppm in dry exh. gas without % O_2 correction	no calculation
	ppm in dry exh. gas with n % O_2 correction	n % O_2 in dry exh.gas
ppm in wet exh. gas	ppm in dry exh. gas	% H_2O in exh. gas : - H_2O in inlet air: - rel.humidity (1) - air flow (2) - H_2O added - H_2O subtracted - H_2O formed by combustion : - % H in fuel (3) - fuel flow
ppm	g/Nm^3	density of pollutant
g/Nm^3	g/kg fuel	exhaust composition air flow (2) fuel flow fuel composition (3)
	or g/GJ	iden+fuel heat value
g/kg fuel	g/h	fuel flow
g/h	g/kW.h or g/BHP.h	engine output

( ) see notes below

Notes:

(1) Water in air: see A9.3.3

Alternatively Graph "water content" can be used - see Figure A9.1.

(2) Inlet air flow

The direct method of air flow measurement is often not practical.

In case of turbocharged DE, deduction from turbine or compressor can be tolerated.

Deductions by calculations from measured O_2 and CO_2 in exhaust are allowed - in this case the two results should not deviate more than 15% and the mean value should be taken.

(3) Fuel composition

In case of liquid fuel % C and % H can be measured in a laboratory. For rapid calculation (before analyses are known) the following can be taken - C:H (weight) = 6.7 for diesel oil and 8.2 for heavy fuel.

Water in the fuel must be treated as water injected with the air.

The calculations shall be based on a dry fuel basis.

A9.2 SYMBOLS AND UNITS

Symbols	Description	Units
c_i	concentration of the component (i)	mg/m^3
$c_{i,n\%O2,dry}$	concentration of the emittent (i), corrected to φ O2 = n%,dry. n : according to regulations	mg/m^3
m_i	mass of component (i) or element (i)	kg
$\dot{m}_i$	mass flow of emittent (i)	kg/h
$\dot{m}_{E(j)}$	exhaust gas mass flow j = dry,wet	kg/s
$\dot{m}_{fuel}$	fuel mass flow	kg/s
$\dot{m}_{H2O(inj)}$	mass flow of injected steam or water	kg/s
$\dot{m}_{H2O(rem)}$	mass flow of removed water	kg/s
n	O_2 reference number	%
$p_{ambient}$	barometric pressure	bar
$p_{H2O(s)}$	H_2O - partial pressure of saturated air at the measured ambient temperature	bar
ϕ_r	relative humidity	%
w_i	mass fraction of the component (i)	mg/kg kg/kg
BHP	brake horse power	
EB_i	mass of the emittent (i) per brake horse power and hour	g/BHPh
EH_i	mass of the emittent (i) per heat input	g/GJ
EM_i	mass of the emittent (i) per kg fuel	g/kg fuel
EP_i	mass of the emittent (i) per work output	g/kWh
H_{obs}	humidity of ambient air	kg H_2O / kg dry air
H_o	higher (gross) heating value	kJ/kg fuel
H_u	lower (net) heating value	kJ/kg fuel

A 9.2 SYMBOLS AND UNITS - cont.

Symbols	Description	Units
M_E	molecular mass of the exhaust gas	kg/kmol
M_i	molecular mass of the component (i)	kg/kmol
P	power output	kW
$V_{E(j)}$	exhaust gas volume per kg fuel j = dry , wet	m^3/kg fuel
$V_{H2O(air)}$	volume of water vapour,originated from air intake volume per kg fuel	m^3/kg fuel
$V_{H2O(inj)}$	volume of injected steam or water per kg fuel	m^3/kg fuel
$V_{H2O(rem)}$	volume of water vapour removed from air intake volume per kg fuel	m^3/kg fuel
$V_{v(E)(j)}$	exhaust gas volume at stoichiometric combustion of 1 kg fuel j = dry,wet	m^3/kg fuel
$V_{v(i)}$	volume of the component (i) at stoichiometric combustion of 1 kg fuel	m^3/kg fuel
V_m	molecular volume	m^3/kmol
T	temperature	°K
λ_i	excess air number i = O_2 : calculated from measured O2-content in the exhaust gas = CO_2: calculated from measured CO2-content in the exhaust gas = M : calculated from engine data	----
ρ_i	density of the gas component (i)	kg/m^3
φ_i	volume fraction of the gas component(i)	cm^3/m^3 (ppm) m^3/m^3
$\varphi_{i,n\%02,dry}$	volume fraction of the gas component(i) corrected to φ02 = n% n : according to regulations	cm^3/m^3 (ppm)
ω	steam or water to fuel ratio	kg/kg fuel

A.9.3 CALCULATION PROCEDURE

9.3.1 Remarks

Units are represented in brackets [ ].

Volume numbers of gaseous components are referred to standard conditions 273.15 K, 1.01325×10^5 Pa. Exceptions are particularly noted.

For applications in the field of emission calculations, the behaviour of gases is considered strictly as "ideal". Therefore the gas constant per mol (R) and furthermore the derived molecular volume (V) are independent of the specific gas component.

In accordance with ISO 2533 [21], the volume fraction of oxygen in dry ambient air is committed to 20.95%.

Steam or water injection rates are taken into account in the calculation procedure for cases of "wet" NOx control as well as water removal from compressed air.

If no water injection or removal occurs $V_{H2O(inj)}$ and $V_{H2O(rem)}$ are set to zero.

In order to calculate the combustion products at stoichiometric conditions from fuel gas, two different procedures are provided:

- a direct method by using eq. 10.2.1 - 10.2.9
- a conversion of volume- or mole-fraction of the fuel gas components to mass fraction and a further conversion to element composition by using eq. 10.3 to 10.4.6. These fuel data can then be employed in eq. 10.1.1 - 10.1.8. [26].

Assumptions are made that sulphur is burned to sulphur dioxide and the fuel-bound nitrogen reacts to nitric oxide, NO.

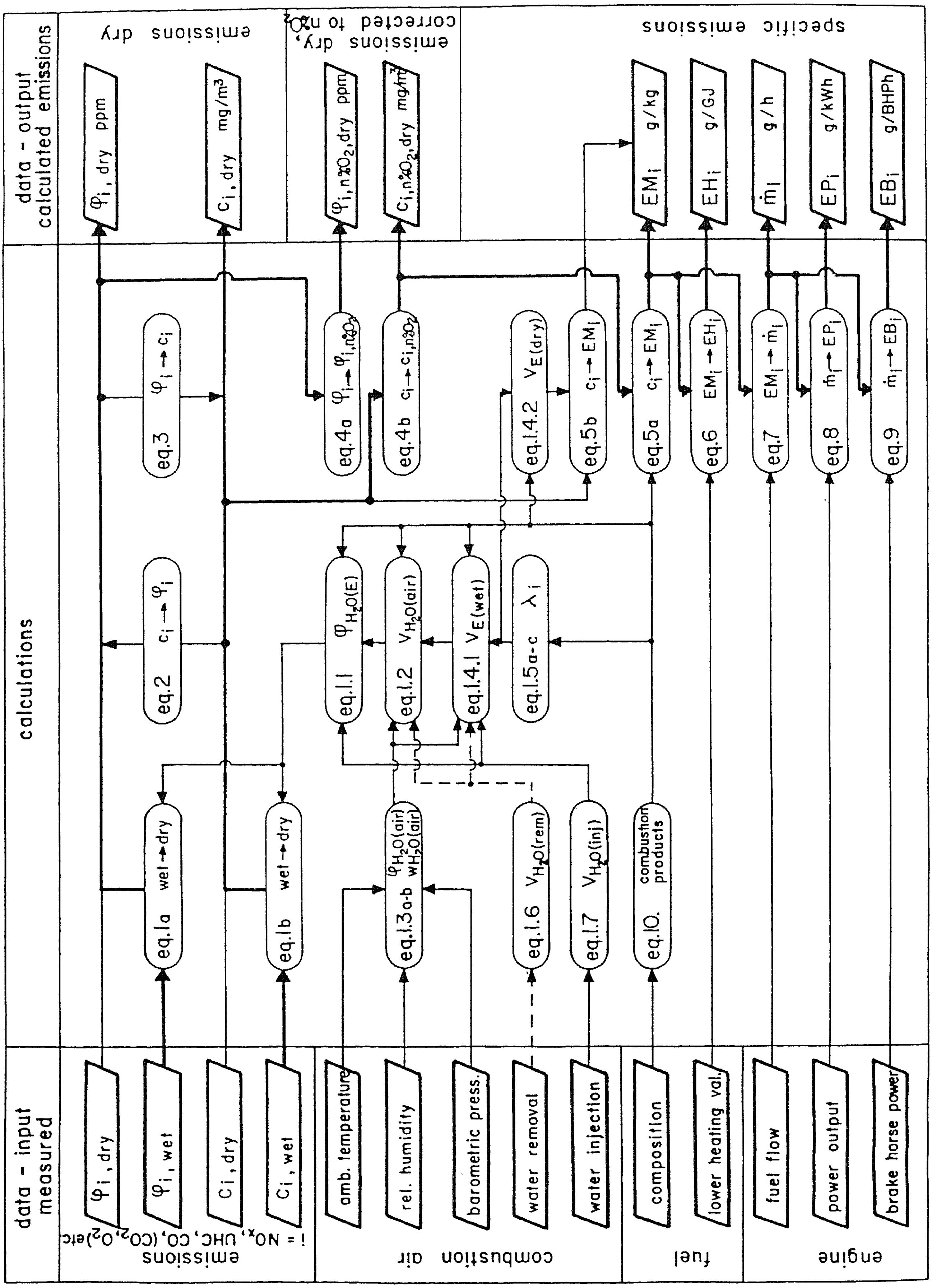
Furthermore, complete combustion is assumed in the calculations. If products of incomplete combustion, such as CO or UHC are present in the flue gas at higher concentrations, a correction of oxygen, carbon dioxide and the exhaust gas volume may be necessary in some equations.

For certain applications it may be necessary to use other emission or engine data than shown in Section App.9.3.2, such as:

- molecular mass of the exhaust gas
- Oxygen and carbon dioxide calculated from the excess air ratio
- SOx and NOx originating from the fuel composition
- intake air mass flow
- exhaust gas mass flow

Corresponding formulae are given in Section App.9.3.5.

A 9.3.2 Flow chart for emission calculations



A9.3.3 Calculation formulae

eq.1.a $$\boxed{\varphi_{i,dry} = \frac{\varphi_{i,wet}}{1 - \varphi_{H2O(E)}}}$$

eq.1.b $$\boxed{c_{i,dry} = \frac{c_{i,wet}}{1 - \varphi_{H2O(E)}}}$$

eq.1.1 $$\varphi_{H2O(E)} = \frac{V_{v(H2O)} + V_{H2O(air)} + V_{H2O(inj)}}{V_{E(wet)}}$$

eq.1.2 $$V_{H2O(air)} = \frac{\lambda_i * V_{v(air)}}{1 - \varphi_{H2O(air)}} * \varphi_{H2O(air)} - V_{H2O(rem)}$$

eq.1.3.a $$\varphi_{H2O(air)} = \frac{p_{H2O(s)} * \phi_r * 10^{-2}}{p_{ambient}}$$

eq.1.3.a.1 $$p_{H2O(s)} = \frac{1.013}{760} * 10^{x}$$

$$x = \left(\frac{-A}{T} + B - C * \log T - D * T + E * T^2 - F * T^3 + G * T^4 \right)$$

$A = 2892.3693$ $D = 4.9369728 * 10^{-3}$ $G = 3.7874 * 10^{-12}$

$B = 19.3011421$ $E = 5.606905 * 10^{-6}$ $T = T_{ambient}$ $[T] = {}^\circ K$

$C = 2.892736$ $F = 4.645869 * 10^{-9}$

A 9.3.3 Calculation formulae - cont.

eq.1.3.b
$$w_{H2O(air)} = \varphi_{H2O(air)} * \frac{\rho_{H2O}}{\rho_{air(wet)}} = \frac{0.80376 * \varphi_{H2O(air)}}{1.2923 - 0.4885 * \varphi_{H2O(air)}}$$

eq.1.3.c
$$H_{obs} = \frac{w_{H2O(air)}}{1 - w_{H2O(air)}}$$

eq.1.4.1
$$V_{E(wet)} = \frac{\lambda_i * V_{v(air)}}{1 - \varphi_{H2O(air)}} + V_{v(E)(wet)} - V_{v(air)} + V_{H2O(inj)} - V_{H2O(rem)}$$

eq.1.4.2
$$V_{E(dry)} = \lambda_i * V_{v(air)} + V_{v(E)(dry)} - V_{v(air)}$$

eq.1.5.a
$$\lambda_{O2} = \frac{\varphi_{O2(dry)} * V_{v(E)(dry)}}{V_{v(air)} * (0.2095 - \varphi_{O2(dry)})} + 1$$

eq.1.5.b
$$\lambda_{CO2} = \frac{V_{v(CO2)} + 0.00033 * V_{v(air)} - \varphi_{CO2(dry)} * V_{v(E)(dry)}}{V_{v(air)} * (\varphi_{CO2(dry)} - 0.00033)} + 1$$

eq.1.5.c
$$\lambda_M = \frac{\dot{m}_{air} * (1 - w_{H2O(air)})}{V_{v(air)} * 1.2923 * \dot{m}_{fuel}}$$

eq.1.6
$$V_{H2O(rem)} = \frac{\dot{m}_{H2O(rem)} * 1.244}{\dot{m}_{fuel}}$$

eq.1.7
$$V_{H2O(inj)} = \frac{\dot{m}_{H2O(inj)} * 1.244}{\dot{m}_{fuel}} = \omega_{(inj)} * 1.244$$

A9.3.3 Calculation formulae - cont.

eq.2

$$\boxed{\varphi_{i,dry} = \frac{c_{i,dry}}{\rho_i}}$$

$_i$ see table 1

eq.3

$$\boxed{c_{i,dry} = \varphi_{i,dry} * \rho_i}$$

$_i$ see table 1

eq.4.a

$$\boxed{\varphi_{i,n\%O2,dry} = \varphi_{i,dry} * \frac{20.95 - n}{20.95 - \varphi_{O2,dry}}}$$

$[O2] = \%$

eq.4.b

$$\boxed{c_{i,n\%O2,dry} = c_{i,dry} * \frac{20.95 - n}{20.95 - \varphi_{O2,dry}}}$$

$[O2] = \%$

eq.5.a

$$\boxed{EM_i = c_{i,n\%O2,dry} * \frac{20.95 * V_{v(E)(dry)}}{20.95 - n} * 10^{-3}}$$

$[n] = \%$

eq.5.b

$$\boxed{EM_i = c_{i,dry} * V_{E(dry)} * 10^{-3}}$$

eq.6

$$\boxed{EH_i = \frac{EM_i}{H_{o(u)}} * 10^6}$$

A9.3.3 Calculation formulae - cont.

eq.7 $$\boxed{\dot{m}_i = EM_i * \dot{m}_{fuel} * 3.6}$$

eq.8 $$\boxed{EP_i = \frac{\dot{m}_i * 10^3}{P}}$$

eq.9 $$\boxed{EB_i = \frac{\dot{m}_i * 10^3}{BHP}}$$

A9.3.4 Calculation of fuel data and combustion products

A9.3.4.1 FUEL OIL

Reactions

$$C + O_2 \quad \text{---->} \quad CO_2$$

$$H + 0,25\ O_2 \quad \text{---->} \quad 0,5\ H_2O$$

$$S + O_2 \quad \text{---->} \quad SO_2$$

$$N + 0,5\ O_2 \quad \text{---->} \quad NO$$

Combustion at stoichiometric conditions

O_2-consumption $V_{v(O2)}$ $[V_{v(O2)}] = m^3/kg$ fuel

eq.10.1.1 $$V_{v(O2)} = w_C * 1.8661 + w_H * 5.5594 + w_S * 0.6990 + \\ + w_N * 0.8001 - w_O * 0.7005$$

A9.3.4 Calculation of fuel data and combustion products - cont.

air-volume $V_{v(air)}$ $\quad [V_{v(air)}] = m^3/kg$ fuel

eq.10.1.2 $$V_{v(air)} = \frac{V_{v(O2)}}{\varphi_{O2(air)}} = \frac{V_{v(O2)}}{0{,}2095}$$

CO_2-volume $V_{v(CO2)}$ $\quad [V_{v(CO2)}] = m^3/kg$ fuel

eq.10.1.3 $$V_{v(CO2)} = w_C * 1.8661$$

H_2O-volume $V_{v(H2O)}$ $\quad [V_{v(H2O)}] = m^3/kg$ fuel

eq.10.1.4 $$V_{v(H2O)} = w_H * 11.1187$$

SO_2-volume $V_{v(SO2)}$ $\quad [V_{v(SO2)}] = m^3/kg$ fuel

eq.10.1.5 $$V_{v(SO2)} = w_S * 0.6990$$

NO-volume $V_{v(NO)}$ $\quad [V_{v(NO)}] = m^3/kg$ fuel

eq.10.1.6 $$V_{v(NO)} = w_N * 1.6002$$

exhaust gas volume $V_{v(E)(wet,dry)}$ $\quad [V_{v(E)}] = m^3/kg$ fuel

eq.10.1.7 $$V_{v(E)(wet)}=V_{v(air)}-V_{v(O2)}+V_{v(CO2)}+V_{v(H2O)}+V_{v(SO2)}+V_{v(NO)}$$

eq.10.1.8 $$V_{v(E)(dry)}=V_{v(air)}-V_{v(O2)}+V_{v(CO2)}+V_{v(SO2)}+V_{v(NO)}$$

A9.3.4.2 FUEL GAS

Reactions

$H_2 + 0.5\ O_2 \longrightarrow H_2O$

$H_2S + 1.5\ O_2 \longrightarrow H_2O + SO_2$

$CO + 0.5\ O_2 \longrightarrow CO_2$

* $CH_4 + 2\ O_2 \longrightarrow CO_2 + 2\ H_2O$

* $C_2H_6 + 3.5\ O_2 \longrightarrow 2\ CO_2 + 3\ H_2O$

* $C_3H_8 + 5\ O_2 \longrightarrow 3\ CO_2 + 4\ H_2O$

* generally: $C_xH_y + (x + \frac{y}{4})\ O_2 \longrightarrow x\ CO_2 + \frac{y}{2}\ H_2O$

N_2 and nobel gases (He,Ar,Ne) are considered as "inert"

A9.3.4 Calculation of fuel data and combustion products - cont.

Combustion at stoichiometric conditions

O$_2$-Consumption $V_{v(O2)}$ $[V_{v(O2)}] = m^3/kg$ fuel

eq.10.2.1 $$V_{v(O2)} = \frac{\Sigma\{\varphi_{CxHy}*(x + \frac{y}{4})\} + \varphi_{H2}*0.5 + \varphi_{CO}*0.5 + \varphi_{H2S}*1.5}{\rho_{fuel}}$$

air-volume $V_{v(air)}$ $[V_{v(air)}] = m^3/kg$ fuel

eq.10.2.2 $$V_{v(air)} = \frac{V_{v(O2)}}{\varphi_{O2(air)}} = \frac{V_{v(O2)}}{0.2095}$$

CO$_2$-volume $V_{v(CO2)}$ $[V_{v(CO2)}] = m^3/kg$ fuel

eq.10.2.3 $$V_{v(CO2)} = \frac{\Sigma(\varphi_{CxHy} * x) + \varphi_{CO} + \varphi_{CO2}}{\rho_{fuel}}$$

H$_2$O-volume $V_{v(H2O)}$ $[V_{v(H2O)}] = m^3/kg$ fuel

eq.10.2.4 $$V_{v(H2O)} = \frac{\Sigma(\varphi_{CxHy} * \frac{y}{2}) + \varphi_{H2} + \varphi_{H2S}}{\rho_{fuel}}$$

SO$_2$-volume $V_{v(SO2)}$ $[V_{v(SO2)}] = m^3/kg$ fuel

eq.10.2.5 $$V_{v(SO2)} = \frac{\varphi_{H2S}}{\rho_{fuel}}$$

Inert-volume $V_{v(inert)}$ $[V_{v(inert)}] = m^3/kg$ fuel

eq.10.2.6 $$V_{v(inert)} = \frac{\varphi_{He} + \varphi_{N2}}{\rho_{fuel}}$$

exhaust gas volume $V_{v(E)(wet,dry)}$ $[V_{v(E)}] = m^3/kg$ fuel

eq.10.2.7 $$V_{v(E)(wet)} = V_{v(air)} - V_{v(O2)} + V_{v(CO2)} + V_{v(H2O)} + V_{v(SO2)} + V_{v(inert)}$$

A9.3.4 Calculation of fuel data and combustion products - cont.

eq.10.2.8 $V_{v(E)(dry)} = V_{v(air)} - V_{v(O2)} + V_{v(CO2)} + V_{v(SO2)} + V_{v(inert)}$

Density of fuel $[\varrho_{fuel}] = \frac{kg}{m^3}$ (at 273 K/1.013 bar)

eq.10.2.9 $\varrho_{fuel} = \Sigma\, \varphi_i * \varrho_i = \Sigma\, \varphi_i * \frac{M_i}{22.414}$

i = fuel component

A9.3.4.3 Conversion of fuel gas components from volume fraction i to mass fraction w_i

$[w_i]$ = kg/kg fuel

eq.10.3 $w_i = \frac{\varphi_i * M_i}{\Sigma\, \varphi_i * M_i}$

A9.3.4.4 Conversion of massfraction of fuel gas components into mass fraction of elements

$[w_i]$ = kg/kg fuel

eq.10.4.1 $w_i = \frac{m_i}{\Sigma m_i}$ i = H , C , S , O , inert

eq.10.4.2 $m_{H(rel)} = \{\Sigma(w_{CxHy} * y) + w_{H2S} * 2 + w_{H2} * 2\} * 1.008$

eq.10.4.3 $m_{C(rel)} = \{\Sigma(w_{CxHy} * x) + w_{CO2} + w_{CO}\} * 12.011$

eq.10.4.4 $m_{S(rel)} = w_{H2S} * 32.066$

eq.10.4.5 $m_{O(rel)} = w_{CO2} * 2 + w_{CO}) * 15.999$

eq.10.4.6 $m_{inert(rel)} = w_{N2} * 28.013 + w_{He} * 4.003$

A9.3.5 Formulas for specific applications

A9.3.5.1 Molecular mass of the exhaust gas M_E $[M_E] = \text{kg/kmol}$

eq.11 $$M_E = (\Sigma \varphi_i * \rho_i) * 22.414$$

A9.3.5.2 O_2 volume fraction in the dry exhaust gas φ_{O2} $[\varphi_{O2}] = m^3/m^3$

eq.12 $$\varphi_{O2,dry} = \frac{(\lambda - 1) * 0.2095 * V_{v(air)}}{(\lambda - 1) * V_{v(air)} + V_{v(E)(dry)}}$$

A9.3.5.3 CO2 volume fraction in the dry exhaust gas φ_{CO2} $[\varphi_{CO2}] = m^3/m^3$

eq.13 $$\varphi_{CO2,dry} = \frac{\lambda * V_{v(air)} * 0.00033 + V_{v(CO2)}}{(\lambda - 1) * V_{v(air)} + V_{v(E)(dry)}}$$

A9.3.5.4 SO_2 volume fraction in the dry exhaust gas φ_{SO2} $[\varphi_{SO2}] = m^3/m^3$

eq.14.a $$\varphi_{SO2,dry} = \frac{w_S * 0.699 * 10^6}{V_{E(dry)}}$$

eq.14.b $$\varphi_{SO2,dry} = \frac{V_{v(SO2)}}{V_{E(dry)}} * 10^6$$

A9.3.5.5 NO volume fraction in the dry exhaust gas, originating from fuel-bound Nitrogen φ_{NO} $[\varphi_{NO}] = m3/m3$

eq.15.a $$\varphi_{NO,dry} = \frac{w_N * 1.60 * 10^6}{V_{E(dry)}}$$

eq.15.b $$\varphi_{NO,dry} = \frac{V_{v(NO)}}{V_{E(dry)}} * 10^6$$

A9.3.5.6 Air intake mass flow $\dot{m}_{air}$

$[\dot{m}_{air}] = kg/s$

eq.16

$$\dot{m}_{air} = \frac{\lambda * V_{v(air)} * 1.2923 * \dot{m}_{fuel}}{1 - w_{H2O(air)}}$$

A9.3.5.7 Exhaust gas mass flow (wet) $\dot{m}_{E(wet)}$

$[\dot{m}_{E(wet)}] = kg/s$

eq.17.a

$$\dot{m}_{E(wet)} = \dot{m}_{air} + \dot{m}_{fuel} + \dot{m}_{H2O(inj)} - \dot{m}_{H2O(rem)}$$

eq.17.b

$$\dot{m}_{E(wet)} = \frac{V_{E(wet)} * M_E * \dot{m}_{fuel}}{22.414}$$

Physical properties of gas components

references: 1) DIN 1871 2) DIN 51850

TABLE A 9.1

component	formulae	molecular mass 1) M kg/kmol	molecular gas volume 1) V_m $m^3/kmol$	gas density ideal $V_m=22.414$ kg/m^3	gas density real 1) kg/m^3	gas density relative to air 1) kg/m^3	real gas factor 1) Z_n	heating value gross 2) Ho kJ/kg	heating value net 2) Hu kJ/kg
Air dry		28.963	22.400	1.2922	1.2930	1.0000	0.99940		
Carbon	C	12.011						32780	32780
Carbon monoxide	CO	28.010	22.400	1.2497	1.2505	0.9671	0.99938	10103	10103
Carbon dioxide	CO2	44.010	22.261	1.9635	1.9770	1.5290	0.99318		
Carbon oxysulfide	COS	60.07	22.08	2.6800	2.721	2.104	0.9849	9093	9093
Methane	CH4	16.043	22.360	0.71576	0.7175	0.5549	0.99756	55498	50013
Ethane	C2H6	30.069	22.191	1.3415	1.3550	1.048	0.99006	51877	47486
Propane	C3H8	44.096	21.928	1.9673	2.011	1.555	0.9783	50345	46354
Iso-Butane	C4H10	58.123	21.550	2.5932	2.697	2.086	0.9615	49356	45571
n-Butane	C4H10	58.123	21.461	2.5932	2.708	2.094	0.9575	49500	45715
Iso-Pentane	C5H12	72.150	(21.06)	3.2190	(3.426)	(2.650)	0.9395	48900	45240
Neo-Pentane	C5H12	72.150	(21.13)	3.2190	(3.415)	(2.641)	0.9428	48740	45081
n-Pentane	C5H12	72.150	(20.90)	3.2190	(3.452)	(2.670)	0.9325	49011	45352
Benzene	C6H6	78.113	(20.9)	3.4850	(3.74)	(2.89)	0.932	42266	40576
n-Hexane	C6H14	86.177	(20.10)	3.8448	(4.29)	(3.315)	0.8968	48678	45104
Toluene	C7H8	92.140	(18.9)	4.1108	(4.88)	(3.77)	0.843	42847	40937
n-Heptane	C7H16	100.203	(18.3)	4.4706	(5.48)	(4.235)	0.8165	48437	44924
n-Octane	C8H18	114.230	(17.0)	5.0964	(6.72)	(5.20)	0.758	48251	44784
Hydrogen	H	1.008							
	H2	2.016	22.428	0.08994	0.08988	0.0695	1.00062	141800	119972
Water	H2O	18.015	(21.1)	0.80374	(0.854)	(0.660)	0.941		
Helium	He	4.003	22.426	0.17859	0.17848	0.1380	1.00054		
Nitrogen	N	14.007							
	N2	28.013	22.403	1.2498	1.2504	0.9671	0.99954		
Ammonia	NH3	17.030	22.065	0.75979	0.7718	0.5969	0.98443	22254	18379
Nitrogen oxide	NO	30.006	22.390	1.3387	1.3402	1.0365	0.99894		
Nitrogen dioxide	NO2	46.006		2.0525					
Oxygen	O	15.999							
	O2	31.999	22.392	1.4276	1.4290	1.1052	0.99903		
Sulfur	S	32.066						9265	9270
Sulfur dioxide	SO2	64.059	21.856	2.8580	2.9310	2.267	0.97511		
Sulfur trioxide	SO3	80.064		3.5721					

Table A 9.2 Partial pressure of water vapour for temperature range -15 °C to +45 °C.

temperature range -15 °C to 0 °C : vapour pressure of ice
temperature range 0 °C to 45 °C : vapour pressure over water

reference : Handbook of Chemistry and Physics

$[p_{H2O}]$ = mbar

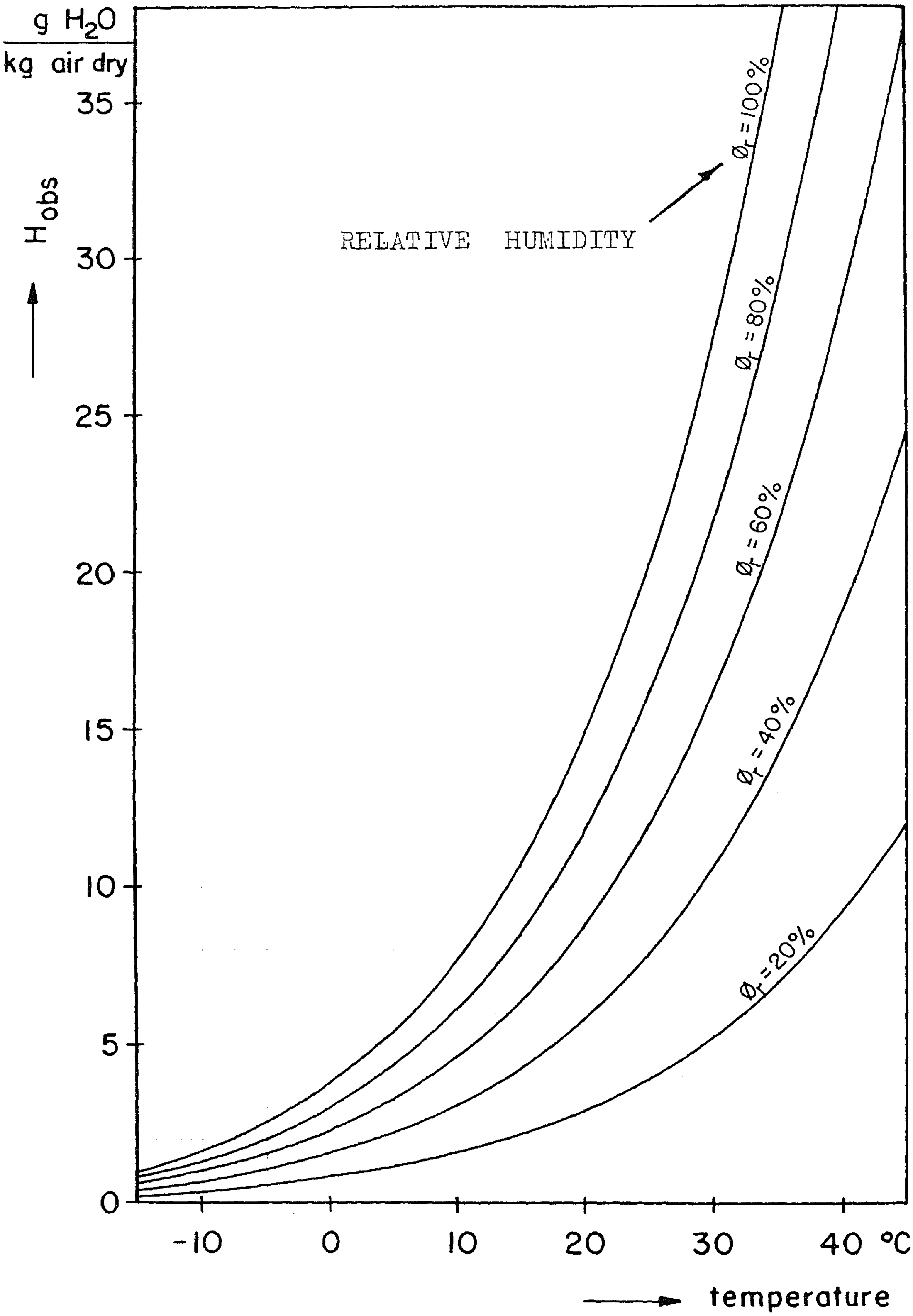
Temp. °C	0.0	0.2	0.4	0.6	0.8
-15	1.66	1.63	1.60	1.57	1.54
-14	1.82	1.78	1.75	1.72	1.69
-13	1.99	1.95	1.92	1.88	1.85
-12	2.18	2.14	2.10	2.06	2.02
-11	2.38	2.34	2.30	2.25	2.21
-10	2.60	2.55	2.51	2.47	2.42
- 9	2.84	2.79	2.74	2.69	2.65
- 8	3.10	3.05	2.99	2.94	2.89
- 7	3.38	3.32	3.27	3.21	3.16
- 6	3.69	3.62	3.56	3.50	3.44
- 5	4.02	3.95	3.88	3.82	3.75
- 4	4.37	4.30	4.23	4.16	4.09
- 3	4.76	4.68	4.60	4.52	4.45
- 2	5.17	5.09	5.00	4.92	4.84
- 1	5.62	5.53	5.44	5.35	5.26
- 0	6.11	6.01	5.91	5.81	5.72
0	6.11	6.20	6.29	6.38	6.47
1	6.57	6.66	6.76	6.86	6.96
2	7.06	7.16	7.26	7.37	7.47
3	7.58	7.69	7.80	7.91	8.02
4	8.13	8.25	8.37	8.48	8.60
5	8.72	8.85	8.97	9.10	9.22
6	9.35	9.48	9.61	9.75	9.88
7	10.02	10.16	10.30	10.43	10.58
8	10.73	10.87	11.02	11.17	11.32
9	11.48	11.64	11.79	11.95	12.11
10	12.28	12.44	12.61	12.78	12.95
11	13.12	13.30	13.48	13.66	13.84
12	14.02	14.21	14.40	14.59	14.78
13	14.97	15.17	15.37	15.57	15.78
14	15.98	16.19	16.40	16.62	16.83

Temp. °C	0.0	0.2	0.4	0.6	0.8
15	17.05	17.27	17.49	17.72	17.95
16	18.18	18.41	18.65	18.89	19.13
17	19.37	19.62	19.87	20.12	20.38
18	20.63	20.90	21.16	21.43	21.69
19	21.97	22.25	22.52	22.80	23.09
20	23.38	23.67	23.96	24.26	24.56
21	24.87	25.17	25.48	25.80	26.11
22	26.43	26.76	27.09	27.42	27.75
23	28.09	28.43	28.78	29.12	29.48
24	29.83	30.20	30.56	30.93	31.30
25	31.67	32.05	32.43	32.82	33.21
26	33.61	34.01	34.41	34.82	35.23
27	35.65	36.07	36.50	36.93	37.36
28	37.80	38.24	38.68	39.14	39.59
29	40.05	40.52	40.99	41.47	41.94
30	42.43	42.92	43.41	43.91	44.41
31	44.92	45.44	45.96	46.48	47.01
32	47.55	48.09	48.63	49.18	49.74
33	50.30	50.87	51.44	52.02	52.60
34	53.19	53.79	54.39	55.00	55.61
35	56.23	56.85	57.48	58.12	58.77
36	59.41	60.07	60.73	61.39	62.07
37	62.75	63.44	64.02	64.83	65.54
38	66.25	66.97	67.69	68.43	69.17
39	69.92	70.67	71.43	72.20	72.98
40	73.76	74.54	75.34	76.14	76.95
41	77.78	78.61	79.43	80.29	81.14
42	81.99	82.85	83.73	84.61	85.49
43	86.39	87.30	88.21	89.14	90.07
44	91.01	91.95	92.91	93.87	94.85
45	95.83				

Figure A 9.1 water content of ambient air (H_{obs}) for temperature range -15 °C to +45 °C.

Data calculated by using H_2O partial pressure from table A9.2

$p_{ambient}$ = 1.013 bar



APPENDIX 10

Presentation of Results

It is recommended that the emission results should be stated at rated load and speed in:

either

- g/kW.h (normally used for diesel engines) related to the useful work produced

or

- ppm Vol referred to by dry exhaust gases with 15% O_2 concentration (normally used for gas turbines)

To refer the actual concentration to dry conditions and 15% O_2, and for other conversions see Appendix 9.

Some authorities require the results to be expressed in other units or related to other percentages of oxygen. Appendix 9 and the following sheets in this Appendix make provision for this.

On completion of the test, a single document shall be prepared which details the following:

Engine test data
Emissions data at each individual speed/load condition
Brake specific emittant (if applicable)
Installation details
Engine build data
Fuel details
Test conditions

It will generally be left to those requesting or undertaking the test to specify whether results are required at other than rated load and speed but recommendations are made in Section 2.4 of this document for methods which might be used.

Appendix 9 gives alternative units and conversions.

This format for presentation of engine emissions results is intended to be applicable in all tests circumstances and in any Country.

From this point of view, the following tables are a recommended format. This suggested format is not intended to prevail over other formats for the presentations of results required from certain regulations.

Record of Emissions Test - Sheet 1 of 13

1. PLANT CHARACTERISTICS

Plant identification
Customer :
Place (final installation) :
Place of measurements :

Engine
Manufacturer :
Type :
Serial Number :
Contract full load .... KW at .... rev/min

Method of emission control :

Emission requirements
NOx :
UHC :
CO :
SOx :
Smoke :
Particulates :
Other :

Test identification
Date :
Time :
Number :

Manager of the tests :
Company :
Date of report :
Place of report :
Signature :

Record of Emissions Test - Sheet 2 of 13

II. INSTRUMENTS IDENTIFICATION - A) EMISSIONS

Component	Make	Model	Type 1)	Serial #	Measuring Range	Measuring Tolerance
O_2						
CO_2						
NOx/NO						
CO						
SOx						
NH_3						
UHC						
SMOKE						
PARTICULATES						
OTHER						

REMARKS - See Sheet 13

* Span Gas (Calibration Gas) Used: List and certificates in Annex 2.
* Sample Location: See sketch in Annex 3.

1) Abbreviations to be used for Instrument Type

BASN	Bacharach Smoke Number	NDIR	Non-dispersive infra-red
BOSN	Bosch Smoke Number	NDUV	Non-dispersive ultra-violet
CL	Chemiluminescent	NMHC	Non-methane hydrocarbons
DP	Dew Point	PM	Paramagnetic
EC	Electrochemical	SPHM	Spectrophotometric
FID	Flame Ionisation Detector	THC	Total Hydrocarbons (with FID)

Record of Emissions Test - Sheet 3 of 13

II. INSTRUMENTS IDENTIFICATION - B) AMBIENT CONDITIONS

Parameter	Make	Model	Type	Serial #	Measuring Range	Measuring Tolerance
Pressure						
Temperature						
Rel. Humid.						

Record of Emissions Test - Sheet 4 of 13

II. INSTRUMENTS IDENTIFICATION - C) ENGINE DATA

Parameter		Make	Model	Type	Serial #	Measuring Range	Measuring Tolerance
Load							
Speed							
Fuel Flow							
Water Inject.							
Water Removal							
Inlet Air Flow	meas.1)						
	der. 2)						
Exhst. Flow	meas.1)						
	der. 2)						
Other							

1) e.g. Diaphragm, nozzle, orifice

2) * Derived from CO2% or O2% in exhaust flow.
** Derived from reference conditions.

Record of Emissions Test - Sheet 5 of 13

III. FUEL CHARACTERISTICS

COMPOSITION Measured or Assumed

GAS		
Component	% Volume	% Mass
N_2		
CO_2		
CO		
O_2		
H_2		
CH_4		
C_2H_4		
C_2H_6		
C_3H_6		
C_3H_8		
C_4H_8		
C_4H_{10}		
C_5H_{12}		
C_6H_{14}		
C_7H_{16}		
Other		
Other		
H_2S		
NH_3		
H_2O		

LIQUID	
Component	Mass %
H_2	
C	
O_2	
N_2	
S	
Ash	
Va (ppm)	
Other	

IF LIQUID:

-L.H.V. [KJ/kg]
-H.H.V. [KJ/kg]
-DENSITY [kg/m^3]
at T = [C]
-VISCOSITY [cSt]
at T = [C]

IF GAS:

-L.H.V. [KJ/kg]
-H.H.V. [KJ/kg]
-MIXTURE MOLAR MASS [kg/Kmol]
-REL. SPC. GRAV. (Air=1)
-DENSITY [kg/Nm$_3$]
-GAS CONSTANT [KJ/kg K]

Record of Emissions Test - Sheet 6 of 13

IV. MEASUREMENTS - A) GENERAL

TEST IDENTIFICATION: Date .... Time .... No. ....

			1	2	3
INLET AIR	- Temperature				
	- Pressure [kPa]				
	- Relative Humidity %				
	- Flow [kg/s]				
OPERATING DATA	- Power Output	Mech. [MW]			
		Elec. [MW]			
		Ther. [MW]			
		Total [MW]			
	- Inlet Manifold or Combustor Inlet 1)	Temp [C]			
		Press [kPa]			
	- Fuel	mass flow [kg/sec]			
		temperature [C]			
	- H_2O 2) injected	Water or Steam			
		Rate [kg/s]			
		H2O/fuel[kg/kg]			
	- removed	Rate [kg/s]			
	- NH_3 H_2O	% mass NH_3 Water Steam			
	- added	Rate [kg/s]			
	- Exhaust flow [kg/s]				
	- Exhaust temperature [C]				

1) or compressor discharge for gas turbines 2) Further details to be attached.

Record of Emissions Test - Sheet 7 of 13

IV. MEASUREMENTS - B) GASEOUS EMISSIONS

TEST IDENTIFICATION: Date .... Time .... No.							
				1)	1	2	3
MEAS. OR CALC. GAS VOLUME CONCENT- RATION	N_2	wet	%				
		dry					
	O_2	wet	%				
		dry					
	H_2O	wet	%				
		dry			0	0	0
	CO_2	wet	%				
		dry					
	NO	wet	ppm				
		dry					
	NOx	wet	ppm				
		dry					
	CO	wet	ppm				
		dry					
	SOx	wet	%				
		dry					
	UHC 2)	wet	%				
		dry					
	NH_3	wet	%				
		dry					

1) M for measured C for calculated 2) To be specified (CH_4, C_3H_8 etc.)

Note. To convert wet to dry use eq. 1a Appendix 9.

Record of Emissions Test - Sheet 8 of 13

IV. MEASUREMENTS - B) PARTICULATE EMISSIONS

TEST IDENTIFICATION Date .... Time .... No.							
				1)	1	2	3
SMOKE	(Units)						
PARTIC-ULATES	Mass on Filter	Quan.	mg	M			
		Rate	mg/h	C			
	For total exh.		g/h				

1) M for measured C for calculated

Record of Emissions Test - Sheet 9 of 13

V. CORRECTIONS TO A PREFIXED PERCENTAGE OF O_2 = ... ON A DRY BASIS

TEST IDENTIFICATION: Date .... Time .... No.					
			1	2	3
CALCULATED GAS VOLUME FRACTION	NOx	ppm			
	CO	ppm			
	SOx	ppm			
	1) UHC	ppm			
	OTHER	ppm			

1) To be specified

REMARK

This table must be filled in only if the ppm values must be referred to as concentration (Volume at standard conditions) and to a specified percentage of oxygen.

The correction is done by eq. 4.b. Appendix 9.

Record of Emissions Test - Sheet 10 of 13

VI. CORRECTIONS TO mg/Nm³ AND TO A PREFIXED PERCENTAGE OF O_2

TEST IDENTIFICATION:	Date	Time	No.		
			1	2	3
CALCULATED	NOx	mg/Nm³			
GAS	CO	mg/Nm³			
MASS	SOx	mg/Nm³			
FRACTION	1) UHC	mg/Nm³			
	OTHER	mg/Nm³			

1) To be specified

REMARK

This table must be filled in only if the emissions levels must be given in mg/Nm³ or referred to as specified percentage of oxygen in the unit mg/Nm³.

The correction is done by eq. 3 and eq. 4.b. Appendix 9.

Record of Emissions Test - Sheet 11 of 13

VII. CORRECTIONS TO SPECIFIC EMISSIONS VALUES

TEST IDENTIFICATION:	Date	Time	No.		
			1	2	3
CALCULATED	NOx	g/GJ			
GAS	CO	g/GJ			
MASS	SOx	g/GJ			
FRACTION	1) UHC	g/GJ			
	OTHER	g/GJ			

1) To be specified

REMARK

This table must be filled in only if the emission levels must be referred to as specific emissions in the unit g/GJ fuel energy input.

The correction is done by eq. 3 and eq. 6 Appendix 9.

Record of Emissions Test - Sheet 12 of 13

VI. CORRECTIONF TO SPECIFIC EMISSIONS VALUES

TEST IDENTIFICATION:	Date		Time		No. ....
			1	2	3
CALCULATED GAS MASS FRACTION	NOx	g/kWh			
	CO	g/kWh			
	SOx	g/kWh			
	1) UHC	g/kWh			
	OTHER	g/kWh			

1) To be specified.

REMARK

This table must be filled in only if the emission levels must be referred to as specific emissions in the unit g/KWh.

The correction is done by eq. 3 and eq. 8 Appendix 9.

Record of Emissions Test - Sheet 13 of 13

VII. APPENDICES

1. DECLARATION
The emission measurements have been carried out in accordance with CIMAC's Exhaust Emission Measurement Recommendations for reciprocating engines and gas turbines dated................
Also in accordance with....................................

The following deviations made

*	....	
**	....	List of deviations
***	....	

2.	SPAN GASES:	List and certificates
3.	PARTICULATES AND GASEOUS SAMPLE LOCATION:	Skethces showing the probe type, location in exhaust stack, stack diameter, stack bends etc.
4.	FUEL ANALYSIS:	Certificate
5.	ENGINE DATA SHEET:	Corresponding to the test

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