



AEROSPACE RECOMMENDED PRACTICE	ARP1533™	REV. D
	Issued Revised	1996-01 2024-03
	Superseding ARP1533C	
(R) Procedure for the Analysis and Evaluation of Gaseous Emissions from Aircraft Engines		

RATIONALE

SAE Aerospace Recommended Practice ARP1533D provides updated information regarding ambient engine inlet air composition and carbon balance values. The ambient air composition is updated to contemporary values. The carbon balance values are updated to be consistent with ARP1533B and ICAO Annex 16 Vol. II Appendix 3.

A new Appendix E is provided to establish a CO₂ EI calculation equation with ambient component correction.

Editorial and clarity updates have been implemented including updating equation format to SAE style.

TABLE OF CONTENTS

1.	SCOPE.....	3
1.1	ARP Sections	3
2.	REFERENCES.....	4
2.1	Applicable Documents	4
2.1.1	SAE Publications.....	4
2.1.2	Other References	4
2.2	Definitions	4
2.3	Nomenclature and Suggested Values	5
2.3.1	Subscripts	7
3.	INTRODUCTION.....	7
4.	COMBUSTION CHEMICAL EQUATION	9
4.1	Modified Combustion Chemical Equation	9
5.	MATRIX SOLUTION OF THE COMBUSTION CHEMICAL EQUATION.....	10
5.1	Basic Matrix.....	10
5.2	Measurements, Interferences, and Corrections.....	11
5.2.1	Interferences of Carbon Dioxide, Water and Oxygen	12
5.2.2	NO _x Converter Efficiency.....	13
5.2.3	Sample Drying.....	13
6.	CALCULATION OF GASEOUS EMISSIONS PARAMETERS.....	15
7.	CALCULATION OF DATA QUALITY INDICATORS	17

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7.1	Sample Stability	17
7.2	Oxygen Balance	17
7.3	Carbon Balance	17
7.4	Fuel/Air Ratio Balance	18
7.5	NO/NO _x Ratio	18
7.6	Trend Plots	18
8.	CALCULATION OF MEASUREMENT UNCERTAINTY	19
9.	NOTES	19
9.1	Revision Indicator	19
APPENDIX A	CALCULATION OF MEASUREMENT UNCERTAINTY	20
APPENDIX B	CALCULATION OF SAMPLE WATER CONTENT FROM FROST OR DEW POINT TEMPERATURE MEASUREMENTS	25
APPENDIX C	SAMPLE CALCULATIONS	28
APPENDIX D	DERIVATION OF EQUATIONS	36
APPENDIX E	CO ₂ Emission Index Calculation	43
Table 1	Typical values of hydrocarbon fuel properties	8
Table 2	Properties of standard air (refer to Reference 2.1.2.8)	8
Table 3	Matrix A (see Equations 2 through 11 and 13) and Matrix B	11
Table 4	Expanded Matrix A and Matrix B	15

1. SCOPE

SAE Aerospace Recommended Practice ARP1533 is a procedure for the analysis and evaluation of the measured composition of the exhaust gas from aircraft engines. Measurements of carbon monoxide, carbon dioxide, total hydrocarbon, and the oxides of nitrogen are used to deduce emission indices, fuel-air ratio, combustion efficiency, and exhaust gas thermodynamic properties. The emission indices (EI) are the parameters of critical interest to the engine developers and the atmospheric emissions regulatory agencies because they relate engine performance to environmental impact.

While this procedure is intended to guide the analysis and evaluation of the emissions from aircraft gas turbine engines (burning conventional hydrocarbon based liquid fuels), the methodology may be applied to the analysis of the exhaust products of any hydrocarbon/air combustor. Some successful applications include:

- Aircraft engine combustor development rig tests (aviation jet fueled)
- Stationary source combustor development rig tests (natural gas and diesel fueled)
- Afterburning military engine tests (aviation jet fueled)
- Internal combustion aircraft engine diagnostics (AVGAS fueled)

Each application may be characterized by very different measured emissions levels (parts per million versus percent by volume) but this common approach solves the same basic combustion chemical equation.

The matrix method of solving the combustion chemical equation is recommended because of all the potential variations in exhaust gas measurement requirements. Changes in the fuel type, addition of diluents, addition of measured species, and options for wet or dry basis measurements are most easily handled by revising individual matrix row equations. Matrix solution software is widely available on personal computers. However, derivation of the algebraic solution of the chemical equation is retained for traceability to previous versions of this document. This document also contains a section pertaining to data quality checks, measurement uncertainty, and water content calculations.

1.1 ARP Sections

This document is divided into the following sections:

2. References

3. Introduction

4. Combustion Chemical Equation

5. Matrix Solution of the Combustion Chemical Equation

6. Calculation of Gaseous Emissions Parameters

7. Calculation of Data Quality Indicators

8. Calculation of Measurement Uncertainty

Appendix A - Calculation of Measurement Uncertainty

Appendix B - Calculation of Sample Water Content from Frost or Dew Point Temperature Measurements

Appendix C - Sample Calculations

Appendix D - Derivation of Equations

Appendix E - CO₂ Emissions Index Calculation

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP1256 Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines

2.1.2 Other References

- 2.1.2.1 Kilpatrick, D.A. (1981). *Calculation methodology for basic engine exhaust gaseous emission parameters* (Report No. National Gas Turbine Establishment Memorandum M81002).
- 2.1.2.2 Machta, L. and Hughes, E. (1970). Atmospheric oxygen in 1967 to 1970. *Science*, 168(3939), 1582–1584.
- 2.1.2.3 Heneghan, S.P. and Frayne, C.W. (2000). *Propagation of errors for combustion analysis using emission analyzer data* (Report No. AIAA-2000-0955).
- 2.1.2.4 Hardy, B. (1998, April). *ITS-90 formulations for vapor pressure, frost point temperature, dew point temperature, and enhancement factors in the range –100°C to +100°C* [Conference presentation]. The Proceedings of the Third International Symposium on Humidity & Moisture, Teddington, London, England.
- 2.1.2.5 BS 1339-1:2002. (2002). Humidity—Part 1: Terms, definitions and formulae.
- 2.1.2.6 JCGM 101:2008. (2008). Evaluation of measurement data—Supplement 1 to the “Guide to the expression of uncertainty in measurement”—Propagation of distributions using a Monte Carlo method.
- 2.1.2.7 Wagner, W. and Pruß, A. (2002). The IAPWS formulation 1995 for the thermodynamic properties of ordinary water substance for general and scientific use. *Journal of Physical and Chemical Reference Data*, 31(2).
- 2.1.2.8 Keeling, R.F. (2022). Atmospheric oxygen and carbon dioxide data for Alert, Cold Bay, Cape Kumukahi, La Jolla Pier, Mauna Loa Observatory, American Samoa, Cape Grim, Palmer Station and South Pole. <https://scrippsco2.ucsd.edu/data.html>.

2.2 Definitions

AIRCRAFT GAS TURBINE ENGINE: Any gas turbine engine used for aircraft propulsion or power generation, including those commonly called turbojet, turbofan, turboprop, or turboshaft type engines.

COMBUSTION EFFICIENCY: The percentage ratio of the energy actually released by the combustion process to the energy which would be realized if all the carbon in the fuel were oxidized to carbon dioxide and the hydrogen to water vapor.

CONCENTRATION: The volume fraction of the component of interest in the gas mixture expressed as volume percentage or as parts per million by volume.

EMISSION INDEX: The mass of emissions of a given constituent per unit mass of fuel, multiplied by 1000.

FUEL-AIR RATIO: The mass rate of fuel flow to the engine divided by the mass rate of dry airflow through the engine.

GASEOUS EMISSIONS: The gaseous products, formed during combustion, found in the exhaust from a gas turbine engine. In this document, the gaseous emissions measured and used to solve the combustion chemical equation are carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, and total hydrocarbon.

MOLE FRACTION: The volume concentration of a gas per unit volume of the gas mixture of which it is a part. In the context of the measurements discussed in this procedure, “volume concentration (or volume fraction)” and “molar concentration (or mole fraction)” are synonymous.

NET HEAT OF COMBUSTION: The energy released per unit mass of fuel due to its complete oxidation at constant pressure as measured by cooling the products to the initial temperature without condensation of the water vapor formed in the reaction.

NO_x: Oxides of nitrogen, specifically, the sum of nitric oxide (NO) and nitrogen dioxide (NO₂).

PARTS PER MILLION VOLUME (ppmV): The unit volume concentration of a gas per million unit volumes of the gas mixture of which it is a part. (Also applicable to mass measurements but only volume relationships are referred to in these procedures.)

PARTS PER MILLION CARBON (ppmC): The mole fraction of hydrocarbon in the exhaust multiplied by 10⁶. Thus, 1 ppm of methane is indicated as 1 ppmC. To convert ppm concentration of the hydrocarbon to an equivalent ppmC value, multiply ppm concentration by the number of carbon atoms per molecule of the gas. For example, 1 ppm propane translates as 3 ppmC hydrocarbon; 1 ppm hexane as 6 ppmC hydrocarbon.

STANDARD AIR: Simplified air composition used for EI calculation.

TOTAL HYDROCARBON: The total of hydrocarbon compounds of all classes and molecular mass.

2.3 Nomenclature and Suggested Values

[CH ₄] _b	Mole fraction of methane in dry inlet air
[CO]	Mole fraction concentration of carbon monoxide in the exhaust
[CO ₂]	Mole fraction concentration of carbon dioxide in the exhaust
[CO ₂] _b	Mole fraction of carbon dioxide in dry inlet air (default value = 0.000417)
[C _x H _y]	Mole fraction concentration of total hydrocarbon in the exhaust, expressed in ppmC
[H ₂ O]	Mole fraction concentration of water in the exhaust
[N ₂] _b	Mole fraction of the balance of dry inlet air without carbon dioxide and oxygen. Mostly nitrogen with minor species. (default value = 0.790281)
[NO]	Mole fraction concentration nitric oxide in the exhaust
[NO ₂]	Mole fraction concentration nitrogen dioxide in the exhaust
[NO _x]	Mole fraction concentration of the oxides of nitrogen in the exhaust
[O ₂]	Mole fraction concentration of oxygen in the exhaust
[O ₂] _b	Mole fraction of O ₂ in dry inlet air (default value = 0.209302)

[SO ₂]	Mole fraction concentration of sulfur dioxide in the exhaust
[Z]	Mole fraction concentration of constituent Z in exhaust
C _m H _n O _p N _q S _r	Chemical formula of 1 mole of hydrocarbon fuel
Diluent	A diluent such as nitrogen or water that is added to the combustion process
El _z	Emission index of constituent Z, g/kg fuel (lb/1000 lb fuel)
f	Water vapor saturation pressure enhancement factor
F/A	Fuel-air ratio by mass
H _c	Net heat of combustion of fuel at constant pressure J/kg (Btu/lb)
h	Water content of the inlet air, moles of water vapor per mole of dry inlet air
h _{sd}	Water content of the semi-dry exhaust sample leaving the dryer, moles of water vapor per mole of dry sample gas
ICAO	International Civil Aviation Organization
J	Oxygen interference coefficient for effect of O ₂ on the measurement of CO ₂ (concentration factor)
K	Ratio of wet concentration to completely dry concentration
L	Interference coefficient for effect of CO ₂ on the measurement of CO (zero shift)
L'	Interference coefficient for effect of CO ₂ on the measurement of NO and NO _x (concentration factor)
$\dot{m}_n$	Mass flow rate of fuel "n"
M	Interference coefficient for effect of H ₂ O on the measurement of CO (zero shift)
M'	Interference coefficient for effect of H ₂ O on the measurement of NO and NO _x (concentration factor)
MAIR	Molecular mass of dry air (default value = 28.8544 g/mol)
Mc	Atomic mass of carbon = 12.0110
MH	Atomic mass of hydrogen = 1.0078
MN	Atomic mass of nitrogen = 14.0067
MO	Atomic mass of oxygen = 15.9994
MS	Atomic mass of sulfur = 32.0600
Mz	Atomic mass of constituent Z
P _T	Total moles of exhaust products
PHYG	Gas sample pressure where the frost or dew point temperature measurement is made

PWV	Ideal water saturation vapor pressure at the measured frost or dew point temperature
PWVE	Effective water saturation vapor pressure at the gas sample pressure, PHYG
THYG	Frost or dew point temperature measured with a hygrometer
X	Moles of dry air/mole of fuel
α	Atomic hydrogen-carbon ratio of the fuel = n/m
γ, ϕ	Intermediate terms in the calculation of the water vapor pressure calculation enhancement factor, f
η	NO _x converter efficiency
η_b	Combustion efficiency, %

2.3.1 Subscripts

d	Completely dry basis
m,n,p,q,r	Molar constants for fuel, $C_mH_nO_pN_qS_r$
ms	Measured value
sd	Semidry basis
T	Combined (total) fuel properties, when fuels are mixed or diluted
w	Wet basis
x,y	Molar constants selected for the unburned hydrocarbon in exhaust, C_xH_y
z	Constituent Z

3. INTRODUCTION

The exhaust gas composition measurements required by this procedure include carbon monoxide (CO), carbon dioxide (CO₂), nitric oxide (NO), oxides of nitrogen (NO_x), total hydrocarbon (C_xH_y), as well as ambient air and sample dew point temperatures. The measured value of oxygen (O₂) content is not required by the analysis but can be used for assessing data quality. Measurement of sulfur dioxide (SO₂) is also not required but has been included herein to illustrate the addition of other species that may become significant and measurable. The instruments used for these measurements may be single-gas analyzers or single analyzers capable of measuring multiple gas compositions. Whichever the approach, each instrument must be fully characterized in terms of limitations in linearity, drift, interferences, repeatability, and biases. Some analyzers require a dried sample while others do not. Correct bookkeeping is required to ensure mixing wet basis, semi-dry and dry basis mole fractions does not occur. These issues are further explained in 5.2.

Ideally, the analysis and evaluation of emissions data should not require facility-measured parameters. However, when mixed fuels and diluents are used, facility metered flow rates are required to specify the number of moles of each reactant.

This procedure is valid for analysis of hydrocarbon/air exhaust products. Regardless of the hydrocarbon fuel; the chemical formula, molecular mass, and the lower heating value must be known. Typical values of these parameters for several fuels are provided in Table 1. However, precise values should be obtained from analysis of pre-and post-test fuel samples or from reference literature. The fuel chemical formula may be expanded to include the oxygen, nitrogen and sulfur in addition to carbon and hydrogen for a more rigorous balance of the reactants and products of combustion.

Table 1 - Typical values of hydrocarbon fuel properties

Fuel	Chemical Composition	H/C Ratio (n/m)	Lower Heating Value, Btu/lbm	Lower Heating Value, MJ/kg
Jet A	C _{11.6} H ₂₂	1.897	18521	43.080
JP-5	C _{7.16} H _{13.87}	1.937	18300	42.567
JP-10	C ₁₀ H ₁₆	1.6	18137	42.187
AVGAS	C _{7.68} H _{16.8}	2.187	18700	43.496
Natural Gas	C _{1.04} H _{4.01}	3.855	20680	48.102
#2 Diesel	C ₁₆ H ₃₀	1.875	18318	42.608

Atmospheric oxygen and carbon dioxide levels in ambient air are, respectively, slowly decreasing and increasing over time. Appropriate standard air values for oxygen and carbon dioxide concentration are listed in Table 2 (these values will be updated in future document versions). The balance of standard air, [N₂]_b includes nitrogen and minor gas species. [N₂]_b is assumed to have equivalent molecular mass to N₂ and is calculated by:

$$[N_2]_b = 1 - [CO_2]_b - [O_2]_b$$

[CH₄]_b is considered negligible for the calculation of [N₂]_b

When large deviations from standard air are encountered (i.e., higher ambient carbon dioxide), actual concentrations should replace the dry air concentrations and [N₂]_b calculated.

A baseline sample of the inlet air should be analyzed, and the frost or dew point temperature measured.

Table 2⁽¹⁾ - Properties of standard air (refer to Reference 2.1.2.8)

Component	Chemical Formula	Molecular Mass	Percent by Volume
Air Balance [N ₂] _b	Assumed N ₂	28.0134	79.0281 (dry)
Oxygen [O ₂] _b	O ₂	31.9998	20.9302 (dry)
Carbon Dioxide [CO ₂] _b	CO ₂	44.0098	0.0417 (dry)
Water vapor	H ₂ O	18.015	Must be measured
Total		28.8544 (dry)	100 (dry)

⁽¹⁾ Table 2 dry values are based on the 2019 yearly average of observational CO₂ and O₂ concentration data of stations around the world from the Scripps O₂ Program (refer to Reference 2.1.2.8) These data are from remote locations or other locations situated so that they represent averages over large portions of the globe rather than local background sources. O₂ is determined using 20.946% (refer to Reference 2.1.2.2) as the baseline.

Data quality checks have been incorporated into this procedure to encourage the use of near real time automated evaluation of the emissions measurement process. While there may be others, the checklist included in Section 7 has proven to aid in the early identification of emissions measurement problems.

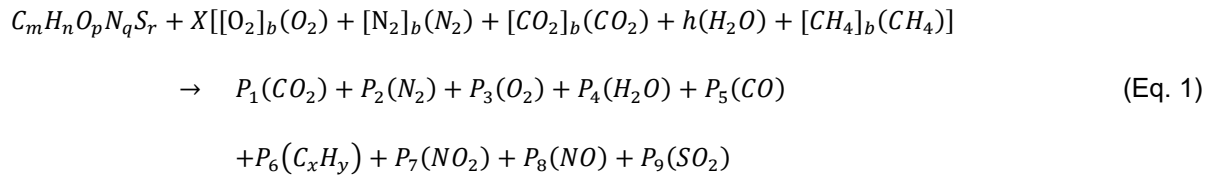
Calculations of emissions measurement uncertainties are increasingly necessary to show compliance with very low atmospheric emissions regulations. A methodology for the propagation of measurement errors in the calculations of the emissions indices (refer to Reference 2.1.2.3) is provided in Appendix A.

A method of calculating sample water content from measured frost and dew point temperatures (refer to Reference 2.1.2.4) is provided in Appendix B.

Two complete sample calculations are provided in Appendix C. The first calculation is the one presented in the version of ARP1533 issued in 1996. It is retained in this version for traceability of existing emissions analysis codes. The second calculation illustrates the expanded method of calculations with the matrix solution.

4. COMBUSTION CHEMICAL EQUATION

The chemical equation for the combustion of 1 mole of hydrocarbon fuel and atmospheric air is:



where:

P_1 through P_9 = number of moles of CO_2 , N_2 , O_2 , H_2O , CO , C_xH_y , NO_2 , NO , and SO_2 respectively

The reading of the hydrocarbon analyzer is expressed in ppmC, not in ppm, Therefore the value of P_6 will depend on the assumption made regarding the composition of the unburned hydrocarbon C_xH_y in the exhaust gas. The balance of the combustion equation will also depend on the ratio between x and y.

This composition may be defined by at least three options between the SAE and ICAO methodologies:

- Equivalent fuel (CH_x , $x = 1$, $y = n/m$) implies that the hydrocarbons in the exhaust gas have the same formulation as the fuel (old SAE method, used in the initial version of this document).
- Equivalent methane (CH_4 , $x = 1$, $y = 4$) implies that all the hydrocarbons in the exhaust gas are assumed to be methane in the absence of contrary evidence (ICAO method).
- Characterized fuel (C_xH_y), used in the current version of this document, requires some knowledge of the composition of the hydrocarbons in the exhaust gas.

The analyst must clearly state which assumption was applied and must be careful about the consistency between the molecular mass and the concentration used to determine the emission index for H_c .

The combustion equation makes no allowance for the small amounts of hydrogen, free carbon, various species of hydrocarbon, and the oxides of nitrogen (other than nitric oxide and nitrogen dioxide) that may be present in the exhaust. Noble gases are unchanged during the combustion reaction. This procedure combines nitrogen, argon, and other trace species together for a total percent by volume of 79.0281. The water content of the inlet air, h , is expressed as moles of water vapor per mole of dry air.

The $P_9(SO_2)$ term may be included in Equation 1 when the fuel has significant sulfur content. However, SO_2 is not a required measurement for the calculation of emission indices.

4.1 Modified Combustion Chemical Equation

Occasionally fuels are mixed or diluents are added to the fuel or gas stream during the development of new engines. When mixed fuels are used, where practical, it is recommended that the fuel mixture be analyzed to determine critical mixed fuel properties (e.g., H/C ratio of the fuel). The Section 4 approach may then be used directly. Where this approach is not sufficient, the user will need to determine what flows need to be monitored and what changes are required to the Section 4 analysis to accurately reflect their test configuration.

5. MATRIX SOLUTION OF THE COMBUSTION CHEMICAL EQUATION

5.1 Basic Matrix

Eleven simultaneous equations are required to solve for the eleven unknowns, P_1 - P_9 , P_T and X , in Equation 1. The procedure for writing the eleven simultaneous equations is the same whether multiple fuels and/or diluents are used or not. The equations for a single fuel and no diluents are defined as follows:

Carbon balance:

$$m + ([CO_2]_b + [CH_4]_b)X = P_1 + P_5 + xP_6 \quad (\text{Eq. 2})$$

Hydrogen balance:

$$n + (2h + 4[CH_4]_b)X = 2P_4 + yP_6 \quad (\text{Eq. 3})$$

Oxygen balance:

$$p + (2[O_2]_b + 2[CO_2]_b + h)X = 2P_1 + 2P_3 + P_4 + P_5 + 2P_7 + P_8 + 2P_9 \quad (\text{Eq. 4})$$

NOTE: The measured oxygen content is not used in the solution of the combustion equation.

Nitrogen balance:

$$q + 2[N_2]_bX = 2P_2 + P_7 + P_8 \quad (\text{Eq. 5})$$

Sulfur balance:

$$r = P_9 \quad (\text{Eq. 6})$$

Moles of carbon dioxide:

$$P_1 = P_T[CO_2]_w \quad (\text{Eq. 7})$$

Moles of carbon monoxide:

$$P_5 = P_T[CO]_w \quad (\text{Eq. 8})$$

Moles of total hydrocarbon:

$$xP_6 = P_T[C_xH_y]_w \quad (\text{Eq. 9})$$

where:

$[C_xH_y]$ = expressed in ppmC

Moles of the oxides of nitrogen:

$$P_7 + P_8 = P_T[NO_x]_w \quad (\text{Eq. 10})$$

Moles of nitric oxide:

$$P_8 = P_T[NO]_w \quad (\text{Eq. 11})$$

Moles of water:

$$P_4 = P_T[H_2O]_w \quad (\text{Eq. 12})$$

Where total number of moles of product:

$$P_T = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 + P_9 \quad (\text{Eq. 13})$$

Equations 2 through 11 and 13 are solved for the constant terms then entered into the 11 x 11 Matrix A (Variables) and the 1 x 11 Matrix B (Constants) in Table 3. Row 1 from Equation 2 reads as $P_1 + P_5 + xP_6 - ([CO_2]_b + [CH_4]_b)X = m$. Row 10 from Equation 13 reads as $-P_T + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 + P_9 = 0$. The inverse of Matrix A is multiplied by Matrix B to obtain the 1 x 11 Matrix C which contains the eleven unknowns, $P_1 - P_9$, P_T and X . Equations 7 through 11 use concentrations on a wet basis. Measurements made on a semidry basis need to be converted to measurements on a wet basis.

The elements of Matrix C are wet basis.

Table 3 - Matrix A (see Equations 2 through 11 and 13) and Matrix B

Equation	Matrix A											Matrix B
	P_T	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	X	Constants
2	0	1	0	0	0	1	x	0	0	0	$-[CO_2]_b - [CH_4]_b$	m
3	0	0	0	0	2	0	y	0	0	0	$-2h-4[CH_4]_b$	n
4	0	2	0	2	1	1	0	2	1	2	$-2[O_2]_b - 2[CO_2]_b - h$	p
5	0	0	2	0	0	0	0	1	1	0	$-2[N_2]_b$	q
6	0	0	0	0	0	0	0	0	0	1	0	r
7	$[CO_2]_w$	-1	0	0	0	0	0	0	0	0	0	0
8	$[CO]_w$	0	0	0	0	-1	0	0	0	0	0	0
9	$[C_xH_y]_w$	0	0	0	0	0	-x	0	0	0	0	0
10	$[NO_x]_w$	0	0	0	0	0	0	-1	-1	0	0	0
11	$[NO]_w$	0	0	0	0	0	0	0	-1	0	0	0
13	-1	1	1	1	1	1	1	1	1	1	0	0

5.2 Measurements, Interferences, and Corrections

In a perfect world all gas analyzers would provide precise, unambiguous measurements of gas composition. In reality, depending on the type of analyzer being used, the emissions measurement must be concerned with:

- The interference of carbon dioxide and water on the measured concentrations of carbon monoxide and the oxides of nitrogen.
- The interference of oxygen on the measured concentration of carbon dioxide.
- The efficiency of the converter that converts the oxides of nitrogen to nitric oxide.
- The basis of measurement (semidry or wet).

This section of the procedure addresses these issues and modifies the equations in Matrix A. Effects such as that of oxygen upon carbon monoxide have been determined to be negligible for modern analyzers currently in use.

5.2.1 Interferences of Carbon Dioxide, Water and Oxygen

The measurement of a single gaseous species may be affected by the presence of other gaseous species. For example, carbon dioxide and water vapor in the exhaust interfere with the non-dispersive infrared measurement of CO and the chemiluminescent measurement of NO. There are two different types of interferences, depending on the effect they have on the measurement.

- With the “zero shift” interference effect, the interfering species creates an offset on the measurement, which does not vary with the concentration measured. This is the case for the interference of CO₂ and H₂O on CO, for example. An interference coefficient is required to quantify the shift of the number of mole measured for species [A] due to the number of mole of interfering species [B] that is present.
- With the “concentration factor” interference effect (or sensitivity effect), the interfering species modifies the slope of the response of the analyzer: therefore, the effect is proportional to the concentration measured. This is the case for the interference of CO₂ and H₂O on NO. An interference coefficient is required that quantifies the modification of the parts per volume measured for species [A] due to the parts per volume of interfering species [B] that is present.

The convention used in defining these effects is that the correction is added to the measured value (or added to unity and multiplied by the measured value where appropriate) to give the best estimate of the true value. Thus, an interference that reduces the reading is expressed as a positive interference effect. L, L', M, M', and J are the interference coefficients for analyzers that should be determined under test conditions. Example values of interference coefficients (refer to Reference 2.1.2.1) are provided below. These values are used in the sample calculations in Appendix C but are not representative of current analyzers performances. It is recommended to measure the real interference coefficients for each new instrument. If this is not possible, the uncertainties on the interference coefficients should be taken into account in the calculation of the uncertainties on the corrected concentrations (see Appendix A).

$L = -1.3 \times 10^{-4}$, mole CO per mole CO₂ (zero shift effect)

$M = -4.5 \times 10^{-4}$, mole CO per mole H₂O (zero shift effect)

$L' = 0.14$, percent of reading of NO per percent CO₂ (concentration factor effect)

$M' = 0.28$, percent of reading of NO per percent H₂O (concentration factor effect)

$J = 0.09$, percent of reading of CO₂ per percent of O₂ (concentration factor effect)

Correct the CO measurement for the CO₂ and H₂O interferences as follows:

$$P_5 = [CO]_{ms}P_T + LP_1 + MP_4 \quad (\text{Eq. 14})$$

Correct the NO_x measurement for the CO₂ and H₂O interferences as follows:

$$P_7 + P_8 = [NO_x]_{ms}P_T + L'[NO_x]_{ms}P_1 + M'[NO_x]_{ms}P_4 \quad (\text{Eq. 15})$$

Correct the NO measurement for the CO₂ and H₂O interferences as follows:

$$P_8 = [NO]_{ms}P_T + L'[NO]_{ms}P_1 + M'[NO]_{ms}P_4 \quad (\text{Eq. 16})$$

Correct the CO₂ measurement for the O₂ interference as follows:

$$P_1 = [CO_2]_{ms}P_T + J[CO_2]_{ms}P_3 \quad (\text{Eq. 17})$$

To include these interference effects in the matrix solution:

For CO, Equation 14 becomes:

$$[CO]_{ms}P_T + LP_1 + MP_4 - P_5 = 0 \quad (\text{Eq. 18})$$

For NO_x, Equation 15 becomes:

$$[NO_x]_{ms}P_T + L'[NO_x]_{ms}P_1 + M'[NO_x]_{ms}P_4 - P_7 - P_8 = 0 \quad (\text{Eq. 19})$$

For NO, Equation 16 becomes:

$$[NO]_{ms}P_T + L'[NO]_{ms}P_1 + M'[NO]_{ms}P_4 - P_8 = 0 \quad (\text{Eq. 20})$$

For CO₂, Equation 17 becomes:

$$[CO_2]_{ms}P_T + J[CO_2]_{ms}P_3 - P_1 = 0 \quad (\text{Eq. 21})$$

5.2.2 NO_x Converter Efficiency

A chemiluminescent analyzer can be used to measure both nitric oxide, NO, and the oxides of nitrogen, NO_x. The nitrogen dioxide concentration, NO₂, is assumed to be the difference between the measured values of NO_x and NO. In the NO_x setting, the entire sample flows through a converter, which converts the NO₂ to NO such that all of the NO_x is measured as NO. In the NO setting, the converter is bypassed and only the sampled NO is measured. The NO_x converter has an efficiency, η , typically between 0.9 and 1.0. Reference 2.1.1 gives the procedure for determining this efficiency. The measured value of NO_x must be corrected for the quantity of NO₂ that was not converted to NO. From the definition of NO_x converter efficiency:

$$[NO_x]_{ms} = \eta[NO_2] + [NO] \quad (\text{Eq. 22})$$

Moles of nitrogen dioxide:

$$P_7 = P_T[NO_2]_w \quad (\text{Eq. 23})$$

Moles of nitric oxide:

$$P_8 = P_T[NO]_w \quad (\text{Eq. 11})$$

Correct the NO_x measurement for converter efficiency as follows:

$$[NO_x]_{ms} = \eta P_7 + P_8 \quad (\text{Eq. 24})$$

The NO_x converter efficiency affects only P₇. Combine Equations 19 and 24 to include the interference effects and the NO_x converter efficiency in the matrix solution:

$$[NO_x]_{ms}P_T + L'[NO_x]_{ms}P_1 + M'[NO_x]_{ms}P_4 - \eta P_7 - P_8 = 0 \quad (\text{Eq. 25})$$

5.2.3 Sample Drying

Some gas analysis systems require a cold trap or membrane dryer in the sample line ahead of the analyzers. Since these dryers do not remove the water vapor completely, the concentrations after the dryer are referred to as semidry. The frost or dew point temperature at the dryer exit is measured and the water vapor saturation pressure is obtained from the appropriate tables. Appendix B provides a method of calculating sample water content based on Reference 2.1.2.4. This method applies to inlet air frost or dew point temperatures as well as frost or dew point temperatures measured before the gas analysis system dryers as long as the local sample pressure is used to correct the ideal vapor pressure.

The water content of the sample after the sample dryer is closely approximated for very dry samples as:

$$h_{sd} = [H_2O]_{sd} = \frac{P_{4sd}}{P_T - P_4 + P_{4sd}} \quad (\text{Eq. 26a})$$

From Equation 26a, we can also write:

$$\begin{aligned} P_{4sd} &= h_{sd} \times (P_T - P_4 + P_{4sd}) = h_{sd} \times (P_T - P_4) + h_{sd} \times P_{4sd} \\ P_{4sd} \times (1 - h_{sd}) &= h_{sd} \times (P_T - P_4) \\ P_{4sd} &= (P_T - P_4) \times \frac{h_{sd}}{1 - h_{sd}} \end{aligned} \quad (\text{Eq. 26b})$$

The number of moles of semidry sample is greater than the number of moles of dry sample by P_{4sd} :

$$P_T - P_4 + P_{4sd} = (P_T - P_4) \left(1 + \frac{h_{sd}}{1 - h_{sd}} \right) = (P_T - P_4) \times \frac{1}{1 - h_{sd}} \quad (\text{Eq. 27})$$

The semidry concentrations of CO, CO₂, NO, NO_x, H₂O and O₂ are:

$$[CO]_{sd} = \frac{P_5}{P_T - P_4 + P_{4sd}} = \frac{P_5}{P_T - P_4} \times (1 - h_{sd}) \quad (\text{Eq. 28})$$

$$[CO_2]_{sd} = \frac{P_1}{P_T - P_4} \times (1 - h_{sd}) \quad (\text{Eq. 29})$$

$$[NO]_{sd} = \frac{P_8}{P_T - P_4} \times (1 - h_{sd}) \quad (\text{Eq. 30})$$

$$[NO_x]_{sd} = \frac{\eta P_7 + P_8}{P_T - P_4} \times (1 - h_{sd}) \quad (\text{Eq. 31})$$

$$[H_2O]_{sd} = \frac{P_{4sd}}{P_T - P_4} \times (1 - h_{sd}) = h_{sd} \quad (\text{Eq. 32})$$

$$[O_2]_{sd} = \frac{P_3}{P_T - P_4} \times (1 - h_{sd}) \quad (\text{Eq. 33})$$

Combining the interference and sample drying effects on the measured concentration of CO, Equation 8 in Matrix A is replaced by:

$$([CO]_{ms} + M h_{sd}) \times \frac{1}{1 - h_{sd}} \times (P_T - P_4) + L P_1 - P_5 = 0 \quad (\text{Eq. 34})$$

Combining the interference and sample drying effects on the measured concentration of CO₂, Equation 7 in Matrix A is replaced by:

$$[CO_2]_{ms} \times \frac{1}{(1 - h_{sd})} \times (P_T - P_4) - P_1 + (J[CO_2]_{ms}) P_3 = 0 \quad (\text{Eq. 35})$$

Combining the interference and sample drying effects on the measured concentration of NO, Equation 11 in Matrix A is replaced by:

$$[NO]_{ms} \times (1 + (h_{sd} \times M')) \times \frac{1}{(1 - h_{sd})} \times (P_T - P_4) + L[NO]_{ms} P_1 - P_8 = 0 \quad (\text{Eq. 36})$$