Final report, Ongoing Key Comparison BIPM.QM-K1, Ozone at ambient level, comparison with NIST, (June 2009)

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Abstract

As part of the ongoing key comparison BIPM.QM-K1, a comparison has been performed between the ozone national standard of the National Institute of Standards and Technology (NIST) and the common reference standard of the key comparison, maintained by the Bureau International des Poids et Mesures (BIPM). The instruments have been compared over a nominal ozone amount-of-substance fraction range of 0 nmol/mol to 500 nmol/mol.

Contents:

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1. Field

Amount of substance.

2. Subject

Comparison of reference measurement standards for ozone at ambient level.

3. Participants

BIPM.QM-K1 is an ongoing key comparison, which is structured as an ongoing series of bilateral comparisons. The results of the comparison with the National Institute of Standards and Technology (NIST) are reported here.

4. Organizing body

BIPM.

5. Rationale

The ongoing key comparison BIPM.QM-K1 has been running since January 2007. It follows the pilot study CCQM-P28 that included 23 participants and was preformed between July 2003 and February 2005 [1]. It is aimed at evaluating the degree of equivalence of ozone photometers that are maintained as national standards, or as primary standards within international networks for ambient ozone measurements. The reference value is determined using the NIST Standard Reference Photometer (BIPM-SRP27) maintained by the BIPM as a common reference.

6. Terms and definitions

- x_{nom}: nominal ozone amount-of-substance fraction in dry air furnished by the ozone generator
- $x_{A,i}$: ith measurement of the nominal value x_{nom} by the photometer A.
- $\bar{x}_A$: the mean of N measurements of the nominal value x_{nom} measured by the photometer A : $\bar{x}_A = \frac{1}{N}\sum_{i=1}^{N} x_{A,i}$
- s_A : standard deviation of N measurements of the nominal value x_{nom} measured by the photometer A : $s_A^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_{A,i} - \bar{x}_A)^2$
- The result of the linear regression fit performed between two sets of data measured by the photometers A and B during a comparison is written: $x_A = a_{A,B} x_B + b_{A,B}$. With this notation, the photometer A is compared versus the photometer B. $a_{A,B}$ is dimensionless and $b_{A,B}$ is expressed in units of nmol/mol.

7. Measurements schedule

The key comparison BIPM.QM-K1 was initially organised 2 years cycles. The 2007-2008 round, the results of which are published in the Key Comparison Database of the BIPM, included 16 participants. The second round of BIPM.QM-K1 started in March 2009 for a period of 4 years, following the decision of the CCQM/GAWG to reduce the repeat frequency of bilateral comparisons. Measurements reported in this report were performed from 21 May to 2 July 2009 at the NIST and the BIPM.

8. Measurement protocol

The comparison protocol is summarised in this section. The complete version can be downloaded from the BIPM website (http://www.bipm.org/utils/en/pdf/BIPM.QM-K1_protocol.pdf).

This comparison was performed following protocol B, corresponding to a comparison between the NIST national standard SRP2 and the common reference standard BIPM-SRP27 maintained at the BIPM via the transfer standard SRP0. The national standard SRP2 and the transfer standard SRP0 were first compared at the NIST in May 2009. Then SRP0 was compared with the common reference standard SRP27 at the BIPM two weeks later. Finally, the national standard SRP2 and the transfer standard SRP0 were again compared at the NIST in July 2009 to test the stability of the transfer standard.

A comparison between two (or more) ozone photometers consists of producing ozone-air mixtures at different mole fractions over the required range, and measuring these with the photometers.

8.1. Comparisons at the NIST

a). Ozone generation

The air is compressed with an oil-free compressor, dried and scrubbed with a commercial purification system so that the mole fraction of ozone and nitrogen oxides remaining in the air is below detectable limits. This air is used to provide reference air as well as the ozone-air mixture to each ozone photometer. Ozone is produced using an external commercial generator. A common dual external manifold in Pyrex is used to furnish the necessary flows of reference air and ozone-air mixtures to the ozone photometers. The two columns of this manifold are vented to atmospheric pressure.

b). Comparison procedure

Prior to the comparison, all the instruments were switched on and allowed to stabilise for a week. Characteristics of the instruments were checked at this time following an internal procedure. Basic adjustments of temperature, pressure, and dark counts following the SRP operating characteristics checkout were performed.

One comparison run includes 10 different mole fractions distributed to cover the range, together with the measurement of reference air at the beginning and end of each run. The nominal mole fractions were measured in a sequence imposed by the protocol (0, 220, 80, 420, 120, 320, 30, 370, 170, 500, 270, and 0) nmol/mol. Each of these points is an average of 10 single measurements.

For each nominal value of the ozone amount-of-substance fraction x_{nom} furnished by the ozone generator, the standard deviation s_{SRP2} on the set of 10 consecutive measurements $x_{\mathrm{SRP2},i}$

recorded by SRP2 was calculated. The measurement results were considered as valid if s_{SRP2} was less than 1 nmol/mol, which ensures that the photometers were measuring a stable ozone concentration. If not, another series of 10 consecutive measurements was performed.

c). Comparison repeatability

The comparison procedure was repeated continuously to evaluate its repeatability.

8.2. Comparisons at the BIPM

a). Ozone generation

The same source of purified air is used for all the ozone photometers being compared. This air is used to provide reference air as well as the ozone-air mixture to each ozone photometer. Ambient air is used as the source for reference air. The air is compressed with an oil-free compressor, dried and scrubbed with a commercial purification system so that the mole fraction of ozone and nitrogen oxides remaining in the air is below detectable limits. The relative humidity of the reference air is monitored and the mole fraction of water in air typically found to be less than 3 μmol/mol. The mole fraction of volatile organic hydrocarbons in the reference air was measured (November 2002), with no mole fraction of any detected component exceeding 1 nmol/mol.

A common dual external manifold in Pyrex is used to furnish the necessary flows of reference air and ozone-air mixtures to the ozone photometers. The two columns of this manifold are vented to atmospheric pressure.

b). Comparison procedure

Prior to the comparison, all the instruments were switched on and allowed to stabilise for at least 8 hours. The pressure and temperature measurement systems of the instruments were checked at this time. If any adjustments were required, these were noted. For this comparison, no adjustments were necessary.

One comparison run includes 10 different mole fractions distributed to cover the range, together with the measurement of reference air at the beginning and end of each run. The nominal mole fractions were measured in a sequence imposed by the protocol (0, 220, 80, 420, 120, 320, 30, 370, 170, 500, 270, and 0) nmol/mol. Each of these points is an average of 10 single measurements.

For each nominal value of the ozone amount-of-substance fraction x_{nom} furnished by the ozone generator, the standard deviation s_{SRP27} on the set of 10 consecutive measurements $x_{SRP27,i}$ recorded by BIPM-SRP27 was calculated. The measurement results were considered as valid if s_{SRP27} was less than 1 nmol/mol, which ensures that the photometers were measuring a stable ozone concentration. If not, another series of 10 consecutive measurements was performed.

c). Comparison repeatability

The comparison procedure was repeated continuously to evaluate its repeatability. The participant and the BIPM commonly decided when both instruments were stable enough to start recording a set of measurement results to be considered as the official comparison results.

d). SRP27 stability check

A second ozone reference standard, BIPM-SRP28, was included in the comparison to verify its agreement with BIPM-SRP27 and thus follow its stability over the period of the ongoing key comparison.

9. Reporting measurement results

The participant and the BIPM staff reported the measurement results in the result form BIPM.QM-K1-R2 provided by the BIPM and available on the BIPM website. It includes details on the comparison conditions, measurement results and associated uncertainties, as well as the standard deviation for each series of 10 ozone amount-of-substance fractions measured by the participant' standard and the common reference standard. The completed form BIPM.QM-K1-R2-NIST-09 is given in appendix 1.

10. Post comparison calculation

All calculations were performed by the BIPM using the form BIPM.QM-K1-R2. It includes the two degrees of equivalence that are reported as comparison results in the Appendix B of the BIPM KCDB (key comparison database). Additionally, the degrees of equivalence at all nominal ozone amount-of-substance fractions are reported in the same form, as well as the linear relationship between the participant standard and the common reference standard.

11. Deviations from the comparison protocol

In this comparison, there was no deviation from the protocol.

12. Measurement standards

All instruments included in this comparison were Standard Reference Photometers built by the NIST. More details on the instrument's principle and its capabilities can be found in [2]. The following section describes the SRP operating principle and uncertainty budget.

12.1. Measurement equation of a NIST SRP

The measurement of the ozone amount-of-substance fraction by an SRP is based on the absorption of radiation at 253.7 nm by ozonized air in the gas cells of the instrument. One particularity of the instrument design is the use of two gas cells to overcome the instability of the light source. The measurement equation is derived from the Beer-Lambert and ideal gas laws. The number concentration (C) of ozone is calculated from:

$$C = \frac{-1}{2\sigma L_{\mathrm{opt}}} \frac{T}{T_{\mathrm{std}}} \frac{P_{\mathrm{std}}}{P} \ln(D) \qquad (1)$$

where

σ is the absorption cross-section of ozone at 253.7 nm under standard conditions of temperature and pressure, 1.1476×10^{-17} cm^2/molecule [3].

L_{opt} is the mean optical path length of the two cells;

T is the measured temperature of the cells;

T_{std} is the standard temperature (273.15 K);

P is the measured pressure of the cells;

P_{std} is the standard pressure (101.325 kPa);

D is the product of transmittances of two cells, with the transmittance (T_r) of one cell defined as

$$T_r = \frac{I_{ozone}}{I_{air}} \quad (2)$$

where

I_{ozone} is the UV radiation intensity measured from the cell when containing ozonized air, and

I_{air} is the UV radiation intensity measured from the cell when containing pure air (also called reference or zero air).

Using the ideal gas law equation (1) can be recast in order to express the measurement results as a amount-of-substance fraction (x) of ozone in air:

$$x = \frac{-1}{2\sigma L_{opt}} \frac{T}{P} \frac{R}{N_A} \ln(D) \quad (3)$$

where

N_A is the Avogadro constant, 6.022142×10^{23} mol^{-1}, and

R is the gas constant, 8.314472 J mol^{-1} K^{-1}

The formulation implemented in the SRP software is:

$$x = \frac{-1}{2\alpha_x L_{opt}} \frac{T}{T_{std}} \frac{P_{std}}{P} \ln(D) \quad (4)$$

where

α_x is the linear absorption coefficient at standard conditions, expressed in cm^{-1}, linked to the absorption cross-section with the relation:

$$\alpha_x = \sigma \frac{N_A}{R} \frac{P_{std}}{T_{std}} \quad (5)$$

12.2. <u>Absorption cross-section for ozone</u>

The linear absorption coefficient under standard conditions α_x used within the SRP software algorithm is 308.32 cm^{-1}. This corresponds to a value for the absorption cross section σ of 1.1476×10^{-17} cm^2/molecule, rather than the more often quoted 1.147×10^{-17} cm^2/molecule. In the comparison of two SRP instruments, the absorption cross-section can be considered to have a conventional value and its uncertainty can be set to zero. However, in the comparison of different methods or when considering the complete uncertainty budget of the method the uncertainty of the absorption cross-section should be taken into account. A consensus value of

2.12 % at a 95 % level of confidence for the uncertainty of the absorption cross-section has been proposed by the BIPM and the NIST in a recent publication [4].

12.3. Condition of the BIPM SRPs

Compared to the original design described in [2], SRP27 and SRP28 have been modified to deal with two biases revealed by the study conducted by the BIPM and the NIST [4]. In 2009, an "SRP upgrade kit" was installed in the instruments, as described in the report [5].

12.4. Uncertainty budget of the common reference BIPM-SRP27

The uncertainty budget for the ozone amount-of-substance fraction in dry air (x) measured by the instruments BIPM-SRP27 and BIPM-SRP28 in the nominal range 0 nmol/mol to 500 nmol/mol is given in Table 1.

Table 1: Uncertainty budget for the SRPs maintained by the BIPM

Component (y)	**Uncertainty $u(y)$**				**Sensitivity coefficient $c_i = \frac{\partial x}{\partial y}$**	**contribution to $u(x)$ $\lvert c_i \rvert \cdot u(y)$ nmol/mol**
	Source	**Distribution**	**Standard Uncertainty**	**Combined standard uncertainty $u(y)$**		
Optical Path L_{opt}	Measurement scale	Rectangular	0.0006 cm	0.52 cm	$-\frac{x}{L_{opt}}$	$2.89 \times 10^{-3}x$
	Repeatability	Normal	0.01 cm			
	Correction factor	Rectangular	0.52 cm			
Pressure P	Pressure gauge	Rectangular	0.029 kPa	0.034 kPa	$-\frac{x}{P}$	$3.37 \times 10^{-4}x$
	Difference between cells	Rectangular	0.017 kPa			
Temperature T	Temperature probe	Rectangular	0.03 K	0.07 K	$\frac{x}{T}$	$2.29 \times 10^{-4}x$
	Temperature gradient	Rectangular	0.058 K			
Ratio of intensities D	Scaler resolution	Rectangular	8×10^{-6}	1.4×10^{-5}	$\frac{x}{D \ln(D)}$	0.28
	Repeatability	Triangular	1.1×10^{-5}			
Absorption Cross section σ	Hearn value		1.22×10^{-19} cm²/molecule	1.22×10^{-19} cm²/molecule	$-\frac{x}{\alpha}$	$1.06 \times 10^{-2}x$

Following this budget, as explained in the protocol of the comparison, the standard uncertainty associated with the ozone amount-of-substance fraction measurement with the BIPM SRPs can be expressed as a numerical equation (numerical values expressed as nmol/mol):

$$u(x) = \sqrt{(0.28)^2 + (2.92 \cdot 10^{-3} x)^2} \quad (6)$$

12.5. Covariance terms for the common reference BIPM-SRP27

As explained in section 14, correlations in between the results of two measurements performed at two different ozone amount-of-substance fractions with BIPM-SRP27 were taken into account in the software OzonE. More details on the covariance expression can be found in the protocol. The following expression was applied:

$$\boldsymbol{u}(\boldsymbol{x}_i, \boldsymbol{x}_j) = \boldsymbol{x}_i \cdot \boldsymbol{x}_j \cdot \boldsymbol{u}_\mathrm{b}^2 \quad (7)$$

where:

$$\boldsymbol{u}_\mathrm{b}^2 = \frac{\boldsymbol{u}^2(\boldsymbol{T})}{\boldsymbol{T}^2} + \frac{\boldsymbol{u}^2(\boldsymbol{P})}{\boldsymbol{P}^2} + \frac{\boldsymbol{u}^2(\boldsymbol{L}_\mathrm{opt})}{\boldsymbol{L}_\mathrm{opt}{}^2} \quad (8)$$

The value of u_b is given by the expression of the measurement uncertainty: $u_\mathrm{b} = 2.92 \times 10^{-3}$.

12.6. Condition of the NIST SRP2

Compared to the original design, the NIST SRP2 has been modified to deal with the two biases revealed in [4]. In 2006, an "SRP upgrade kit" was installed by NIST, as already described in the previous comparison report [6].

12.7. Uncertainty budget of the NIST SRP2

The uncertainty budget for the ozone amount-of-substance fraction in dry air x measured by the NIST standard SRP2 in the range 0 nmol/mol to 500 nmol/mol will follow the BIPM/NIST paper [4] (see Table 1) with an additional component based on the temperature probe heating effect. The initial uncertainty can be summarised by the formula:

$$u(x) = \sqrt{(0.28)^2 + (2.92 \times 10^{-3} x)^2} \quad (9)$$

After correcting for the temperature probe heating bias, the final uncertainty is calculated by:

$$\begin{aligned} u(x)^+ &= u(x) \\ u(x)^- &= u(x) - 0.001x \end{aligned} \quad (10)$$

Because the BIPM.QM-K1-R2 spreadsheet does not allow the uncertainty to be expressed by different positive and negative amounts, it has been expressed as:

$$u(x) = u(x) + 0.001x \quad (11)$$

No covariance term for the NIST SRP2 was included in the calculations.

12.8. Transfer standard SRP0

SRP0 uncertainty budget is the same as SRP2.

13. Measurement results and uncertainties

Details of the measurement results, the measurement uncertainties and the standard deviations at each nominal ozone amount-of-substance fraction can be found in the form BIPM.QM-K1-R2-NIST-09 given in appendix 1.

14. Analysis of the measurement results by generalised least-square regression

The relationship between the national and reference standards was first evaluated with a generalised least-square regression fit, using the software OzonE. This software, which is documented in a publication [7], is an extension of the previously used software B_Least recommended by the ISO standard 6143:2001 [8]. It includes the possibility to take into account correlations between measurements performed with the same instrument at different ozone amount-of-substance fractions. It also facilitates the use of a transfer standard, by handling of unavoidable correlations, which arise since this instrument needs to be calibrated by the reference standard.

The two comparisons performed via the transfer standard were treated as follows:

- The first comparison results are calculated by performing a linear regression on the twelve data points from the BIPM visit (x_{RS}, x_{TS}) (calibration of the transfer standard) followed by a second linear regression of the twelve data points from the **pre** BIPM visit (x_{NS}, x'_{TS}), x'_{TS} being the corrected values of the transfer standard calibrated by the reference standard.

- The second comparison results are calculated by performing a linear regression on the twelve data points from the BIPM visit (x_{RS}, x_{TS}) (calibration of the transfer standard) followed by a second linear regression of the twelve data points from the **post** BIPM visit (x_{NS}, x'_{TS}), x'_{TS} being the corrected values of the transfer standard calibrated by the reference standard.

For each comparison, a linear relationship between the ozone amount-of-substance fractions measured by SRP*n* and SRP27 is obtained:

$$x_{\mathrm{SRP}n} = a_0 + a_1 x_{\mathrm{SRP27}} \quad (12)$$

The associated uncertainties on the slope $u(a_1)$ and the intercept $u(a_0)$ are given by OzonE, as well as the covariance between them and the usual statistical parameters to validate the fitting function.

14.1. Least-square regression results

The two relationships between SRP2 and SRP27 are:

$$x_{\mathrm{SRP2}} = -0.16 + 1.0036 \cdot x_{\mathrm{SRP27}} \quad (13)$$

from the pre BIPM visit, with the uncertainties $u(a_0)$ = 0.33 nmol/mol, $u(a_1)$ = 0.0042, $\mathrm{cov}(a_0, a_1) = -5.1 \times 10^{-4}$, and $$x_{\mathrm{SRP2}} = -0.05 + 1.0042 \cdot x_{\mathrm{SRP27}} \tag{14}$$

from the post BIPM visit, with the uncertainties $u(a_0)$ = 0.33 nmol/mol, $u(a_1)$ = 0.0042, $\mathrm{cov}(a_0, a_1) = -5.1 \times 10^{-4}$.

To asses the agreement of the standards from equations 11 and 12, the difference between the calculated slope value and unity, and the intercept value and zero, together with their measurement uncertainties need to be considered. In both comparisons, the value of the intercept is consistent with an intercept of zero, considering the uncertainty in the value of this parameter; i.e $|a_0| < 2u(a_0)$, and the value of the slope is consistent with a slope of 1; i.e. $|1 - a_1| < 2u(\mathrm{a}_1)$.

15. Degrees of equivalence

Degrees of equivalence are calculated at two nominal ozone amount-of-substance fractions among the twelve measured in each comparison, in the nominal range 0 nmol/mol to 500 nmol/mol: 80 nmol/mol and 420 nmol/mol. These values correspond to points number 3 and 4 recorded in each comparison. As an ozone generator has limited reproducibility, the ozone amount-of-substance fractions measured by the ozone standards can differ from the nominal values. However, as stated in the protocol, the value measured by the common reference SRP27 was expected to be within ±15 nmol/mol of the nominal value. Hence, it is meaningful to compare the degree of equivalence calculated for all the participants at the same nominal value.

15.1. <u>Definition of the degrees of equivalence</u>

Within protocol B, the degree of equivalence of the participant i, at a nominal value x_{nom} is defined as:

$$D = x_i - \hat{x}_{\mathrm{SRP27}} \tag{15}$$

Where x_{i} is the measurement results of the national standard at the nominal value x_{nom}, and $\hat{x}_{SRP27}$ is the predicted value of SRP27 at the same nominal value, deduced from the transfer standard measurement result during its comparison with the national standard.

Its associated standard uncertainty is:

$$u(D) = \sqrt{u^2(x_i) + u^2(\hat{x}_{\mathrm{SRP27}})} \tag{16}$$

where $u(x_{\mathrm{i}})$ is the measurement uncertainties of the participant i and $u(\hat{x}_{SRP27})$ is the uncertainty associated with the predicted value of SRP27.

15.2. <u>Calculation of SRP27 predicted values and their related uncertainties</u>

The comparison performed at the BIPM between the transfer standard and the reference standard SRP27 is used to calibrate the transfer standard. The data $\overline{x}_{\mathrm{RS}}$ and $\overline{x}_{\mathrm{TS}}$ are fitted using the generalised least square program OzonE, taking into account the associated uncertainties $u(\overline{x}_{RS})$ and $u(\overline{x}_{TS})$, as well as covariance terms between the reference standard measurement results.

The parameters $a_{RS,TS}$ and $b_{RS,TS}$ of the linear relationship between x_{RS} and x_{TS} ($x_{RS} = a_{RS,TS}$ x_{TS} $+b_{RS,T}$) are calculated as well as their uncertainties.

Then, for each value $\overline{x}_{TS}$ measured with the transfer standard during its comparison with the national standard, a predicted value $\hat{x}_{RS}$ for the reference standard is evaluated using the linear relationships between the two instruments calculated above.

The standard uncertainties associated with the predicted values $\hat{x}_{RS}$ are evaluated according to the equation:

$$u(\hat{x}_{RS}) = \sqrt{u^2(b_{RS,TS}) + x_{TS}^2 \cdot u^2(a_{RS,TS}) + a_{RS,TS}^2 \cdot u^2(x_{TS}) + 2 \cdot x_{TS} \cdot u(a_{RS,TS}, b_{RS,TS})} \quad (17)$$

Where the uncertainty components $u(a_{RS,TS})$, $u(b_{RS,TS})$ and $u(a_{RS,TS}, b_{RS,TS})$ are calculated with the generalised least-square software OzonE.

15.3. Values of the degrees of equivalence

When protocol B is followed, the national and reference standards are compared twice to monitor the transfer standard stability. Therefore, two degrees of equivalence are calculated at each nominal ozone amount-of-substance fraction.

The degrees of equivalence and their uncertainties calculated in the form BIPM.QM-K1-R2-NIST-09 are reported in the table below. Corresponding graphs of equivalence are displayed in Figure 1. The expanded uncertainties are calculated with a coverage factor $k = 2$.

Table 2 : degrees of equivalence of the NIST at the ozone nominal mole fractions 80 nmol/mol and 420 nmol/mol

Nominal value	x_i / (nmol/mol)	u_i / (nmol/mol)	x_{SRP27} / (nmol/mol)	u_{SRP27} / (nmol/mol)	D_i / (nmol/mol)	$u(D_i)$ / (nmol/mol)	$U(D_i)$ / (nmol/mol)
80	81.47	0.45	81.26	0.54	0.21	0.70	1.40
420	419.11	1.67	417.62	2.17	1.48	2.74	5.48
80	80.87	0.45	80.64	0.54	0.23	0.70	1.40
420	419.37	1.68	417.80	2.17	1.57	2.74	5.48

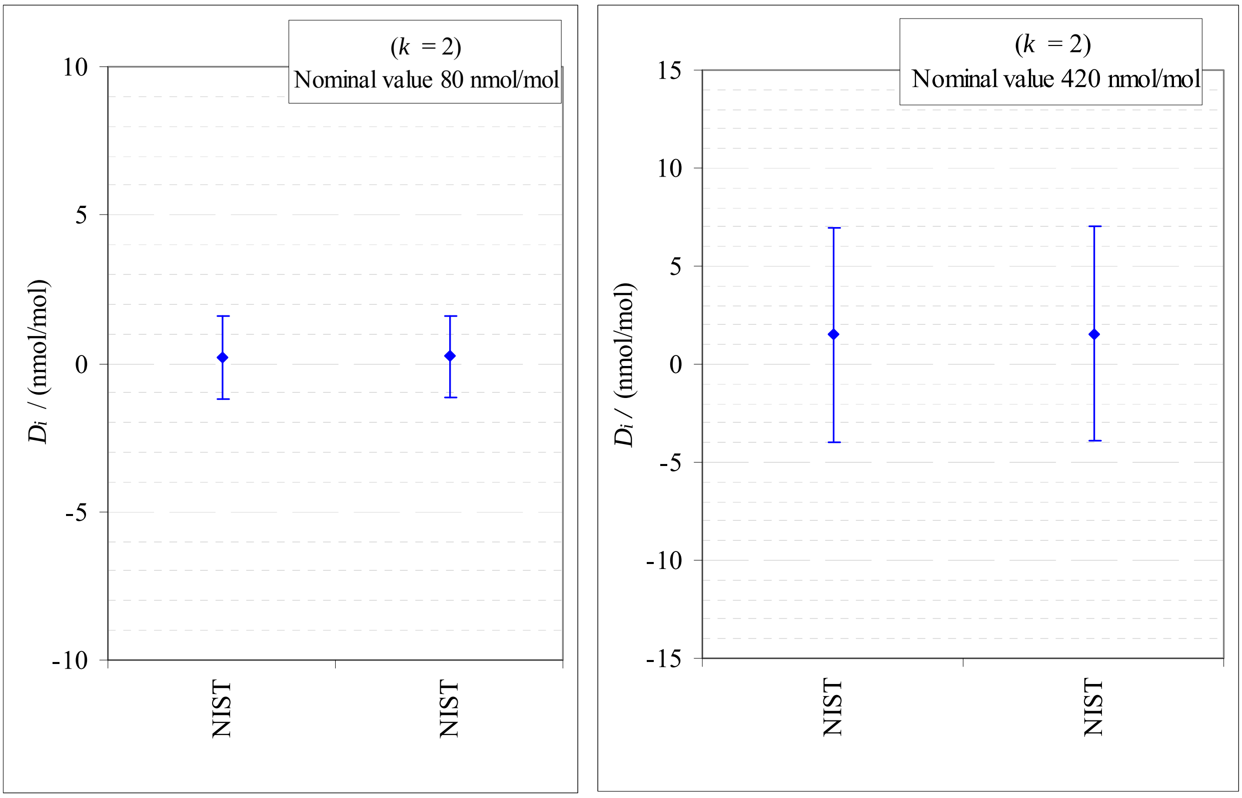

Figure 1: degrees of equivalence of the NIST at the two nominal ozone amount-of-substance fractions 80 nmol/mol and 420 nmol/mol

The degrees of equivalence between the NIST standard and the common reference standard BIPM SRP27 indicate good agreement between the standards. A discussion on the relation between degrees of equivalence and CMC statements can be found in [1].

16. Stability of the transfer standard

The slope of the linear relationship deduced from the two comparisons performed between the NIST national standard SRP2 and the common reference standard SRP27 shows a decrease of 0.06% (equations 13 and 14). This is very small compared to the uncertainties. The transfer standard SRP0 can be considered stable over the course of this comparison.

17. History of comparisons between BIPM SRP27, SRP28 and NIST SRP2

Results of the previous comparison performed with NIST during the pilot study CCQM-P28 and the first cycle of the key comparison BIPM.QM-K1 are displayed in Figure 2 together with the results of this comparison. The slopes a_1 of the linear relation $x_{SRPn} = a_0 + a_1\, x_{\mathrm{SRP27}}$ are represented together with their associated uncertainties calculated at the time of each comparison. Results of previous comparisons have been corrected to take into account the changes in the reference BIPM-SRP27 described in [5], which explains the larger uncertainties associated with the corresponding slopes. Figure 2 shows that all standards included in these comparisons stayed in close agreement.

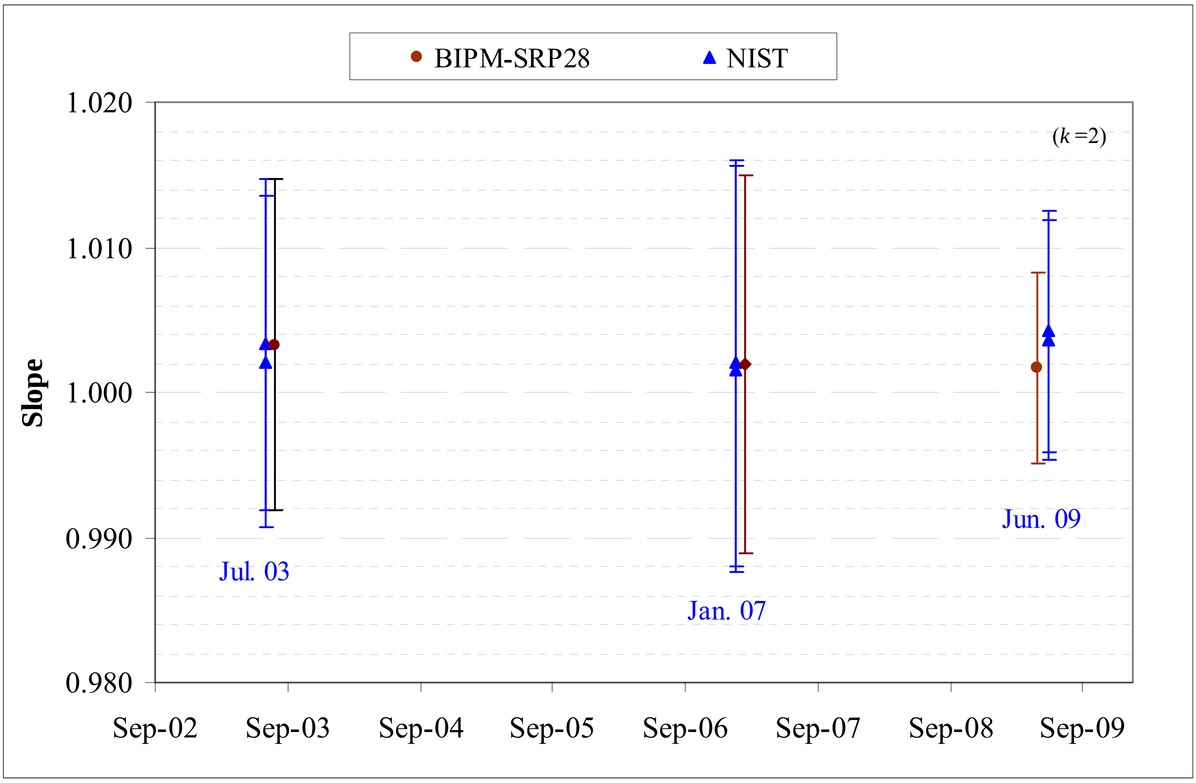

Figure 2 : Results of previous comparisons between SRP27, SRP28 and NIST-SRP2 realised at the BIPM. Uncertainties are calculated at k = 2, with the uncertainty budget in use at the time of each comparison.

18. Summary of previous comparisons included in BIPM.QM-K1

The comparison with NIST is the first one in the 2009-2012 round of BIPM.QM-K1. An updated summary of BIPM.QM-K1 results can be found in the key comparison database: http://kcdb.bipm.org/appendixB/.

19. Conclusion

For the second time since the launch of the ongoing key comparison BIPM.QM-K1, a comparison has been performed between the ozone national standard of the NIST and the common reference standard of the key comparison, maintained by the BIPM. The instruments have been compared over a nominal ozone amount-of-substance fraction range of 0 nmol/mol to 500 nmol/mol. Degrees of equivalence of this comparison indicated very good agreement between both standards.

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Appendix 1 - Form BIPM.QM-K1-R2-NIST-09

See the following pages.

OZONE COMPARISON RESULT - PROTOCOL B - WITH A TRANSFER STANDARD

Participating institute information	
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Instruments information			
	Reference Standard	**National Standard**	**Transfer Standard**
Manufacturer	NIST	NIST	NIST
Type	SRP	SRP	SRP
Serial number	SRP27	SRP2	SRP0
ozone cross-section value	308.32 atm^{-1} cm^{-1}	308.32 atm-1 cm-1	308.32 atm-1 cm-1

Content of the report

This workbook contains macros. It is recommended not to use them.

Please complete the cells containing blue stars only.

comparison national standard (RS) vs reference standard (NS)

Summary of comparison results

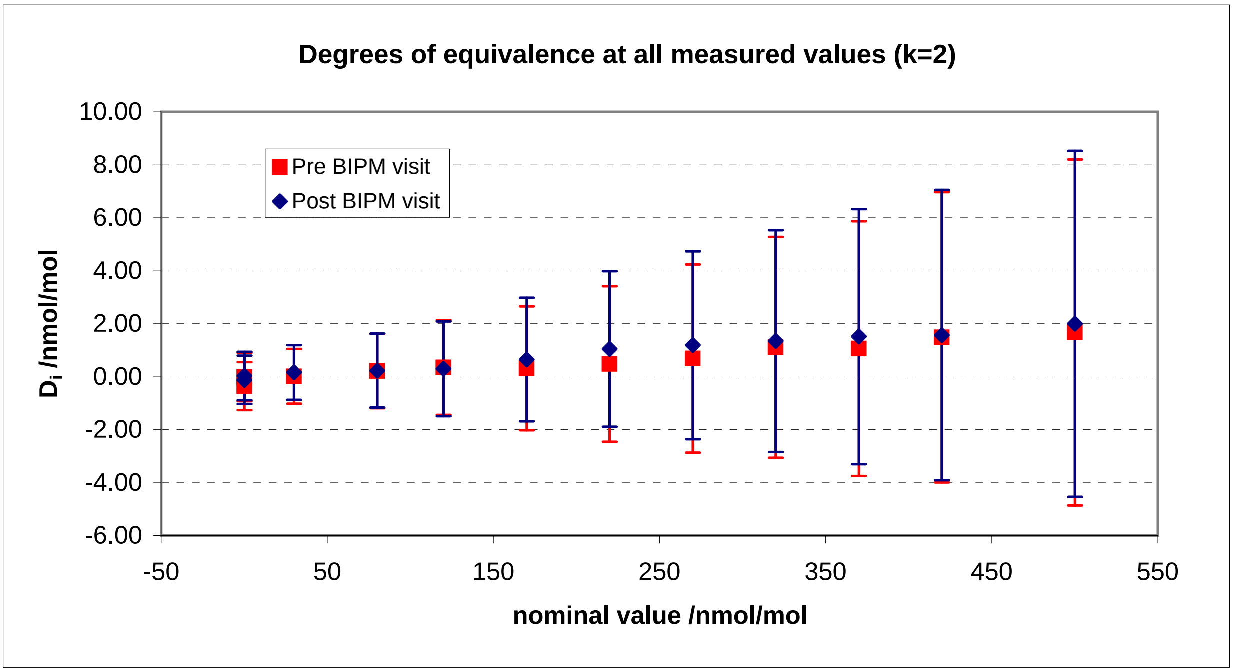
Equation $$x_{NS} = a_{NS,RS}\, x_{RS} + b_{NS,RS}$$

Least-square regression parameters

	$a_{NS,RS}$	$u(a_{NS,RS})$	$b_{NS,RS}$ (nmol/mol)	$u(b_{NS,RS})$ (nmol/mol)	$u(a,b)$
first comparison	1.0036	0.0042	-0.16	0.33	-5.11E-04
second comparison	1.0042	0.0042	-0.05	0.33	-5.12E-04

Degrees of equivalence at 80 nmol/mol and 420 nmol/mol:

	Nom value (nmol/mol)	D_i (nmol/mol)	$u(D_i)$ (nmol/mol)	$U(D_i)$ (nmol/mol)
first comparison	80	0.21	0.70	1.40
	420	1.48	2.74	5.48
second comparison	80	0.23	0.70	1.40
	420	1.57	2.74	5.48



Calculation of the National Standard vs Reference Standard comparison results through the first National Standard vs Transfer Standard comparison

First comparison results						
	National standard measurement results		Transfer standard measurement results		Reference Standard prediced values	
Nominal value	x_{NS} nmol/mol	$u(x_{NS})$ nmol/mol	x_{TS} nmol/mol	$u(x_{TS})$ nmol/mol	x'_{RS} nmol/mol	$u(x'_{RS})$ nmol/mol
0	-0.19	0.28	0.08	0.28	0.16	0.36
220	217.38	0.91	217.36	0.91	216.90	1.15
80	81.47	0.45	81.38	0.45	81.26	0.54
420	419.11	1.67	418.59	1.67	417.62	2.17
120	119.29	0.57	119.16	0.57	118.95	0.69
320	316.48	1.28	316.08	1.28	315.37	1.65
30	34.32	0.33	34.31	0.33	34.31	0.40
370	367.08	1.47	366.86	1.47	366.02	1.90
170	167.21	0.73	167.23	0.73	166.89	0.91
500	501.32	1.99	500.82	1.99	499.65	2.59
270	267.06	1.10	266.97	1.10	266.38	1.40
0	-0.08	0.28	-0.16	0.28	-0.07	0.36

Reference standard predicted values are deduced from the transfer standard measurement results using the calibration performed at the BIPM, with the parameters calculated in Excel Worksheet 4 (page 7)

$$x'_{RS} = a_{RS,TS}x_{TS} + b_{RS,TS} \qquad u(x'_{RS}) = \sqrt{a^2_{RS,TS}\cdot u(x_{TS})^2 + x^2_{TS}\cdot u(a_{RS,TS})^2 + u(b_{RS,TS})^2 + 2\cdot x_{TS}\cdot u(a_{RS,TS}, b_{RS,TS})}$$

$a_{RS,TS}$	0.9975	$b_{NRS,TS}$ (nmol/mol)	0.09	$u(a,b)$	-2.30E-04
$u(a_{RS,TS})$	0.0034	$u(b_{RS,TS})$ (nmol/mol)	0.22		

Degrees of Equivalence		$D_i = x_{NS} - x'_{RS}$		
Point Number	**Nom value (nmol/mol)**	D_i *(nmol/mol)*	$u(D_i)$ *(nmol/mol)*	$U(D_i)$ *(nmol/mol)*
1	**0**	-0.36	0.45	0.91
2	**220**	0.48	1.47	2.94
3	**80**	0.21	0.70	1.40
4	**420**	1.48	2.74	5.48
5	**120**	0.34	0.89	1.79
6	**320**	1.11	2.09	4.17
7	**30**	0.01	0.52	1.03
8	**370**	1.06	2.41	4.81
9	**170**	0.31	1.17	2.34
10	**500**	1.67	3.27	6.53
11	**270**	0.68	1.78	3.55
12	**0**	-0.01	0.45	0.91

Least-square regression parameters				
$a_{NS,RS}$	$u(a_{NS,RS})$	$b_{NS,RS}$ (nmol/mol)	$u(b_{NS,RS})$ (nmol/mol)	$u(a,b)$
1.0036125	**0.0041513**	**-0.1637675**	**0.3257132**	**-0.0005114**

Calculation of the National Standard vs Reference Standard comparison results through the second National Standard vs Transfer Standard comparison

Second comparison results

	National standard measurement results		Transfer standard measurement results		Reference Standard prediced values	
Nominal value	x_{NS} nmol/mol	$u(x_{NS})$ nmol/mol	x_{TS} nmol/mol	$u(x_{TS})$ nmol/mol	x'_{RS} nmol/mol	$u(x'_{RS})$ nmol/mol
0	0.00	0.28	0.04	0.28	0.12	0.36
220	217.57	0.91	216.98	0.91	216.52	1.15
80	80.87	0.45	80.76	0.45	80.64	0.54
420	419.37	1.68	418.77	1.67	417.80	2.17
120	119.11	0.57	119.02	0.57	118.81	0.69
320	317.42	1.29	316.78	1.28	316.07	1.65
30	34.09	0.33	33.93	0.33	33.93	0.40
370	367.81	1.48	367.14	1.48	366.30	1.90
170	166.75	0.73	166.43	0.73	166.10	0.91
500	501.87	1.99	501.05	1.99	499.87	2.59
270	266.90	1.10	266.30	1.09	265.71	1.40
0	0.02	0.28	-0.09	0.28	0.00	0.36

Reference standard predicted values are deduced from the transfer standard measurement results using the calibration performed at the BIPM, with the parameters calculated in Excel Worksheet 4 (page 7)

$$x'_{RS} = a_{RS,TS} x_{TS} + b_{RS,TS} \qquad u(x'_{RS}) = \sqrt{a_{RS,TS}^2 \cdot u(x_{TS})^2 + x_{TS}^2 \cdot u(a_{RS,TS})^2 + u(b_{RS,TS})^2 + 2 \cdot x_{TS} \cdot u(a_{RS,TS}, b_{RS,TS})}$$

$a_{RS,TS}$	0.9975	$b_{NRS,TS}$ (nmol/mol)	0.09	$u(a,b)$	-2.30E-04
$u(a_{RS,TS})$	0.0034	$u(b_{RS,TS})$ (nmol/mol)	0.22		

Degrees of Equivalence $D_i = x_{NS} - x'_{RS}$

Point Number	Nom value (nmol/mol)	D_i (nmol/mol)	$u(D_i)$ (nmol/mol)	$U(D_i)$ (nmol/mol)
1	**0**	-0.12	0.45	0.91
2	**220**	1.05	1.47	2.94
3	**80**	0.23	0.70	1.40
4	**420**	1.57	2.74	5.48
5	**120**	0.30	0.89	1.79
6	**320**	1.34	2.09	4.18
7	**30**	0.16	0.52	1.03
8	**370**	1.51	2.41	4.82
9	**170**	0.65	1.16	2.33
10	**500**	1.99	3.27	6.54
11	**270**	1.19	1.77	3.55
12	**0**	0.03	0.45	0.91

Least-square regression parameters

$a_{NS,RS}$	$u(a_{NS,RS})$	$b_{NS,RS}$ (nmol/mol)	$u(b_{NS,RS})$ (nmol/mol)	$u(a,b)$
1.0042192	**0.0041558**	**-0.0525996**	**0.3257567**	**-0.0005117**

Data reporting sheet
First comparison of transfer standard (TS) vs national standard (NS)

Operator	Jim Norris	**Location**	NIST
Comparison begin date / time	21 May 2009/12:50 AM	**Comparison end date / time**	21 May 2009/14:46 PM

measurement results

	Transfer standard (TS)			National Standard (NS)		
Nominal value	x_{TS} nmol/mol	s_{TS} nmol/mol	$u(x_{TS})$ nmol/mol	x_{NS} nmol/mol	s_{NS} nmol/mol	$u(x_{NS})$ nmol/mol
0	0.1	0.2	0.280	-0.2	0.2	0.280
220	217.4	0.4	0.911	217.4	0.3	0.911
80	81.4	0.1	0.449	81.5	0.1	0.449
420	418.6	0.2	1.673	419.1	0.2	1.675
120	119.2	0.2	0.566	119.3	0.2	0.566
320	316.1	0.3	1.281	316.5	0.2	1.282
30	34.3	0.3	0.332	34.3	0.1	0.332
370	366.9	0.2	1.474	367.1	0.2	1.475
170	167.2	0.2	0.730	167.2	0.3	0.730
500	500.8	0.2	1.990	501.3	0.2	1.992
270	267.0	0.1	1.095	267.1	0.2	1.096
0	-0.2	0.2	0.280	-0.1	0.2	0.280

Note : according to the protocol, these measurement results are the last TS-NS comparison measurement results recorded

Covariance terms in between two measurement results of the national standard

Equation $u(x_i, x_j) = \alpha \cdot x_i \cdot x_j$ Value of α 0.00E+00

Comparison conditions	
Ozone generator manufacturer	Environics
Ozone generator type	Model 6100
Ozone generator serial number	3355
Room temperature(min-max) / °C	21.06/21.21
Room pressure (average) / hpa	1009.24
Zero air source	Addco 737
Reference air flow rate (L/min)	9
Sample flow rate (L/min)	9
Instruments stabilisation time	months
Instruments acquisition time /s (one measurement)	25
Instruments averaging time /s	275
Total time for ozone conditioning	2 hours
Ozone mole fraction during conditioning	950 nmol/mol
Comparison repeated continously (Yes/No)	Yes
If no, ozone mole fraction in between the comparison repeats	***
Total number of comparison repeats realised	10

Instruments checks and adjustments

National Standard

These measurements were performed at NIST in accordance with the Gas Metrology Group Quality Manual (QM-III-839.03), following TP 839.0312B [Validation of Standard Reference Photometers].

Transfer Standard

These measurements were performed at NIST in accordance with the Gas Metrology Group Quality Manual (QM-III-839.03), following TP 839.0312B [Validation of Standard Reference Photometers].

calibration of the transfer standard (TS) by the reference standard (RS)

Operator	Moussay, F. Idrees, J. Nor	**Location**	BIPM
Comparison begin date / time	05/06/2009 14:41	**Comparison end date / time**	05/06/2009 16:42

Calibration results

Equation $x_{RS} = a_{RS,TS} x_{TS} + b_{RS,TS}$

Least-square regression parameters				
$a_{RS,TS}$	$u(a_{RS,TS})$	$b_{RS,TS}$ (nmol/mol)	$u(b_{RS,TS})$ (nmol/mol)	$u(a,b)$
0.9974852	**0.0034230**	**0.0871930**	**0.2233702**	**-0.0002299**

(Least-square regression parameters will be computed by the BIPM using the sofwtare OzonE v2.0)

Measurement results

	Transfer standard (TS)			Reference Standard (RS)		
Nominal value	x_{TS} nmol/mol	s_{TS} nmol/mol	$u(x_{TS})$ nmol/mol	x_{RS} nmol/mol	s_{RS} nmol/mol	$u(x_{RS})$ nmol/mol
0	0.02	0.16	0.28	0.07	0.26	0.28
220	217.42	0.18	0.91	217.03	0.09	0.69
80	78.28	0.19	0.44	78.30	0.28	0.36
420	414.12	0.47	1.66	413.05	0.56	1.24
120	117.86	0.18	0.56	117.81	0.20	0.44
320	314.98	0.12	1.28	314.03	0.20	0.96
30	28.80	0.22	0.32	28.79	0.30	0.29
370	364.73	0.26	1.47	363.60	0.32	1.10
170	167.00	0.19	0.73	166.66	0.25	0.56
500	496.73	0.16	1.97	495.58	0.34	1.47
270	267.45	0.15	1.10	266.85	0.15	0.83
0	0.02	0.26	0.28	0.08	0.19	0.28

Note : according to the protocol, these measurement results are the last TS-RS comparison measurement results

Covariance terms in between two measurement results of the reference standard

Equation $u(x_i, x_j) = \alpha \cdot x_i \cdot x_j$

Value of α 8.50E-06

Comparison conditions

Ozone generator manufacturer	Environics
Ozone generator type	Model 6100
Ozone generator serial number	***
Room temperature(min-max) / °C	***
Room pressure (average) / hpa	***
Zero air source	Addco 737
Reference air flow rate (L/min)	***
Sample flow rate (L/min)	***
Instruments stabilisation time	***
Instruments acquisition time /s (one measurement)	25 s
Instruments averaging time /s	***
Total time for ozone conditioning	120 min.
Ozone mole fraction during conditioning	***
Comparison repeated continously (Yes/No)	Yes
If no, ozone mole fraction in between the comparison repeats	***
Total number of comparison repeats realised	14
Data files names and location	c090602001 - c090605004
	***

***

Instruments checks and adjustments

Reference Standard

Transfer Standard

These measurements were performed in accordance with the Gas Metrology Group Quality Manual (QM-III-839.03), following TP 839.0312B [Validation of Standard Reference Photometers].

Data reporting sheet
Second comparison of transfer standard (TS) vs national standard (NS)

Operator	Jim Norris	**Location**	NIST
Comparison begin date / time	02/07/2009 15:21	**Comparison end date / time**	02/07/2009 17:17

measurement results

	Transfer standard (TS)			National Standard (NS)		
Nominal value	x_{TS} nmol/mol	s_{TS} nmol/mol	$u(x_{TS})$ nmol/mol	x_{NS} nmol/mol	s_{NS} nmol/mol	$u(x_{NS})$ nmol/mol
0	0.0	0.1	0.28	0.0	0.2	0.28
220	217.0	0.3	0.91	217.6	0.2	0.91
80	80.8	0.2	0.45	80.9	0.1	0.45
420	418.8	0.2	1.67	419.4	0.1	1.68
120	119.0	0.3	0.57	119.1	0.2	0.57
320	316.8	0.2	1.28	317.4	0.2	1.29
30	33.9	0.2	0.33	34.1	0.1	0.33
370	367.1	0.2	1.48	367.8	0.4	1.48
170	166.4	0.2	0.73	166.7	0.1	0.73
500	501.0	0.2	1.99	501.9	0.2	1.99
270	266.3	0.1	1.09	266.9	0.2	1.10
0	-0.1	0.2	0.28	0.0	0.2	0.28

Note : according to the protocol, these measurement results are the last TS-NS comparison measurement results recorded

Covariance terms in between two measurement results of the national standard

Equation $u(x_i, x_j) = \alpha \cdot x_i \cdot x_j$ Value of α 0.00E+00

Comparison conditions

Ozone generator manufacturer	Environics
Ozone generator type	Model 6100
Ozone generator serial number	3355
Room temperature(min-max) / °C	20.92/21.27
Room pressure (average) / hpa	993.3
Zero air source	Addco 737
Reference air flow rate (L/min)	9
Sample flow rate (L/min)	9
Instruments stabilisation time	SRP 2 - months, SRP 0 - 1 week
Instruments acquisition time /s (one measurement)	25
Instruments averaging time /s	275
Total time for ozone conditioning	2 hours
Ozone mole fraction during conditioning	980 nmol/mol
Comparison repeated continously (Yes/No)	Yes
If no, ozone mole fraction in between the comparison repeats	***
Total number of comparison repeats realised	31

Instruments checks and adjustments

National Standard

These measurements were performed at NIST in accordance with the Gas Metrology Group Quality Manual (QM-III-839.03), following TP 839.0312B [Validation of Standard Reference Photometers].

Transfer Standard

These measurements were performed at NIST in accordance with the Gas Metrology Group Quality Manual (QM-III-839.03), following TP 839.0312B [Validation of Standard Reference Photometers].

Uncertainty budgets (description or reference)

Reference Standard

Transfer Standard

The uncertainty budget for NIST SRP 0 will follow the BIPM/NIST bias paper with the addition of an additional component based on the temperature probe heating affect. The initial uncertainty can be summarised by the formula:

$$u(x) = \sqrt{(0.28)^2 + \left(2.92 \times 10^{-3}\, x\right)^2}\; nmol/mol$$

After correcting for the temperature probe heating bias, the final uncertainty is calculated by:

$$u(x)^+ = u(x);\;\; u(x)^- = u(x) + (-\,0.001 \times x)\, nmol/mol$$

Because the BIPM.QM-K1-R2 spreadsheet does not allow the uncertainty to be expressed with different positive and negitive amounts, it has been expressed as:

$$u(x) = u(x) + (0.001 \times x)\, nmol/mol$$

Because NIST SRP 0 has the new 3 degree angled cell windows, there is no path-length correction.

National Standard

The uncertainty budget for NIST SRP 2 will follow the BIPM/NIST bias paper with the addition of an additional component based on the temperature probe heating affect. The initial uncertainty can be summarised by the formula:

$$u(x) = \sqrt{(0.28)^2 + \left(2.92 \times 10^{-3}\, x\right)^2}\ nmol/mol$$

After correcting for the temperature probe heating bias, the final uncertainty is calculated by:

$$u(x)^+ = u(x);\ \ u(x)^- = u(x) + (-\,0.001 \times x)\,nmol/mol$$

Because the BIPM.QM-K1-R2 spreadsheet does not allow the uncertainty to be expressed with different positive and negitive amounts, it has been expressed as:

$$u(x) = u(x) + (0.001 \times x)\,nmol/mol$$

Because NIST SRP 2 has the new 3 degree angled cell windows, there is no path-length correction.