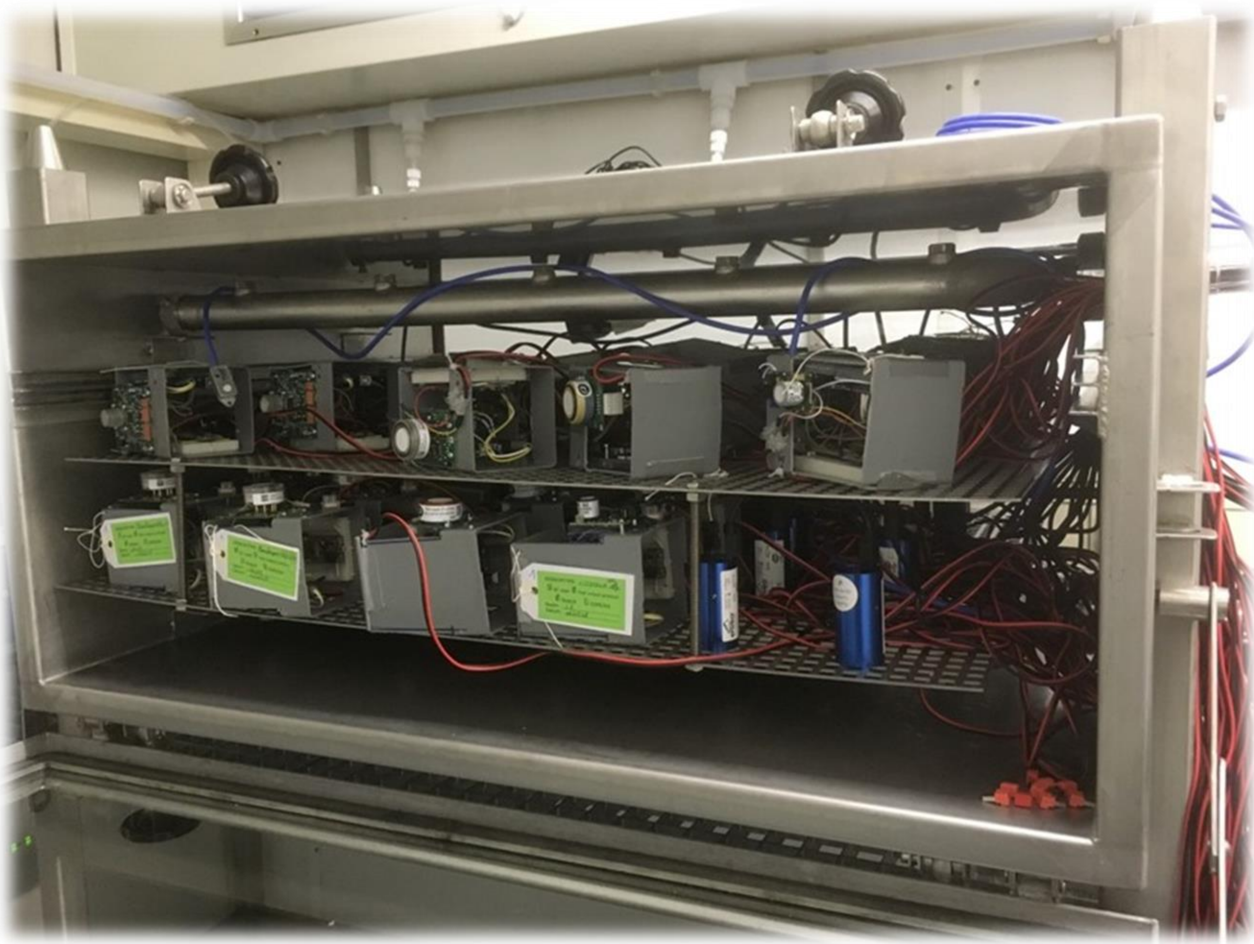
Evaluation of the laboratory testing of nitrogen dioxide sensor systems

Author: Ernie Weijers



VAQUUMS

Index

1 Introduction

The performance characteristics of the nitrogen dioxide (NO_2) sensors determined in our laboratory study were: accuracy (deviation from reference), linearity (coefficient of determination, slope, intercept; compared to reference), sensor stability (standard deviation of the sensor signal), between-sensor uncertainty, influence of temperature and relative humidity and cross-interference.

In total, the laboratory tests took 77 hours. Essential part of the testing schedule was the ramping experiment at constant temperature and relative humidity. During this experiment concentrations (NO_2, O_3) were kept constant for two hours followed by a stepwise change to another concentration level. For further details on the experimental setup, the reader is referred to the test protocol.

The VAQUUMs project started with the selection of a number of gas sensors (nitrogen dioxide and ozone) for the comparative testing (laboratory and field). The following sensor systems were finally chosen (Table 1):

Table 1 The list of NO_2-sensors as selected in the VAQUUMS project

NO_2	**O_3**
Alphasense B43F	Aeroqual SM50
Envea Cairclip NO_2	Alphasense B431
Citytech 3E50*	Citytech 3E1F*
Membrapor C1	Envea Cairclip O3
Membrapor C20	Membrapor C5

Note that no lab test results can be shown for the Citytech sensors. The sensors were not installed properly, due to a mistake by the VAQUUMS-team. Thus, no trustworthy data have been collected in the laboratory.

In this report we will discuss the results of the NO_2 sensors. First a summary is given, followed by a report per sensor type.

2 Summary NO_2 sensors

Already at the start of the experiment, it turned out that not every NO_2-sensor copy operated in a satisfactory manner. Here, only the sets of Alphasense and Membrapor C1 types measured without noticeable malfunctioning. For the remaining sensor systems, at least one copy appeared unreliable (and therefore excluded from the experiment).

During the ramping experiment all the sensor copies tracked reasonably well with the step changes in concentration (measured by the reference instrument). As an example, see the results for the Alphasense and Membrapor C1 NO_2-sensors in Figure 1.

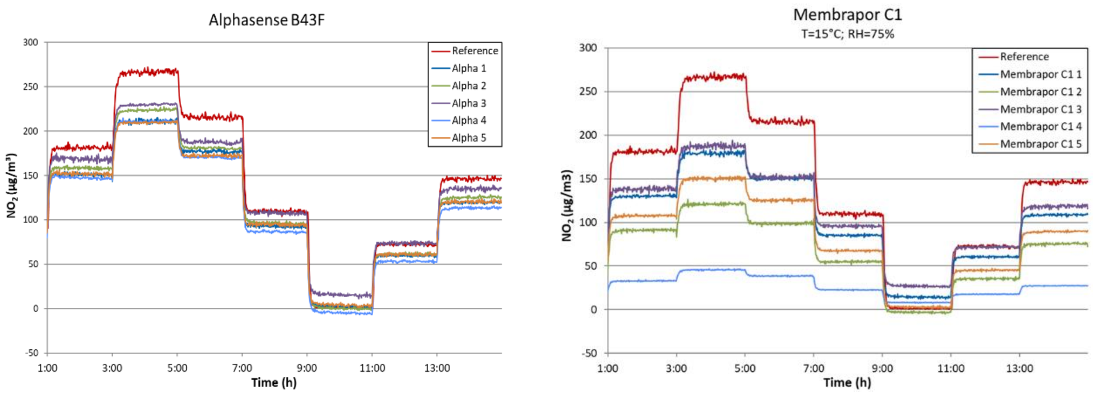


Figure 1 Examples of sensors' responses (Alphasense and Membrapor C1) compared to the reference instrument (indicated in red) during the ramping experiment; time resolution: one minute

The **accuracy** of the different sensor systems (uncalibrated) is variable (Figure 2, average per sensor type). Systematically, the sensor systems underestimate the reference concentration levels. The Alphasense and Cairclip perform best (less than 40 µg/m^3 difference) though deviations are substantial. Clearly, the need for (additional) calibration is demonstrated here.

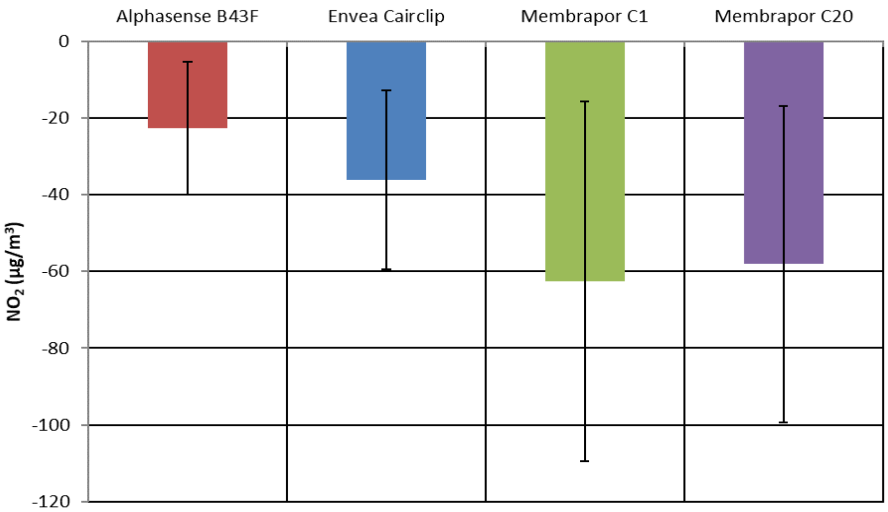


Figure 2 Average deviation (per sensor system) from the average reference concentration during the ramping experiment

The evaluated NO_2-sensor systems all exhibit a high degree of **linearity** (typically $r^2 > 0.9$) over the concentration range examined in this study (0-260 µg/m³). As can already be deduced from Figure 1, slopes and intercepts differ considerably between systems (see Figure 3 for examples and Table 2 for an overview of average linear regression coefficients per system).

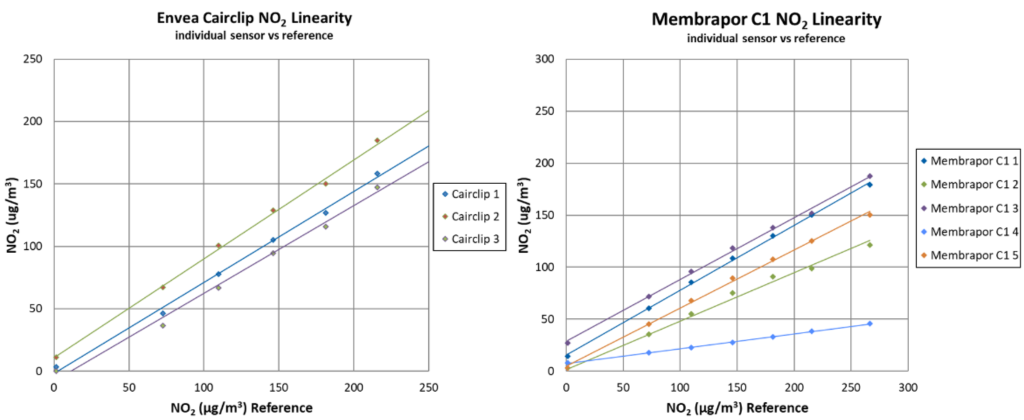


Figure 3 Examples of linearity (Envea Cairclip and Membrapor C1)

Table 2 average linear regression coefficients per system

$y = ax+b$	*a*	*b*	*n*
Alphasense	0.81	4	5
Cairclip	0.74	0	3
Membrapor C1	0.48	13	5
Membrapor C2	0.88	9	2

Regression equations per sensor copy were applied for calibration of the sensor outcomes. After doing so, results of the ramping experiment look like in Figure 4 for the Alphasense and Membrapor C1 NO_2-sensors (as in Figure 1).

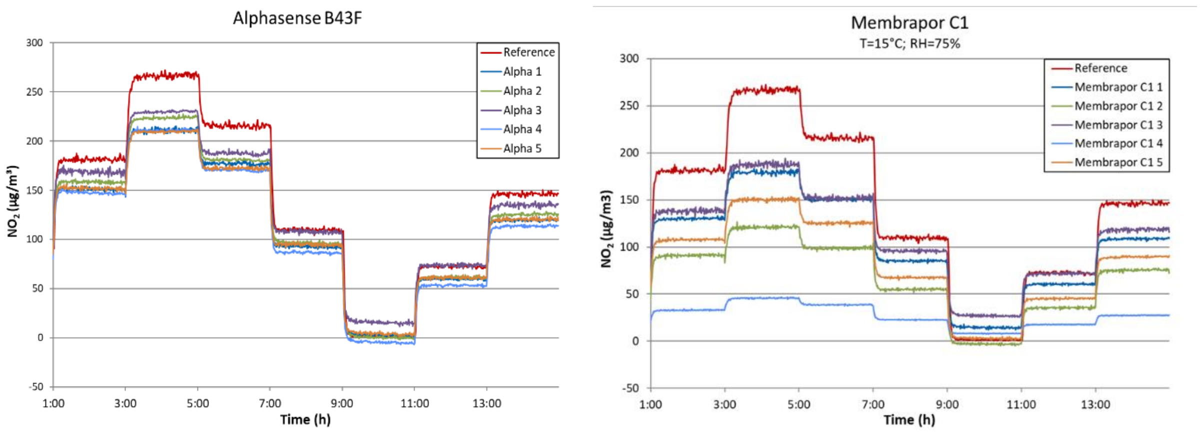


Figure 4 Examples of sensors' (Alphasense and Membrapor C1) responses in the ramping experiment after calibration; time resolution: one minute, reference indicated in red

Sensor **stability** is defined here as the standard deviation during each of the seven steady-state conditions of the ramping experiment (also denoted by 'repeatability'). Results are presented in Figure 5 for all the available sensor copies and systems (as function of concentration level; after calibration). The right column is the average stability (for each sensor system). Clearly, the Alphasense NO_2-sensors systematically show the lowest standard deviations (1.6 µg/m^3, when averaged over the entire experiment) and relatively small differences between sensors. Next 'best' are the Membrapor C1 (2.1 µg/m^3) and Membrapor C20 (2.9 µg/m^3) while the Cairclip systems indicate a much higher value (6.8 µg/m^3 and more variability between copies.

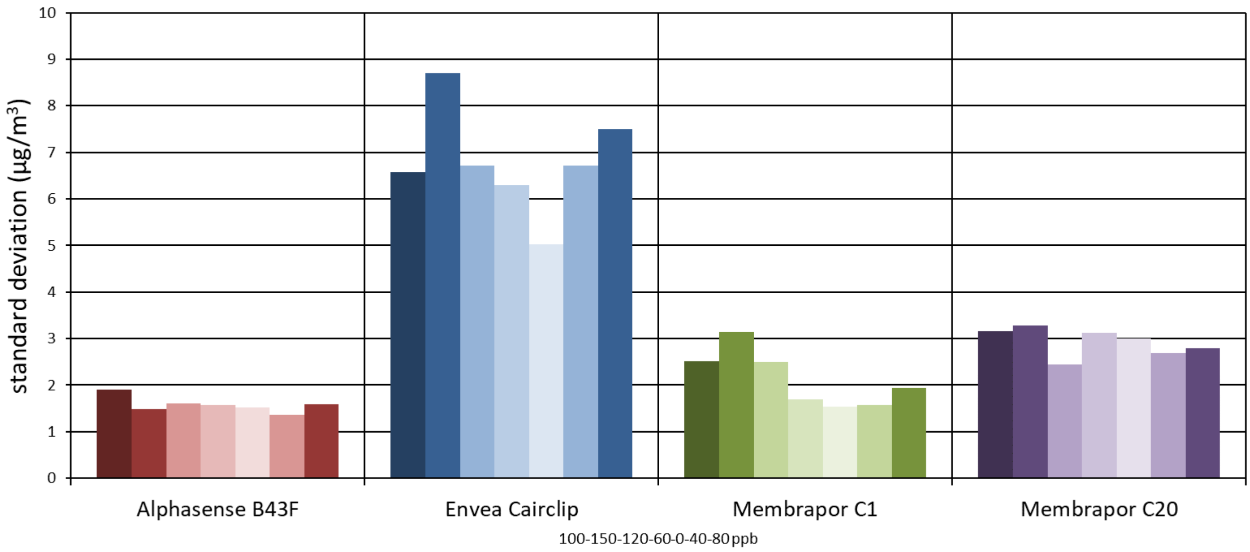


Figure 5 Standard deviation of the NO2 sensors for each of the seven concentration levels of the ramping experiment; for each sensor the right bar is the average value

As a measure of the variation between sensors of one type the **between sensor uncertainty** (BSU) has been calculated (after calibration) and shown in Figure 6 (for its definition see *link report*). Clearly, the Alphasense, Cairclip and Membrapor C1 show the lowest BSU here while the Membrapor C20 performs (much) worse.

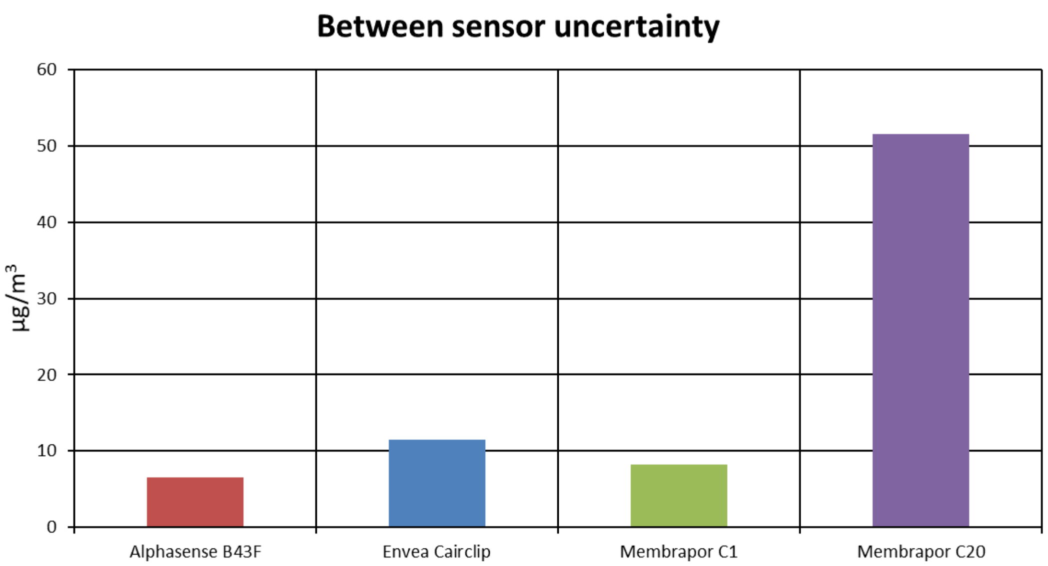


Figure 6 Between sensor uncertainty for each sensor system

The readings of gas sensor systems are known to be affected by (changes in) **relative humidity** (RH) and **temperature** (T). As RH and T in the atmosphere are highly (inversely) correlated, focus here is on the influence of a changing RH (from 45 to 65%) keeping T (15ºC) and chamber NO_2-concentration (80 ppb) constant. In Figure 7 the respective responses for each NO_2-sensor are shown (uncalibrated data).

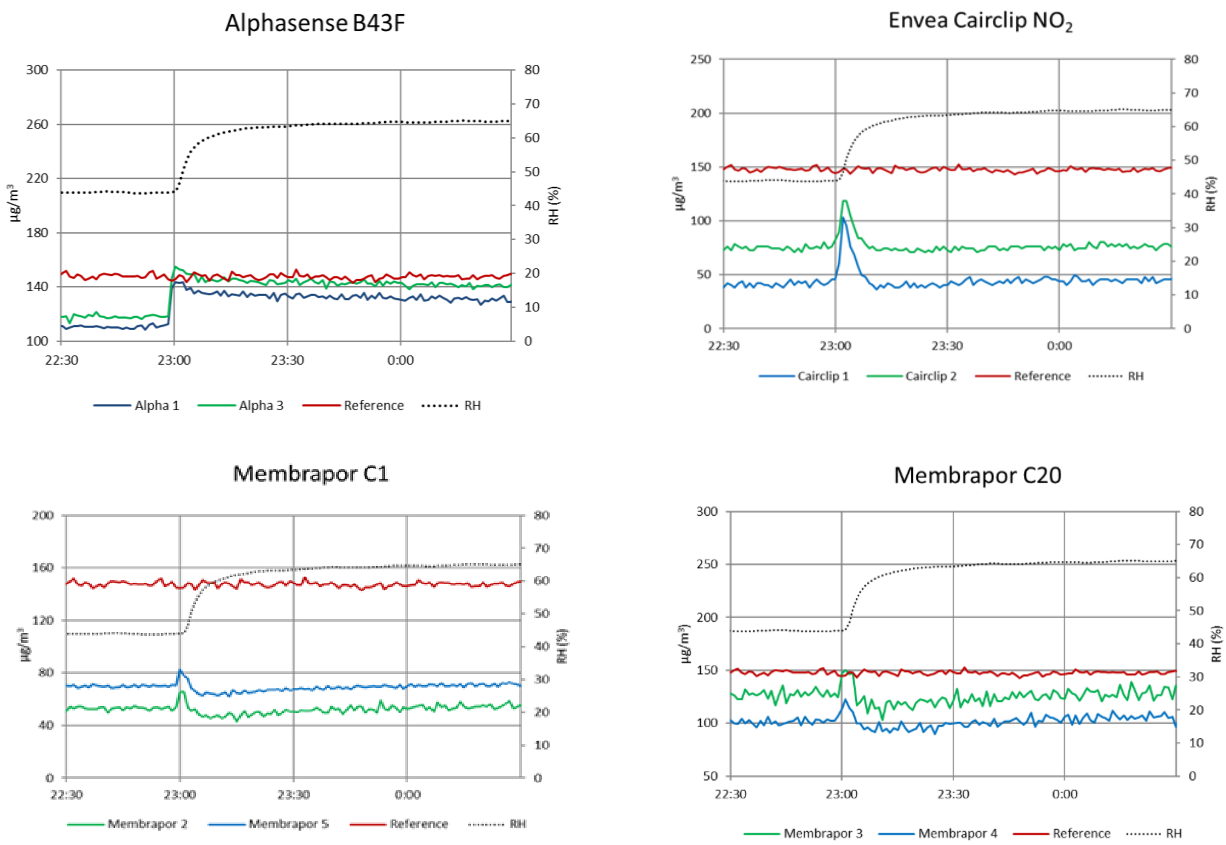


Figure 7 Responses of NO_2-sensors due to a step change in RH (at fixed T and NO_2)

All the NO_2 sensors investigated appear sensitive for changes in RH but not in the same way. Responses differ in magnitude, sign and duration. Generally, the change in RH leads to an increase in the values measured by the systems

Comparing the various systems, as can be seen in Figure 8, the Membrapor systems show relatively small deviations. Their duration is less than 1 hour. Deviations are larger for the Cairclip and but th signal returns faster to ambient level (in less than 15 minutes). The Alphasense does not indicate any return within the step change duration (2 hours). In general, the sensor systems reacted more sensitive to larger steps of RH, and to higher ambient T and NO_2-concentration levels (leaving conclusions above unchanged).

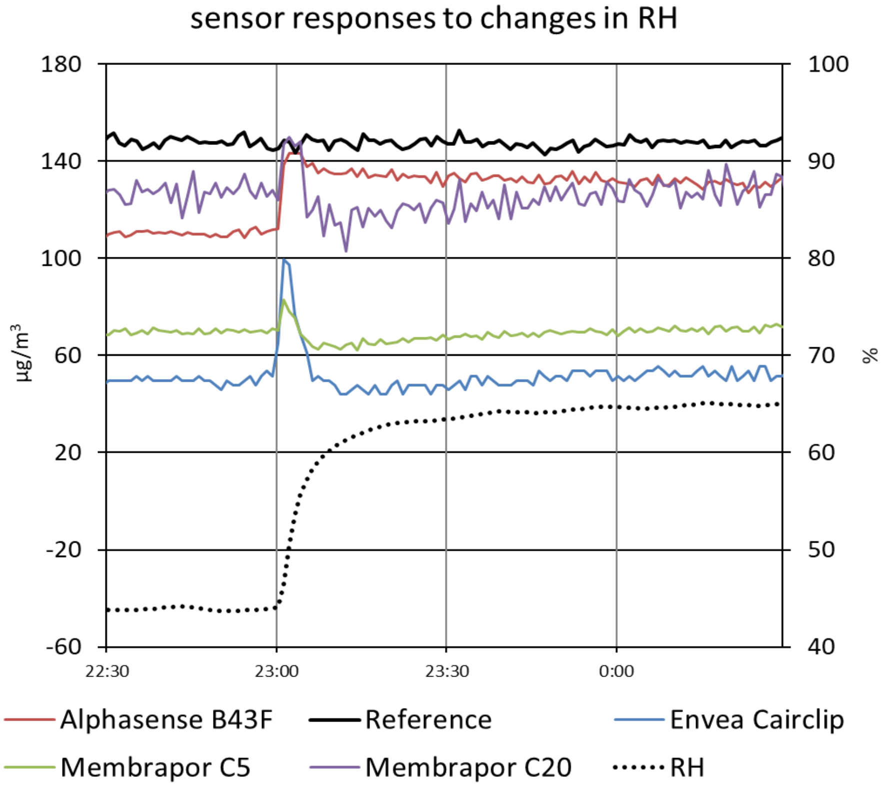


Figure 8 Responses of various NO_2-sensors when increasing RH (at fixed T and NO_2)

To test the **cross sensitivity**, the sensors in the exposure box were exposed to different levels of ozone at zero and nonzero NO_2-levels. The results for individual sensor copies in the case that NO_2 (in the exposure box) remains at 0 µg/m³ (and stepwise changes in ozone) is shown in Figure 9 (uncalibrated data).

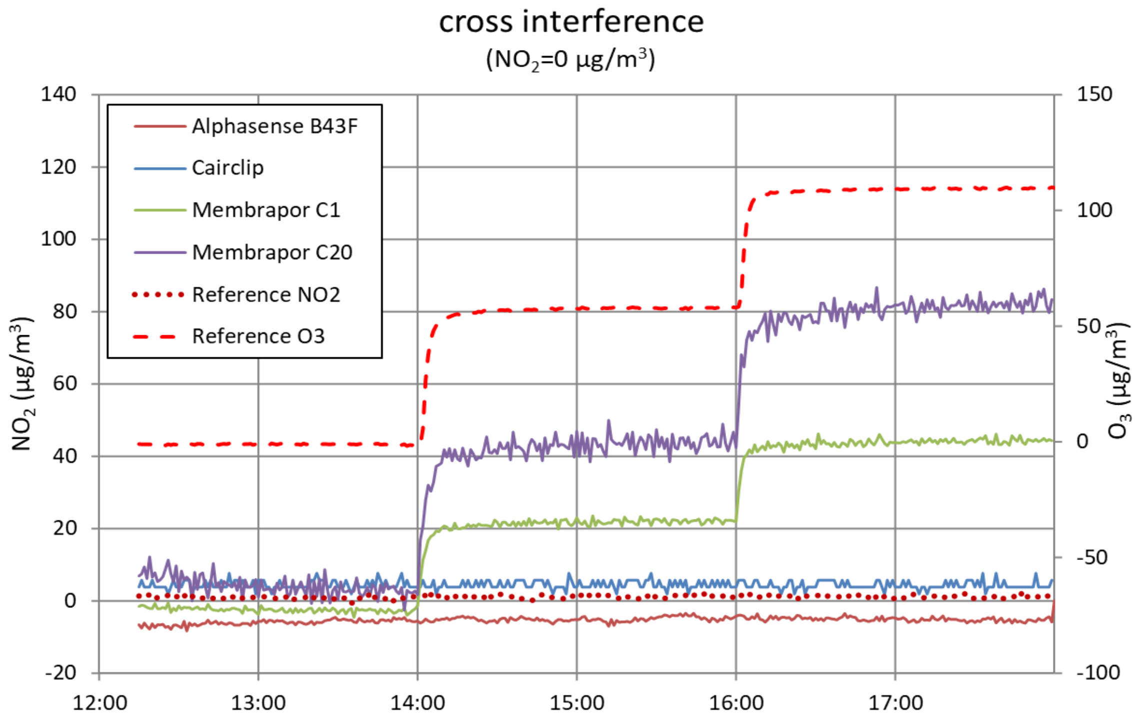


Figure 9 Response of NO_2 sensors at different levels of O_3 (with NO_2 = 0 µg/m^3)

From the figure it is deduced that three (out of five) sensor types appear affected by the presence of ozone (Citytech and the Membrapors) in the absence of NO_2. The Alphasense and Cairclip show the best performance here by remaining at a constant level throughout the experiment.

For the case that NO_2 is nonzero the ratio NO_2-sensor versus NO_2-reference has been estimated at different levels of O_3 (uncalibrated data). The average result per sensor is then given in Figure 10 (and compared with the case that O_3 is zero).

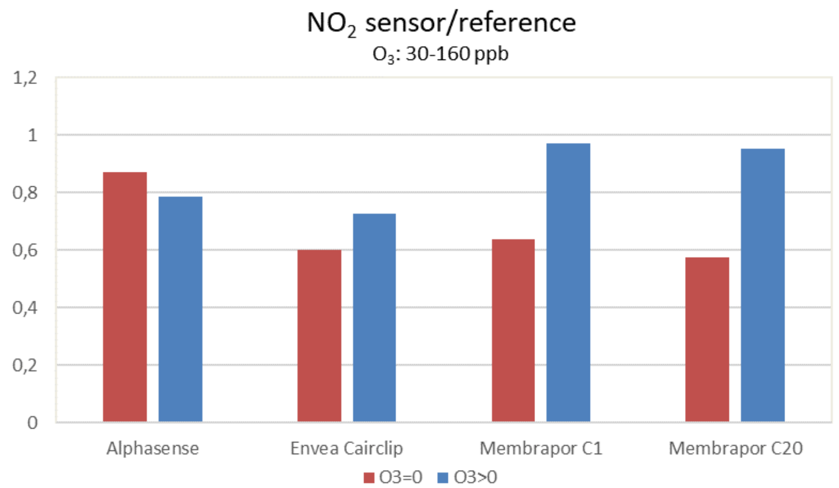


Figure 10 Ratios sensor versus reference (per sensor) with NO_2>0 (and O_3=0 or O_3>0)

It is seen that every sensor type is influenced by the presence of ozone. The least affected is the Alphasense B43F while the Membrapors are largely distorted with increasing values in the presence of O_3.

2.1 Remarks on laboratory experiment

- The examination via a characterized gas chamber and exposure box proves to be an adequate means for establishing basic behavioral properties of gas sensors. There was no direct evidence of gas phase interaction (reactivity) between exposure box and sensor systems that might have influenced results in the various stages of the tests. This indicates that the chamber and its supporting components (gas delivery system, environmental controls) were of sufficient quality.

- Characterization of the chamber and box prior to the testing (e.g., reference monitors response versus change in test atmosphere, stability of test atmosphere under static conditions, impact of changing environmental conditions upon reference monitors) ensured a reasonable evaluation of the devices under the testing scenarios. However, during one of the tests, at (very) high temperature and relative humidity, the gas tubing to the reference monitor showed indications of condensation effects that influenced the reading of the reference monitor (leaving the qualitative results of the susceptibility experiment unchanged).

- A comparison between the sensors' performances is not straightforward. Except for the Alphasense B34F and B431 it was unclear if the sensor system included built-in calibration features. In order to obtain an equal 'level playing field' all the NO_2 and O_3 sensors were calibrated (simple linear regression) by using the data of the ramping experiment (for more information on this, see the performance summaries).

2.2 General remarks and recommendations

- All sensors appear to offer detection sensitivities in the low range with a stability (repeatability) within acceptable values. Such findings are encouraging for their potential applicability for citizen science and probably for professionally-performed.

- Of significance here is that the rise and lag times observed with the sensors are in good correspondence with the reference instrument (in the order of a few minutes). The sharp stair-step pattern of response in the graphical displays of the ramping experiment is an indication of how quickly most of the sensors respond. This indicates that such sensors also have a potential for use in non-static situations (movement with respect to spatial setting). However, the tests performed here were not of sufficient design to evaluate very short temporal impacts.

- Some positive and negative bias occurred when pollutant-free air was being supplied to the exposure box. Linked to the often high linearity of response, this is an indication that for the sensors tested, commonly used zero and span procedures might be replaced with simple collocation comparisons with reference monitors preferably in the users environmental setting.

- Some sensor copies provided for evaluation yielded no usable data and were discarded for the evaluations to proceed. This is an important finding: users need to ensure that their device has been calibrated or compared with ambient monitoring data from collocation trials before being used in data collections.

- This evaluation did not have the capability of examining long-term performance response characteristics (e.g., drift of signal over extended time periods, stability of response with respect to sensor lifetime). End users should perform at least one of the evaluation procedures described above on a reoccurring basis to ensure the operation status of their device.

- The evaluations performed here represent a first step in understanding how the low cost sensor compares to recognized reference specifications. The results were encouraging with respect to how well the devices performed for certain performance characteristics (e.g., linearity, stability).

- Additional testing, i.e. evaluation of sensors under true ambient conditions, will provide enhanced understanding of how well these sensors respond to changing environmental conditions and their applicability for various data collection scenarios.

VAQUUMS

3 Reports per sensor type: NO_2 sensors

3.1 Tested parameters

The calculations carried out in the examination of the VAQUUMS sensor data sets are defined here:

1. linearity

Correlation of sensors (of one type) with reference equipment is calculated using orthogonal regression on the (average) concentrations of each step in the ramping experiment. To exclude irregular behaviour after changing the climate chamber conditions, the data for the first fifteen minutes of each step have been discarded. The calibration of sensors used the slope and intercept as determined in this analysis.

2. accuracy

The accuracy has been calculated as follows:

$$\text{accuracy (\%)} = 100 - \left(\frac{|\overline{\text{sensor}} - \overline{\text{reference}}|}{\overline{\text{reference}}}\right) * 100,$$

where $\overline{\text{sensor}}$ and $\overline{\text{reference}}$ indicate the average concentration levels as measured by the sensor and reference equipment in the ramping experiment.

3. stability during ramping experiment

The stability of a sensor or a set of sensors (of one type) is expressed by the standard deviation (SD) of the concentration datasets collected in the ramping experiment. The average standard deviation ($SD_{average}$) for a set of *n* sensors is calculated by

$$SD_{average} = \sqrt{\sum_{i=1}^{n} \frac{SD_i^2}{n}} \; .$$

The relative standard deviation (SD_{rel}) is the standard deviation divided by the corresponding average concentration.

4. between sensor uncertainty

The variation between the various sensors (of one type) over a measurement period is given by the between-sensor uncertainty (BSU_{sensor}):

$$BSU_{sensor} = \sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{k}(\text{sensor}_{ij} - \text{average}_i)^2}{k(n-1)}},$$

with *n* the number of sensors and *k* the number of measurements. The BSU has been derived from 5-min averages derived from the ramping experiment.

Laboratory Evaluation
Alphasense B43F NO_2 sensor

Manufacturer: Alphasense

[Link to website manufacturer]

Link to test protocol

3.2 Alphasense B43F versus Reference

Five **Alphasense B43F** NO_2 sensors were evaluated in the RIVM Testing Laboratory under controlled NO_2 concentrations, temperature and relative humidity. These sensors were also tested in the field (at the reference monitoring station in Borgerhout).

Alphasense B43F

- Electrochemical sensor
- Time resolution is 1 minute (mean value)
- Unit ID's: Alpha1, Alpha2, Alpa3, Alpha4, Alpha5

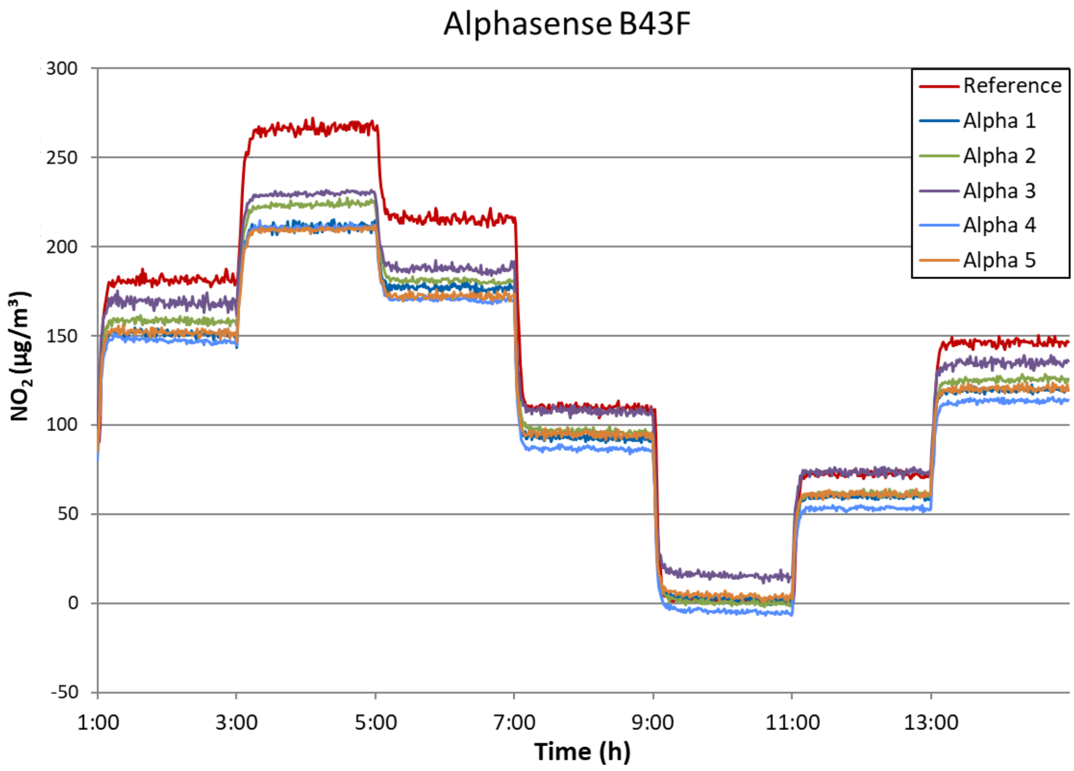
Reference instrument

- Teledyne API Chemiluminescence Nitrogen Oxides Analyzer Model 200E
- Time resolution: 1 minute

For the details about the laboratory protocol followed here, consult our test protocol.

3.2.1 Ramping experiment (T=15°C; RH=75%)

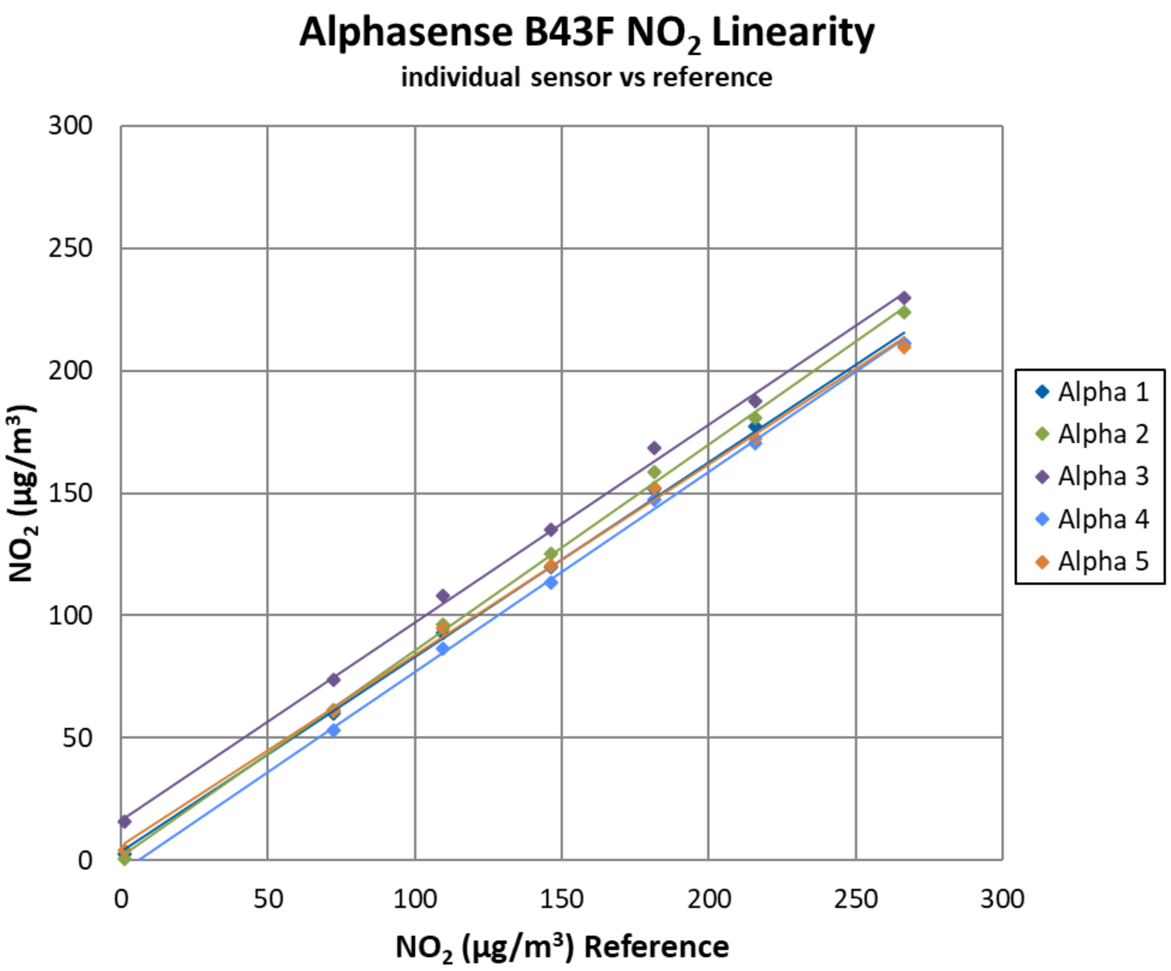
In the first test sensors were exposed to different concentration levels to check linearity, agreement between sensors and agreement with the reference.



- The Alphasense sensors followed the step changes in NO2 concentration (between 0 and 260 µg/m3) quite well. In comparison to the reference instrument all units underestimated the NO2 concentrations (except at the lower levels).
- Three units (Alpha1, Alpha2 and Alpha5) had baseline readings close to zero whereas Alpha 3 and Alpha4 read around -5 and + 16 µg/m^3, respectively.

3.2.2 Linearity

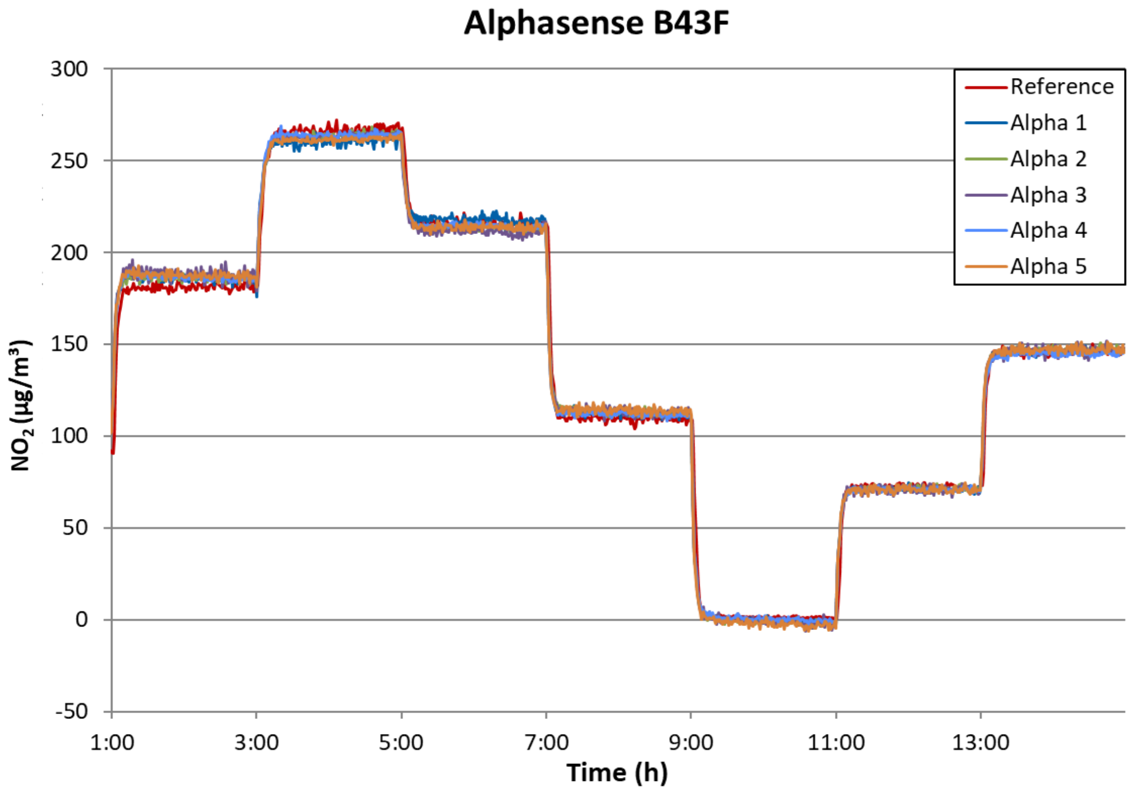
Average concentrations per step were calculated and used for lineair regression (y=ax+b).



Sensor	Slope	Intercept	r^2
Alpha 1	0.80	3.2	0.9977
Alpha 2	0.84	1.3	0.9982
Alpha 3	0.81	16.3	0.9971
Alpha 4	0.82	-4.9	0.9985
Alpha 5	0.78	5.9	0.9971

- All units showed a very high correlation (r^2>0.99) with the corresponding reference data during this ramping experiment. The slopes in the regression equations were near 0.8; intercepts varied between -5 and 16 µg/m^3.

3.2.3 Ramping experiment after calibration



- The slopes and intercepts calculated in the ramping experiment were used for a (simple) calibration of the sensor units. After applying such a procedure, all the units produced concentration data that were (very) close to the levels measured by the Teledyne reference instrument.

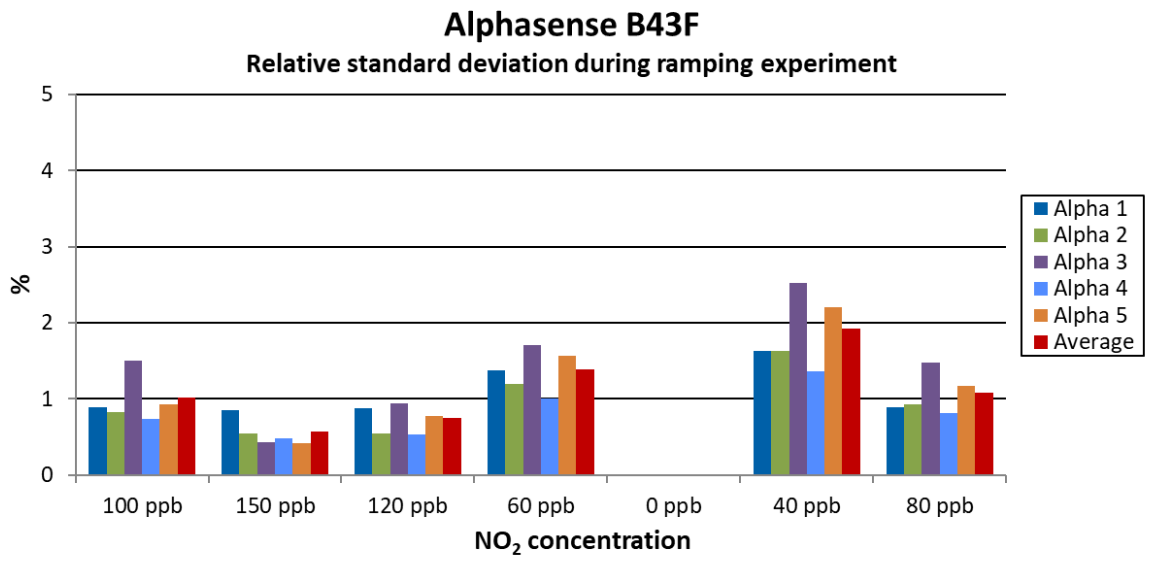
3.2.4 Accuracy

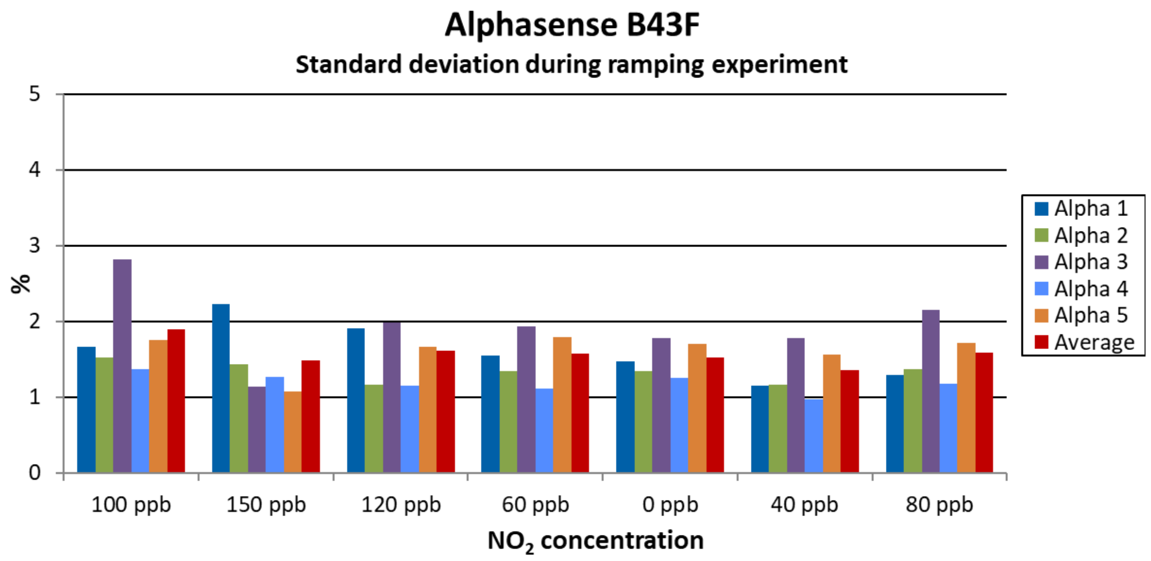
Reference mean (µg/m3)	Sensor mean (µg/m3)	Accuracy (%)
72	71	98
110	113	97
146	146	100
181	187	97
216	214	99
267	263	99

- After calibration, the sensors showed an accuracy close to 100%.

3.2.5 Stability under steady-state conditions

Sensor stability is defined here as the standard deviation during each of the seven steady-state conditions of the ramping experiment (also see the Appendix). The standard deviation of the reference is 0.9 µg/m³ (range: 0.7-1.1 µg/m³); relative standard deviation is 0.6 (0.3-1.0).





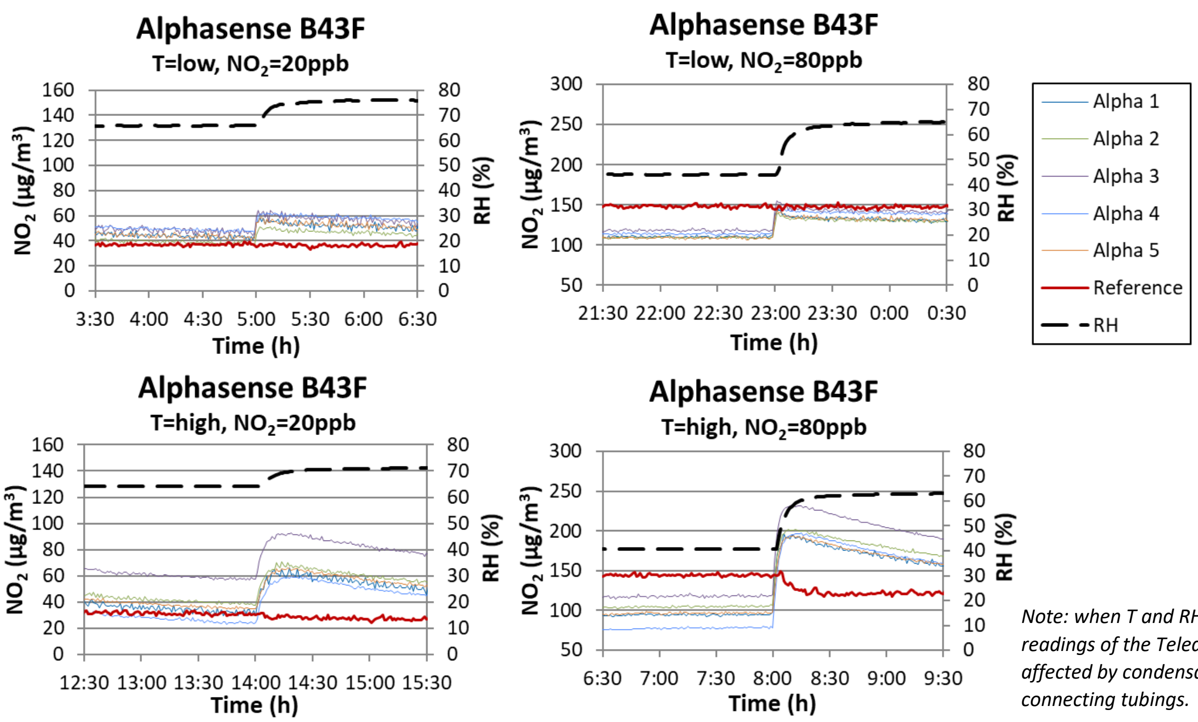
- In most cases, the standard deviations of the sensors' output were less than 2 µg/m³ (after calibration). Some units (Alpha4) performed better than others (Alpha3). There was no dependence on the ambient NO_2-level.
- The relative standard deviations were, in most cases, less than 2%. Since absolute SD's were quite constant, the RSD's were lower at higher concentration levels.

3.2.6 Between sensor uncertainty

As a measure of the variation between sensors of one type the between sensor uncertainty (BSU) has been calculated. For this sensor the result was 6.5 µg/m^3 (being the best result).

3.2.7 Influence of temperature and relative humidity

The readings of gas sensor systems are known to be affected by changes in meteorological parameters (RH, T). Here, the effect of a changing RH (at constant levels for temperature and concentration) is shown.

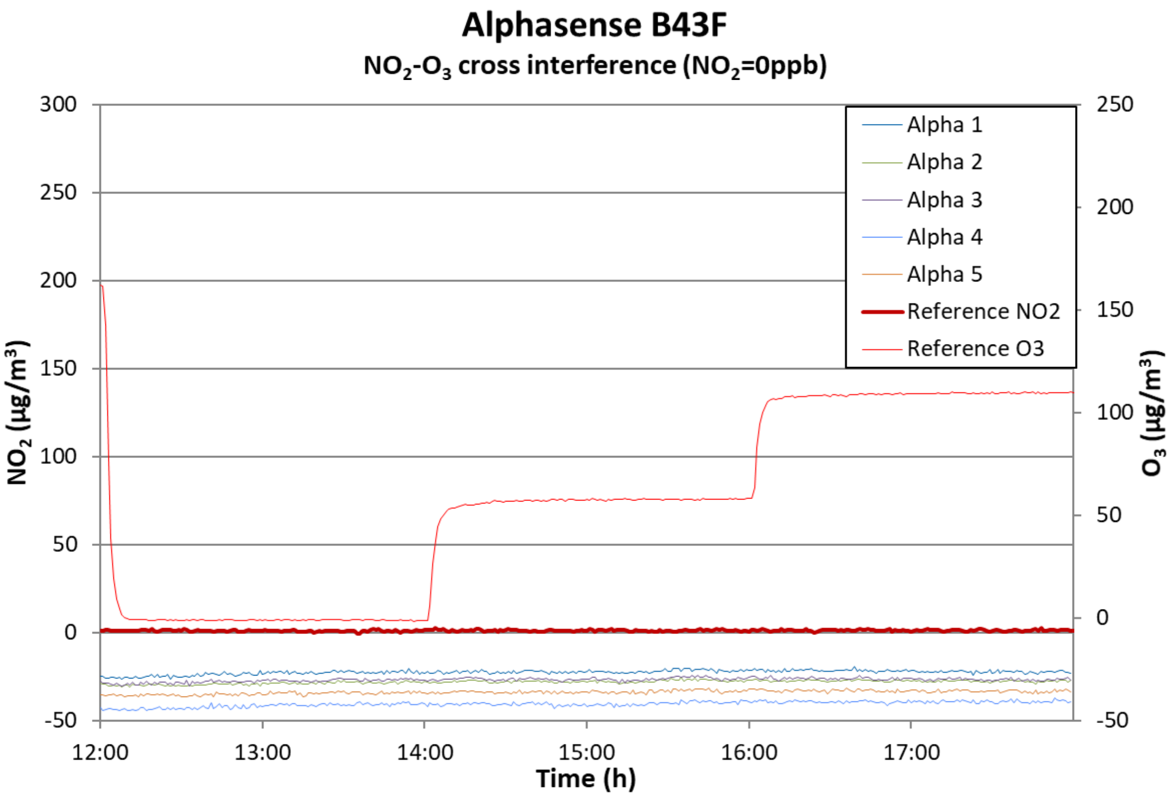


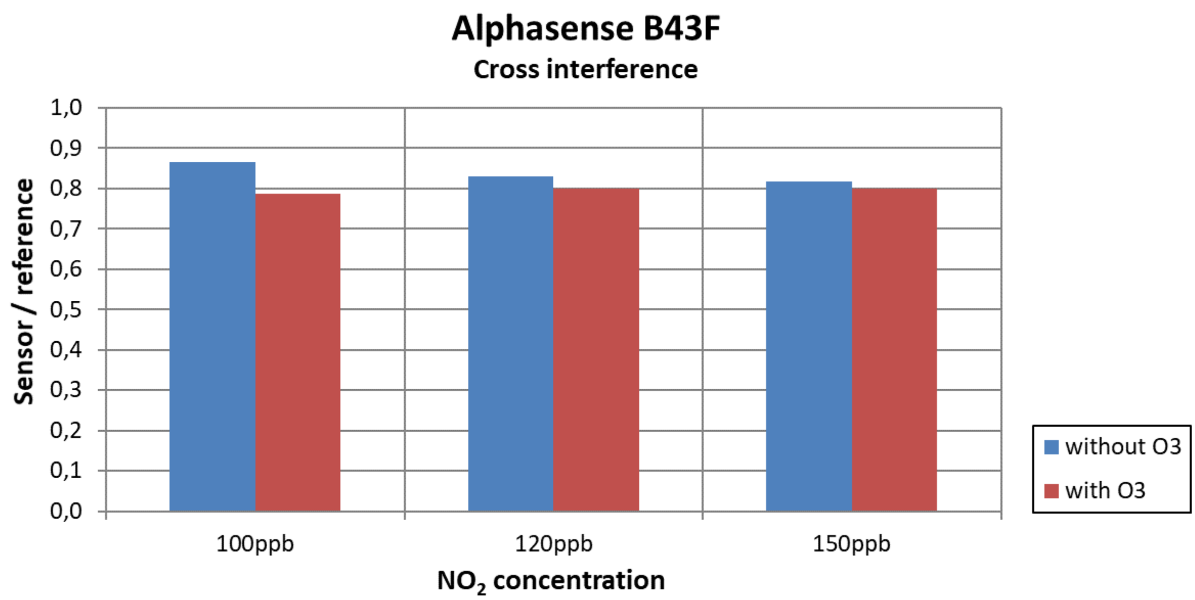
Note: when T and RH are high, the readings of the Teledy were affected by condensation in the connecting tubings.

- Generally, a (rapid) increase in relative humidity resulted in a higher value produced by the sensors (at a constant level for NO_2); the overestimation was larger at a higher ambient temperature.
- This increase was followed by a rather slow decrease (at least two hours) in the sensor signals.

3.2.8 Cross sensitivity

To test the cross sensitivity, the sensors in the exposure box were exposed to different levels of ozone at zero and nonzero NO_2-levels.





- No cross-interference for ozone was observed in the case that NO_2 was kept at zero level. Every sensor unit maintained their readings when ozone stepwise increased from 0 to 110 µg/m^3.
- At nonzero levels for NO_2, the sensors underestimate the ambient NO_2 concentration in the presence of ozone (becoming less at higher NO_2 concentrations).

3.2.9 Summary

- **Linearity of sensor response**: All sensor units show a very high correlation (r^2>0.99) compared to corresponding Teledyne NO_2-measurements (between 0-260 µg/m^3 and after calibration).

- **Accuracy**: All the units have a high accuracy after calibration. On an individual basis, accuracies are around 98%. Before calibration, the accuracy of an individual sensor can be lower than 80%.

- **Stability:** The standard deviations of the sensors' signals are less than 2 µg/m^3 (during stationary conditions over 2 hours) and appear independent of concentration level.

- **Between-sensor uncertainty**: The uncertainty between the sensors is 6.5 µg/m^3 (being the best result with five different types of sensors).

- **Effect of relative humidity and temperature**: A rise in relative humidity increases the sensor readings. This effect is larger at higher temperatures and concentration levels.

- **Cross sensitivity**: The sensor units appear unaffected by the presence of ozone (at different levels of NO_2 and O_3).

- **Data recovery**: In this study, the data recovery for every unit is 100% (for a measurement period of 77 hours in total).

VAQUUMS

Laboratory Evaluation
Envea Cairclip NO_2 sensor

Manufacturer: Envea

[Link to website manufacturer]

[Link to test protocol]

3.3 Envea Cairclip NO_2 versus Reference

Three **Envea Cairclip NO_2** sensors were evaluated in the RIVM Testing Laboratory under controlled NO_2 concentration, temperature and relative humidity. These sensors were also tested in the field (at the reference monitoring station in Borgerhout).

Envea Cairclip NO_2

- Electrochemical sensor
- Time resolution is 1 minute
- Units IDs: Cairclip1, Cairclip2, Cairclip3; fourth unit due to deviant behavior

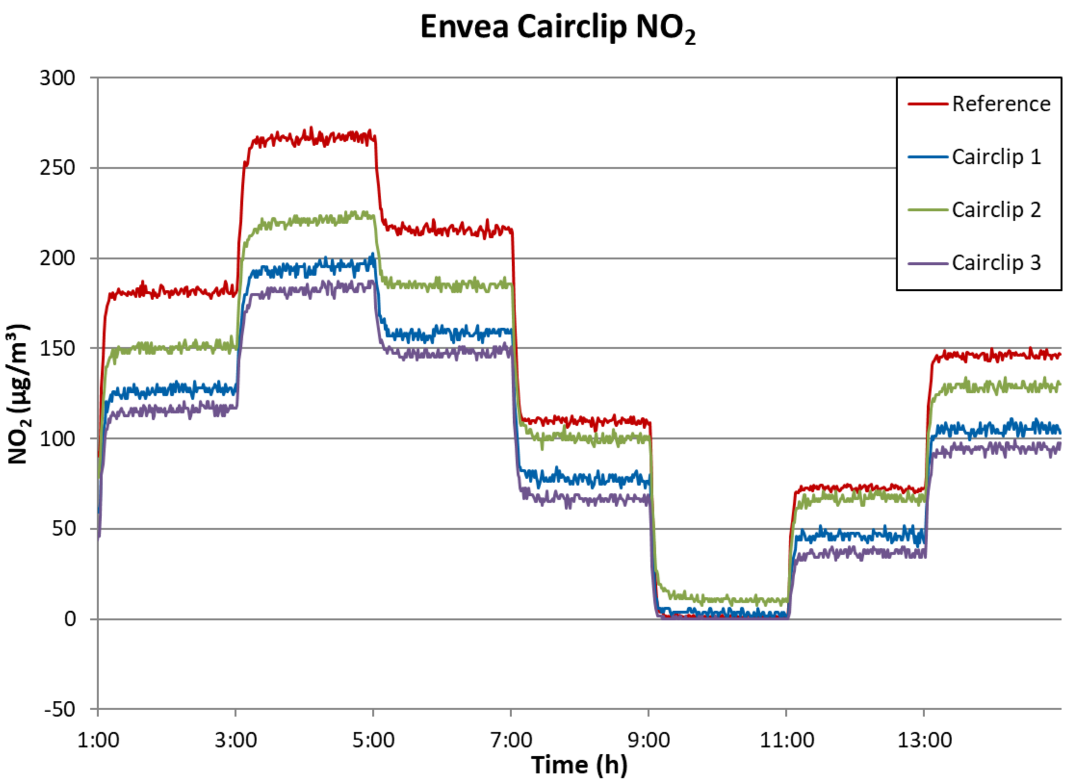
Reference instrument:

- Teledyne API Chemiluminescence Nitrogen Oxides Analyzer Model 200E
- Time resolution: 1 minute

For the details about the laboratory protocol followed here, consult our test protocol.

3.3.1 Ramping experiment (T=15°C; RH=75%)

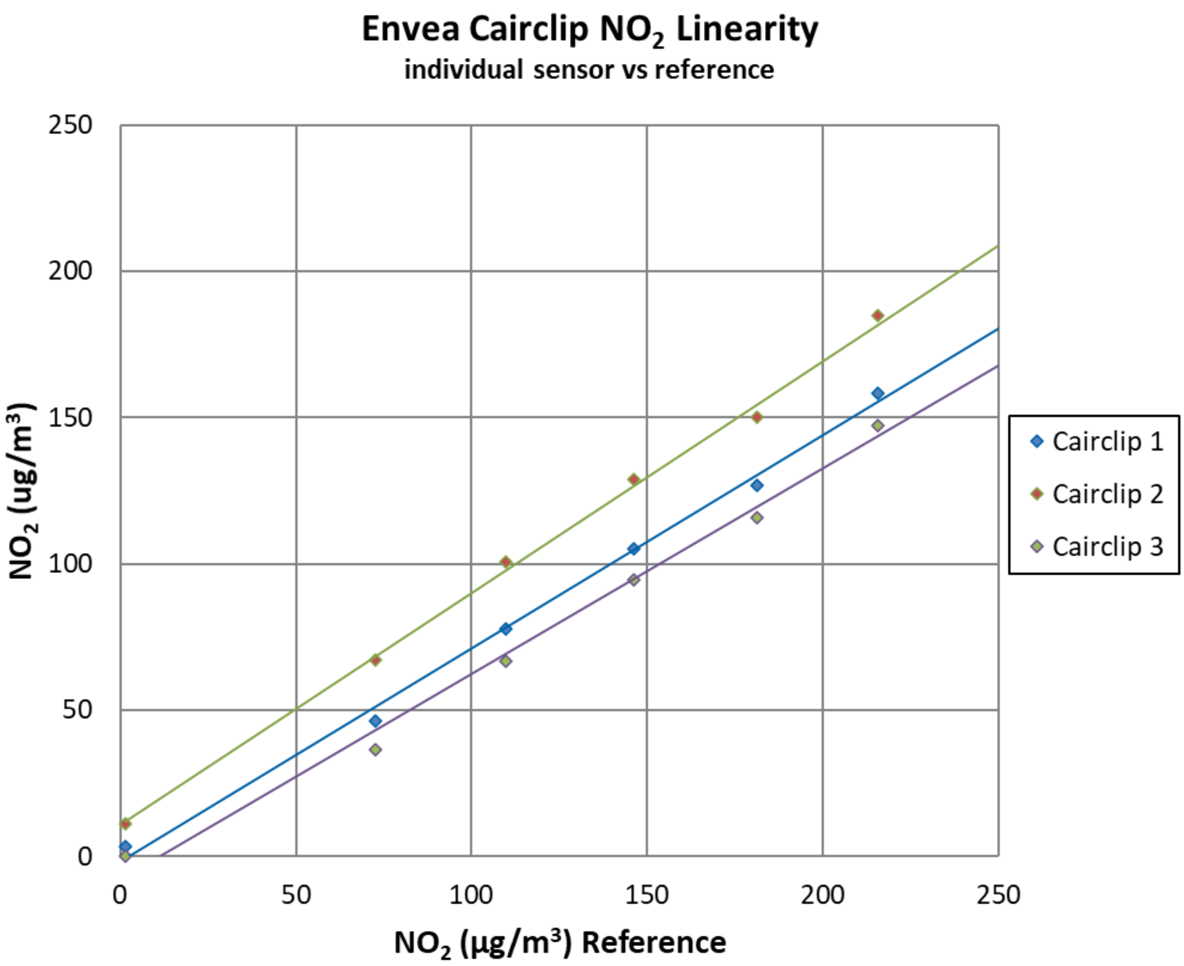
In the first test sensors were exposed to different concentration levels to check linearity, agreement between sensors and agreement with the reference.



- The Envea Cairclip sensors followed the step changes in NO2 concentration (between 0 and 260 µg/m3) quite well. In comparison to the reference instrument all units underestimated the NO2 concentrations (except at the lower levels).
- One unit (Cairclip3) has a baseline reading close to the zero level, whereas Cairclip1 and Cairclip2 read around +3 and +11 µg/m^3, respectively.

3.3.2 Linearity

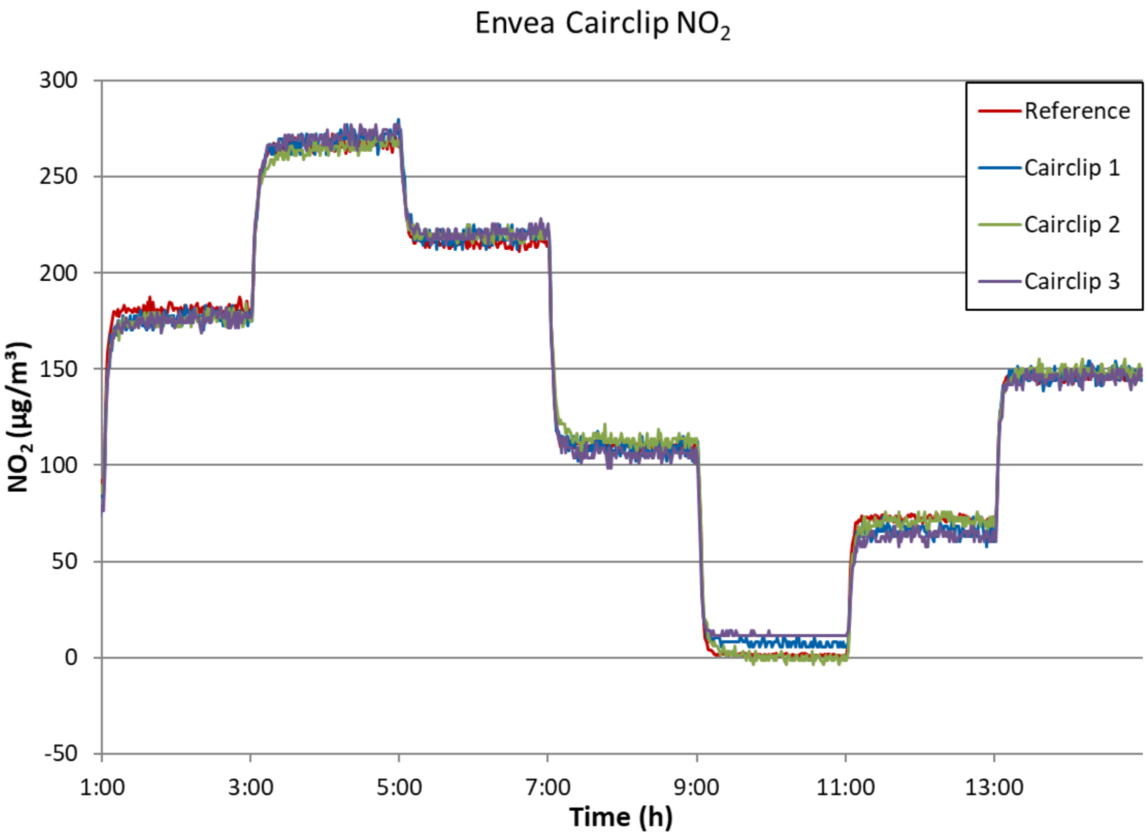
Average concentrations per step were calculated and used for lineair regression (y=ax+b).



Sensor	Slope	Intercept	r^2
Cairclip 1	0.73	-1.9	0.9985
Cairclip 2	0.79	10.8	0.9974
Cairclip 3	0.70	-7.9	0.9944

- All units showed a very high correlation (r^2>0.99) with the corresponding reference data during this ramping experiment. The slopes in the regression equations were between 0.7 and 0.8; intercepts varied between -8 and 11 µg/m^3.

3.3.3 Ramping experiment after calibration



- The slopes and intercepts calculated in the ramping experiment were used for a (simple) calibration of the sensors units. After applying such a procedure, all the units produced concentration data that were (very) close to the levels measured by the Teledyne reference instrument.

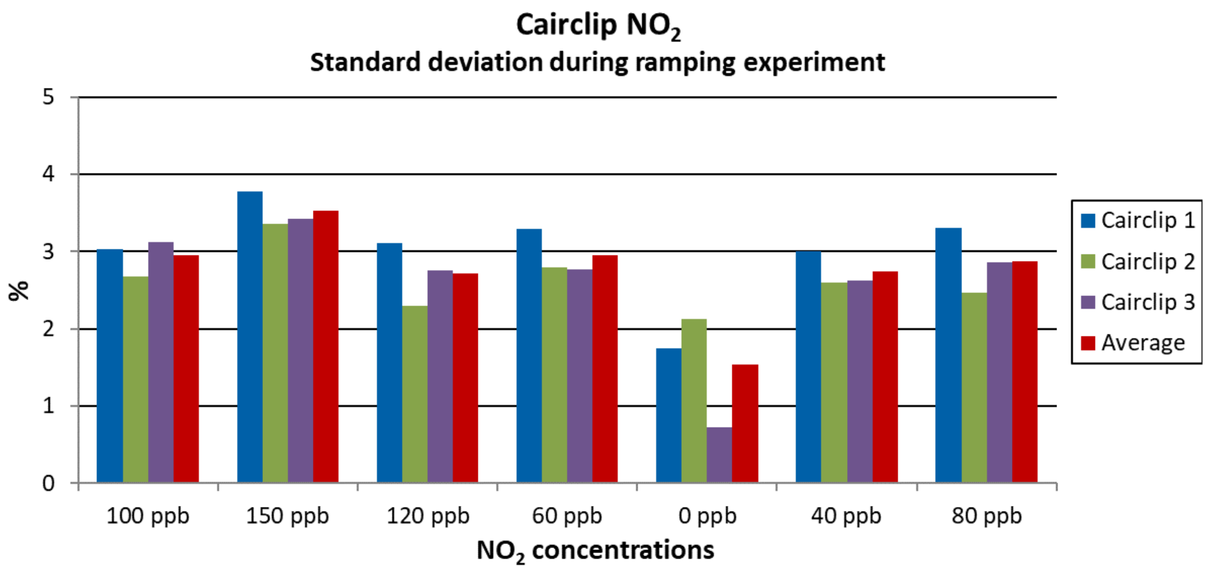
3.3.4 Accuracy

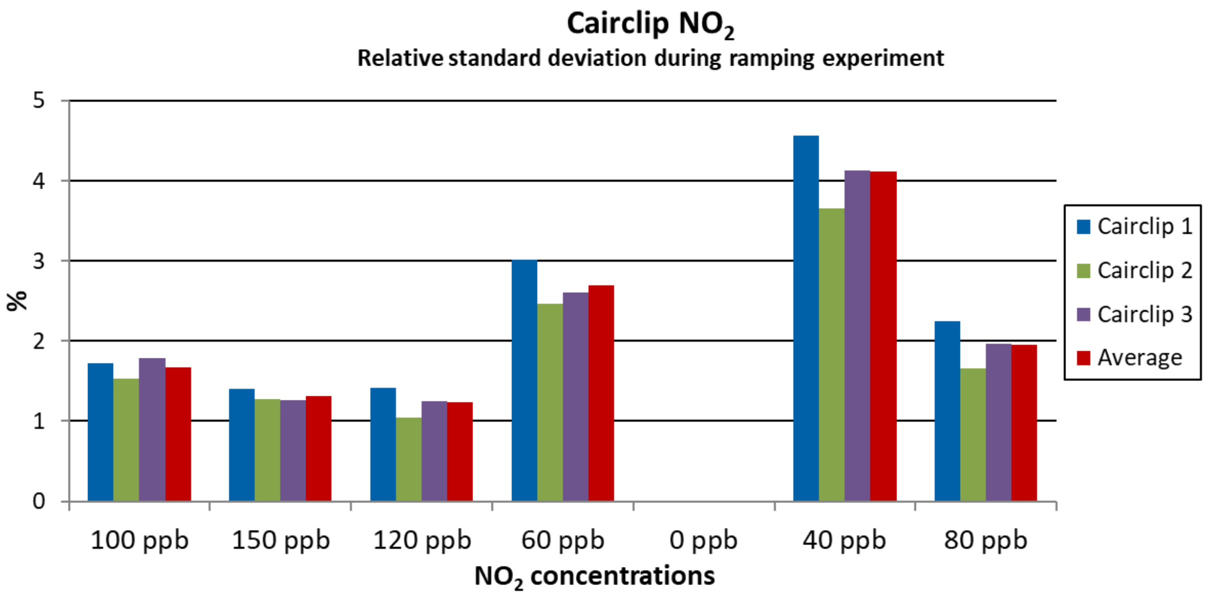
Reference mean (µg/m3)	Sensor mean (µg/m3)	Accuracy (%)
72	67	92
110	109	100
146	147	99
181	176	97
216	220	98
267	268	99

- After calibration, most sensors showed an accuracy close to 100%.

3.3.5 Stability under steady-state conditions

Sensor stability is defined here as the standard deviation during each of the seven steady-state conditions of the ramping experiment (also see the Appendix). The standard deviation of the reference is 0.9 µg/m^3 (range: 0.7-1.1 µg/m^3); relative standard deviation is 0.6 (0.3-1.0).





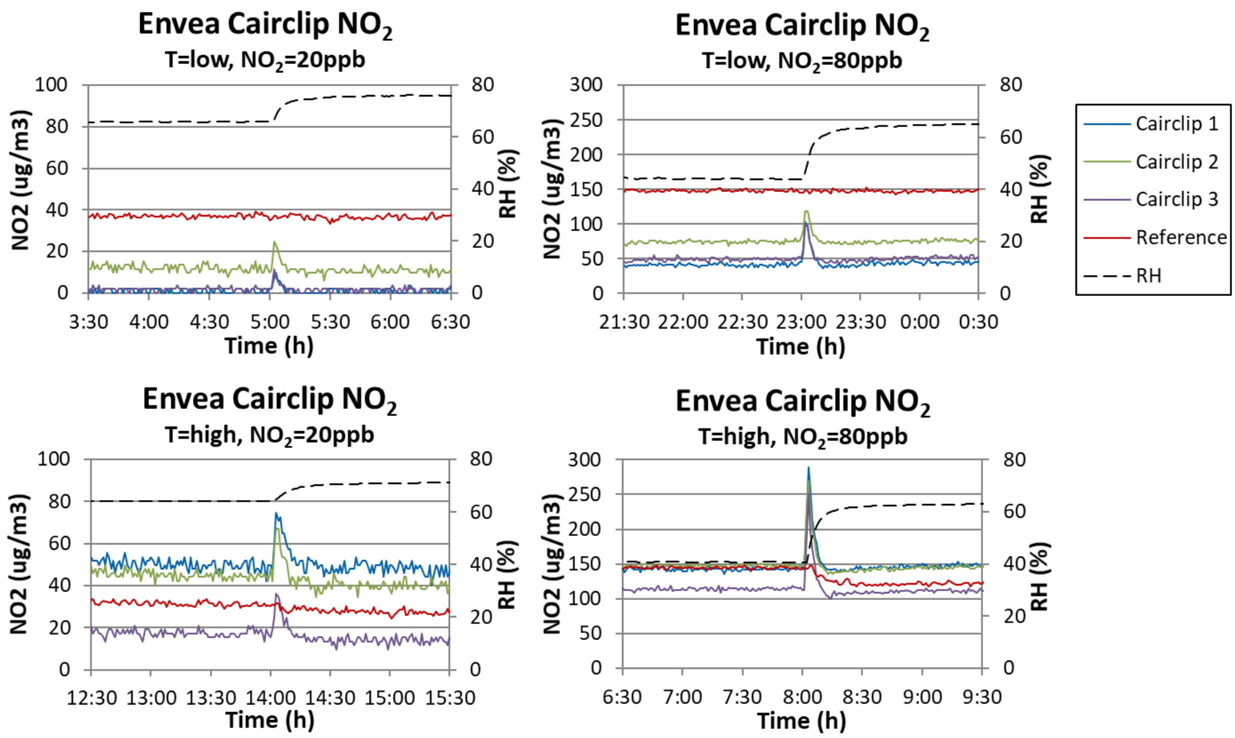
- In most cases, the standard deviations of the sensors' output were less than 4 µg/m^3 (after calibration). One unit (Cairclip 2) performed better than others (e.g., Cairclip1). There was no dependence on the ambient NO_2-level.
- The relative standard deviations were, in most cases, less than 4%. Since absolute SD's were quite constant, the RSD's were lower at higher concentration levels.

3.3.6 Between sensor uncertainty

As a measure of the variation between sensors of one type the between sensor uncertainty (BSU) has been calculated. For this sensor the result was 11.5 µg/m^3 (slightly better than the average result).

3.3.7 Influence of temperature and relative humidity

The readings of gas sensor systems are known to be affected by changes in meteorological parameters (RH, T). Here, the effect of a changing RH (at constant levels for temperature and concentration) is shown.

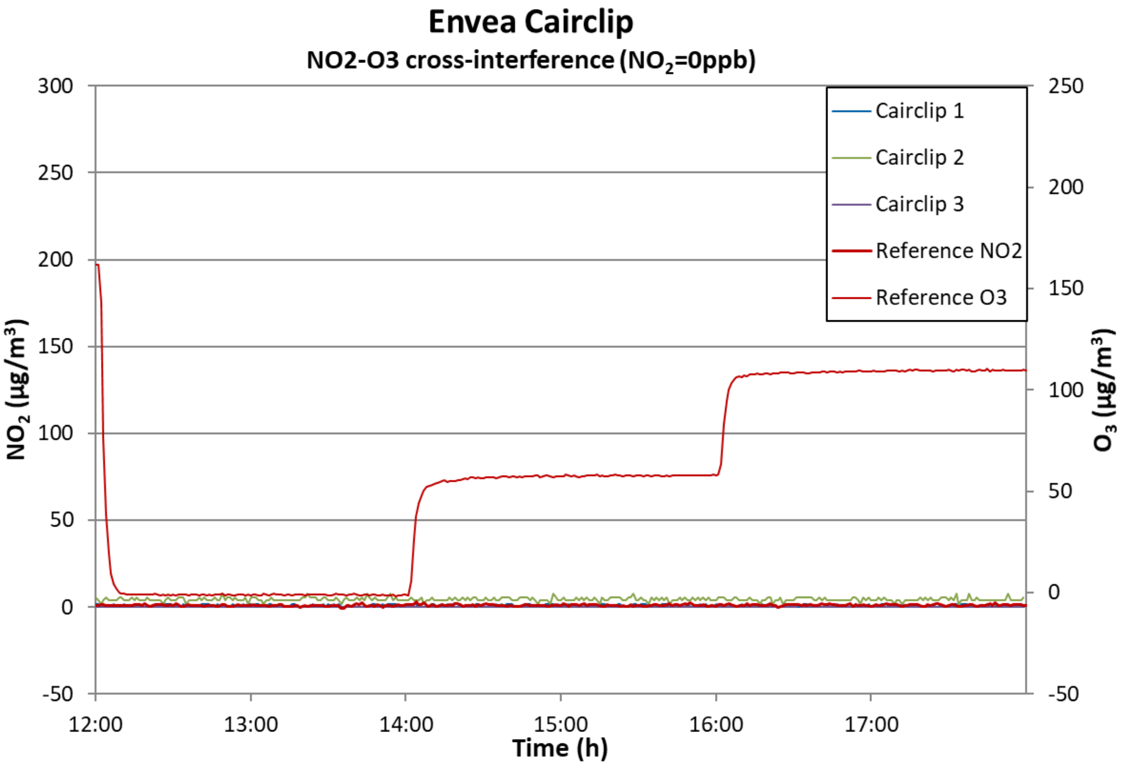


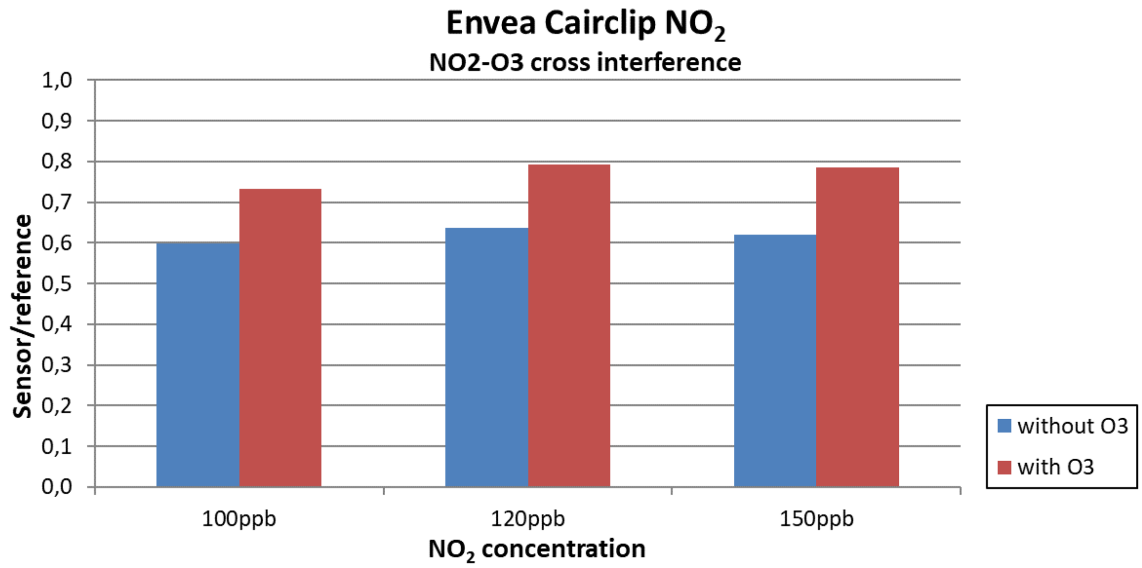
Note: At T =30 °C and RH = 90%, the readings of the Teledyne instrument were discarded due to condensation in connecting tubings.

- Generally, a (rapid) increase in relative humidity resulted in a positively peaked value produced by the sensors (at a constant level for NO_2). This peak value was higher at an enhanced temperature and a higher ambient NO_2-concentration.
- After attaining the peak value the signal returned to the original level roughly within 15-60 minutes.

3.3.8 Cross sensitivity

To test the cross sensitivity, the sensors in the exposure box were exposed to different levels of ozone at zero and nonzero NO_2-levels.





- No cross-interference for ozone was observed when NO2 was kept at zero level. Every sensor unit maintained their readings when ozone stepwise increased from 0 to 110 $\mu g/m^3$.
- At nonzero levels of NO_2 (100, 120, 150 ppb) the sensors tend to measure higher NO_2-values in the presence of ozone.

3.3.9 Summary

- **Linearity of sensor response**: all the three sensor units show a very high correlation (r^2>0.99) compared to the corresponding Teledyne NO_2-measurements (between 0-230 µg/m^3 and after calibration).

- **Accuracy**: All the units have a high accuracy after calibration. On an individual basis, accuracies are around 97%. Before calibration, the individual accuracy can be lower than 60%.

- **Stability**: The standard deviations of the sensors' signals are less than 4 µg/m3 (during stationary conditions over 2 hours) and appear independent of concentration level.

- **Between-sensor uncertainty**: The uncertainty between the sensors is 11.5 µg/m^3 (slightly better than the average result with five different types of sensors).

- **Effect of relative humidity and temperature**: A rise in relative humidity affects the sensor readings by performing a positive peak value in the measured NO_2-concentrations. The peak increases at higher temperatures and ambient levels for NO_2.

- **Cross sensitivity**: The units appear unaffected by the presence of ozone when NO_2 is at zero level. At nonzero levels, however, the sensor measurements indicate higher measured values for NO_2 in the presence of O_3

- **Data recovery**: In this study, the data recovery for every unit is 100% (for a measurement period of 77 hours in total). One unit (out of four) was excluded before testing due to deviant behavior.

Laboratory Evaluation
Membrapor C1 sensor

Manufacturer: Membrapor

[Link to website manufacturer]

[Link to test protocol]

3.4 Membrapor C1 versus Reference

Five **Membrapor C1** NO_2 sensors have been evaluated in the RIVM Testing Laboratory under controlled NO_2 concentrations, temperature and relative humidity. These sensors will also be tested in the field (at the Borgerhout station).

Membrapor :

- Electrochemical
- Unit measures NO_2
- Time resolution: 1 minute
- Units IDs: Membrapor1, Membrapor2, Membrapor3, Membrapor4, Membrapor5.

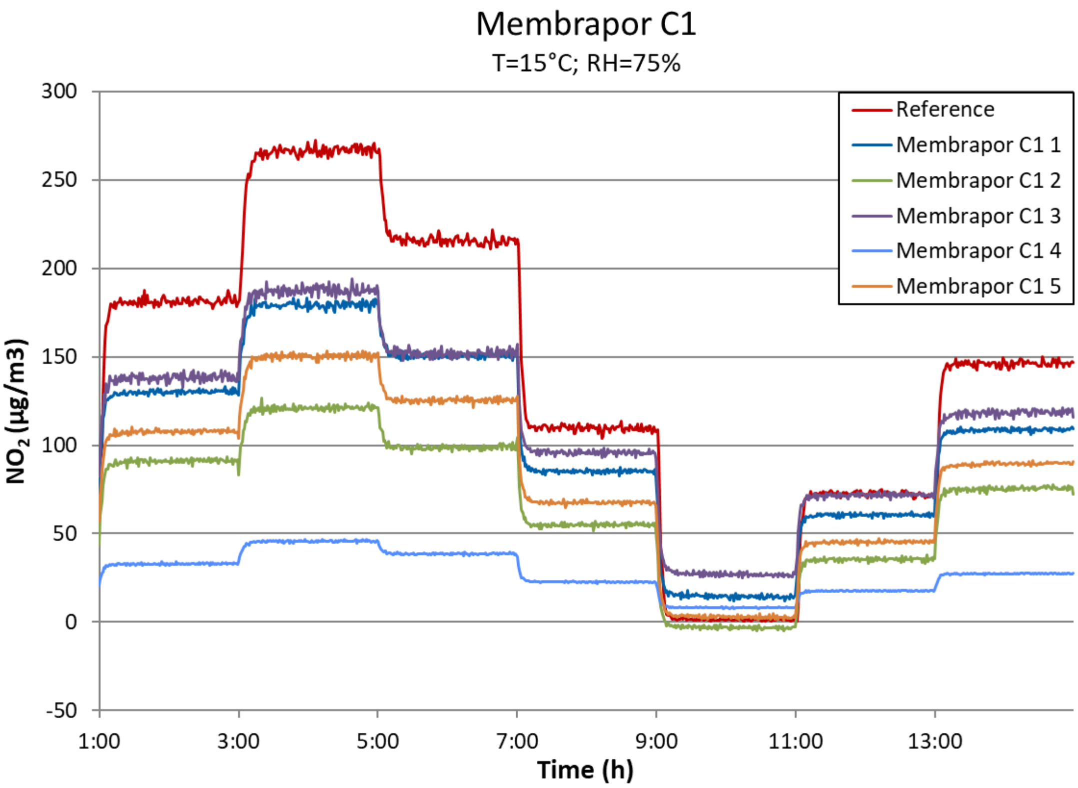
Reference instrument

- Teledyne API Chemiluminescence Nitrogen Oxides Analyzer Model 200E
- Time resolution: 1 minute

For the details about the laboratory protocol followed here, consult our test protocol.

3.4.1 Ramping experiment (T=15°C; RH=75%)

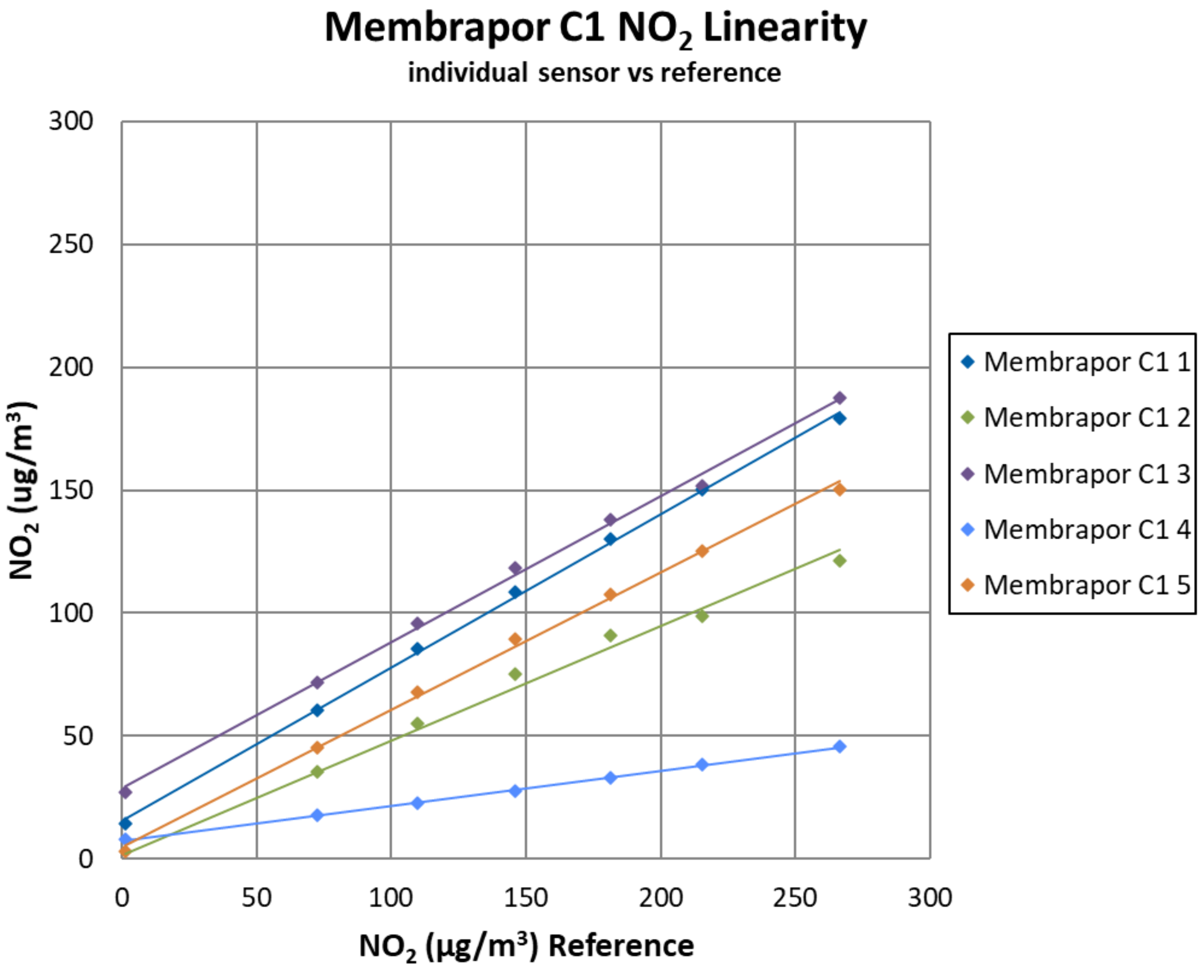
In the first test sensors were exposed to different concentration levels to check linearity, agreement between sensors and agreement with the reference.



- Most Membrapor NO_2 units tracked reasonably with the NO_2 concentration changes (between 0 and 260 µg/m^3) measured by the Teledyne reference. All units underestimated the NO_2 concentrations as measured by the Teledyne. Clearly, the sensitivity of the units differed (considerably).
- The baseline readings varied between -3.0 and 27.0 µg/m^3, respectively.

3.4.2 Linearity

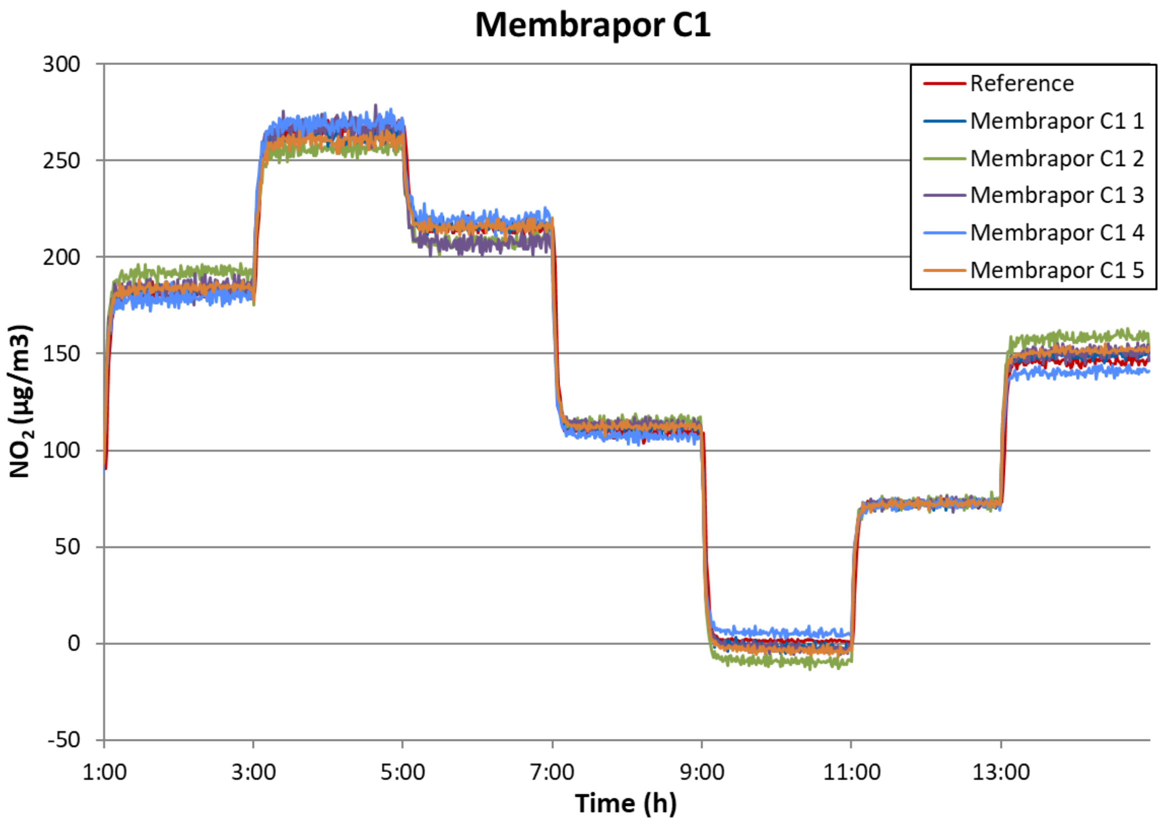
Average concentrations per step were calculated and used for lineair regression (y=ax+b).



Sensor	Slope	Intercept	r^2
Membrapor 1	0.62	15.6	0.9991
Membrapor 2	0.47	1.3	0.9883
Membrapor 3	0.60	28.4	0.9974
Membrapor 4	0.14	7.4	0.9984
Membrapor 5	0.56	4.9	0.9979

- All units showed a very high correlation (r^2>0.99) with the corresponding Teledyne data (derived from the ramping experiment).
- The slopes in the regression equations between 0.14 and 0.62; intercepts varied between 4.9 and 28.4 µg/m^3.

3.4.3 Ramping experiment after calibration



- The slopes and intercepts calculated in the linearity experiment were used for a (simple) calibration of the sensors units. After applying such a procedure, all sensors produced concentration data that were (very) close to the levels measured by the Teledyne reference instrument.

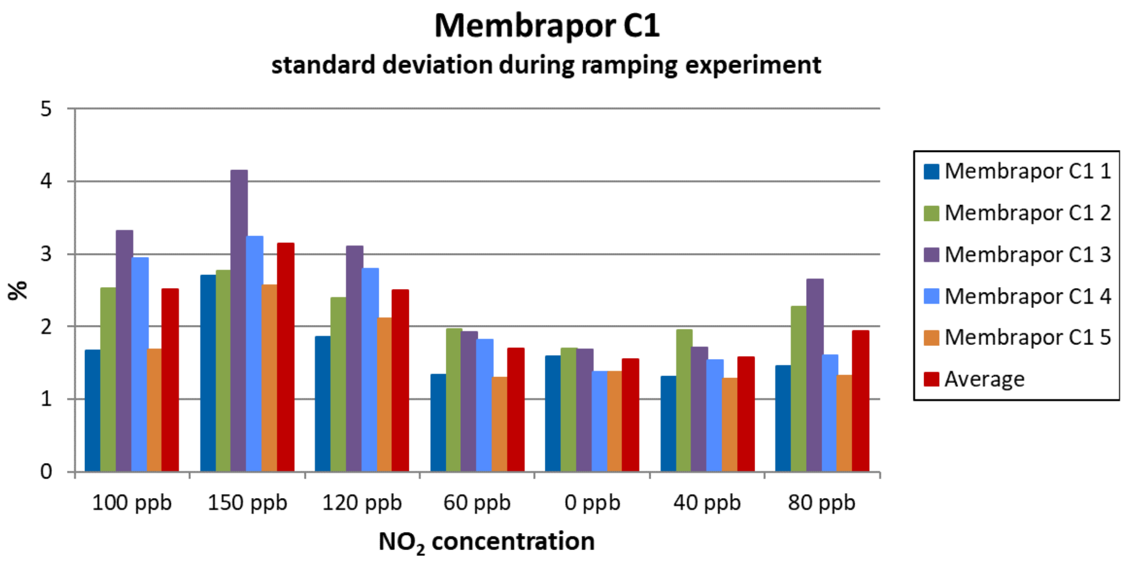
3.4.4 Accuracy

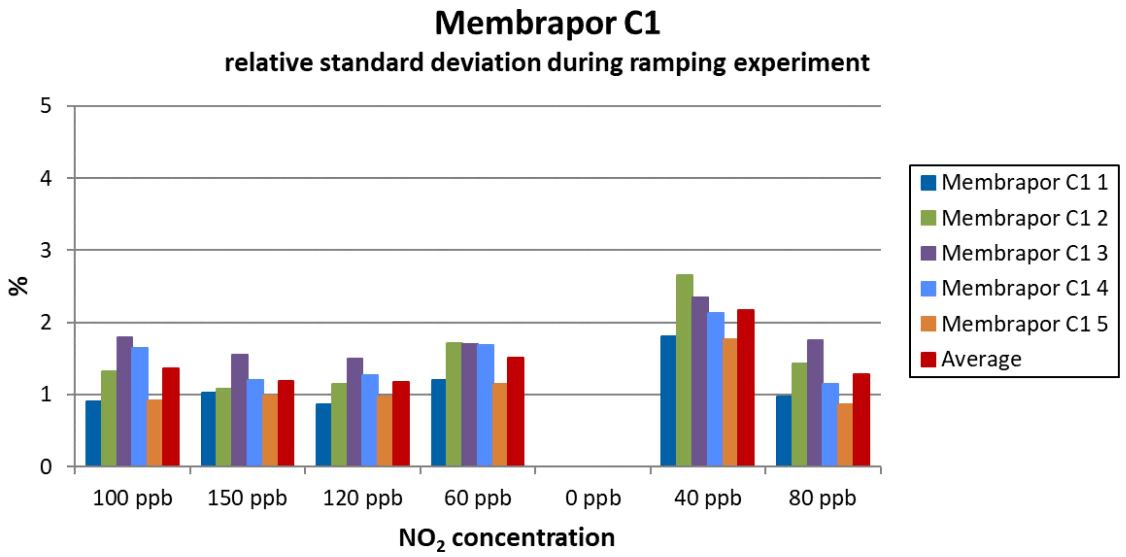
Reference mean (µg/m3)	Sensor mean (µg/m3)	Accuracy (%)
72	72	100
112	112	98
150	149	97
185	185	98
213	212	99
263	265	99

- After calibration, the sensors showed an accuracy close to 100%.

3.4.5 Stability under steady-state conditions

Sensor stability is defined here as the standard deviation during each of the seven steady-state conditions of the ramping experiment (also see the Appendix). The standard deviation of the reference is 0.9 µg/m^3 (range: 0.7-1.1 µg/m^3); relative standard deviation is 0.6 (0.3-1.0).





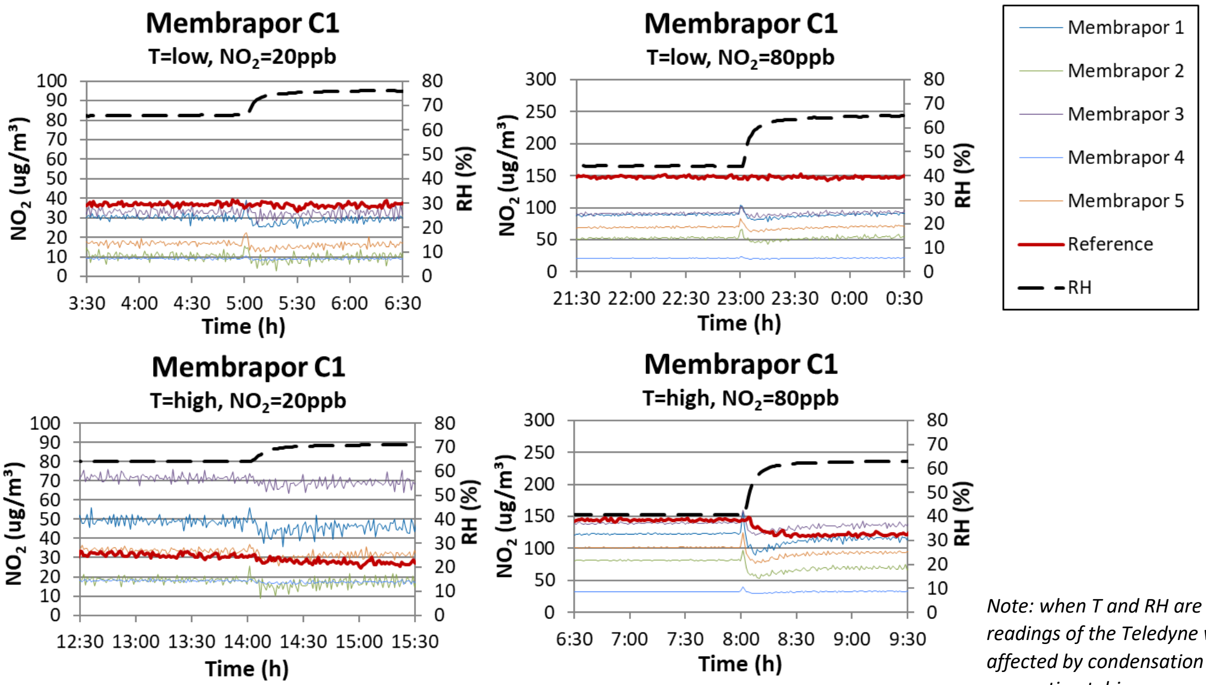
- In general, the standard deviations of the sensors' output were less than 3 µg/m^3 (after calibration). Some units (Membrapor C1 1 and 4) performed better than others (Membrapor C1 3). An increase at the higher concentration levels of NO_2 was observed.
- The relative standard deviations were, in most cases, less than 2%.

3.4.6 Between sensor uncertainty

The calculated uncertainty between the sensors' data sets was 8.2 μg/m^3 (the second best result in this study).

3.4.7 Influence of temperature and relative humidity

The readings of gas sensor systems are known to be affected by changes in meteorological parameters (RH, T). Here, the effect of a changing RH (at constant levels for temperature and concentration) is shown.

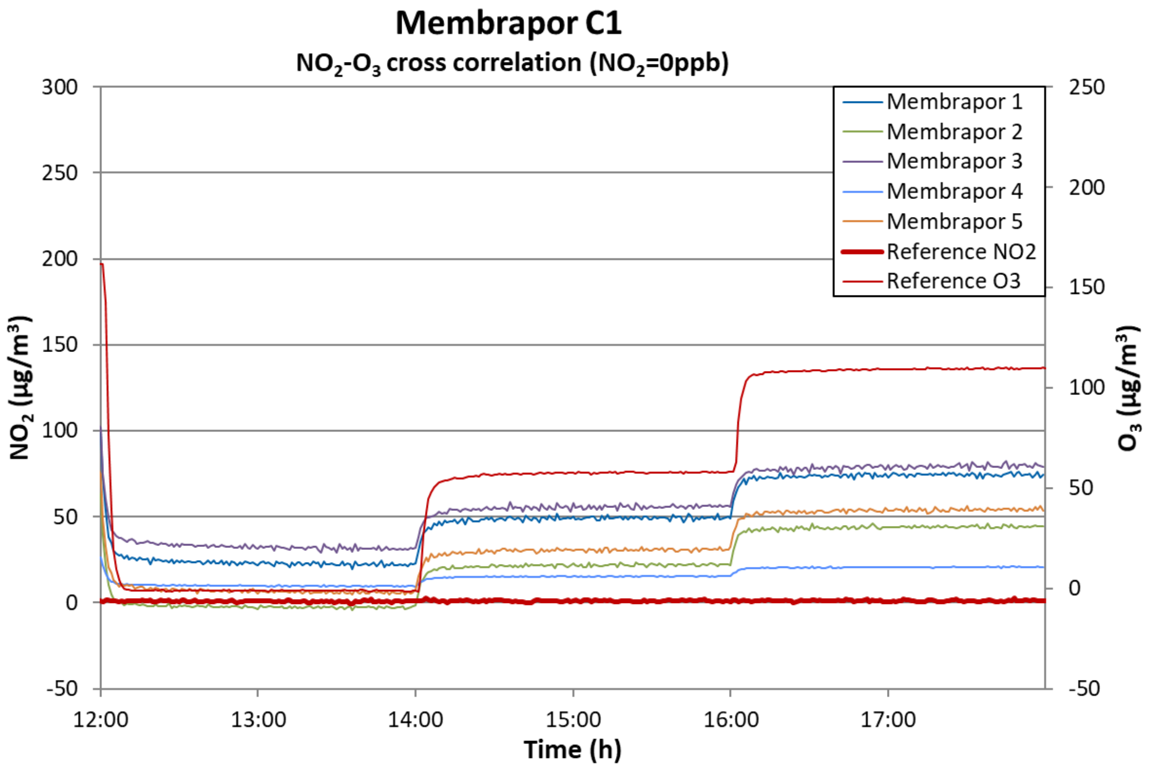


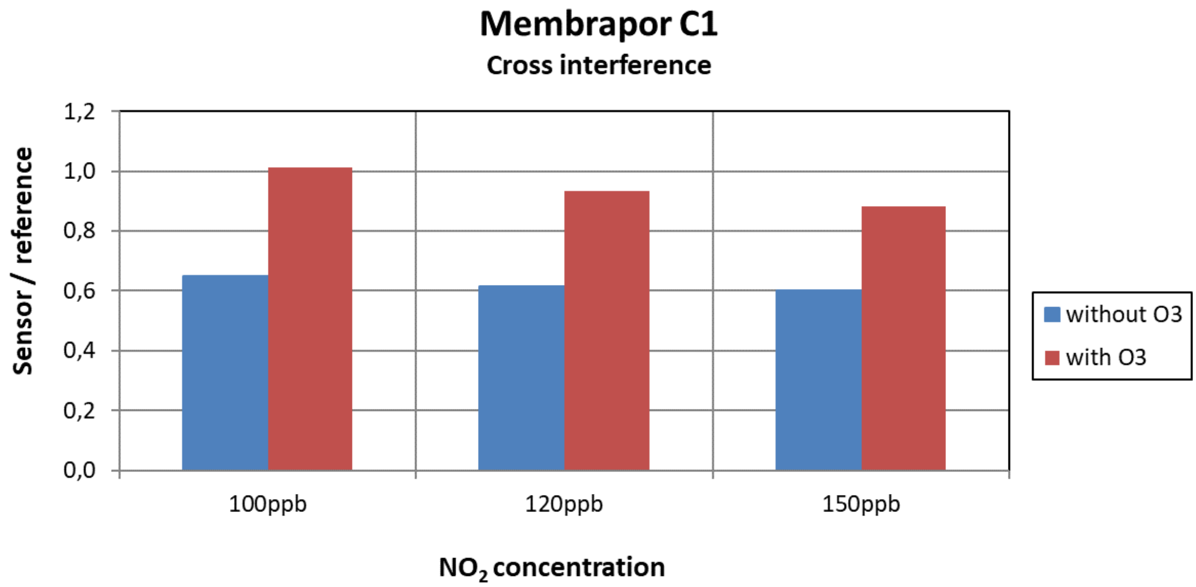
Note: when T and RH are high, the readings of the Teledyne were affected by condensation in the connecting tubings.

- Generally, the increase in relative humidity (sometimes) resulted in a (small) positive peak in the sensor signal that was followed by a negative deviation aberration (lasting in the range of 1 hour or more). This effect was more apparent at a higher temperature.

3.4.8 Cross sensitivity

To test the cross sensitivity, the sensors in the exposure box were exposed to different levels of ozone at zero and nonzero NO_2-levels.





- Clearly, interference by ozone was observed in all units at zero and nonzero levels for NO_2 in the exposure box. The ambient concentrations were overestimated (becoming less apparent at higher NO_2 level).

3.4.9 Summary

- **Accuracy**: All the units indicate a very high accuracy compared to the reference instrument (after calibration). On an individual basis, accuracies are around 98%. Before calibration, the individual accuracy can be lower than 50%.

- **Stability:** The standard deviations of the sensors' signals are less than 3 µg/m^3 (during stationary conditions over 2 hours) and appear dependent of concentration level.

- **Linearity of sensor response**: All sensor units show a very high coefficient of determination (r^2>0.99) compared to corresponding Teledyne NO_2 measurements (between 0-230 µg/m^3 and after calibration).

- **Between-sensor uncertainty**: The uncertainty between the sensors is 8.2 µg/m^3 (being the highest value of the five different types of sensors).

- **Effect of relative humidity and temperature**: Generally, an increase in relative humidity results in a (small) peak concentration followed by a negative aberration (lasting more than one hour). The response seems to depend on the magnitude of the step in relative humidity and the temperature.

- **Cross sensitivity**: Interference by ozone is observed in all units resulting in overestimated concentrations of NO_2.

- **Data recovery:** the data recovery for all units is 100% (for a measurement period of 77 hours in total).

VAQUUMS

Laboratory Evaluation
Membrapor C20 sensor

Manufacturer: Membrapor
[Link to website manufacturer]

[Link to test protocol]

3.5 Membrapor C20 versus Reference

Two **Membrapor C20** sensors have been evaluated in the RIVM Testing Laboratory under controlled NO_2 concentration, temperature and relative humidity. These sensors will also be tested in the field (at the Borgerhout station).

Membrapor C20:

- Electrochemical sensors
- Unit measures NO_2
- Time resolution: 1 minute
- Units IDs: Membrapor2, Membrapor3, Membrapor4, Membrapor5; two of these units (2 and 3) have been removed due to deviant behavior during testing

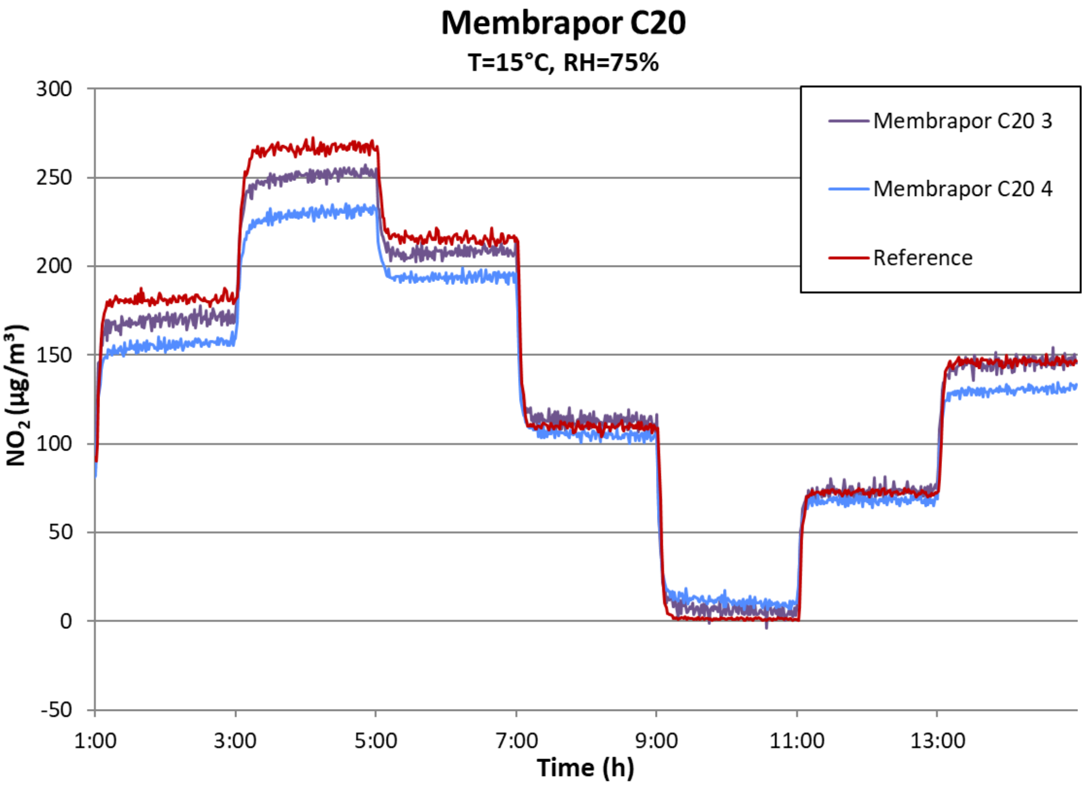
Reference instrument

- Teledyne API Chemiluminescence Nitrogen Oxides Analyzer Model 200E
- Time resolution: 1 minute

For the details about the laboratory protocol followed here, consult our test protocol.

3.5.1 Ramping experiment (T=15°C; RH=75%)

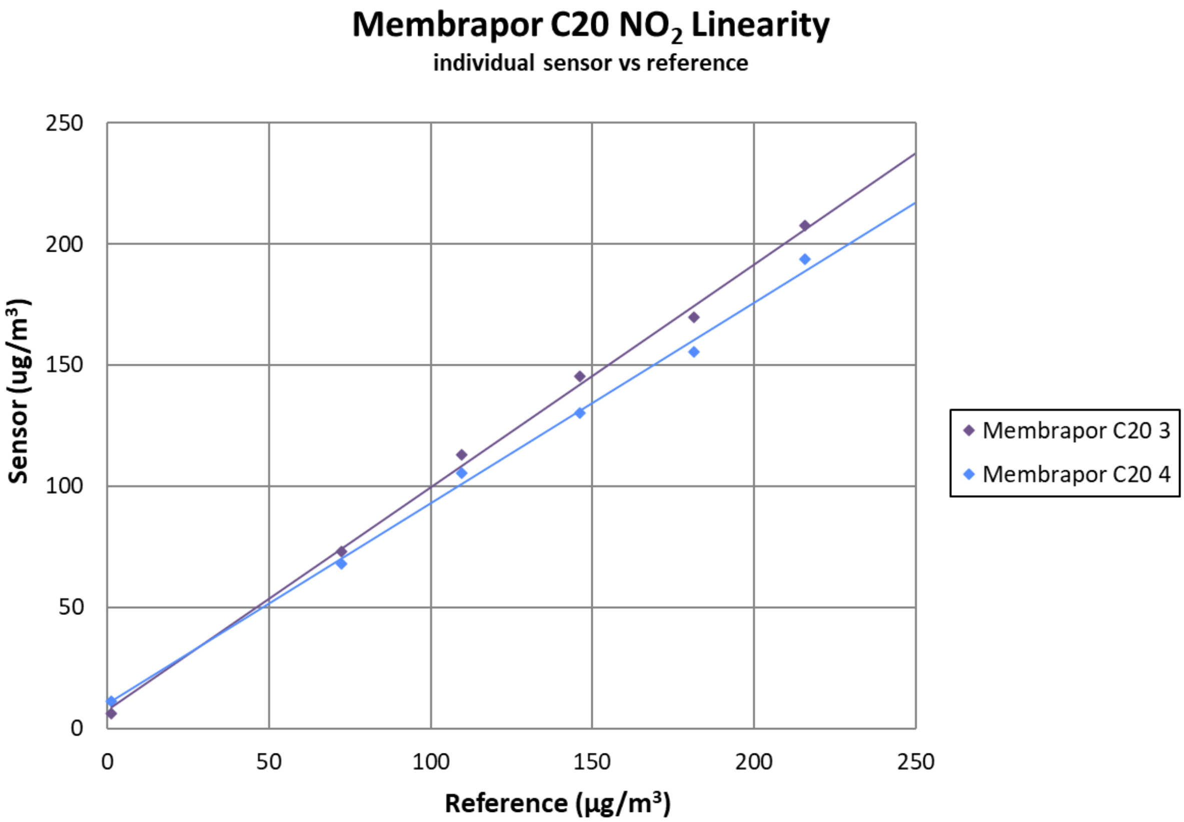
In the first test sensors were exposed to different concentration levels to check linearity, agreement between sensors and agreement with the reference.



- The two Membrapor NO_2 units tracked well with the NO_2 concentration changes (between 0 and 260 µg/m^3) as measured by the Teledyne reference instrument. All units underestimate the NO_2 (reference) concentration.

3.5.2 Linearity

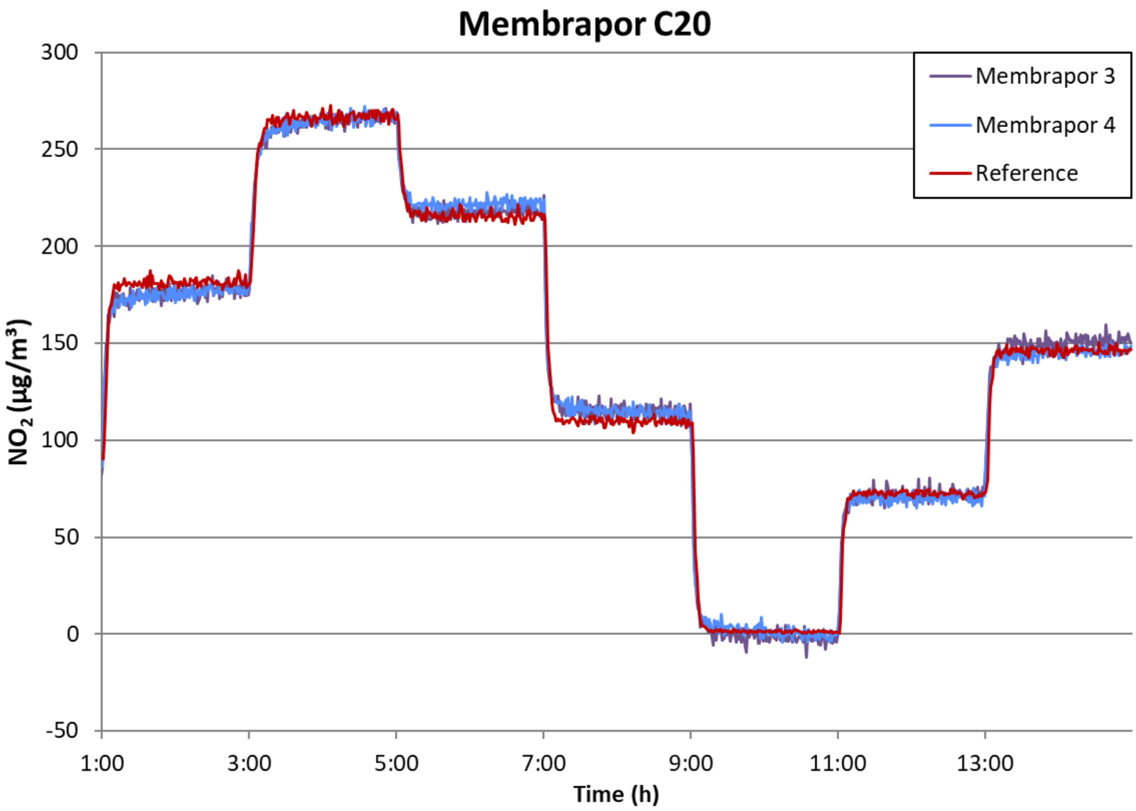
Average concentrations per step were calculated and used for lineair regression (y=ax+b).



Sensor	Slope	Intercept	r^2
Membrapor 3	0.92	7.2	0.9983
Membrapor 4	0.83	10.0	0.9978

- The two units showed a very high correlation with the corresponding Teledyne data (r^2>0.99) (derived from the ramping experiment). The slopes in the regression equations were 0.83 and 0.92; intercepts were 7.2 and 10.0 µg/m3, respectively.

3.5.3 Ramping experiment after calibration



- The slopes and intercepts calculated in the linearity experiment were used for a (simple) calibration of the sensors units. After applying such a procedure, all sensors produced concentration data that were (very) close to the levels measured by the Teledyne reference instrument.

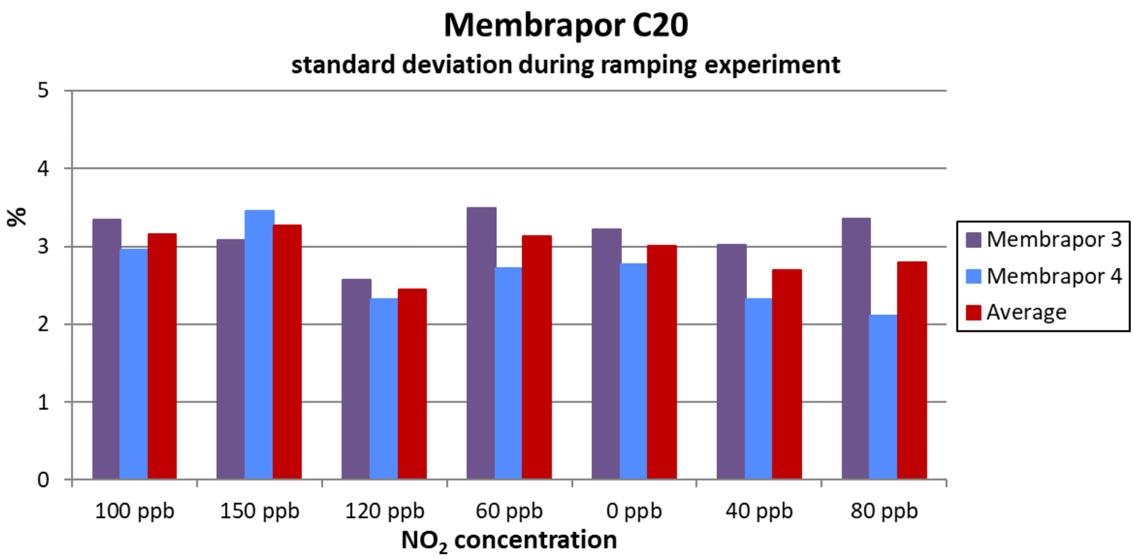
3.5.4 Accuracy

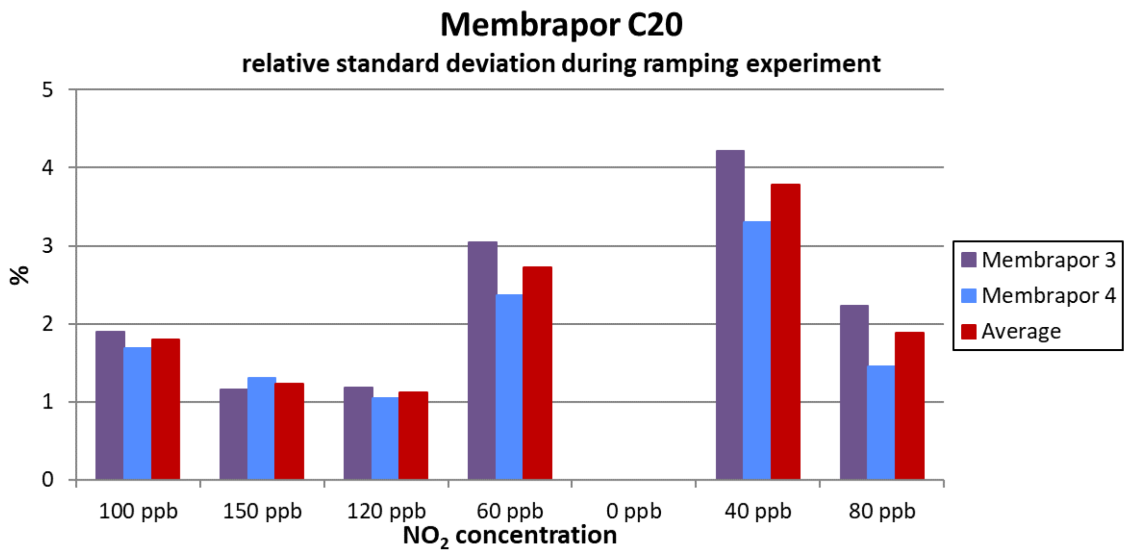
Reference mean (µg/m3)	Sensor mean (µg/m3)	Accuracy (%)
72	71	98
110	115	95
146	147	99
181	176	97
216	220	98
267	264	99

- After calibration, the sensors showed an accuracy close to 100%.

3.5.5 Stability under steady-state conditions

Sensor stability is defined here as the standard deviation during each of the seven steady-state conditions of the ramping experiment (also see the Appendix). The standard deviation of the reference is 0.9 µg/m^3 (range: 0.7-1.1 µg/m^3); relative standard deviation is 0.6 (0.3-1.0).





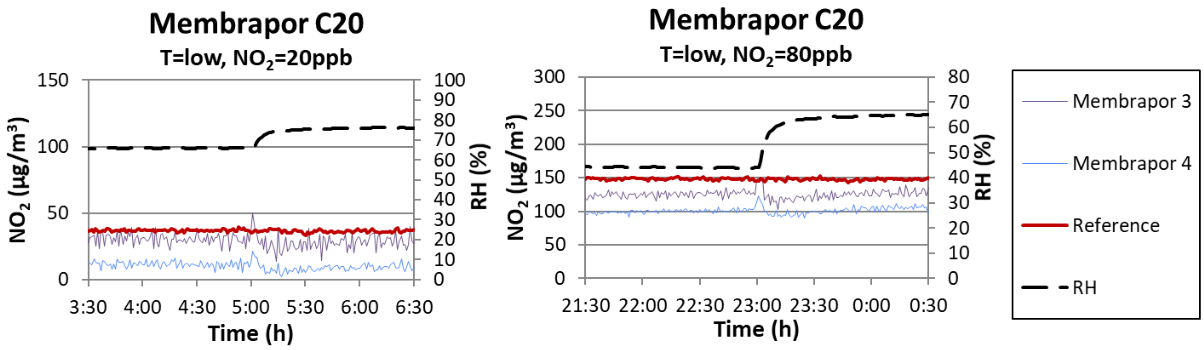
- In most cases, the standard deviations of the sensors' output were close to 3 µg/m^3 (after calibration). One unit (Membrapor3) performed better than the other (Membrapor4). There was no dependence on the ambient NO_2-level.
- The relative standard deviations were, in most cases, less than 4%. The performance was (much) better at higher concentration levels.

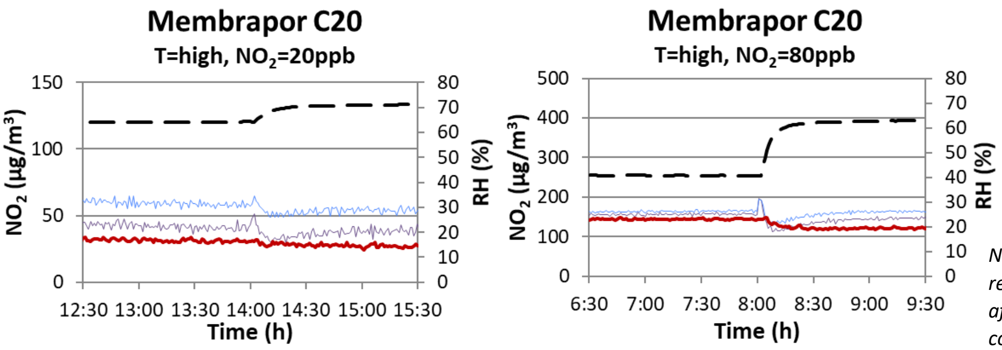
3.5.6 Between sensor uncertainty

The calculated uncertainty between the sensors' data sets is 9.9 µg/m^3 (better than the average result).

3.5.7 Influence of temperature and relative humidity

The readings of gas sensor systems are known to be affected by changes in meteorological parameters (RH, T). Here, the effect of a changing RH (at constant levels for temperature and concentration) is shown.



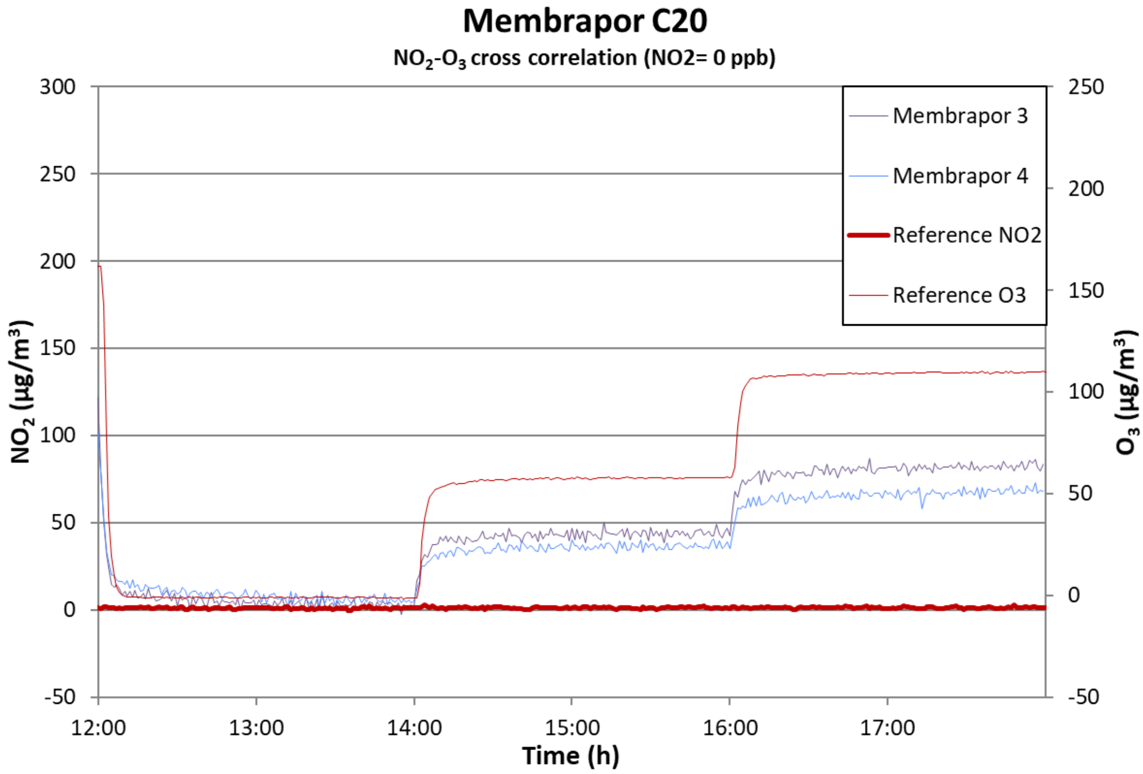


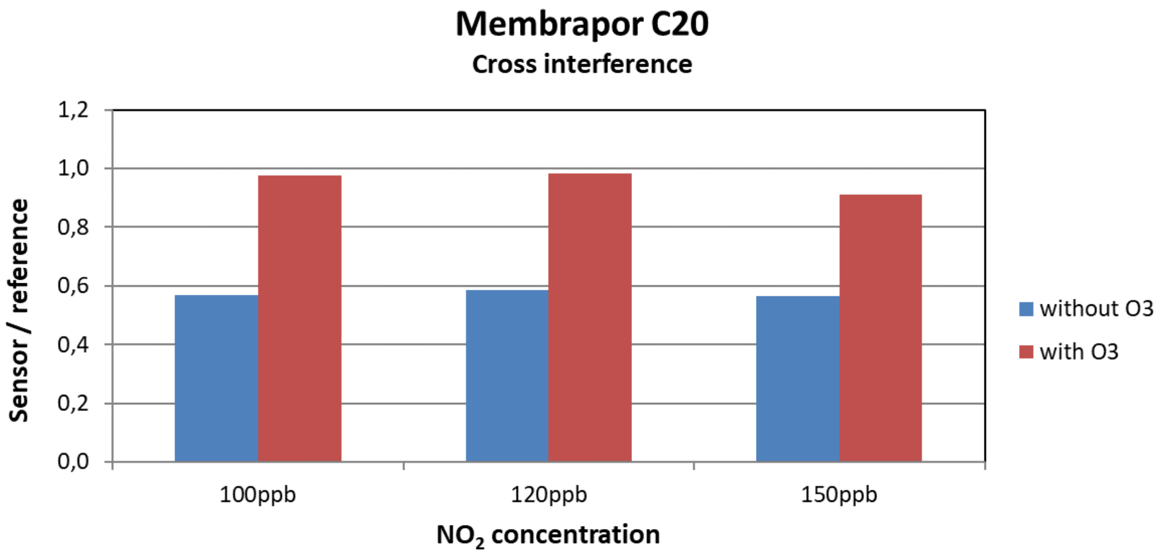
Note: when T and RH are high, the readings of the Teledyne were affected by condensation in the connecting tubings.

- Generally, an increase in relative humidity resulted in a small peak value followed by negative aberration (lasting in the order of one hour). The latter effect appeared more apparent at a higher temperature and ambient NO_2 concentration level.

3.5.8 Cross sensitivity

To test the cross sensitivity, the sensors in the exposure box were exposed to different levels of ozone at zero and nonzero NO_2-levels.





- Clearly, cross interference due to ozone was observed in all units for zero or nonzero levels of NO_2 in the exposure box. The interference resulted in an overestimation of the NO_2 concentration in the exposure box.

3.5.9 Summary

- **Accuracy**: All the units indicate a very high accuracy compared to the reference instrument (after calibration). On an individual basis, accuracies are around 97%. Before calibration, the individual accuracy can be as low as 50%.

- **Linearity of sensor response**: Membrapor C20 sensors showed very good linear correlation (r^2>0.99) with the corresponding Teledyne NO_2 measurements (between 0-260 µg/m^3 and after calibration).

- **Stability:** The standard deviations of the sensors' signals are around 3 µg/m^3 (during stationary conditions over 2 hours) and appear independent of concentration level.

- **Between-sensor uncertainty**: The uncertainty between the sensors is 9.9 µg/m^3 (better than average result).

- **Effect of relative humidity and temperature**: Generally, an increase in relative humidity results in a (small) peak concentration followed by a negative aberration (lasting in the order of one hour). The response is influenced by temperature and ambient NO2 concentration level.

- **Cross sensitivity**: The sensor units are affected by the presence of ozone (at zero and nonzero levels of NO_2).

- **Data recovery** for the Membrapor C20 units was 100% (for a measurement period of 77 hours in total).