NBCIP

Carbon Dioxide Transmitters

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National Building Controls Information Program

Outline

- **Carbon Dioxide Transmitters**
  - Ties to Title 24
  - Technologies
  - NBCIP Testing
  - Preliminary results

Title 24 DCV Overview

- DCV required for single zone units having the following characteristics:
  - They have an outdoor air economizer, and
  - They serve spaces where occupant density is ≤ 40 ft^2/person
- Exceptions
  - Classrooms (permitted to use DCV, but not required to)
  - Exhaust is large (where exhaust > design ventilation – 0.2 cfm/ft^2)
  - Spaces having processes or operations that generate dusts, fumes, mists, vapors, or gases and are not provided with local exhaust ventilation

Title 24 DCV Requirements

Where DCV is employed the controls must meet all of the following requirements:

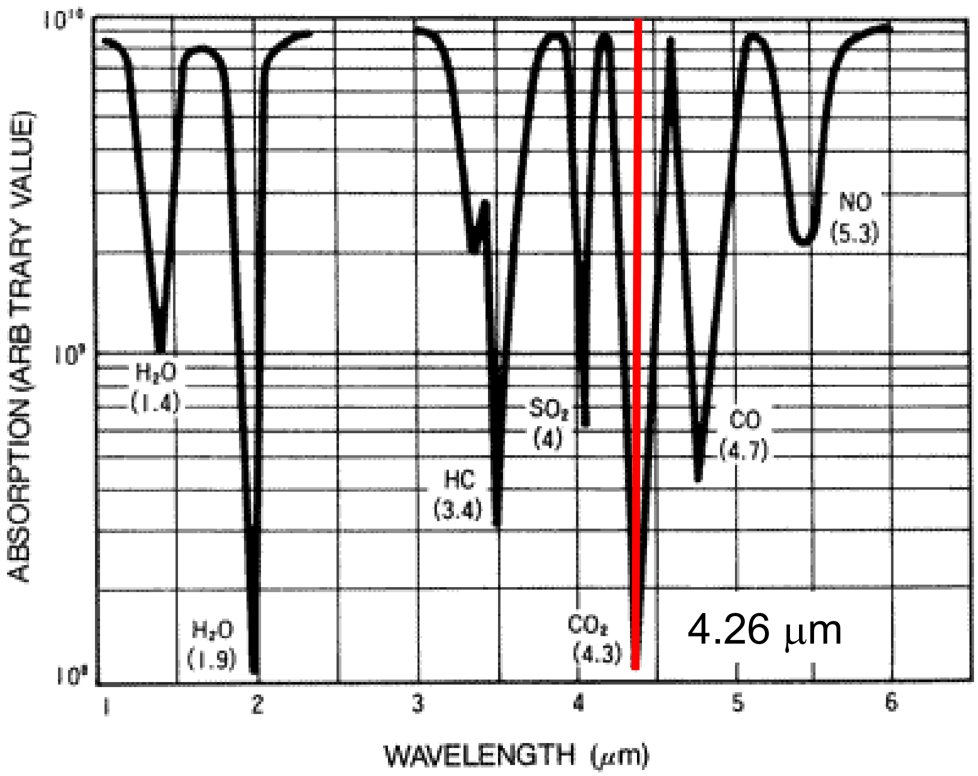
- Sensor must be provided in each room served by the system that has a design occupancy of 40 ft^2/person or less.
- Sensors must be located in the breathing zone (1-6 ft above the floor).
- Ventilation rate must be maintained that will result in a concentration of CO_2 at or below 600 ppm above the ambient level. Ambient levels can either be assumed to be 400 ppm or dynamically measured.
- Regardless of the CO_2 sensor's reading, the system is not required to provide more than the minimum ventilation rate required by §121(b)
- CO_2 sensor must be factory certified to have an accuracy of no less than 75 ppm over a 5-year period without recalibration in the field.

Operating Principles

Non-dispersive infrared (NDIR) photometric principle

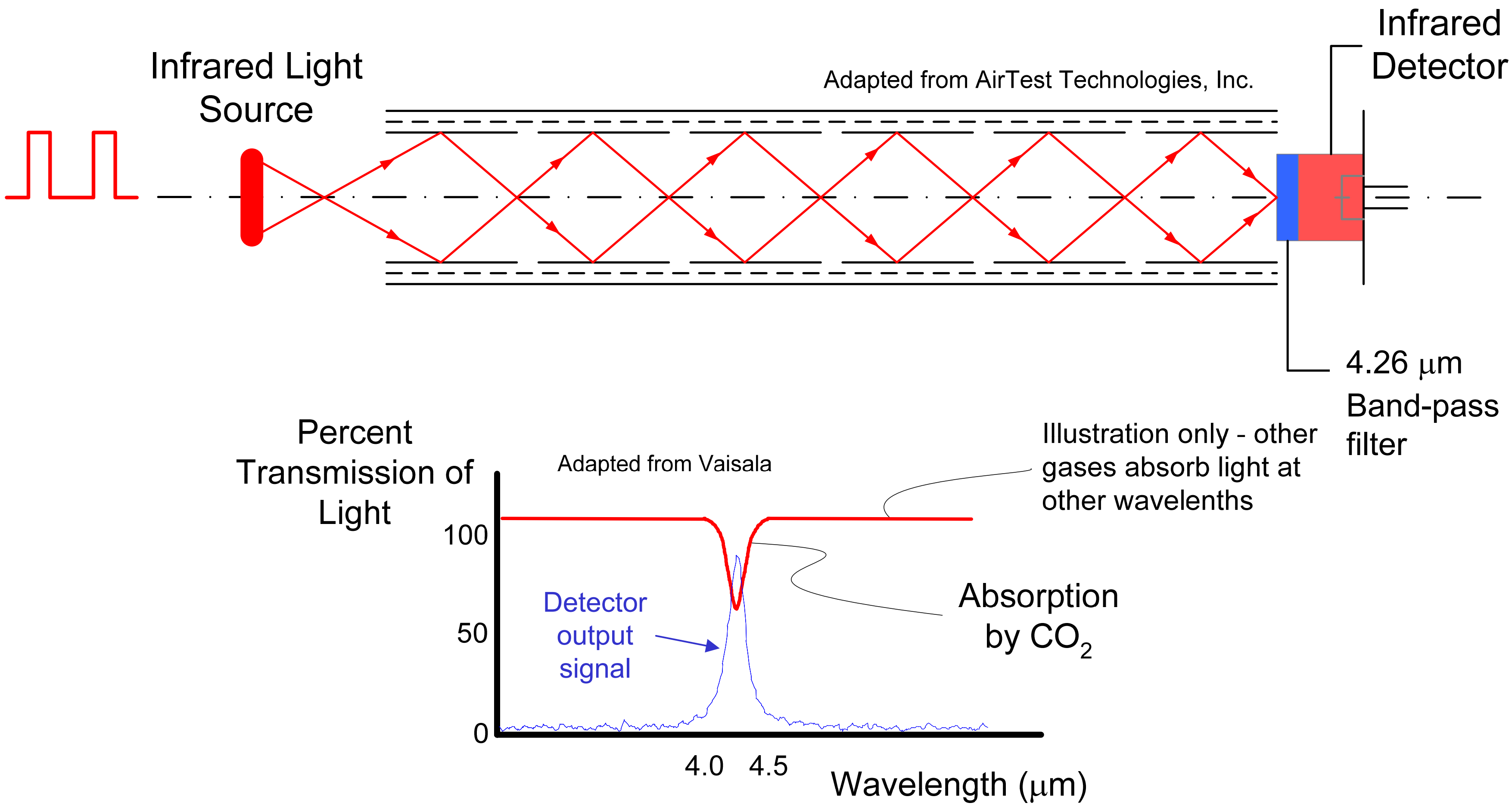
CO_2 absorption band at 4.26 μm. Other common components of air do not absorb light at this wavelength.

(Figure adapted from http://rebar.ecn.purdue.edu/ECT/Other/InfraredGasSensor.aspx)



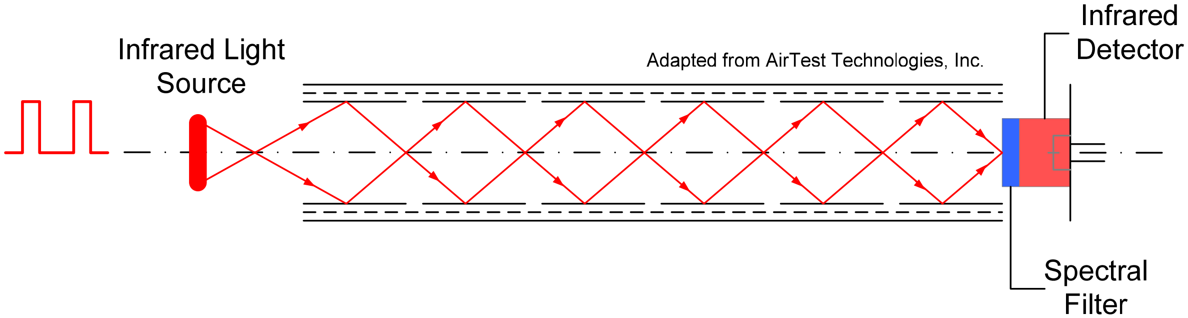
NDIR Photometric Principle

Attenuation of IR beam is proportional to the number density of CO_2 molecules in the optical path (molecules/volume).



What affects the number density of CO_2 in the optical path?

- Gas composition
- Pressure
- Temperature



Calibrate detector with a mixture of CO_2 and N_2 at a fixed pressure and temperature with a know CO_2 concentration (ppm).

Zero: N_2 (99.9xxx%) +trace gases (mainly water vapor and CO_2)

Span: 500, 1000, 1500, 2000 ppm CO_2 (± x%) + N_2 + trace gases

Compensate for operating pressures and temperatures that differ from the calibration conditions.

P&T affects are reported by most manufacturers.

Pressure and Temperature Compensation

Johnson Controls

Specifications

(http://cgproducts.johnsoncontrols.com//CAT_PDF/1900159.PDF)

	CD-Wxx-00-0 Wall Mount CO_2 Transmitter
Measuring Range	0 to 2,000 ppm CO_2
Accuracy at 77°F (25°C)	<±(30 ppm CO_2 + 2.0% of reading) (includes manufacturing deviation and drift). All accuracy specifications reflect testing the transmitters using high-grade, certified gases. Transmitters are intended for an altitude range of 0 to 1,969 ft (0 to 600m) above sea level without compensation. To compensate for higher altitudes, see the Johnson Controls installation instructions for this device.
Non-Linearity	<1.0% of Full Scale
Temperature Dependence of Output	<0.056% of Full Scale/F° (<0.1% of Full Scale/C°)

Reference temp.

25 C?

Pressure and Temperature Compensation

Altitude Compensation

The sensors are calibrated for an altitude of 984 ft (300m) above sea level and are intended for applications within the range of 0 to 1,969 ft (0 to 600m) without compensation.

Reference altitude

(http://cgproducts.johnsoncontrols.com//MET_PDF/240960127.PDF)

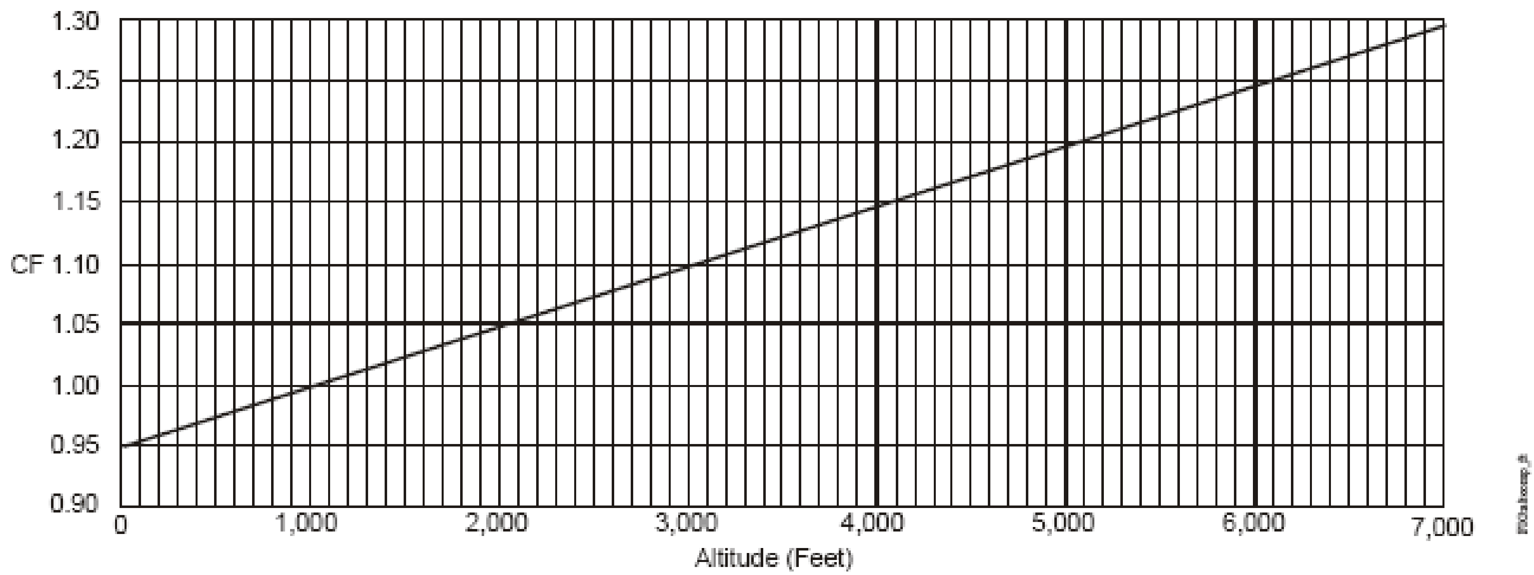


Figure 7: Altitude Compensation in Feet above Sea Level

Pressure and Temperature Compensation

GREYSTONE ENERGY SYSTEMS INC

Specifications

CO_2 DETECTOR - Product # CDD

(http://www.greystoneenergy.com/English/products/airandgas/products_gas_co2.html)

Product	CDD1A1, 1A2, 1A3, 1A6	CDD1A7 & CDD1A8	CDD1A4 & CDD1A5
Range	0-2000 ppm standard, programmable from 1500 up to 10,000 ppm		0-2000 ppm
Standard Accuracy	±50 PPM or +3% of reading @22 C(72 F) when compared to certified calibration gas		
Sensing Element	Non-Dispersive Infrared Detector (NDIR)		
Operation Conditions	0-50ºC (32-122ºF), 0-95% RH non-condensing		
Temperature Dependance	0.2% FS per ºC		
Stability	< 2 % FS over life of sensor (15 years typical)		
Output Signal	4-20 mA active (sourcing), 0-5Vdc and 0-10Vdc, jumper selectable (Note correct part number)	(1A7)4-20 mA active (sourcing) or (1A8) 0-5Vdc or 0-10Vdc	4-20 mA active (sourcing), 0-5Vdc(1A5) or 0-10Vdc(1A4)
Output Drive Capability	Current - 550 ohm max Voltage - 10 Kohm min	Current - 550 ohm max Voltage - 2 Kohm min	Current - 550 ohm max Voltage - 10 Kohm min
Pressure Dependance	0.13% of reading per mm Hg		
Alitiude Correction	Programmable from 0-5000 ft in 500 ft increments		Not Applicable

Reference temp.

22 C?

Reference pressure?

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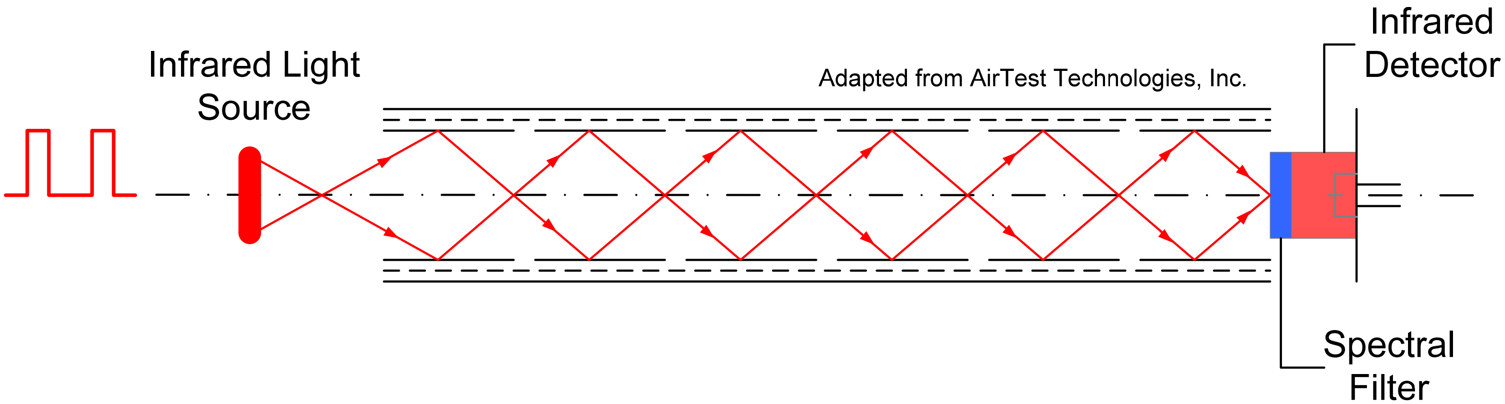
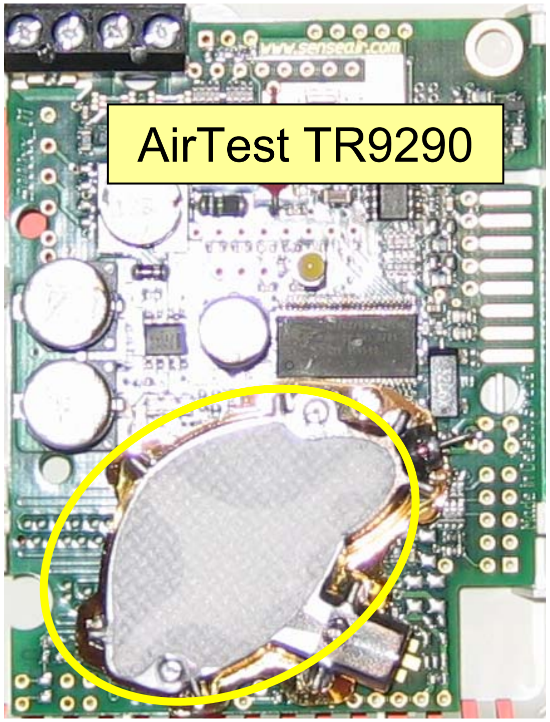
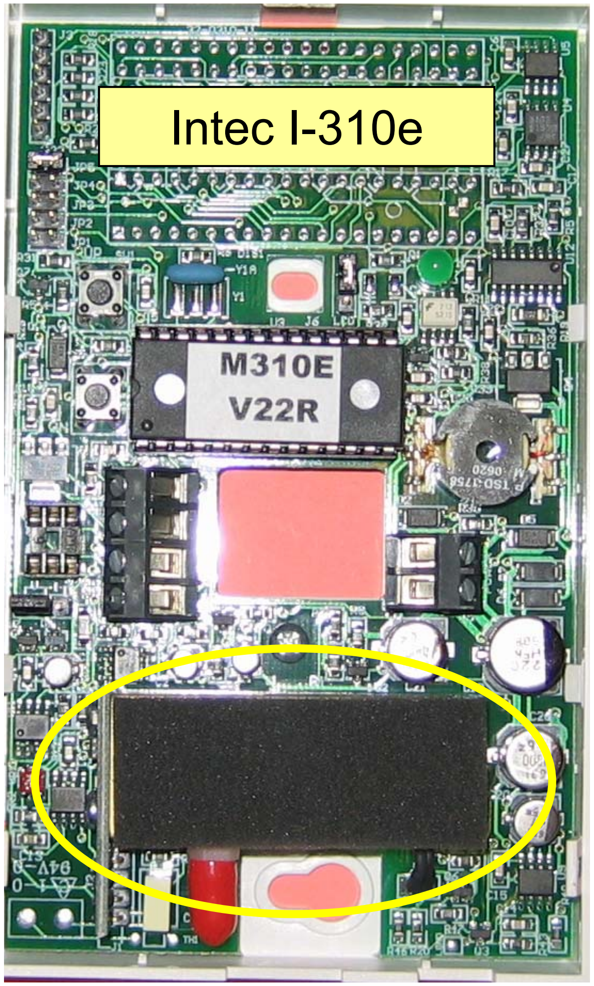
What affects the performance of CO_2 sensor?

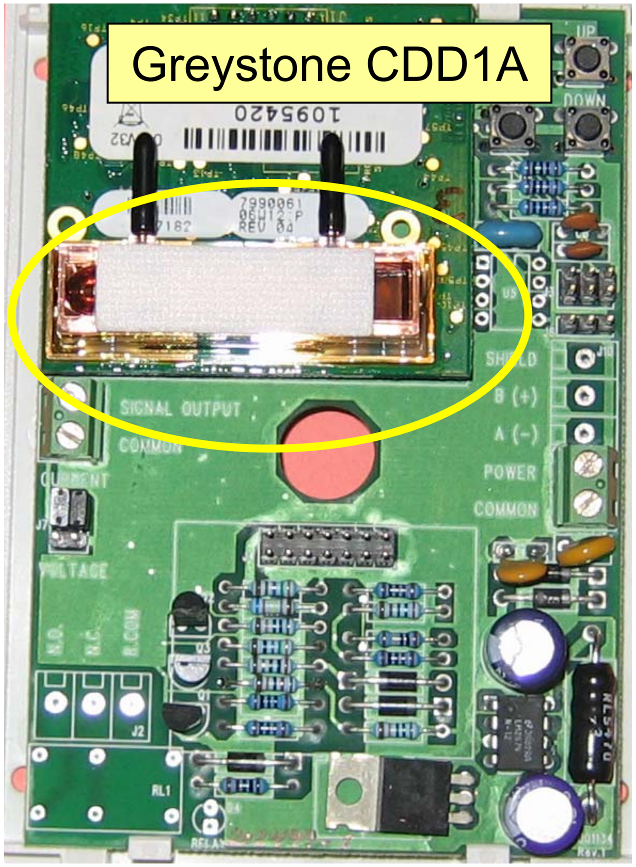


- Light source intensity (ageing).
- Changes to the optical path (dust, condensate).
  - Dust filter applied to optical cavity
  - Recommended RH ranges (non-condensing)
- Humidity? (no mention of humidity effects on sensor performance)
- Pressure and temperature (already discussed)

Optical Cavity Dust Filters







Strategies to compensate for lamp ageing

- Photometric Compensation

  Single beam – dual wavelength

  Dual beam – single wavelength

- Automatic Background Calibration (ABC)

Single beam

Dual beam

7 beams

Terminology is confusing (even for the manufacturer)

(http://www.edinst.com/pdf/telaire/ventostat81018102.pdf)

Ventostat® 8101/8102
Dual Beam CO2
Ventilation Controllers

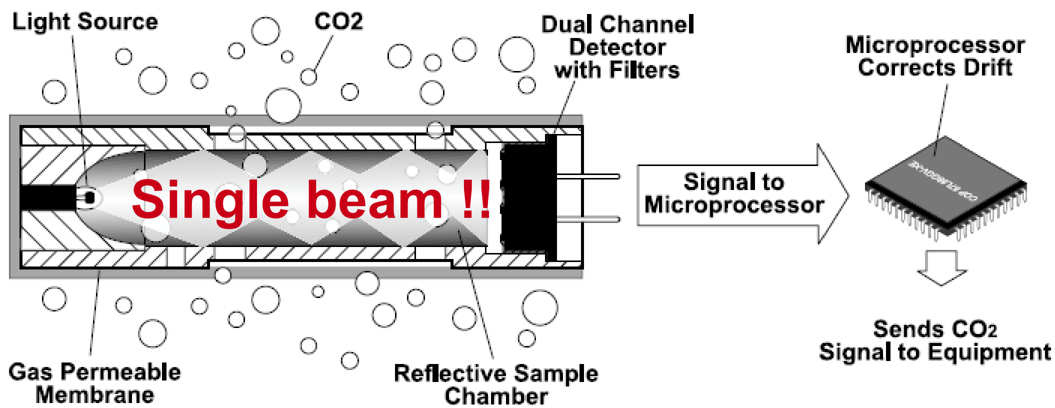
Specifications

Method

Dual Beam Absorption Infrared Diffusion sample method

How The Precision Grade Sensor Works

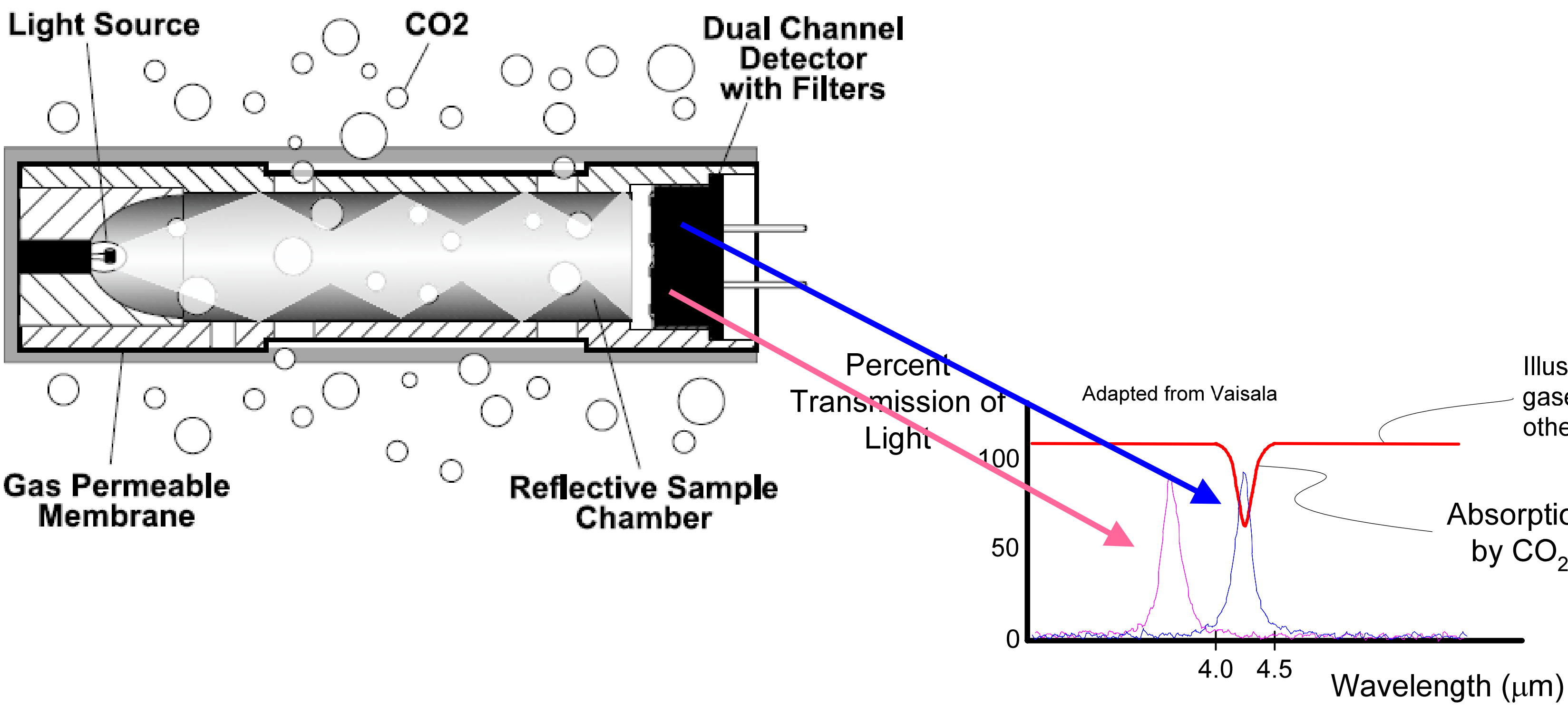
Telaire's Infrared sensor design can detect gases based on the fact that gases will absorb light at very specific wavelengths in the infrared spectrum. In the Telaire® sensor, gas diffuses into the sample chamber through a gas permeable membrane that allows gas molecules to pass freely but that prevents the entry of particulates. A light source at one end of the chamber generates a broad band of infrared energy that is directed through the sample chamber. Because much of the light bounces off the gold plated walls of the sensor, a longer effective sample path can be achieved in a small distance.
At the other end of the sensor are two light detectors covered by two different optical filters. One optical filter is designed to only admit light at the wavelength where CO_2 is known to absorb light. The small change in light intensity caused by a change in CO_2 concentrations is then measured by the detector is converted into a CO_2 measurement by the sensor microprocessor. The second optical filter and detector looks at a wavelength know not to be affected by any gases. This second channel, called a reference, looks for small changes in the optics of the system that may cause sensor drift. These changes are primarily caused by aging of the infrared light source. The microprocessor monitors the reference channel and corrects the CO_2 measurement based on any long term changes detected.



Photometric compensation

Single Beam (lamp) – Dual Wavelength (λ_1, λ_2)

(Adapted from Telaire http://www.edinst.com/pdf/telaire/ventostat81018102.pdf)



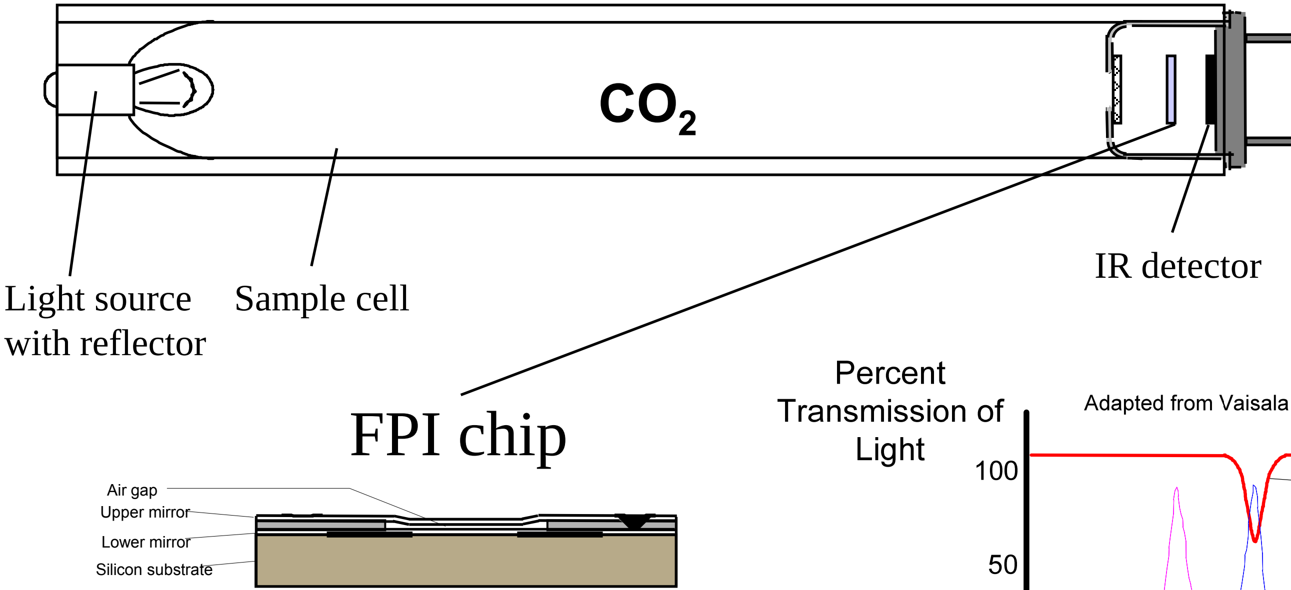
λ_1 4.26 µm

λ_2 Non-absorbing

Photometric compensation

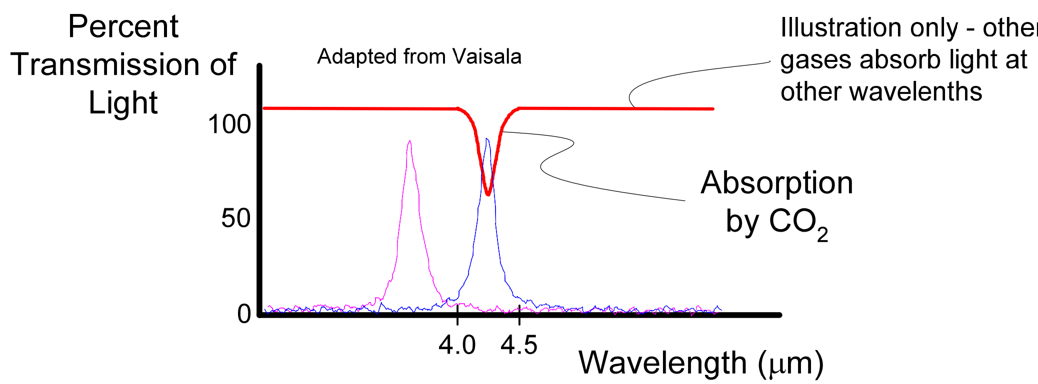
Single Beam (lamp) – Dual Wavelength (λ_1, λ_2)

Courtesy Vaisala



Applied voltage toggles between filter wavelengths

Courtesy Vaisala



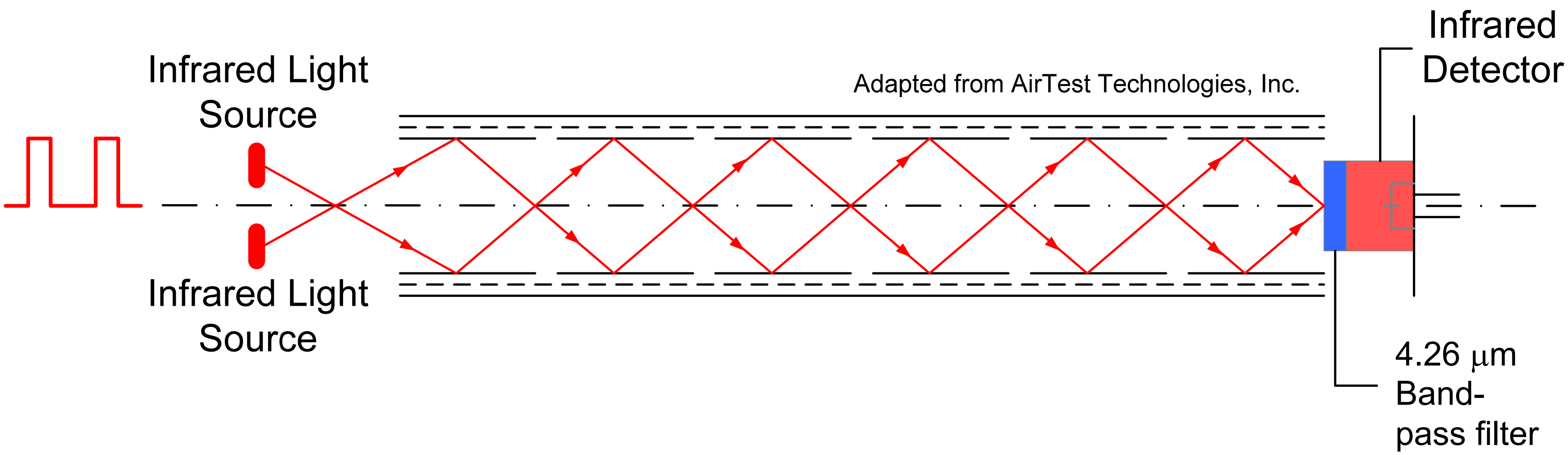
λ_1 4.26 μm

λ_2 Non-absorbing

Photometric compensation

Dual Beam (two lamps) – Single Wavelength (λ_1)

Second light source pulsed infrequently (i.e. once or twice per day) to slow its ageing. Comparison made between two lamps.



Automatic Background Calibration (ABC)

How Do They Work?

Rely on the fact that many buildings experience unoccupied periods during which CO_2 levels drop to outdoor levels.

Depends on building and ventilation schedule (night purge)

Sensor resets the baseline value (nominally 400 ppm) according to minimum CO_2 concentration observed.

Algorithms vary with manufacturer and are not well documented.

Spaces with CO_2 levels always above outdoor levels can not use ABC.

Automatic Background Calibration (ABC)

Self-Calibration Algorithms (statements from 3 manufacturers)

Correction frequency: 7.5 days. Maximum allowed rate of change 25 ppm.

A patented self-calibration technique used in application where concentrations will drop to outside ambient conditions (approximately 400 ppm) at least 3 times in a 14 day period, typically during unoccupied intervals.

Unit will reset to 400 ppm if the readings have been <400 ppm for more than 1 hour.

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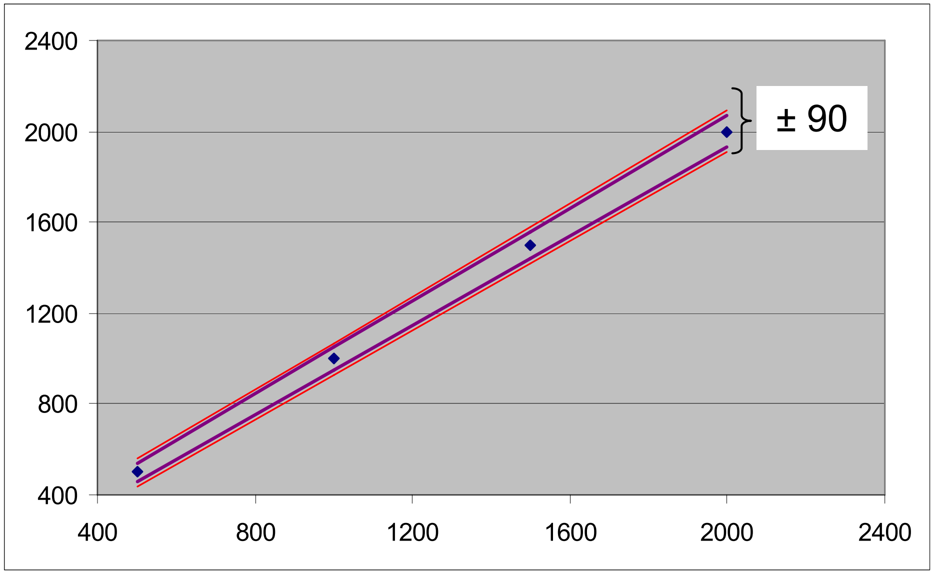
CO_2 Sensor Accuracy Statement

Beware of additive effects (non-linearity not included with accuracy)

Specifications (http://cgproducts.johnsoncontrols.com/MET_PDF/216527.PDF)

Product	CD-Wxx-00-0 Series Wall Mount CO_2 Transmitter
Measuring Range	0 to 2,000 ppm CO_2
Accuracy at 68°F (20°C)	<±[30 ppm CO_2 + 2.0% of reading] (includes manufacturing deviation and drift). All accuracy specifications reflect testing the transmitters using high-grade, certified gases. Transmitters are intended for an altitude range of 0 to 1,969 ft (0 to 600m) above sea level without compensation. To compensate for higher altitudes, see the Johnson Controls installation instructions for this device.
Non-Linearity	<1.0% of Full Scale (FS)

Reading (ppm)	Accuracy	Non-linearity	Combined (ppm)
500	± 40	± 20	± 60
1000	± 50	± 20	± 70
1500	± 60	± 20	± 80
2000	± 70	± 20	± 90



CO_2 Sensor Accuracy Statement

Non-linearity included in the accuracy statement

VAISALA

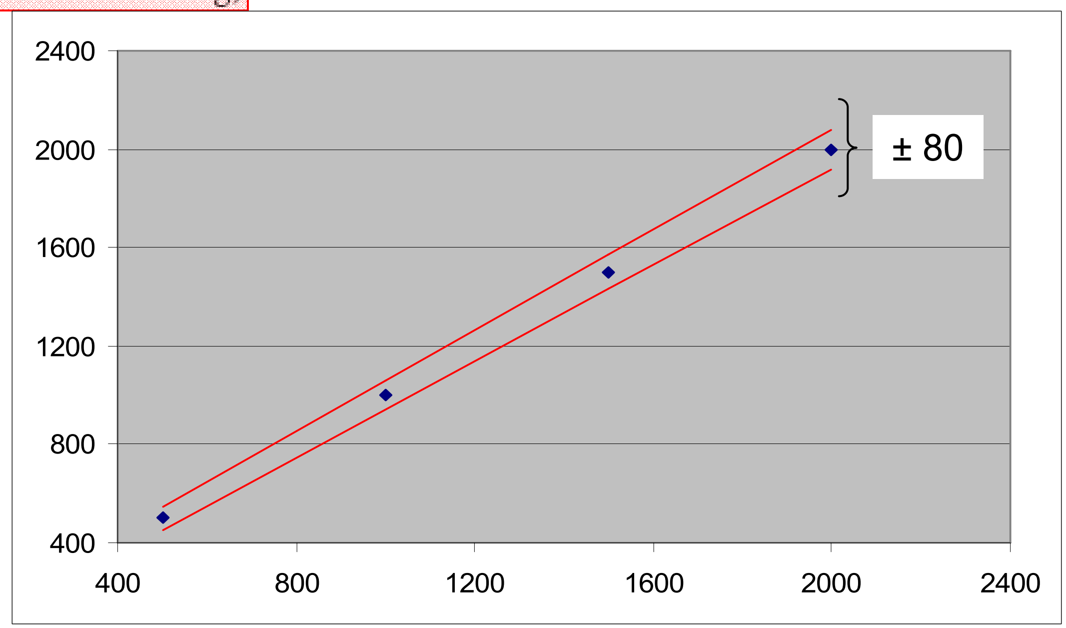
(http://www.vaisala.com/instruments/products/carbondioxide/gm20/product%20documentation/brochures/gm20%20brochure%20in%20english.pdf?SectionUri=%2finstruments%2fproducts%2fcarbondioxide%2fgm20%2fproduct%2520documentation&TabDoc=open)

Performance

Carbon dioxide measurement

Measurement range	0 ... 2000 ppm (nominal; can be calibrated for other ranges: 0 ... 5000 ppm, 0 ... 10,000 ppm, 0 ... 20,000 ppm)
Accuracy (including repeatability, non-linearity and calibration uncertainty)	± (2 % of range + 2% of reading)

Reading (ppm)	Accuracy (ppm)
500	± 50
1000	± 60
1500	± 70
2000	± 80



CO_2 Sensor Accuracy Statement

Multiple statements (same sensor)

AirTest™ Sensors That Make Buildings Smart!

(1) Screen shot from website

(https://www.airtesttechnologies.com/product/co2-ventilation/tr9290.htm)

Model TR9290

CO2 with Passive Temp Option

- Measures: 0-2,000 ppm CO2, Factory adjustable to 10,000 ppm
- Accuracy: ± 30 ppm + 3% of reading

(2) PDF file downloaded from website

(https://www.airtesttechnologies.com/support/datasheet/TR9290.pdf)

Performance

CO_2 Measurement Range: 0-2000 ppm (factory set),
CO_2 Accuracy: +/- 1% of measurement range + 5% of measured value.

Reading (ppm)	(1) (ppm)	(2) (ppm)
500	± 45	± 45
1000	± 60	± 70
1500	± 75	± 95
2000	± 90	± 120

CO_2 Transmitter Testing Process

- Develop method of test and obtain external peer review
- Set up test apparatus and instrumentation
- Procure devices to be tested
- Test according to approved method of test
- Report

Specifications for CO_2 Transmitters to be Tested

- Wall-mounted
- HVAC grade (0 – 2000 ppm)
- Calibration every three years or longer
- CO_2 only … not CO_2 and VOCs

NBCIP Product Testing

- Accuracy, Linearity, Hysteresis - compare measurements with gas mixtures of known concentration.
- Operating Conditions – affects of pressure, temperature, humidity.
- Drift – repeat sensor testing periodically to quantify drift.

CO_2 Sensors Tested

Three sensors from each model

Sensor Manufacturer and Model	Technology (NDIR)
AirTest Technologies (TR9220)	Single lamp, single wavelength (ABC)
Telaire (Ventostat 8001)	Single lamp, single wavelength (ABC)
Automation Components Inc. (ACI/CO2-VDC)	Single lamp, single wavelength (ABC)
Digital Control Systems (AirSence M307)	Single lamp, single wavelength (ABC)
Greystone Energy Systems (CDD)	Single lamp, single wavelength (ABC)
Honeywell (C7232)	Single lamp, single wavelength (ABC)
Intec Controls (I-310e)	Single lamp, single wavelength (ABC)
Veris Industries (CWE SC)	Single lamp, single wavelength (ABC)
Johnson Controls (CD-WA0-00-0)	Single lamp, dual wavelength
Telaire (Ventostat 8102)	Single lamp, dual wavelength
Vaisala (GMW21)	Single lamp, dual wavelength
Sensata (Texas Instruments) (4GS-1)	Two lamps, single wavelength
Siemens (QPA2000)	Two lamps, single wavelength
Vulcain (90DM4SM-C-2000)	Two lamps, single wavelength
AirTest Technologies (EE80)	Two lamps, single wavelength

CO_2 Sensor Accuracy Statement

AirTest Technologies (TR9220)	± 30 ppm + 3% of reading (Website) [± 60 ppm] ± 1% of measurement range + 5% of measured value (Product manual) [± 70 ppm]
AirTest Technologies (EE80)	< ± (50 ppm +2% of measure value) (at 20ºC) [± 70 ppm]
Automation Components Inc. (ACI/CO2-VDC)	± 50 ppm or +3% of reading (@ 25ºC at standard pressure) [± 80 ppm]
Digital Control Systems (AirSence M307)	± 5% of reading or 75 ppm, (whichever is greater) [± 75 ppm]
Greystone Energy Systems (CDD)	±50 ppm or +3% of reading (@22 ºC(72 F)) [± 50 ppm]
Honeywell (C7232)	± (30 ppm +2% of reading) [± 50 ppm]
Intec Controls (I-310e)	± 5% of reading or ± 75 ppm [± 75 ppm]
Johnson Controls (CD-WA0-00-0)	<±[30 ppm CO2 + 2.0% of reading] ±non-linearity(<1%FS) [± 70 ppm]

[± accuracy] evaluated at 1,000 ppm

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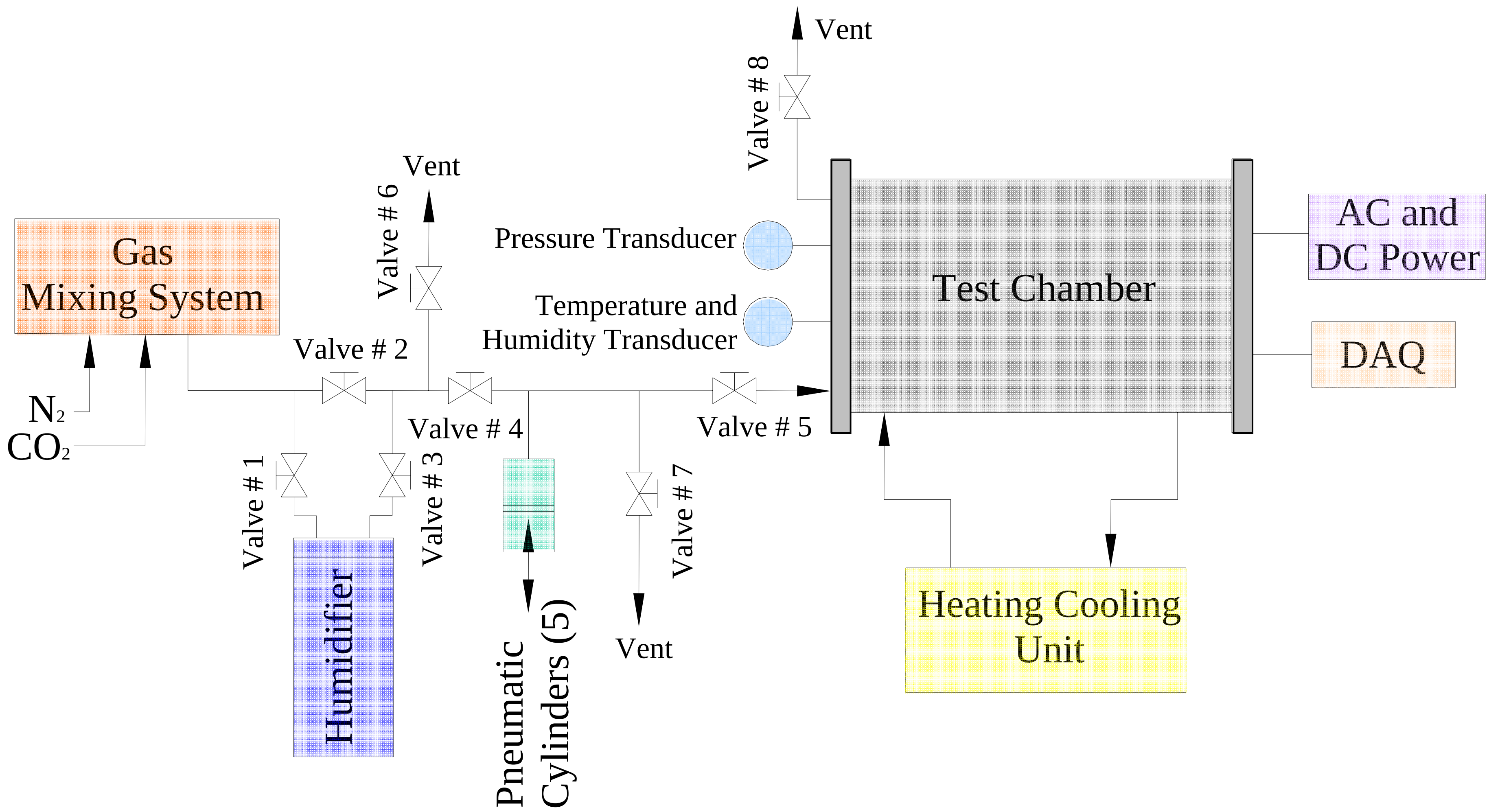
CO_2 Sensor Accuracy Statement

Sensata (Texas Instruments) (4GS-1)	± 75 ppm if 0-1500ppm: ± 5% if > 1500ppm (readings @ standard pressure 760 mm Hg & 25°C) [± 75 ppm]
Siemens (QPA2000)	≤±50 ppm +2% of measured value [± 70 ppm]
Telaire (Ventostat 8001)	±100 ppm or 7% whichever is greater [± 100 ppm]
Telaire (Ventostat 8101)	± 50 ppm or 5% whichever is greater (7% for levels over 1500 ppm) @ 60-90°F (15-32°C) [± 50 ppm]
Vaisala (GMW21)	± (2 % of range + 2% of reading) [± 60 ppm]
Veris Industries (CWE SC)	±30 ppm ±5% of measured value [± 80 ppm]
Vulcain (90DM4SM-C-2000)	±100 ppm + 3% of reading [± 130 ppm]

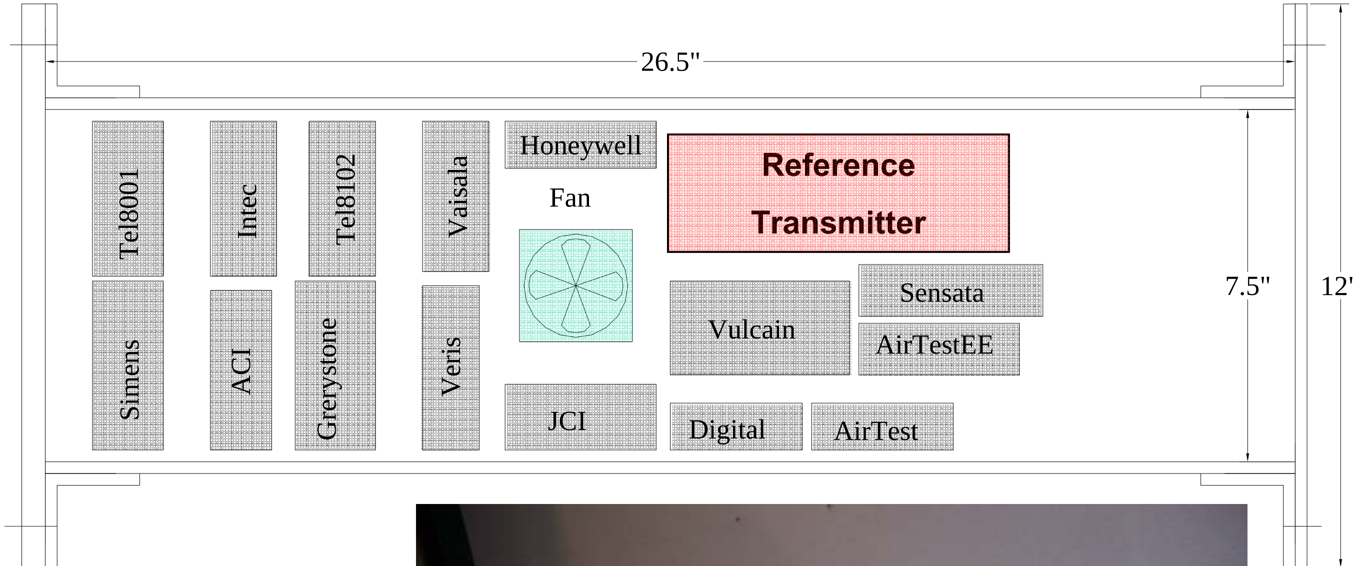
[± accuracy] evaluated at 1,000 ppm

Accuracy Testing Apparatus

Temperature, Pressure, Relative humidity, CO_2 concentration



Accuracy Testing Apparatus



Three identical trays each holds 15 test transmitters plus the reference transmitter

Accuracy Testing Apparatus

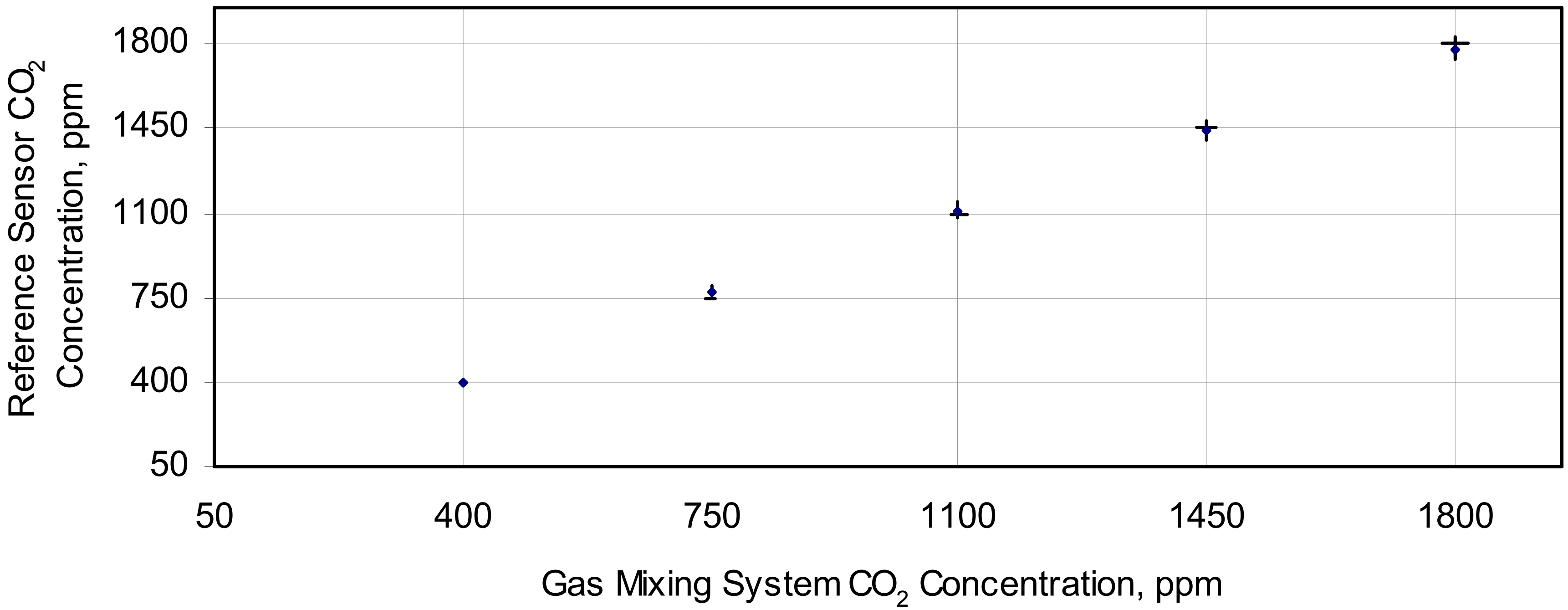
Gas Mixing System Specifications

Accuracy	
Concentration	± 1.0% Setpoint
Flow	± 1.0% Setpoint
Repeatability	± 0.05% Setpoint

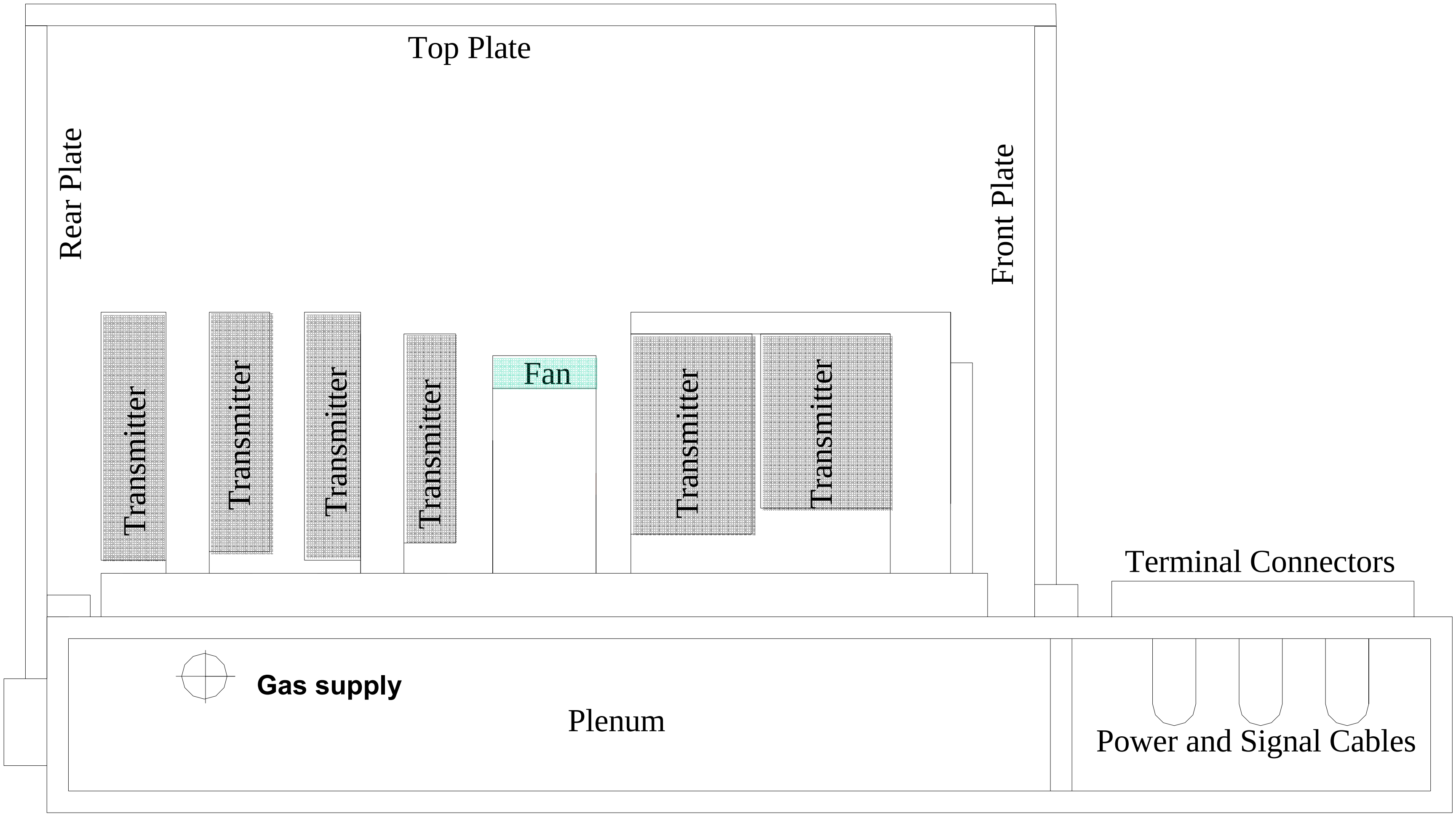
Reference CO_2 Transmitter Specifications

Description	Value
Accuracy	± 2.5% of reading
Accuracy below 300 ppm CO_2	± 5 ppm
Long-term stability (for easy operating conditions)	< ± 2% reading / year

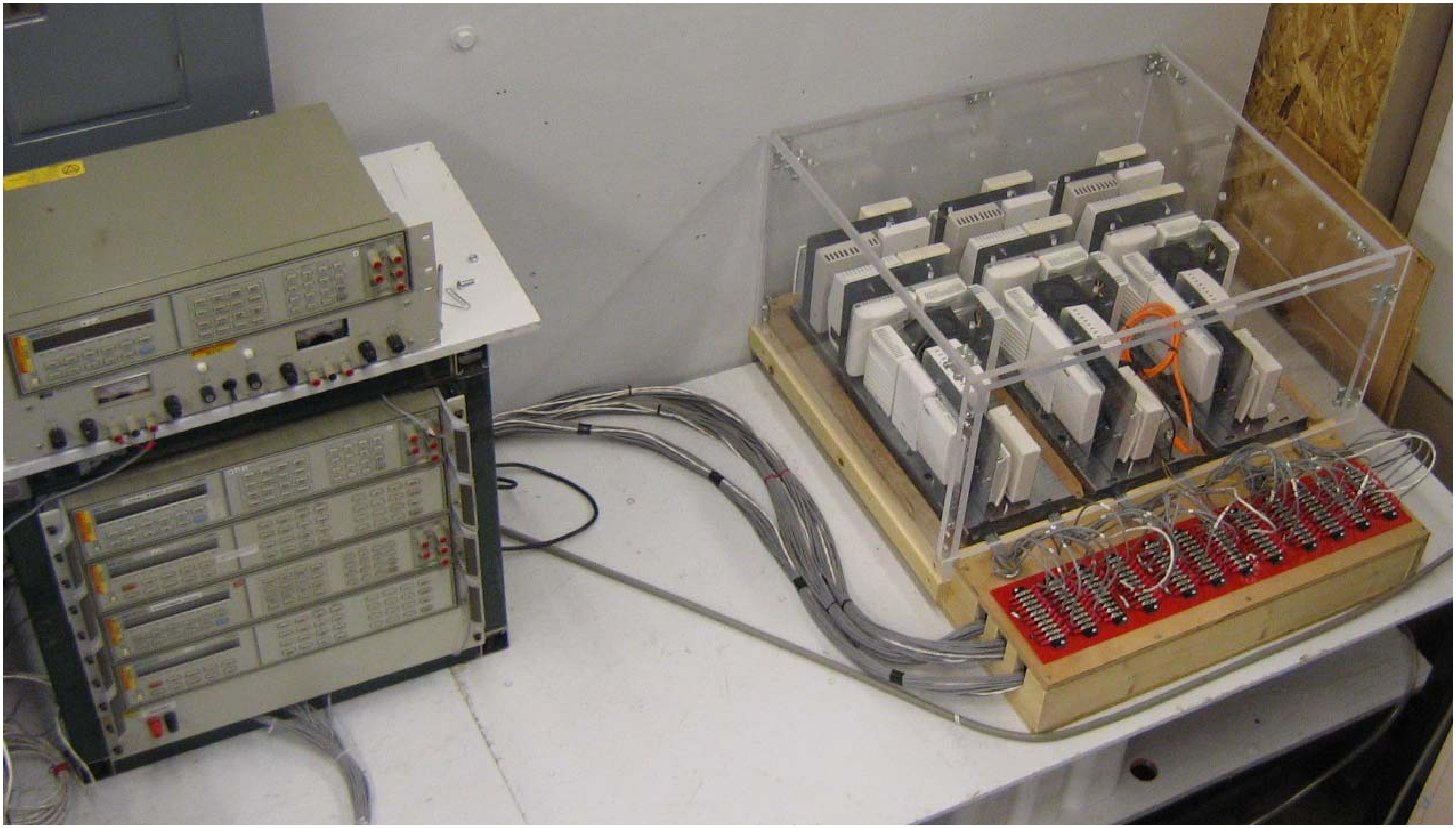
Comparison of Reference Transmitter to Gas Mixing System



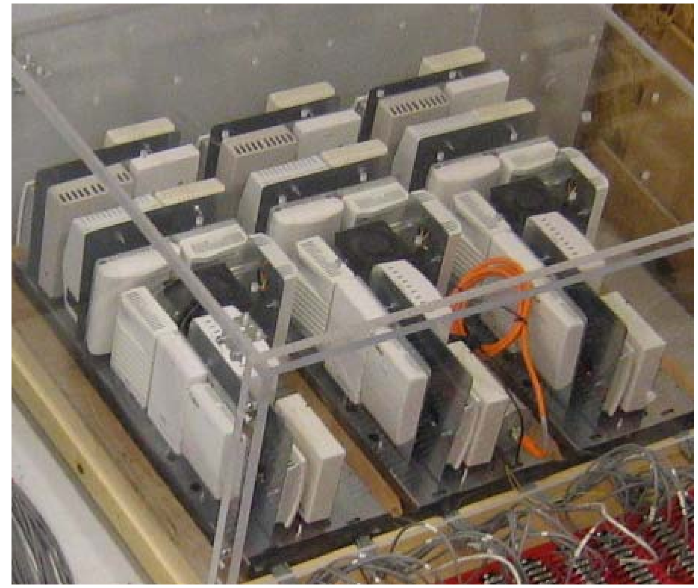
Long-term Testing Apparatus



Long-term Testing Apparatus



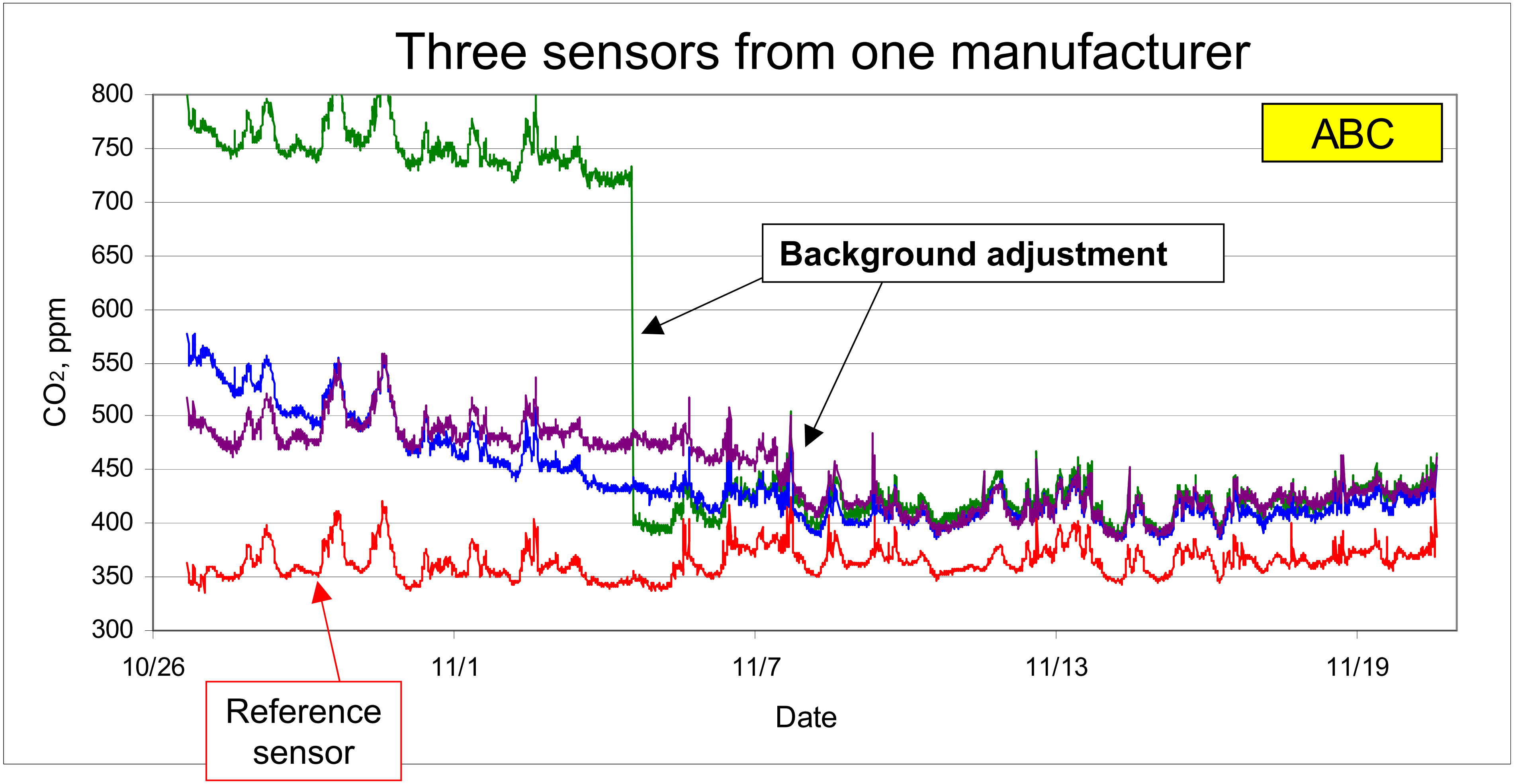
Initial Power Up and Conditioning



Some sensors require a "break-in" period of up to 3 weeks.

All 45 sensors (plus reference) powered up and exposed to laboratory conditions.

Initial Power Up and Conditioning



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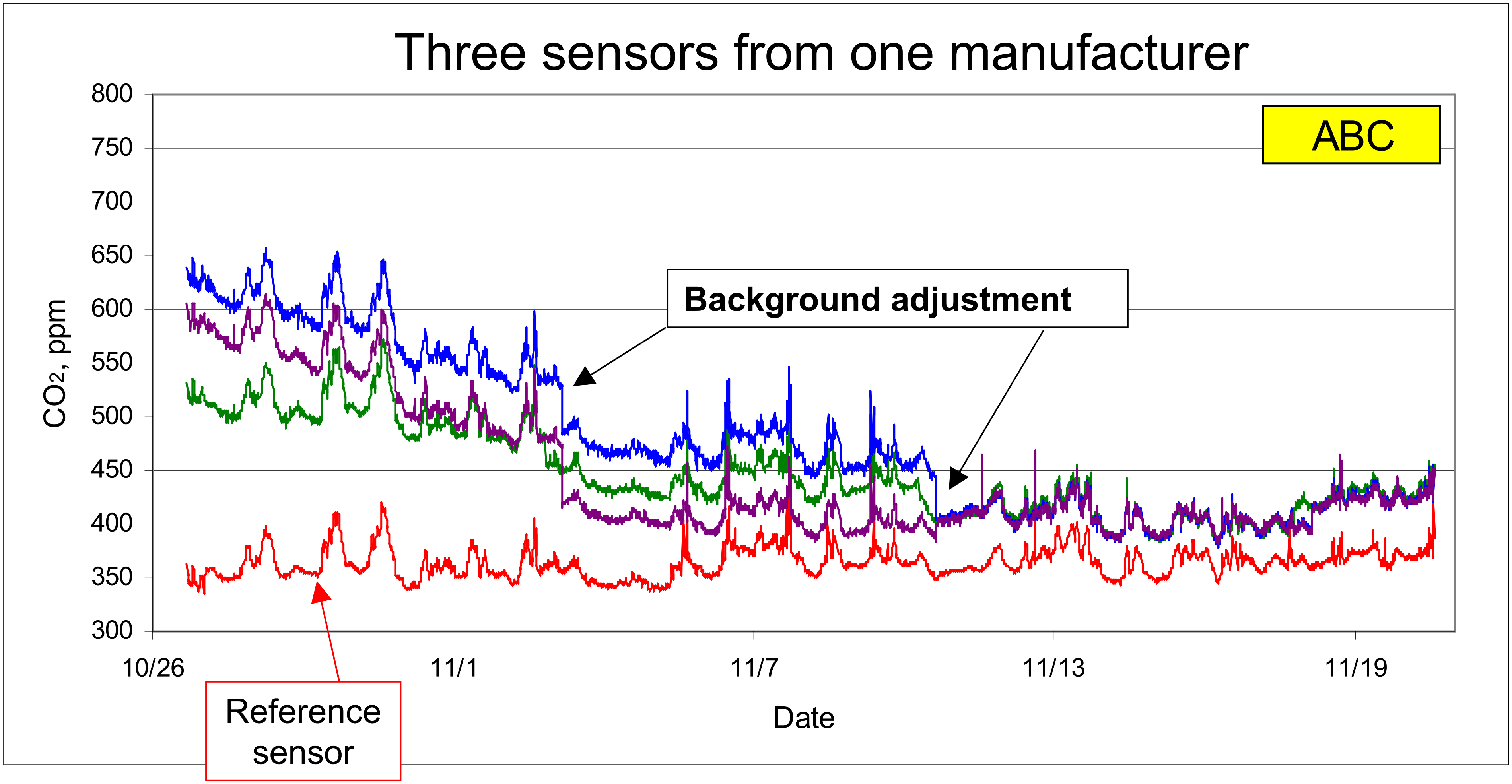
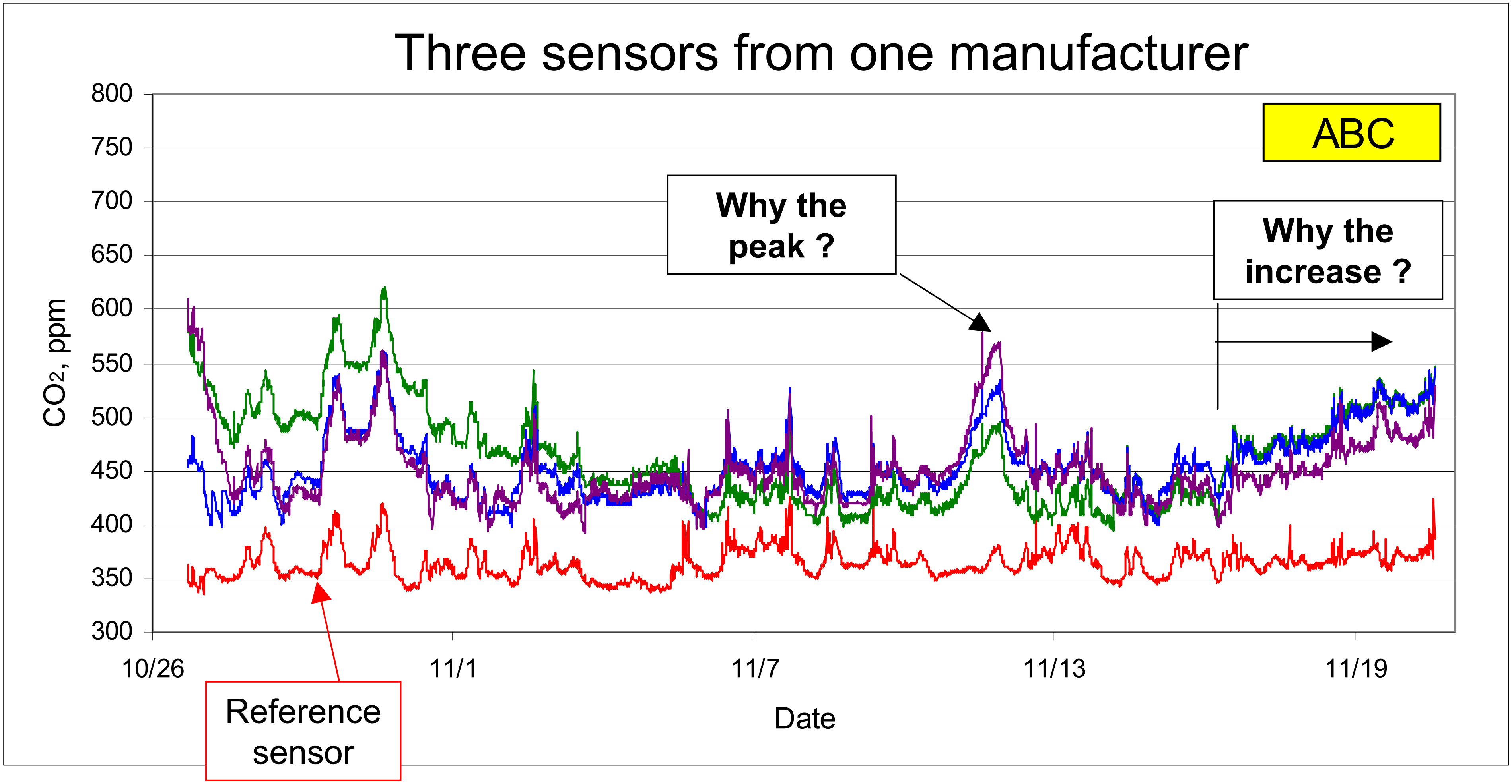


Initial Power Up and Conditioning



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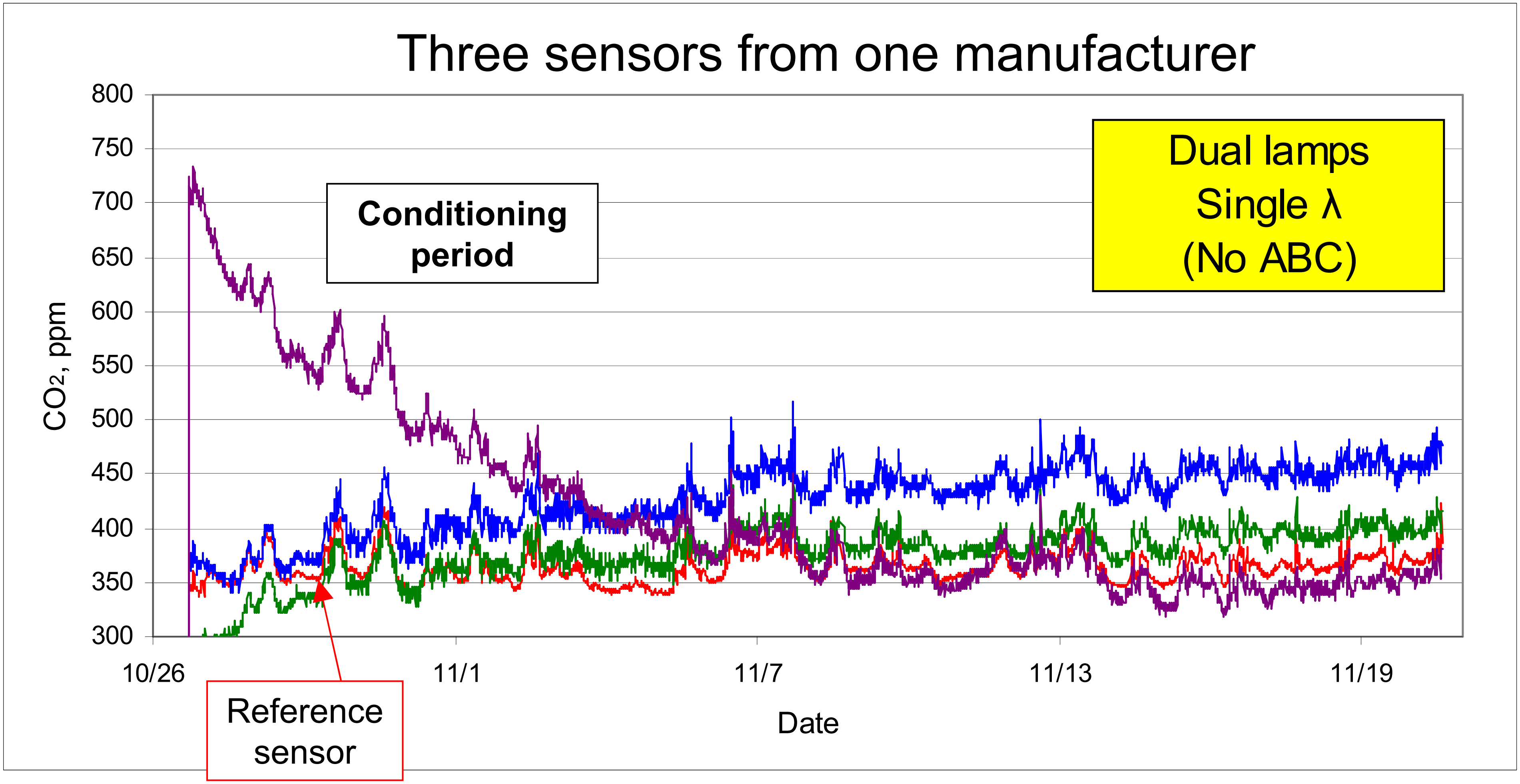
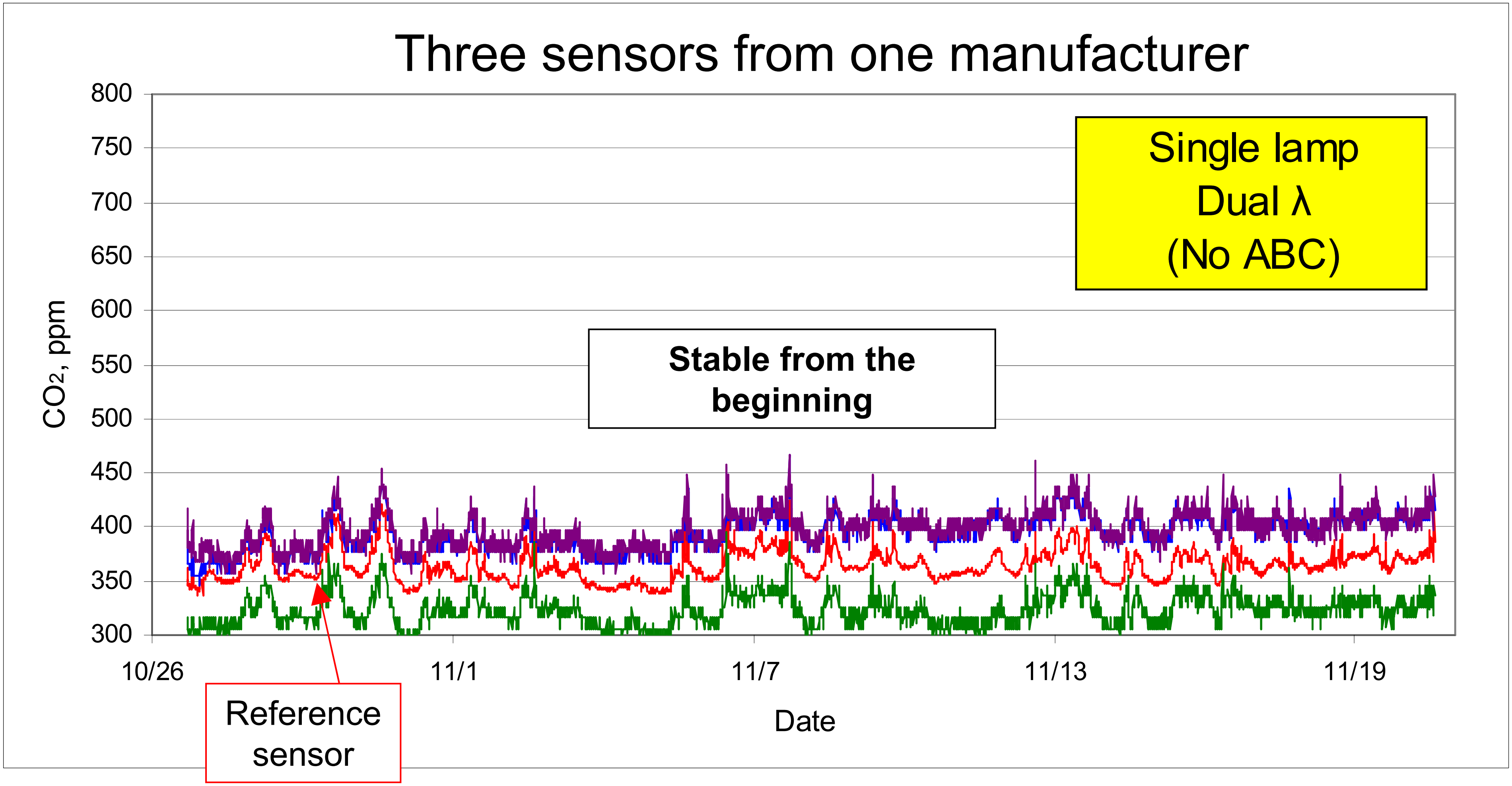
Initial Power Up and Conditioning



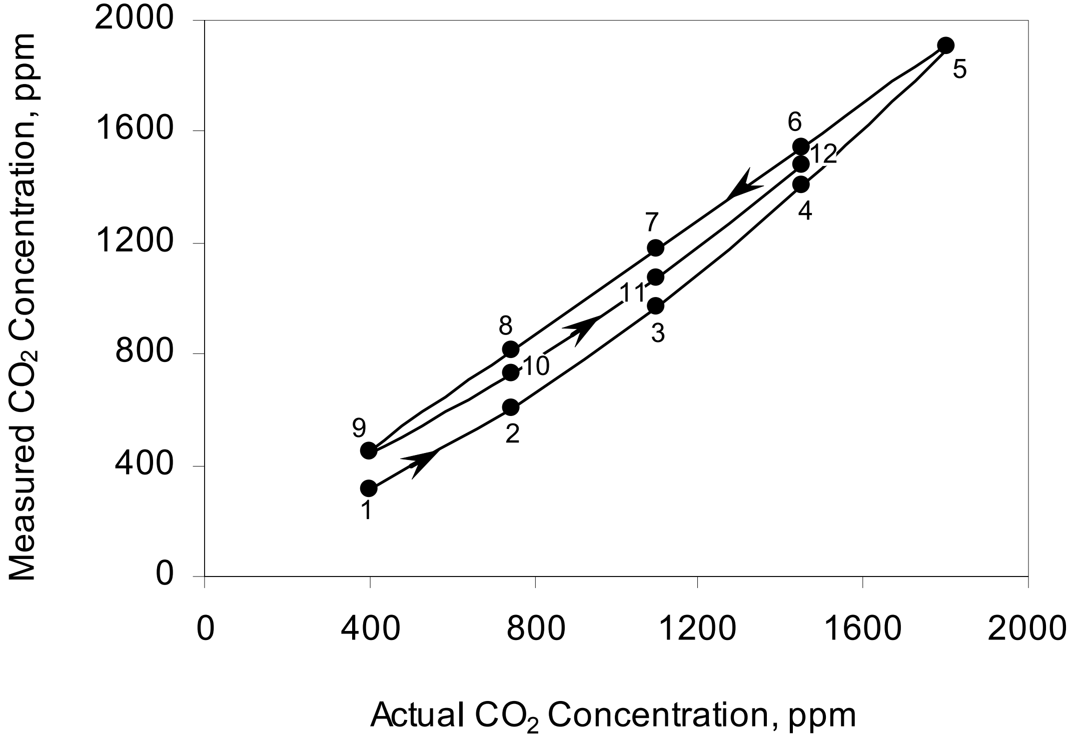
Initial Power Up and Conditioning



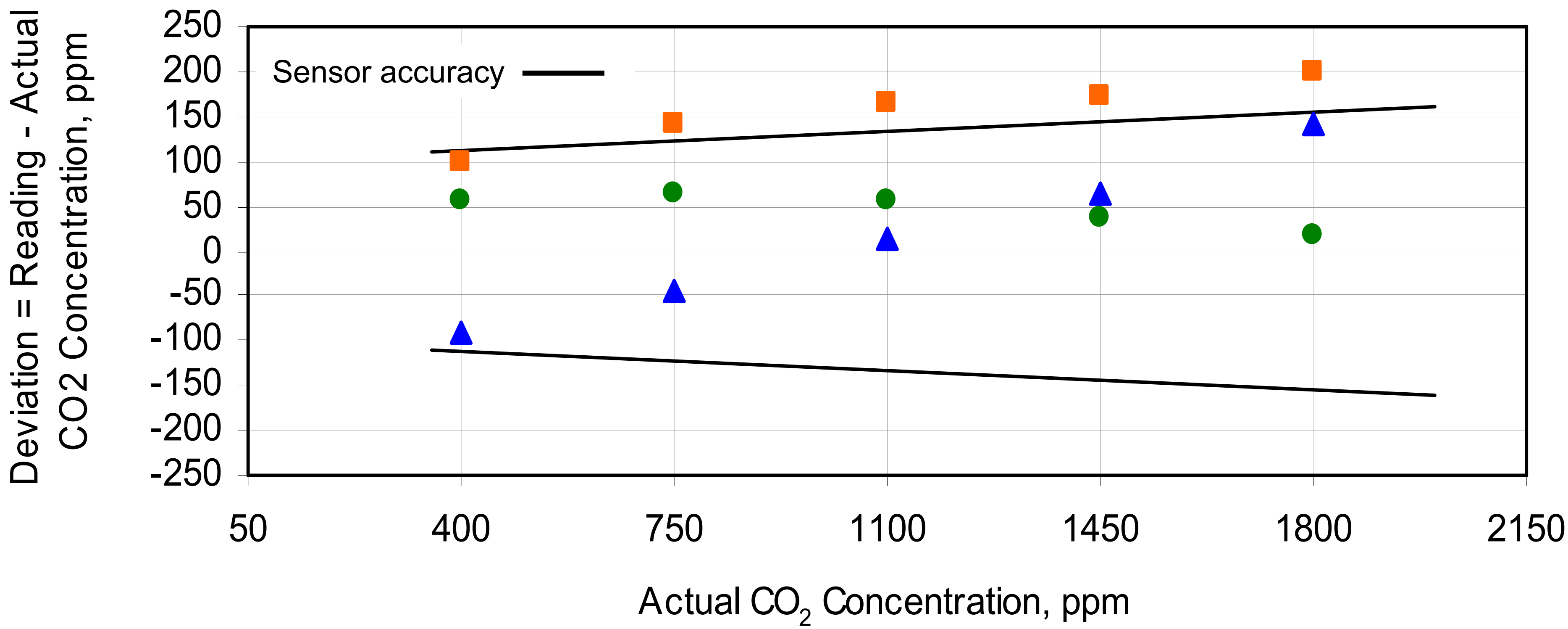
Accuracy and Linearity Testing

CO_2 Concentrations (ppm): 400, 750, 1100, 1450, 1800

Fixed conditions: 40% RH; 73ºF (22.8ºC); 14.7 psia



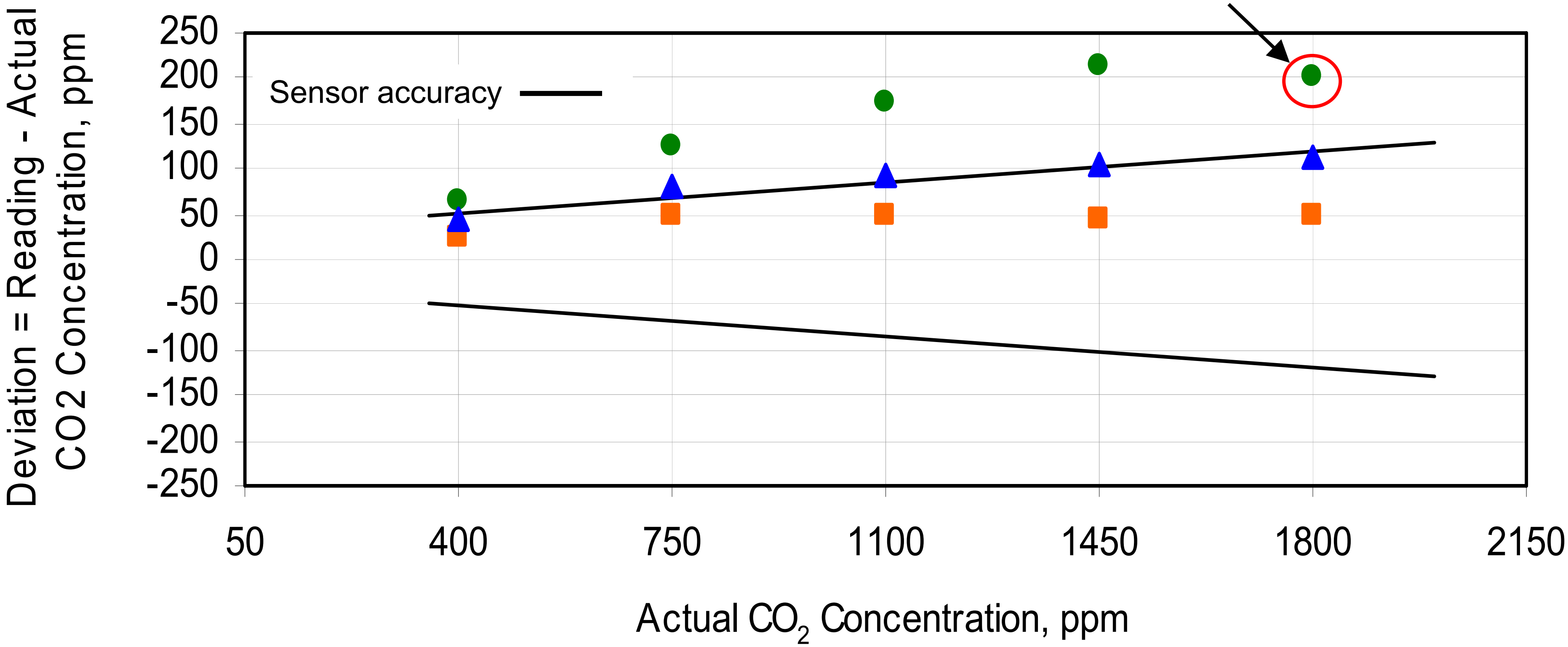
Accuracy



Two lamps, single wavelength

Accuracy

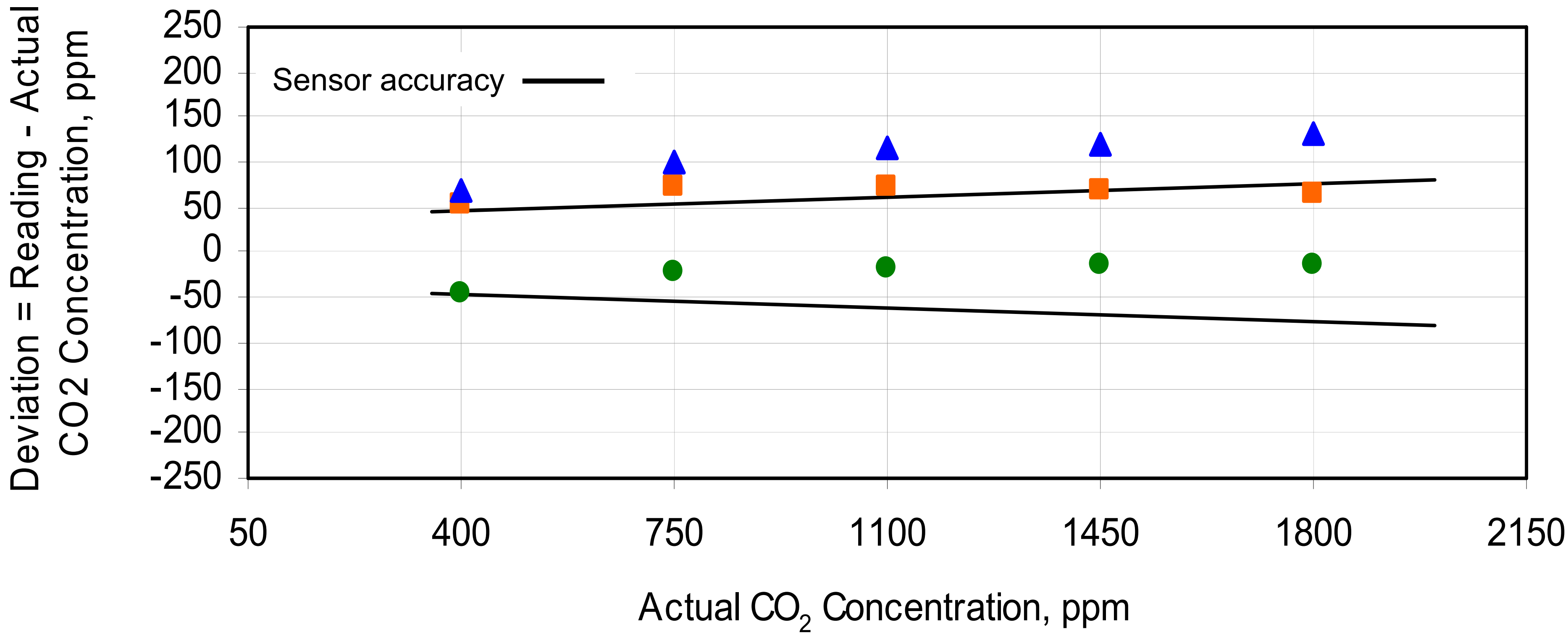
Data does not indicate sensor accuracy since the sensor output is saturated.



Single lamp, single wavelength

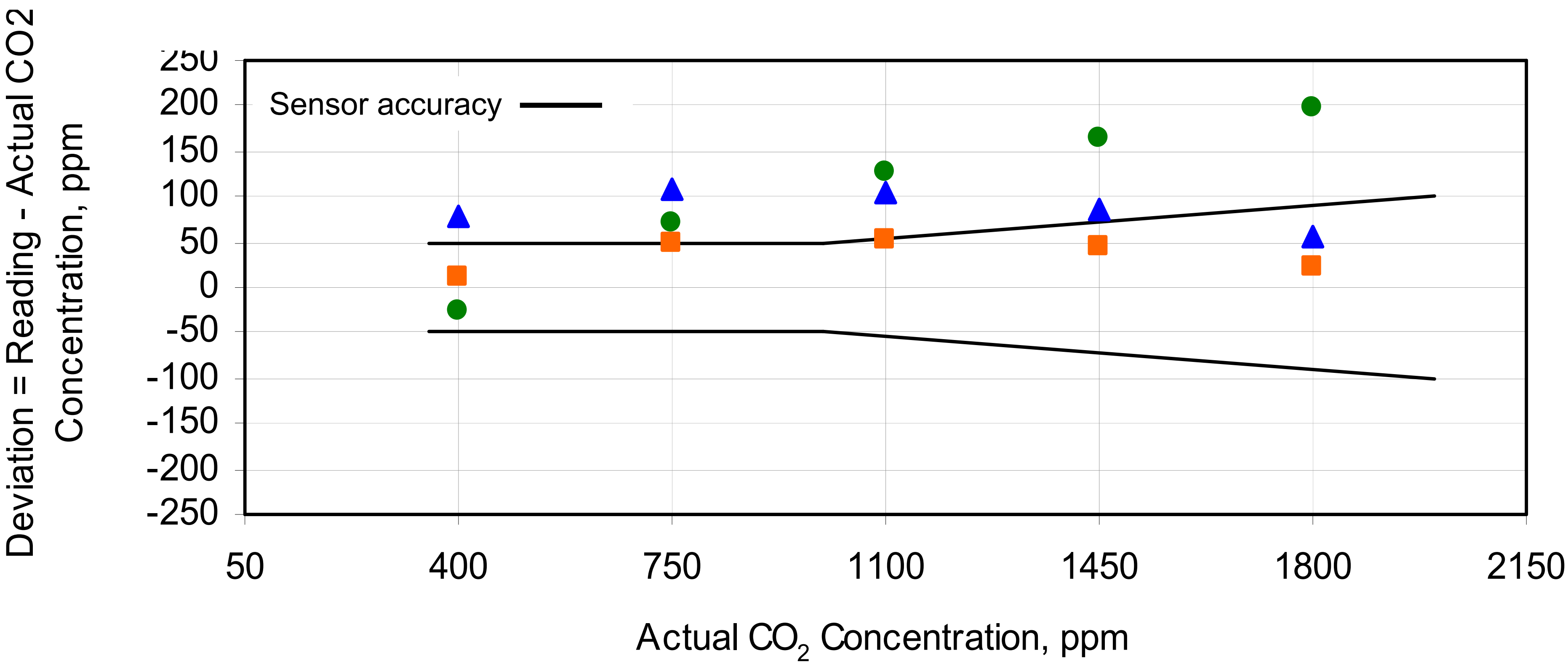
(ABC)

Accuracy



Single lamp, dual wavelength

Accuracy



Single lamp, dual wavelength

Accuracy

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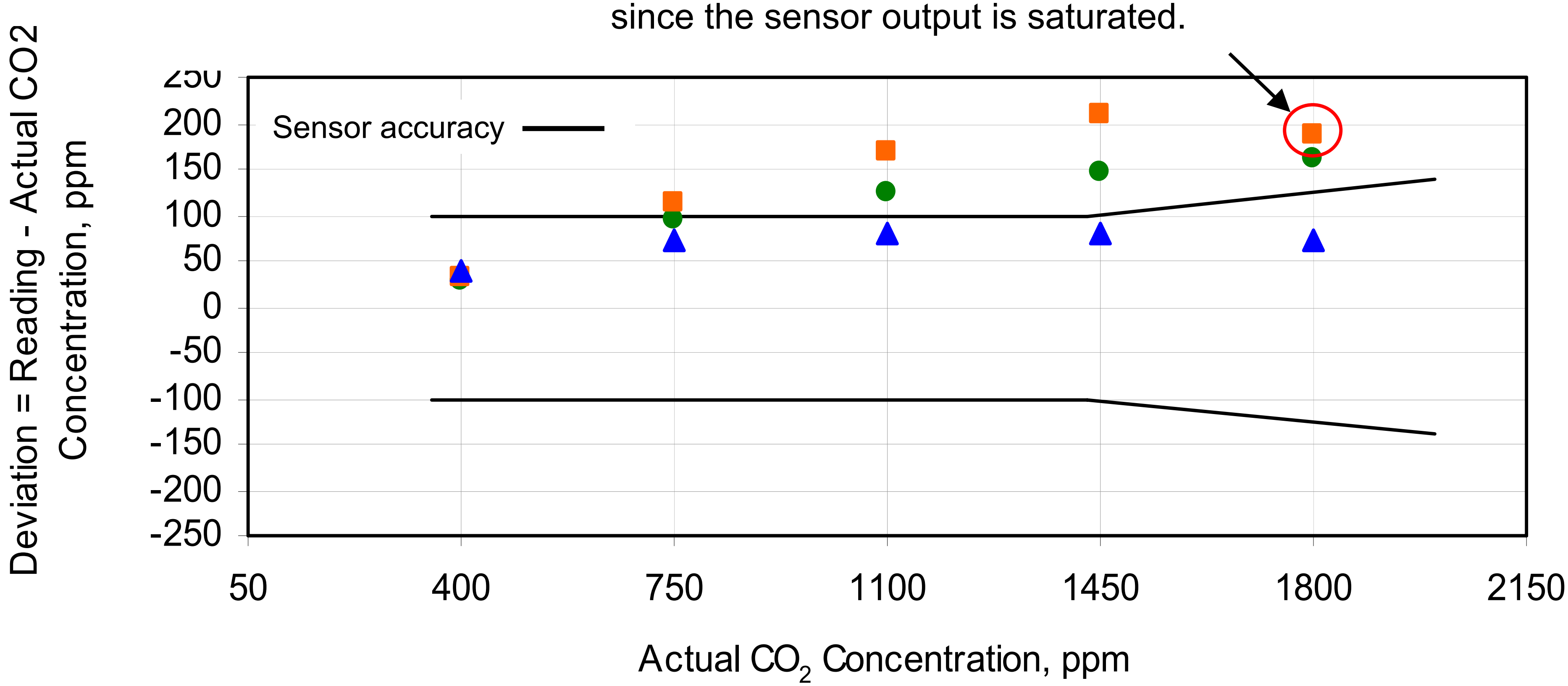
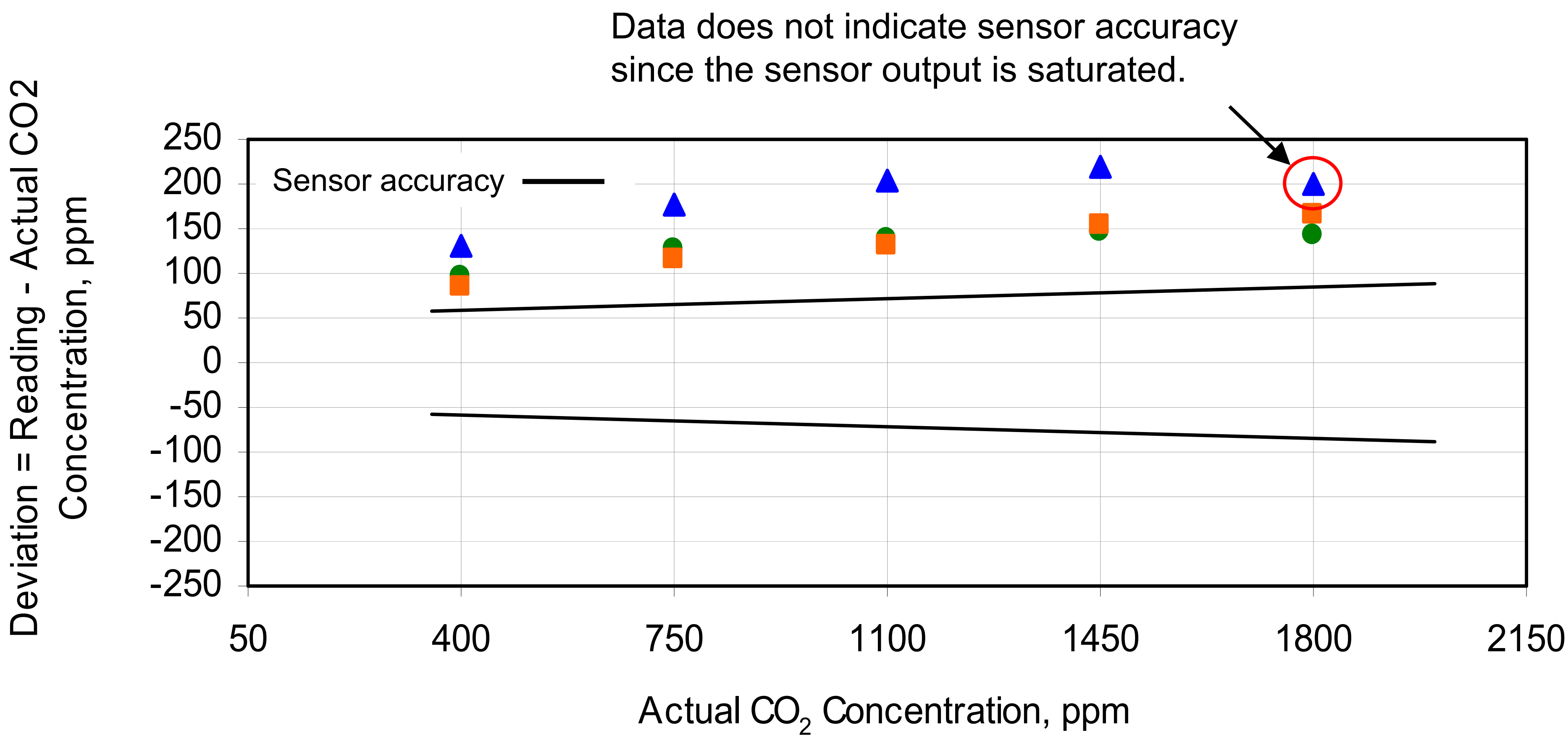


Single lamp, single wavelength

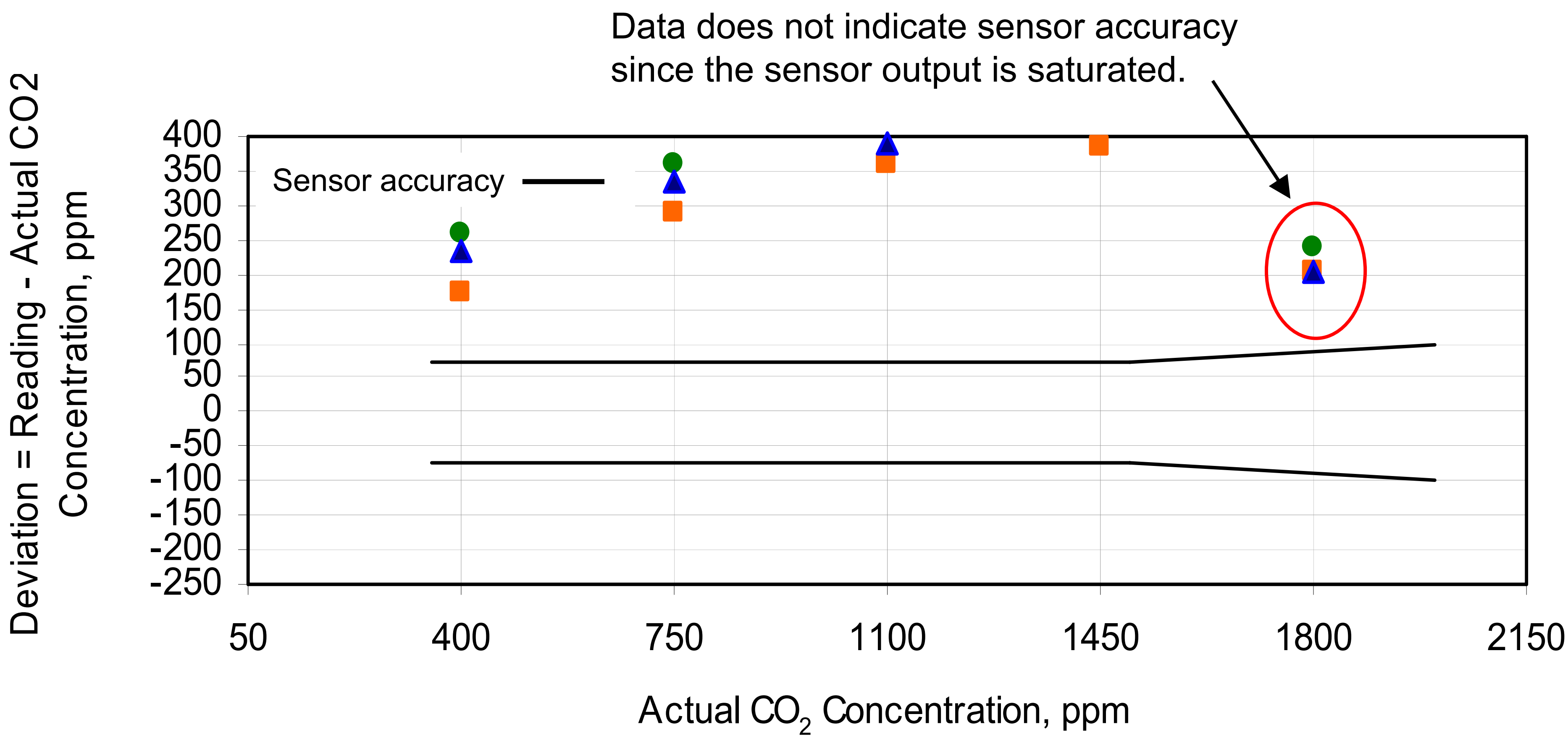
(ABC)

Accuracy



Two lamp, single wavelength

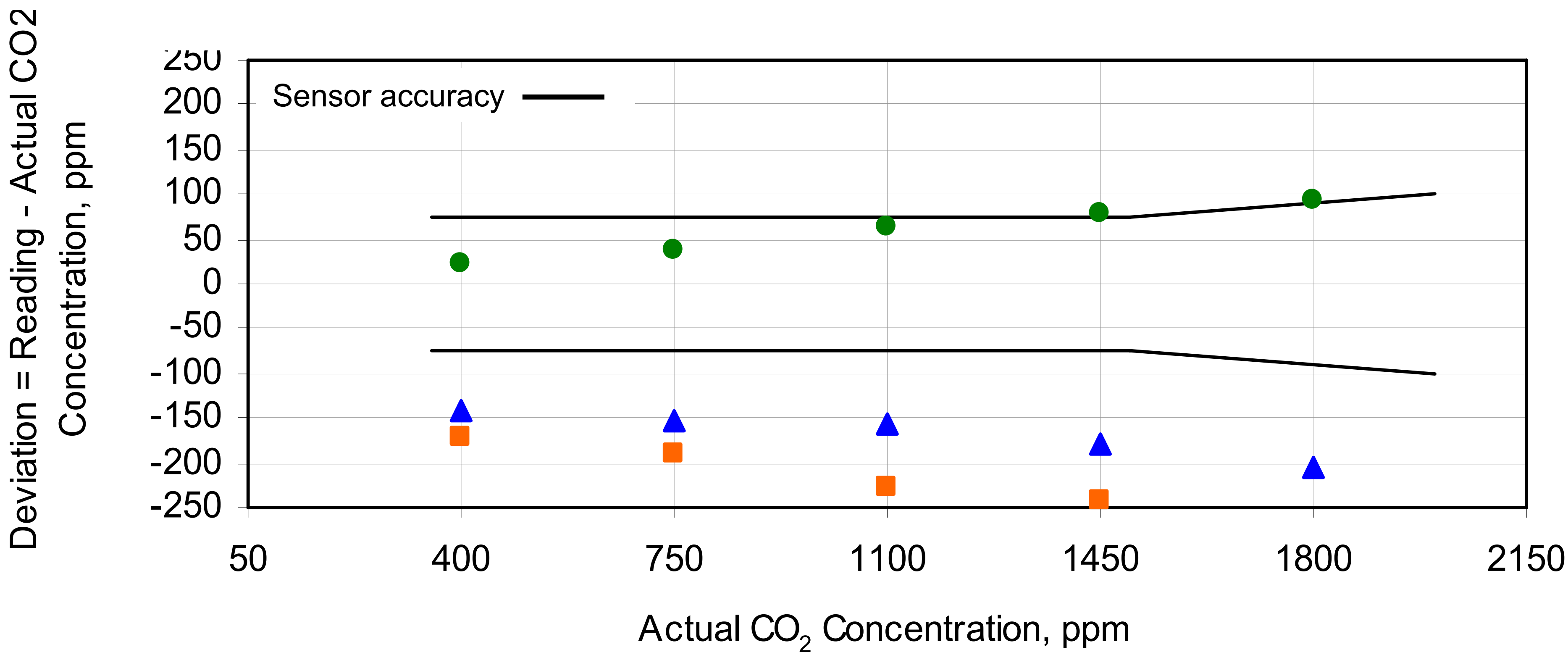
Accuracy



Single lamp, single wavelength

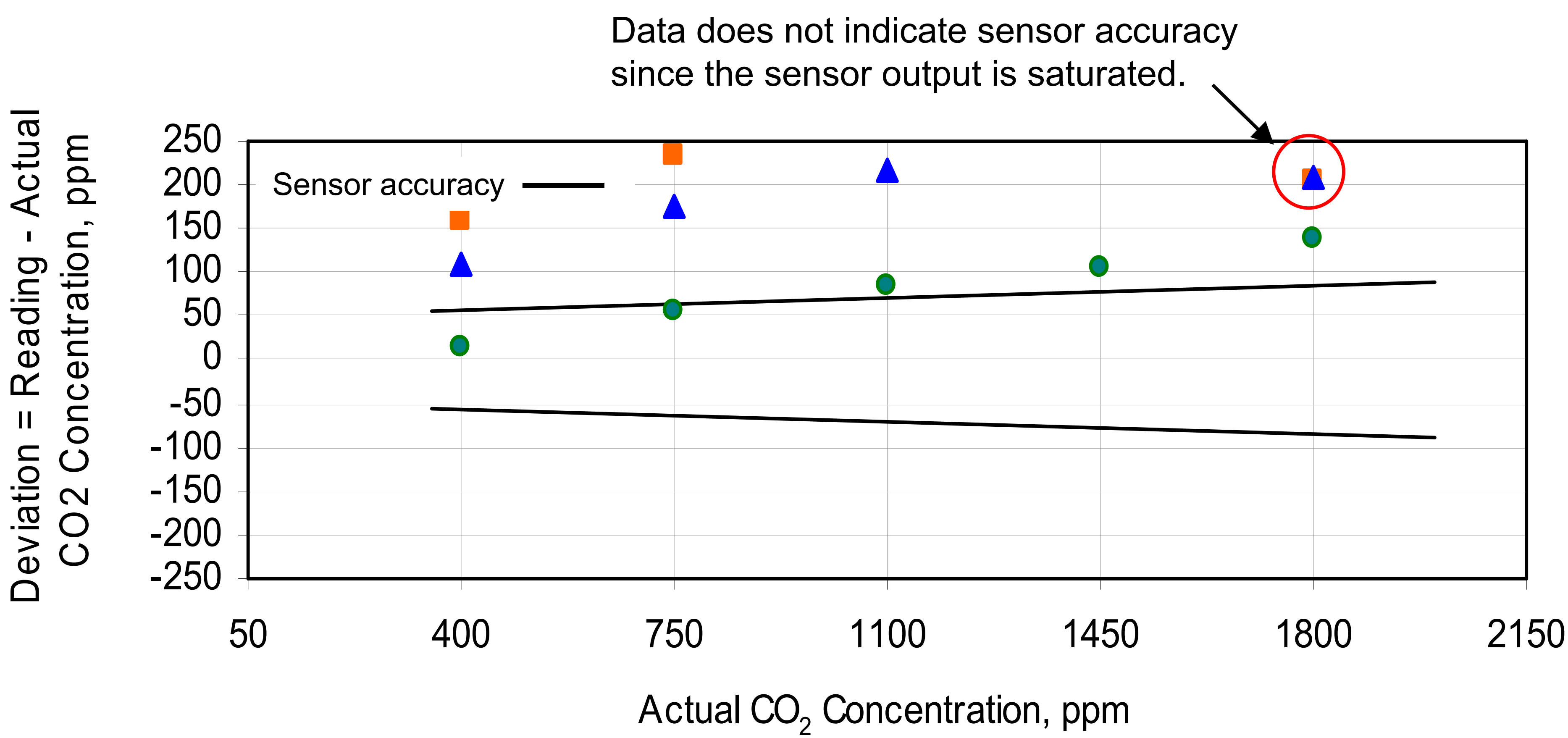
(ABC)

Accuracy



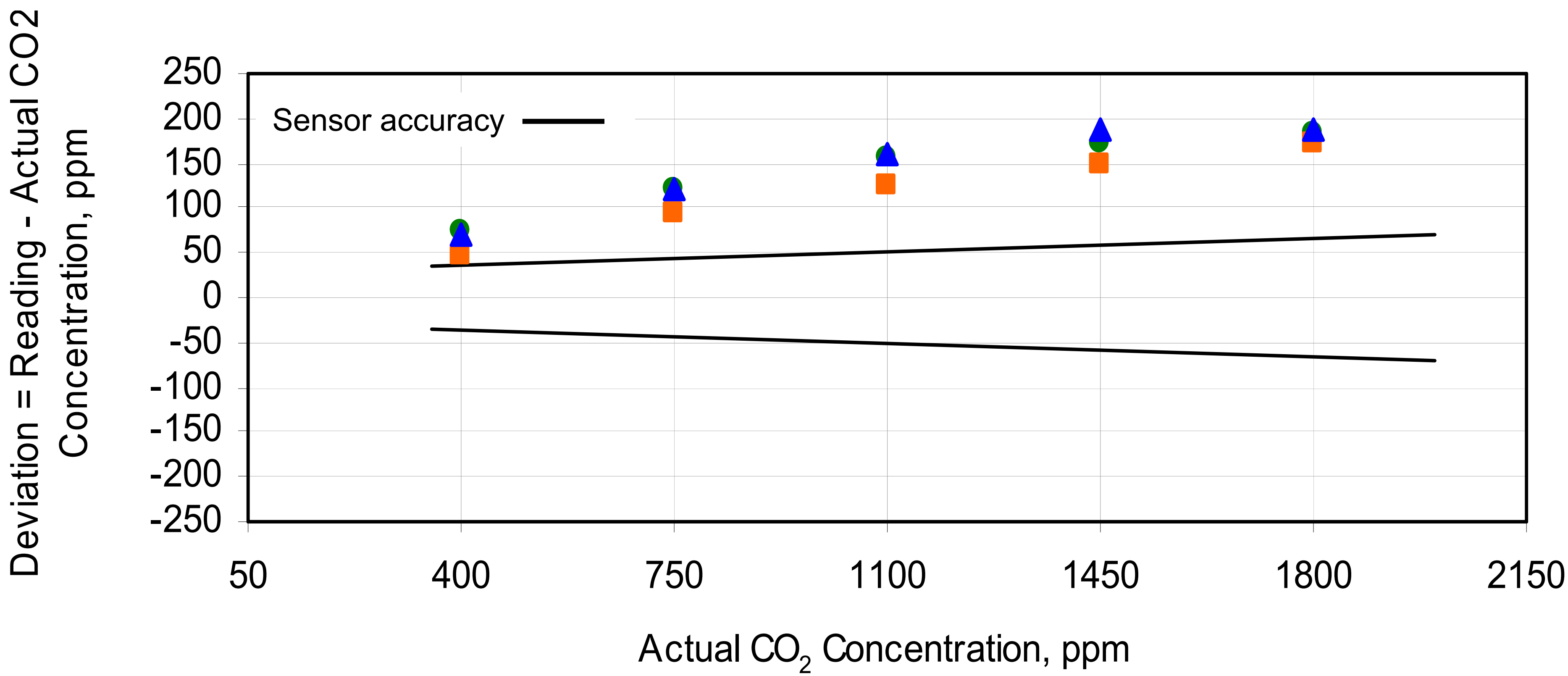
Two lamp, single wavelength

Accuracy



Single lamp, dual wavelength

Accuracy

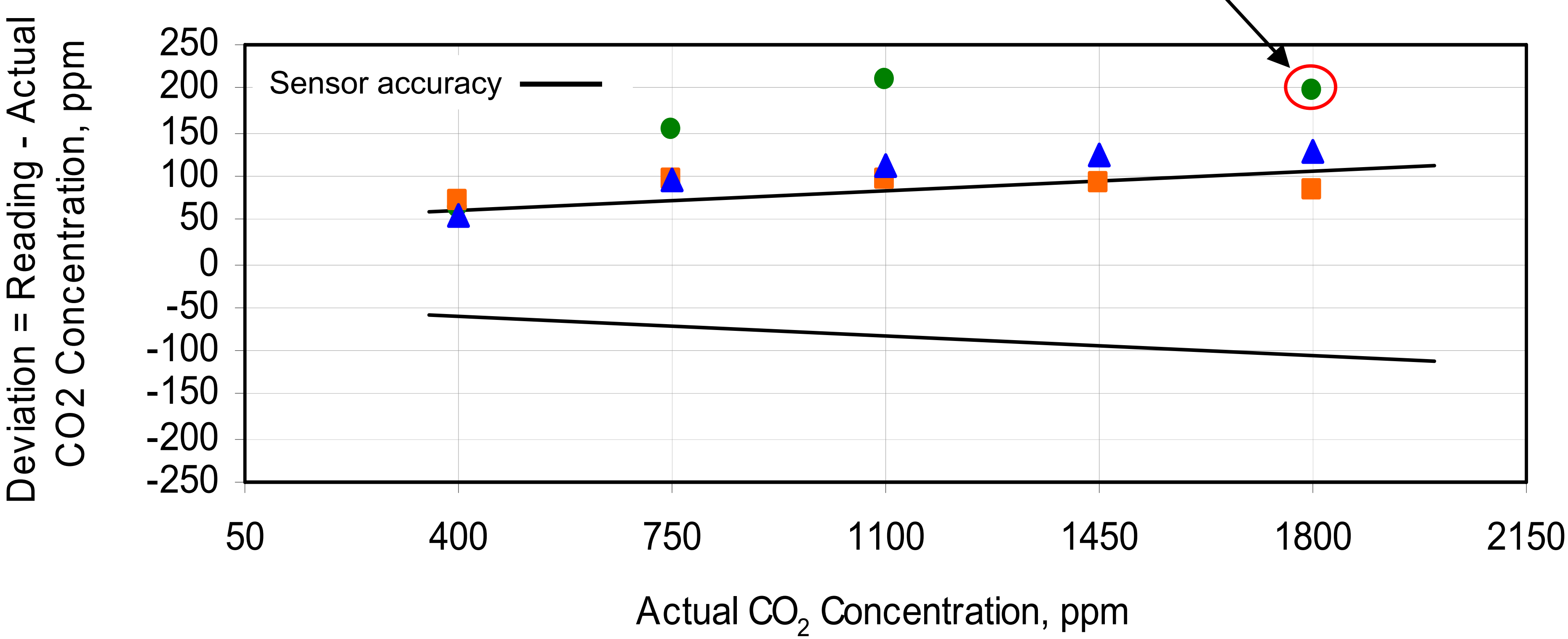


Single lamp, single wavelength

(ABC)

Accuracy

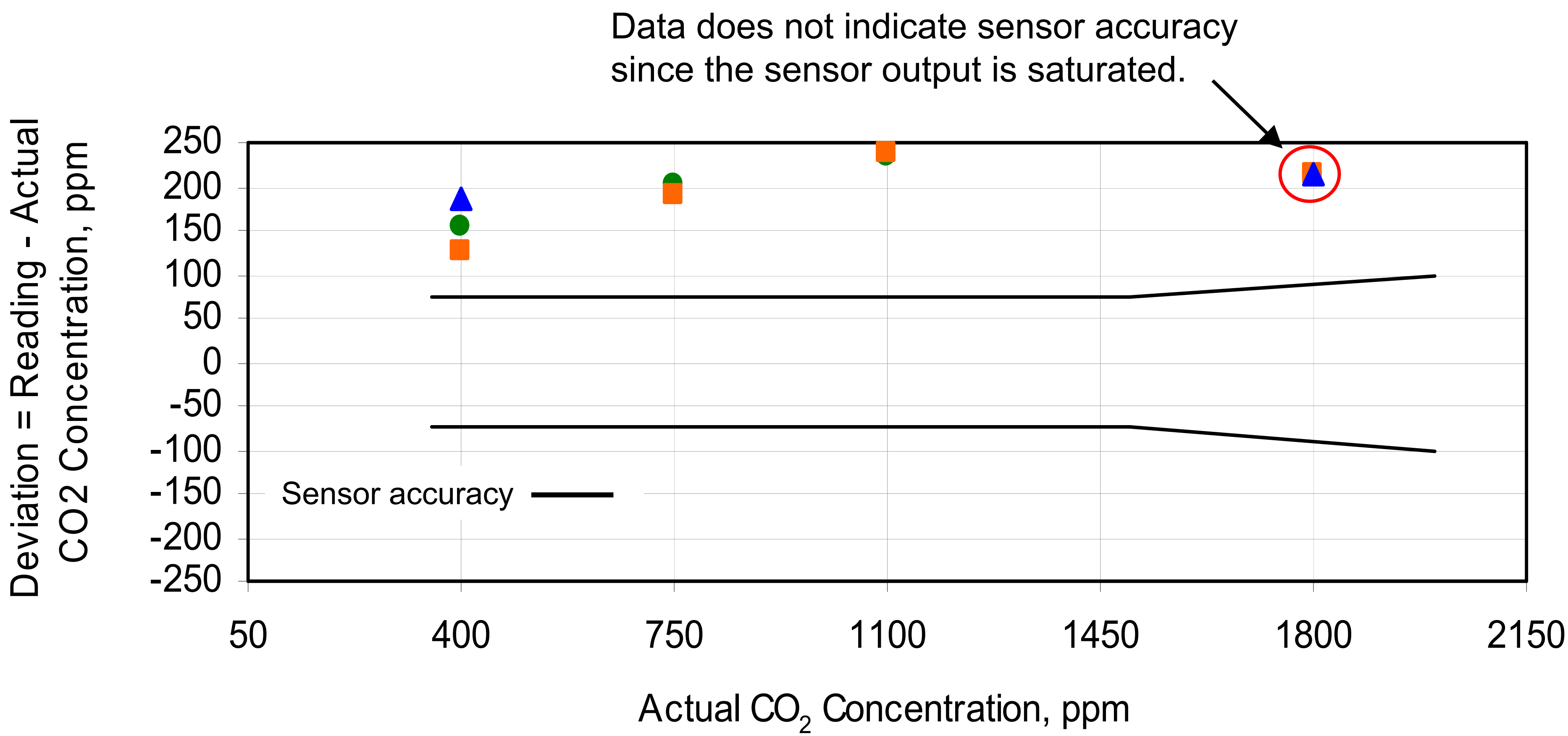
Data does not indicate sensor accuracy since the sensor output is saturated.



Single lamp, single wavelength

(ABC)

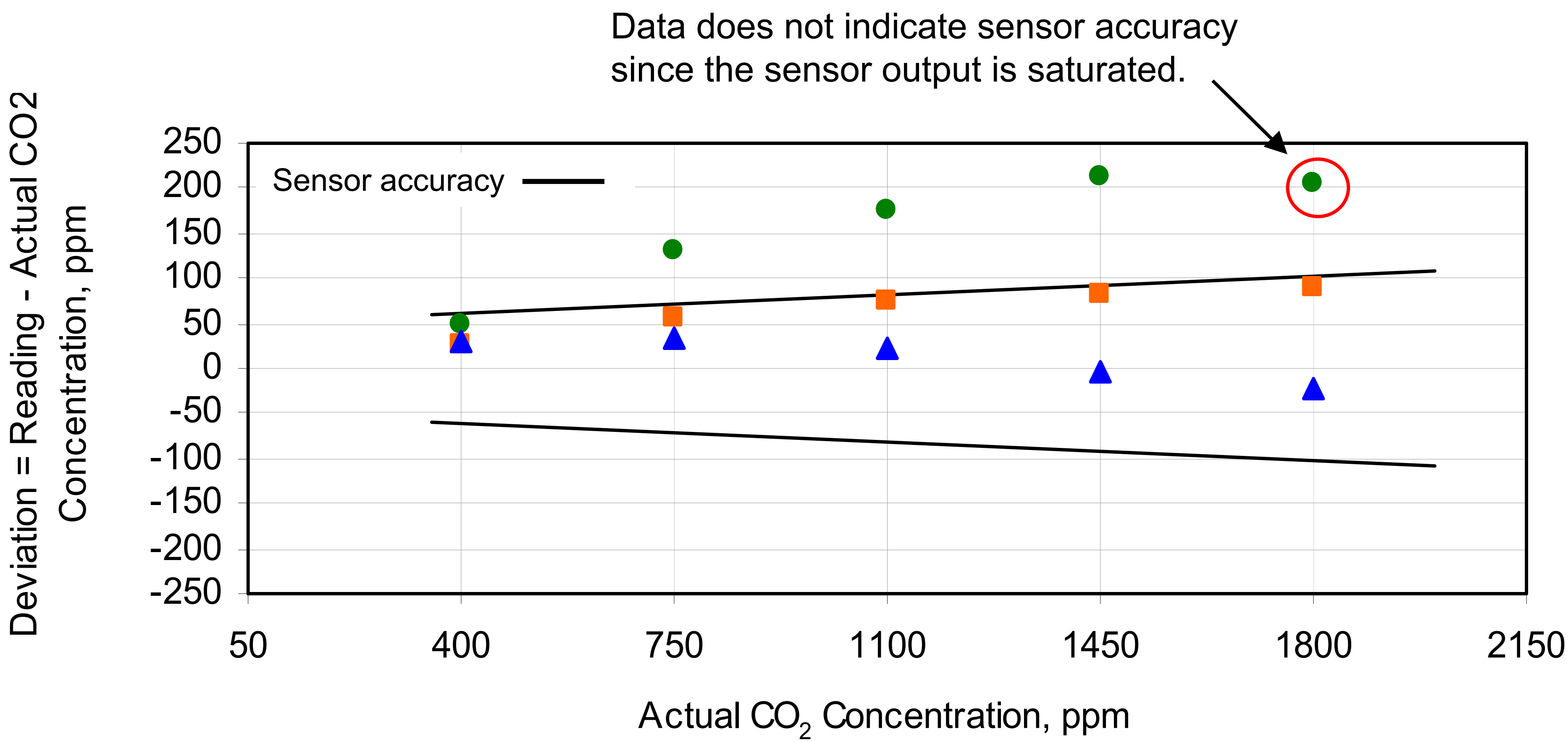
Accuracy



Single lamp, single wavelength

(ABC)

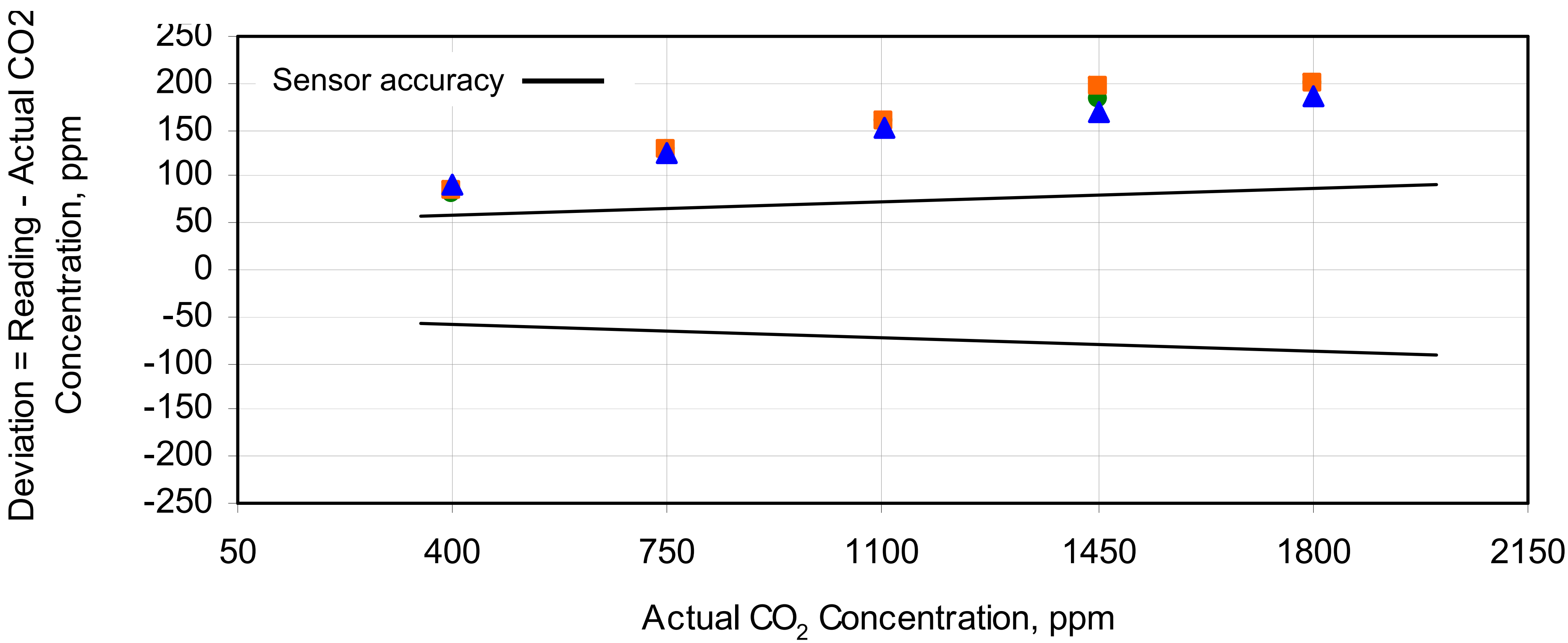
Accuracy



Single lamp, single wavelength

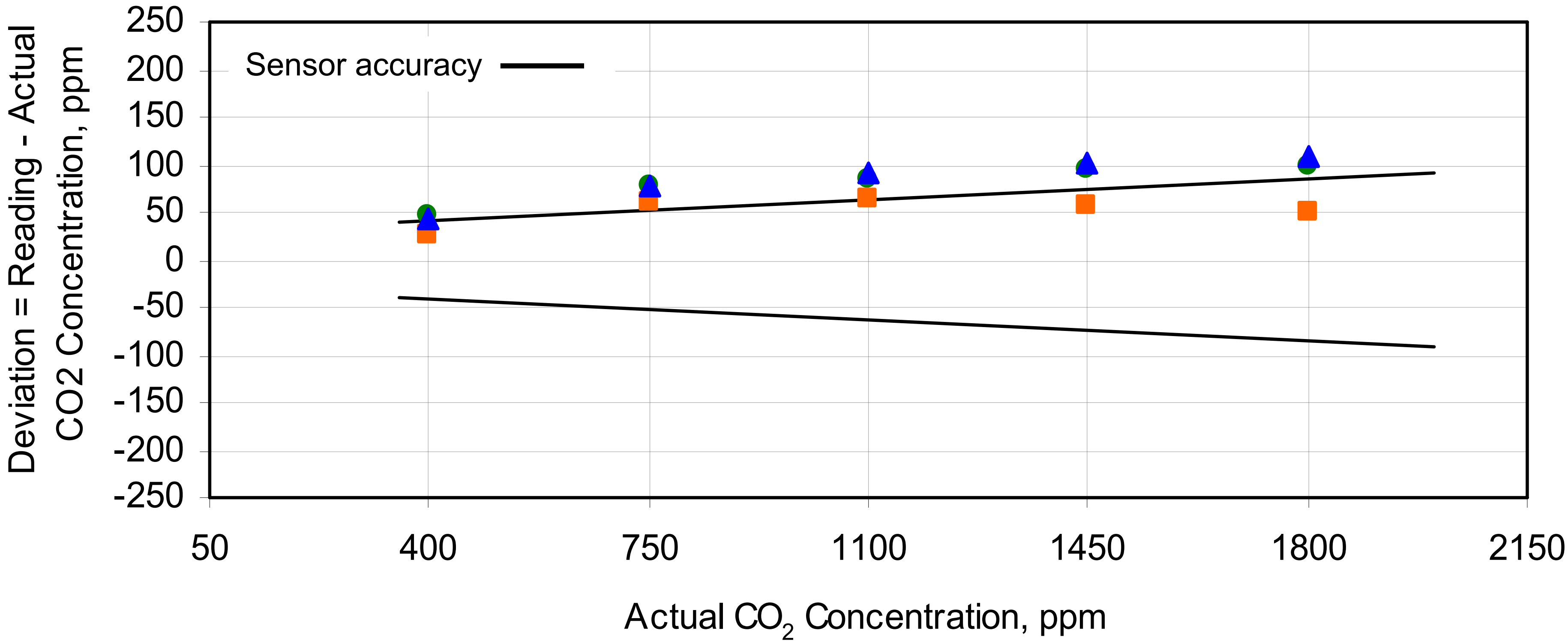
(ABC)

Accuracy



Two lamp, single wavelength

Accuracy



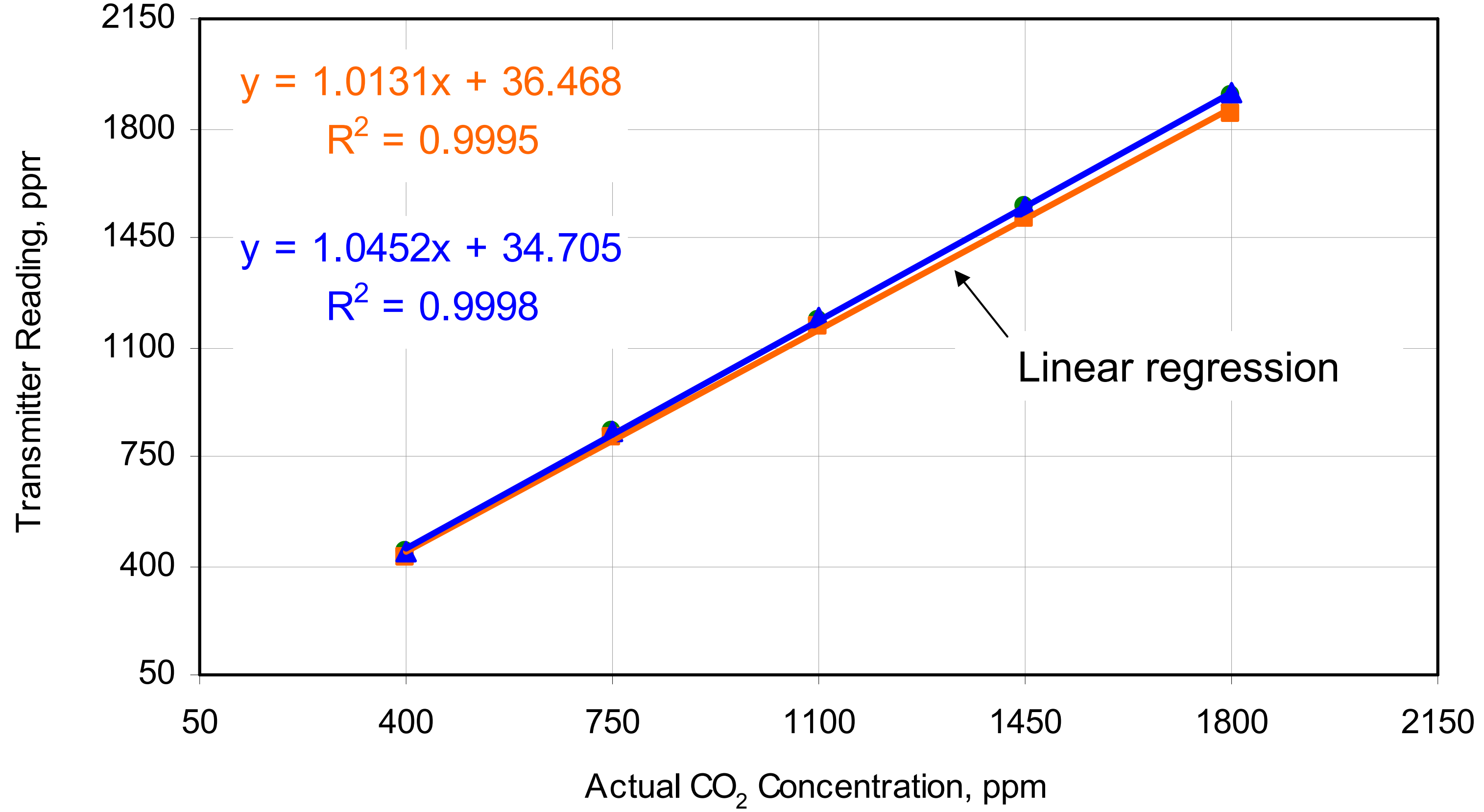
Single lamp, single wavelength

(ABC)

NBCIP

Linearity

Linearity determines how well the sensor input/output is defined by a straight line



Linearity

Example linear regression

$$y = 1.0452x + 34.705$$

Actual (ppm)	Measured (ppm)	Calculated from regression (ppm)	Difference (ppm)
400	442	453	11
750	828	819	-9
1100	1191	1184	-6
1450	1552	1550	-2
1800	1909	1916	7

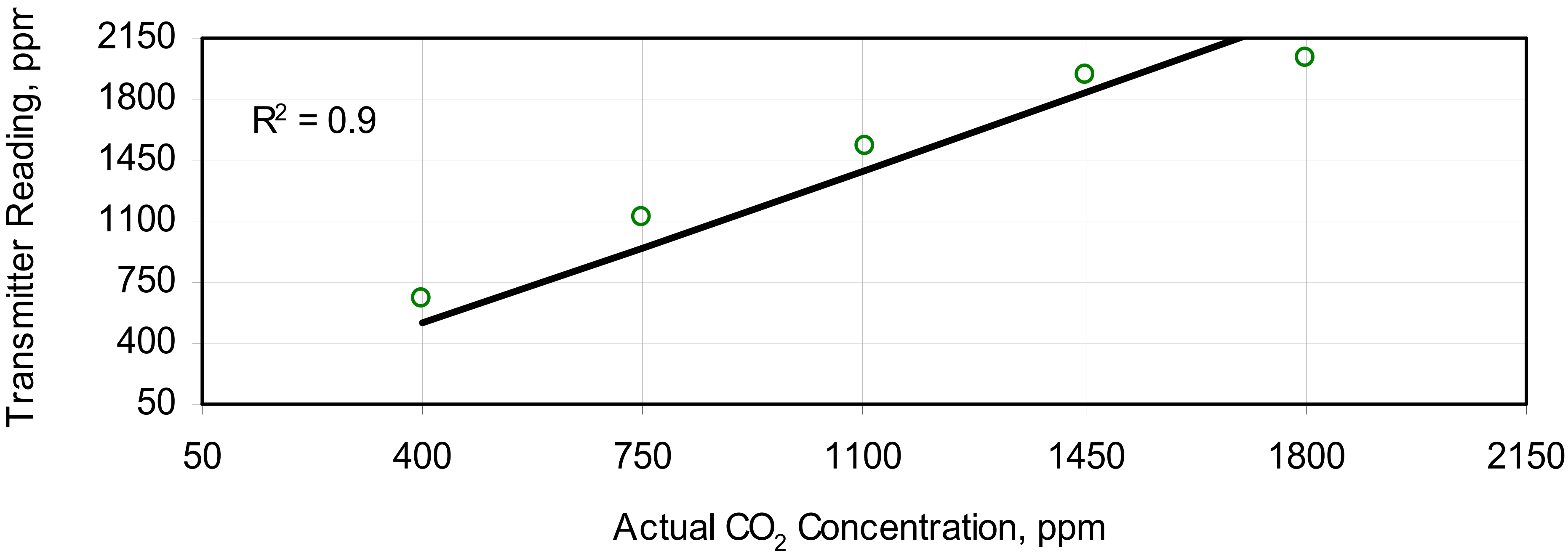
Non-linearity often expressed as: $< \pm 1\% FS$

If 2,000 ppm full scale: $< \pm 20$ ppm

Sensor meets the non-linearity statement.

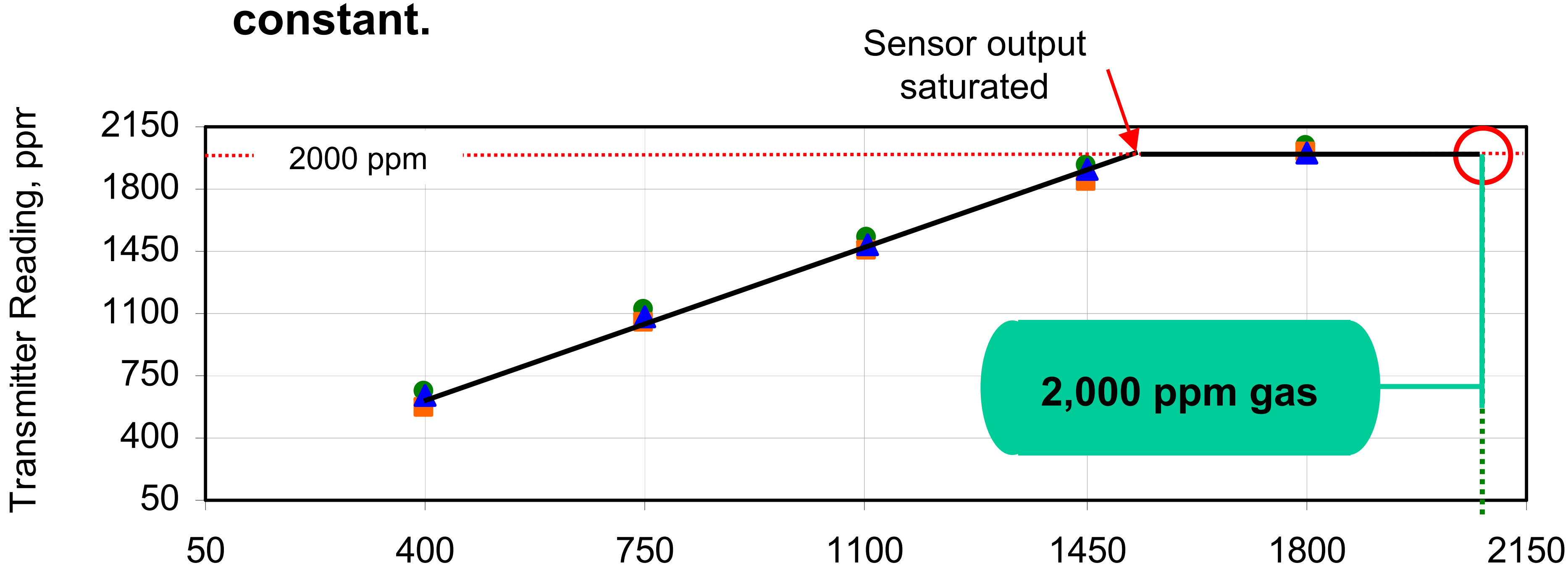
Linearity

Non-linearity ? What's happening ?



Linearity

Beyond saturation value, sensor output remains constant.



Checking this sensor in the field with 2,000 ppm CO_2 gas would leave you with a false impression about the accuracy of the sensor.

Testing Affects of Humidity, Pressure and Temperature

Relative Humidity (%): 40, 60, 80

Fixed conditions: 1,100 ppm CO_2; 73ºF (22.8ºC); 14.7 psia

Pressure (psia): 14.7 (sea level), 13.25 (2,838 ft), 11.8 (5,948 ft)

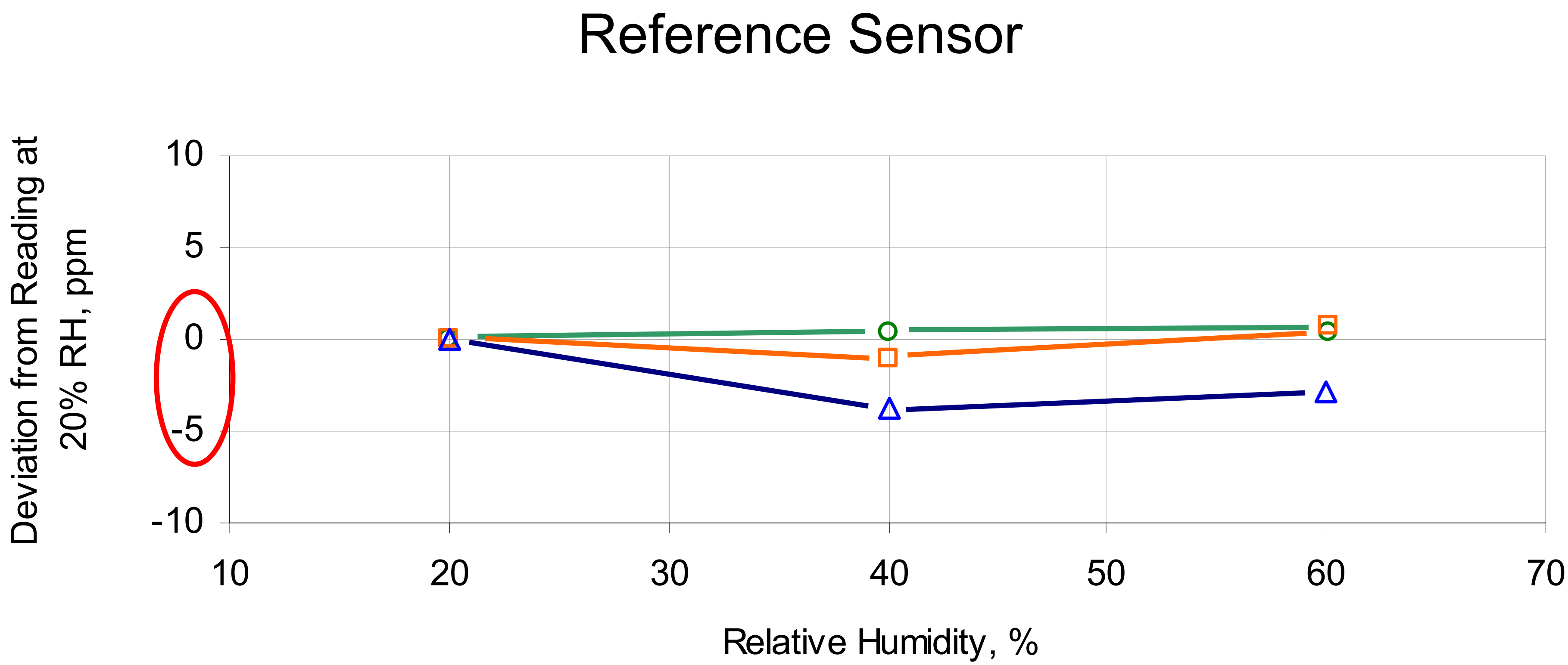
Fixed conditions: 1,100 ppm CO_2; 73ºF (22.8ºC); 40% RH

Temperature: 80°F (26.7°C), 73ºF (22.8ºC), 66°F (18.9°C)

Fixed conditions: 1,100 ppm CO_2; 14.7 psia, 40% RH

Affects of Humidity

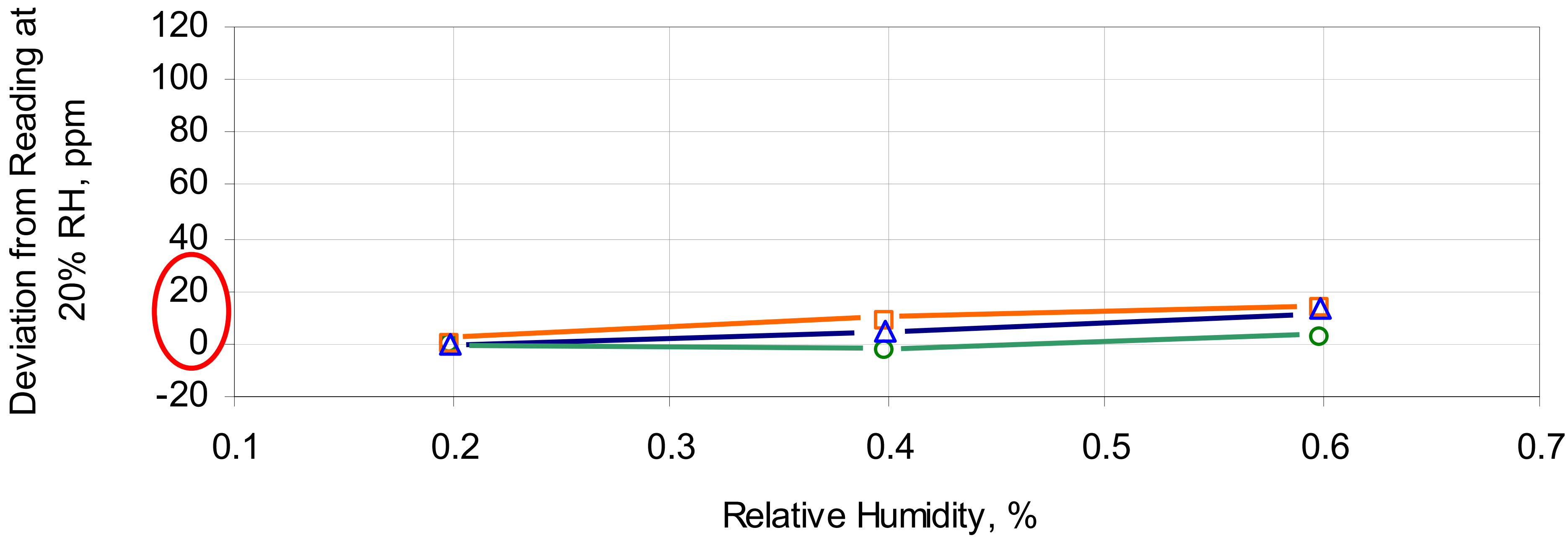
1,100 ppm CO_2; 73ºF; 14.7 psia



Affects of Humidity

1,100 ppm CO_2; 73ºF; 14.7 psia

Three sensors from one manufacturer

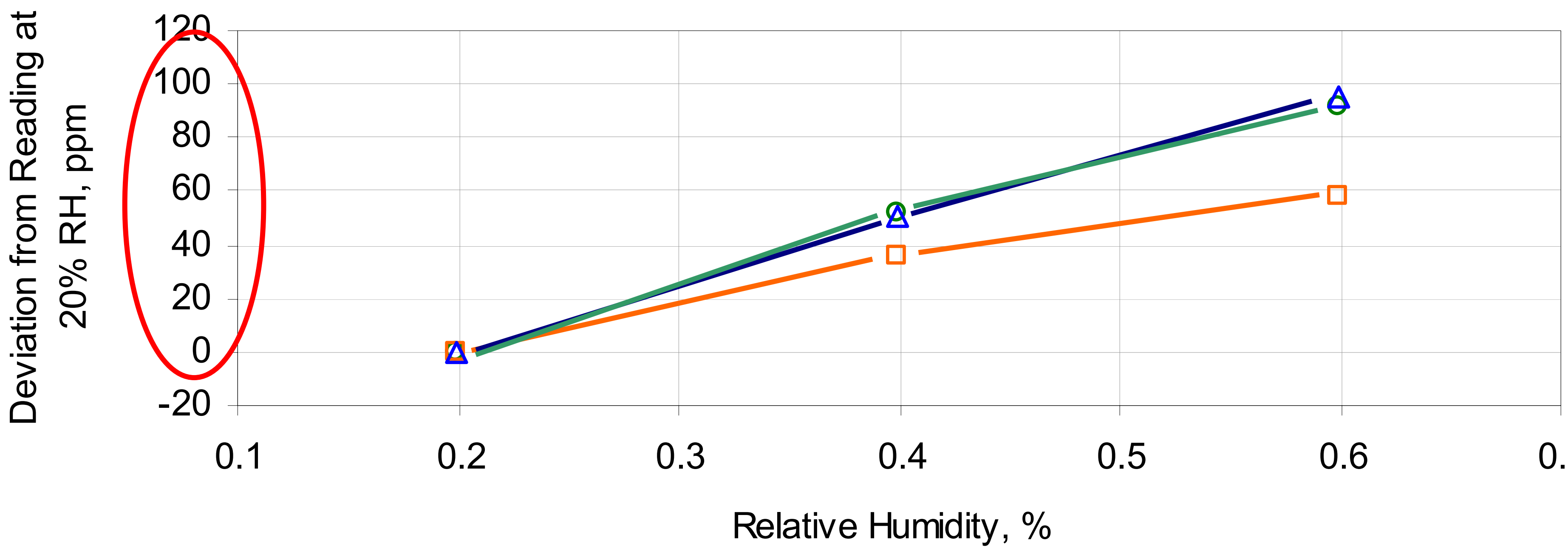


Many of the manufacturers' transmitters showed similar response to variations in humidity.

Affects of Humidity

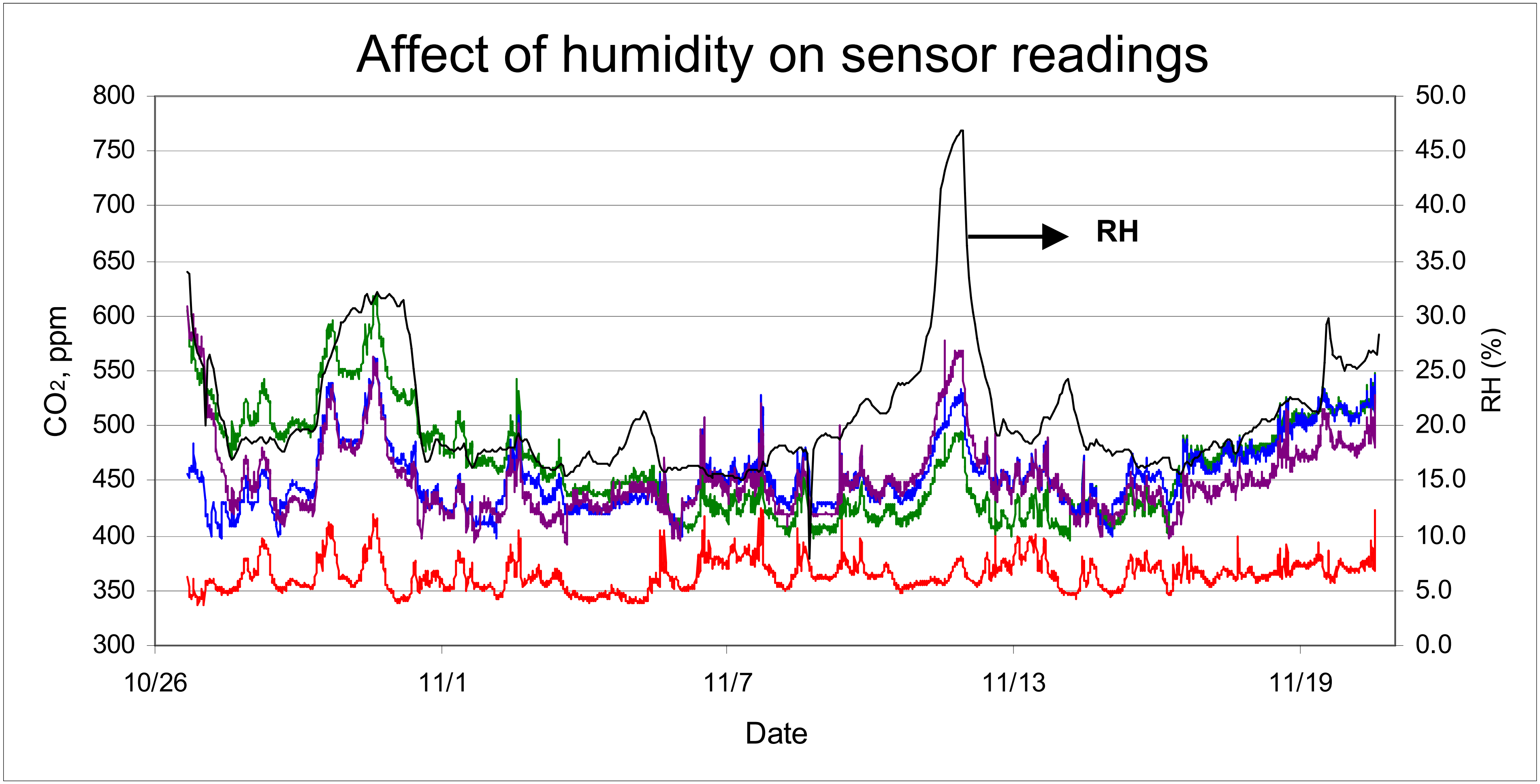
1,100 ppm CO_2; 73ºF; 14.7 psia

Three sensors from another manufacturer



Much stronger dependence on humidity.

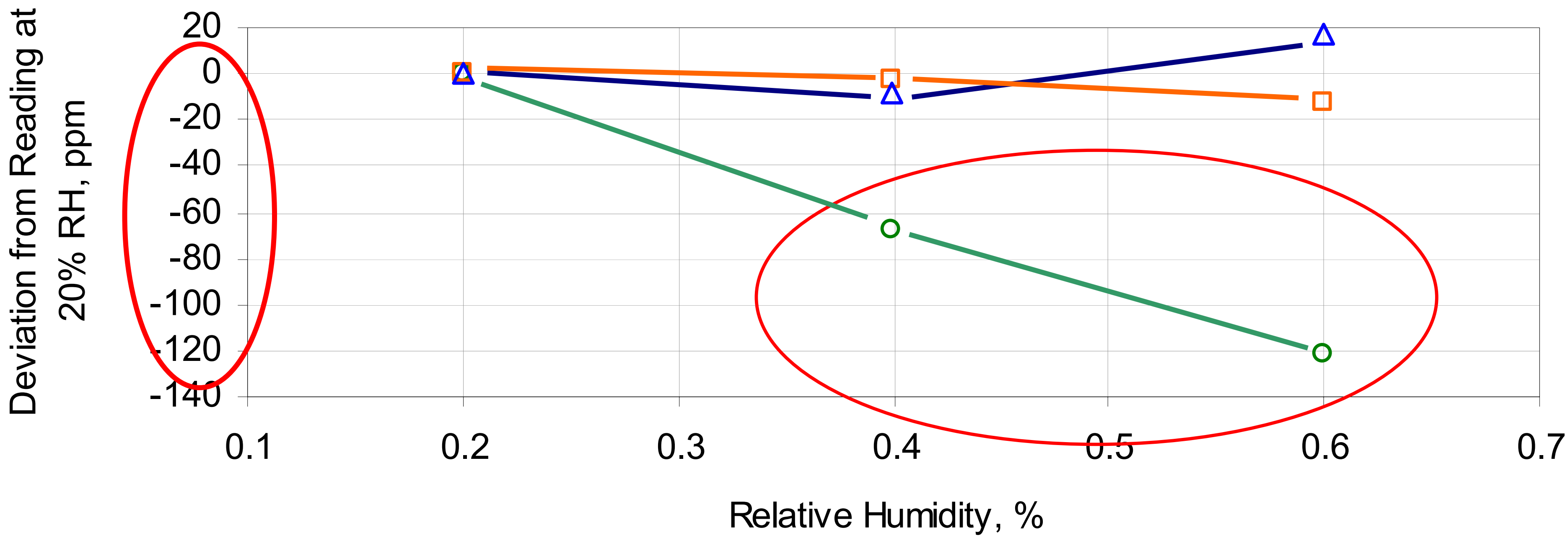
Remember the power up test?



Affects of Humidity

1,100 ppm CO_2; 73ºF; 14.7 psia

Three sensors from a third manufacturer

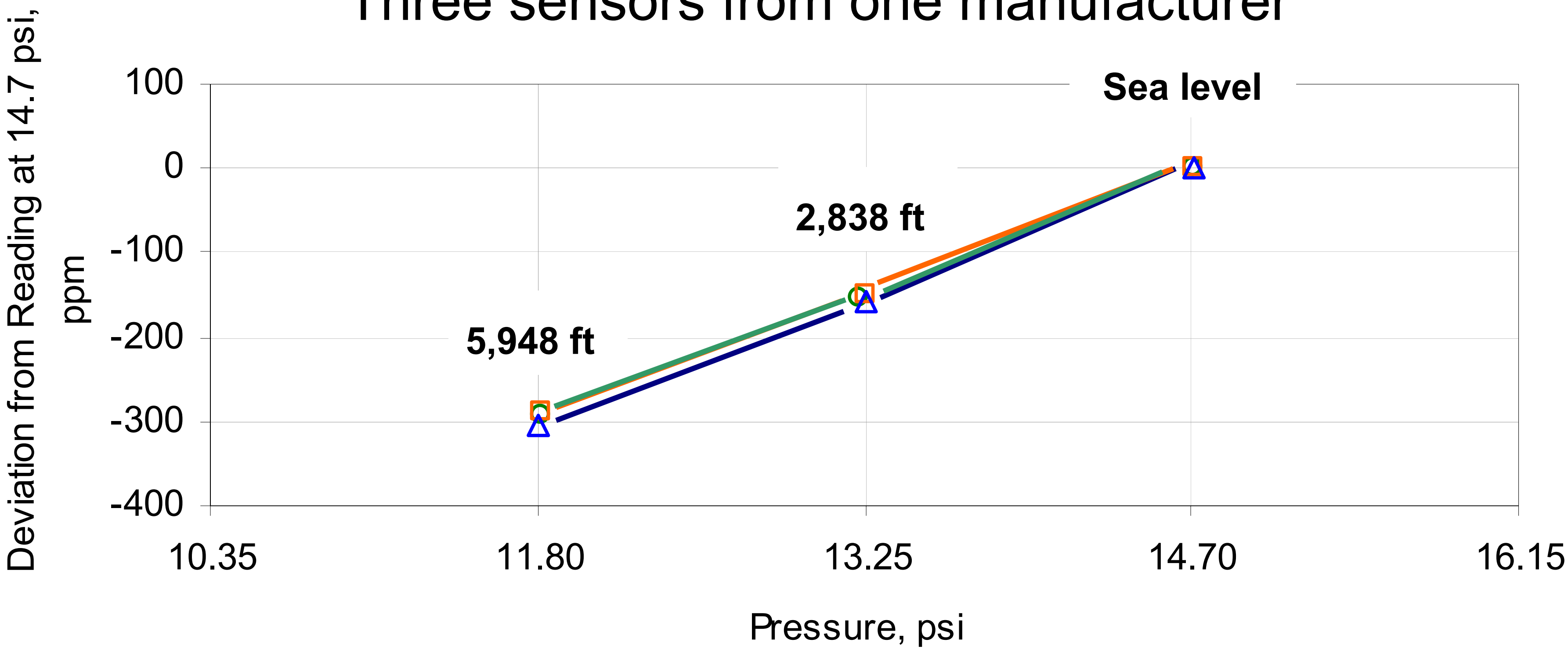


Couldn't decide if the transmitter should depend on humidity or not. (This test was repeatable.)

Affects of Pressure

1,100 ppm CO_2; 73ºF; 40% RH

Three sensors from one manufacturer



All of the manufacturers' transmitters showed similar response to variations in pressure: ~106 ppm/psi

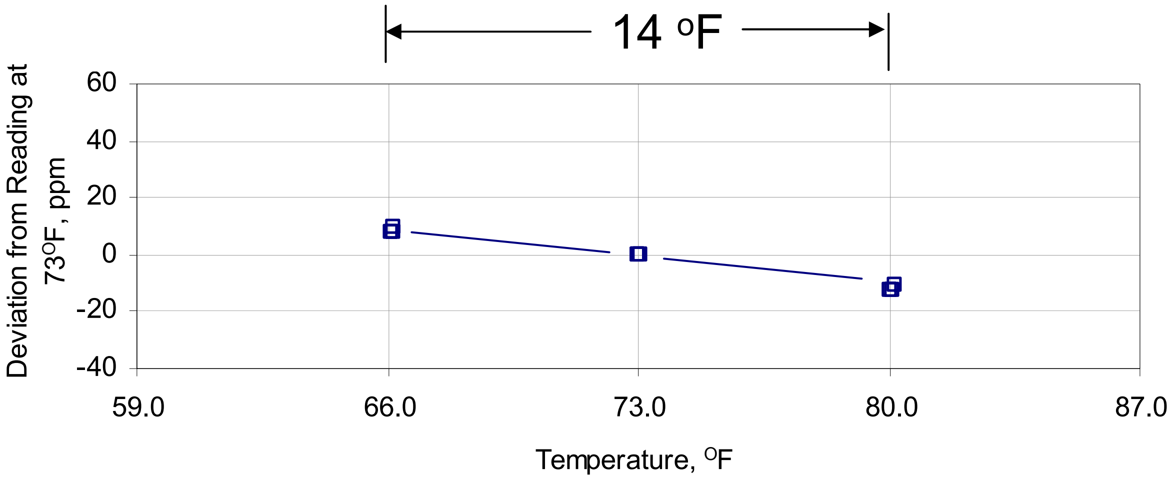
Expected variation in CO_2 transmitter output due to variation in local barometric pressure (TMY2 weather)

Location	Variation in barometric pressure (psia)	Variation in CO_2 reading (ppm)
San Francisco	0.493	53
Sacramento	0.435	46
Los Angeles	0.566	60
Chicago	0.855	91
Denver	0.590	63
Boston	0.860	92

Affects of Temperature

1,100 ppm CO_2; 14.7 psia, 40% RH

Reference Sensor



± 15 ppm

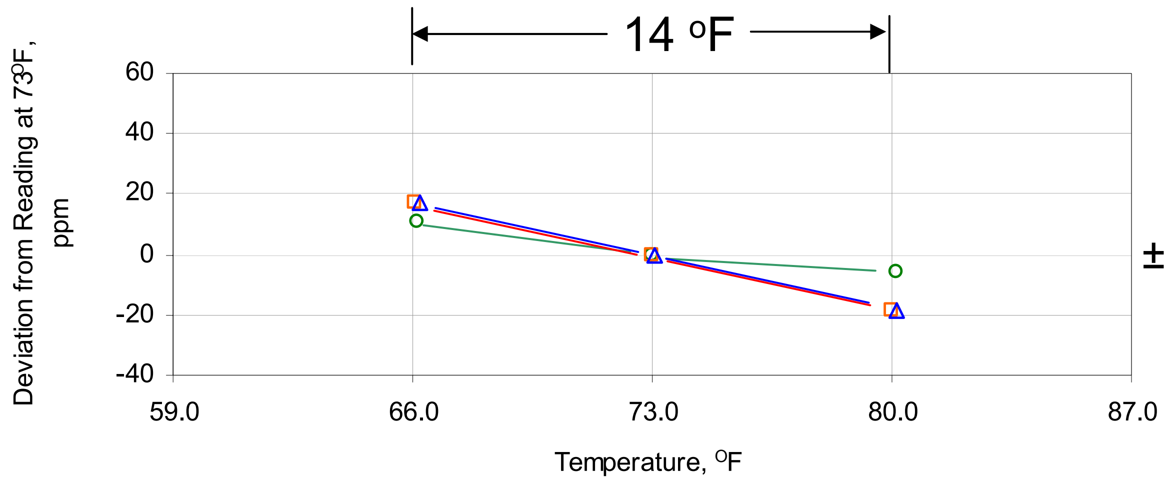
-0.35% of reading/°C

(25°C reference)

-0.194% of reading/°F

Affects of Temperature

1,100 ppm CO_2; 14.7 psia, 40% RH

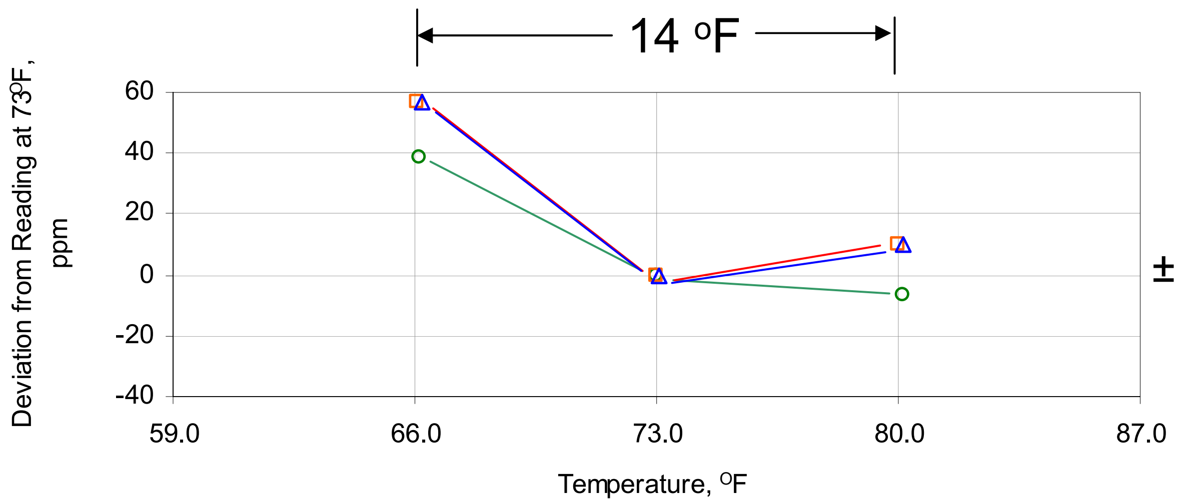


± 11.7 ppm

Typically 0.15% FS/°C

(25°C reference)

1.67 ppm/°F



± 19.5 ppm

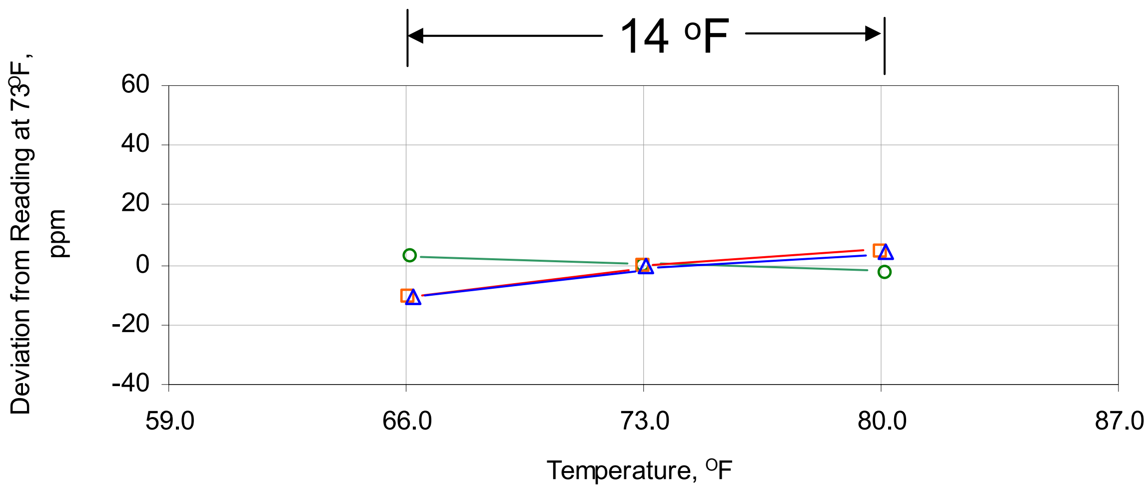
Typically 5 ppm/°C

(no reference temp.)

2.78 ppm/°F

Affects of Temperature

1,100 ppm CO_2; 14.7 psia, 40% RH

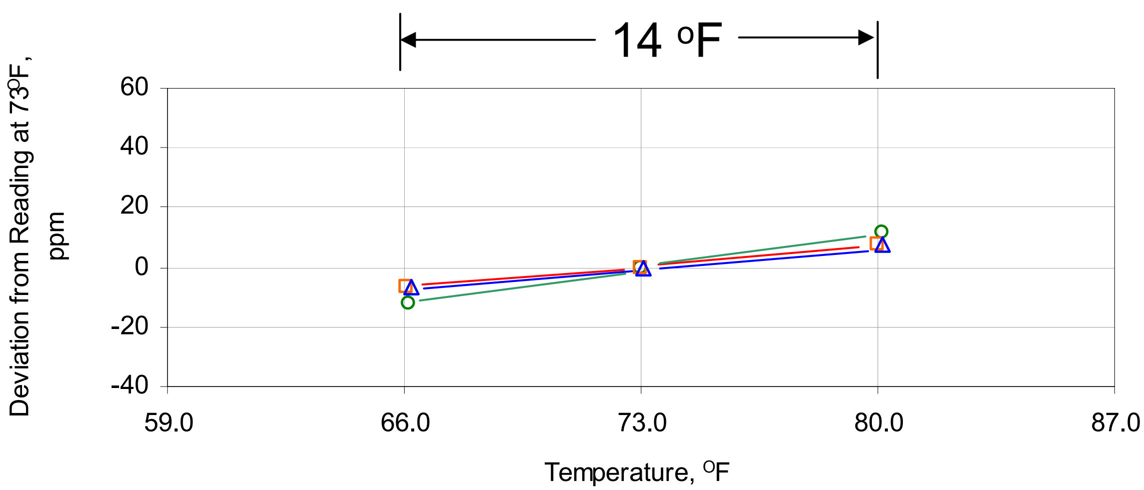


± 15.5 ppm

Typically 0.2% FS/°C

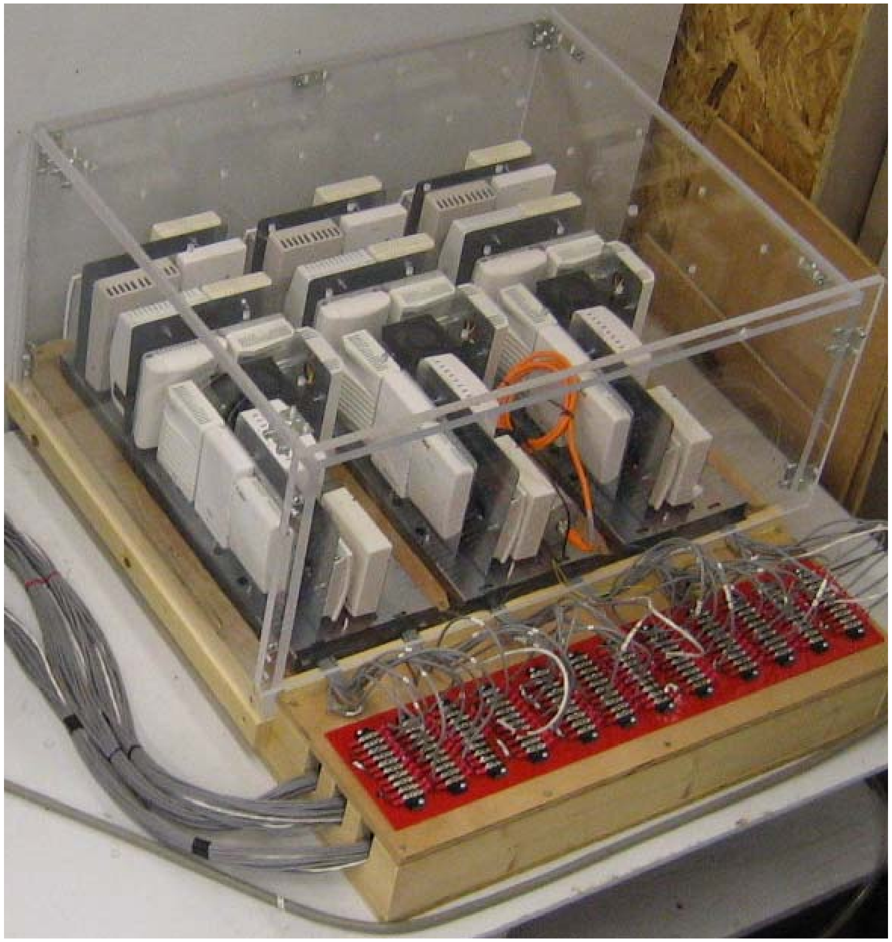
(no reference)

2.22 ppm/°F



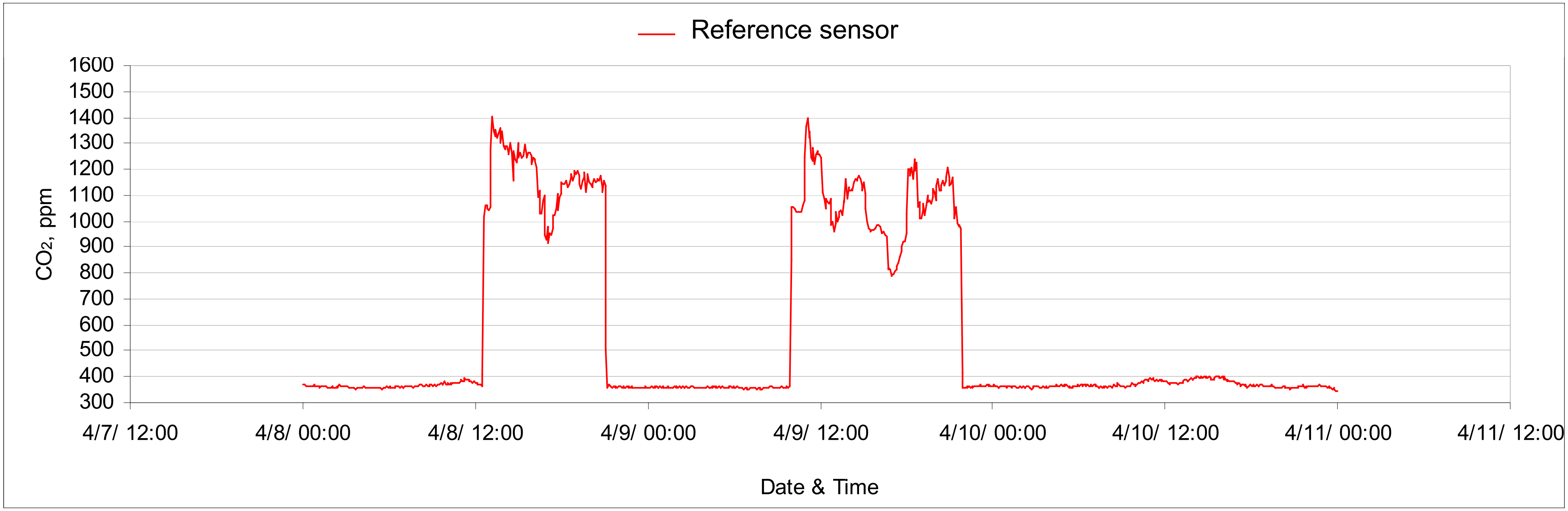
No temperature dependence specified

Long-term exercises



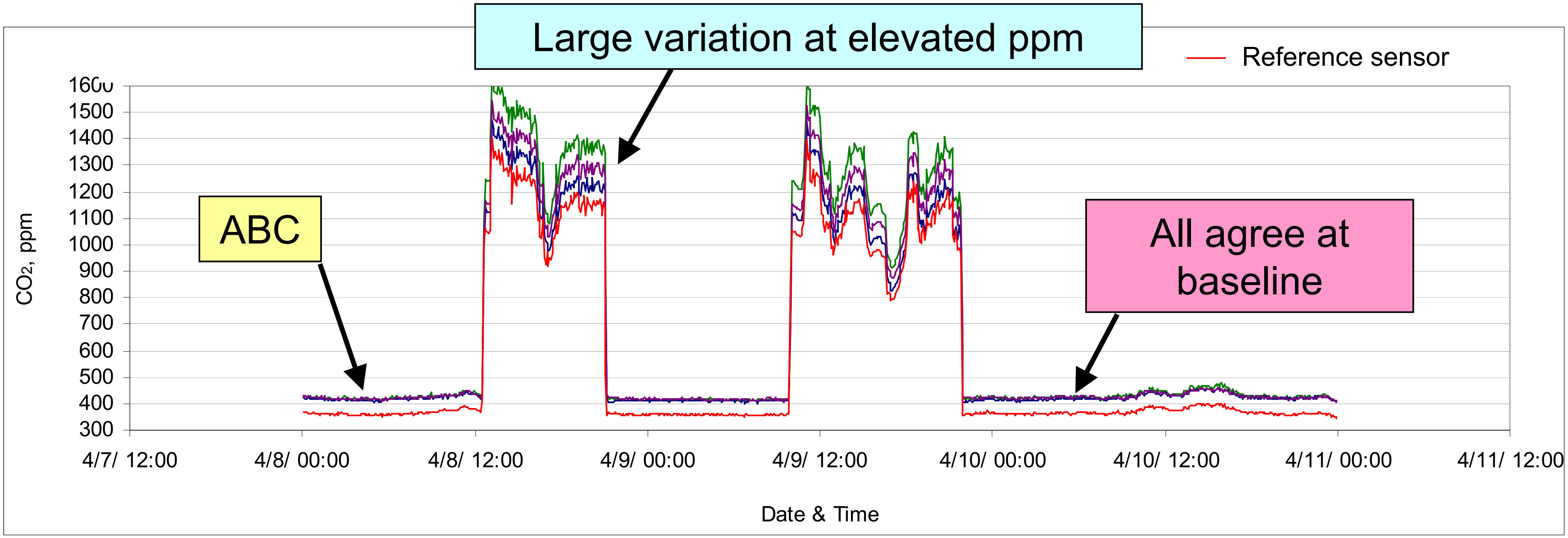
Long-term exercises

Periodically expose all sensors to elevated CO_2 levels



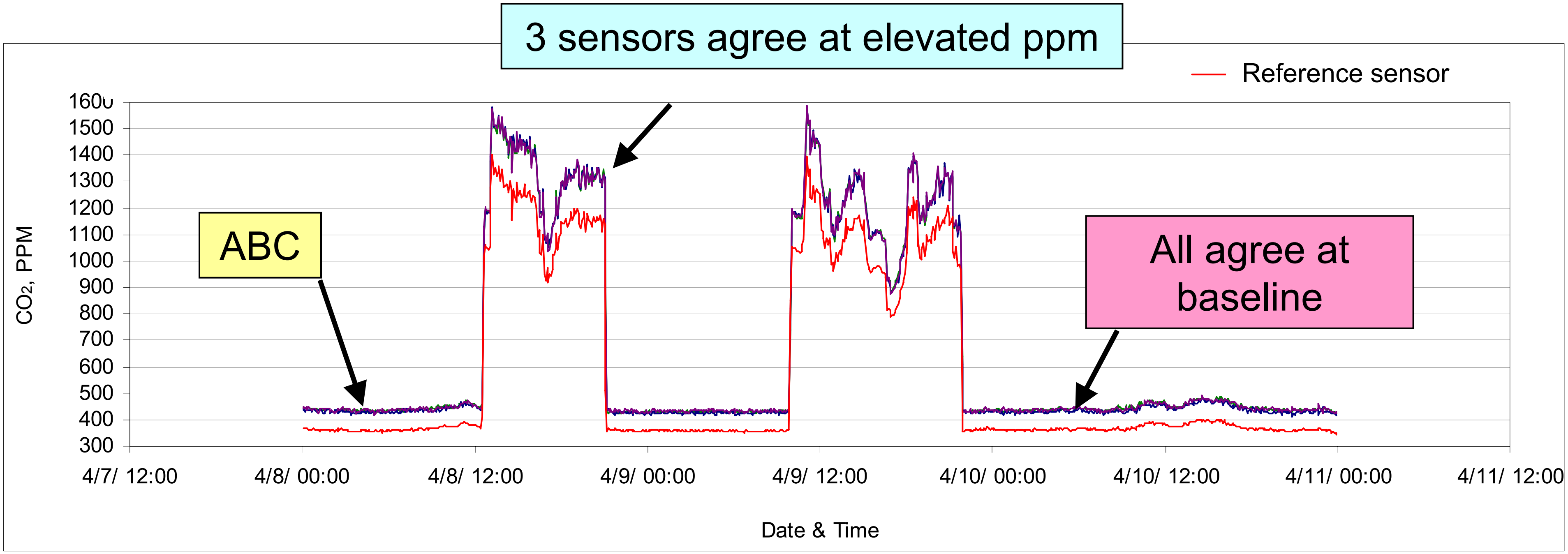
Long-term exercises

Three sensors from one manufacturer



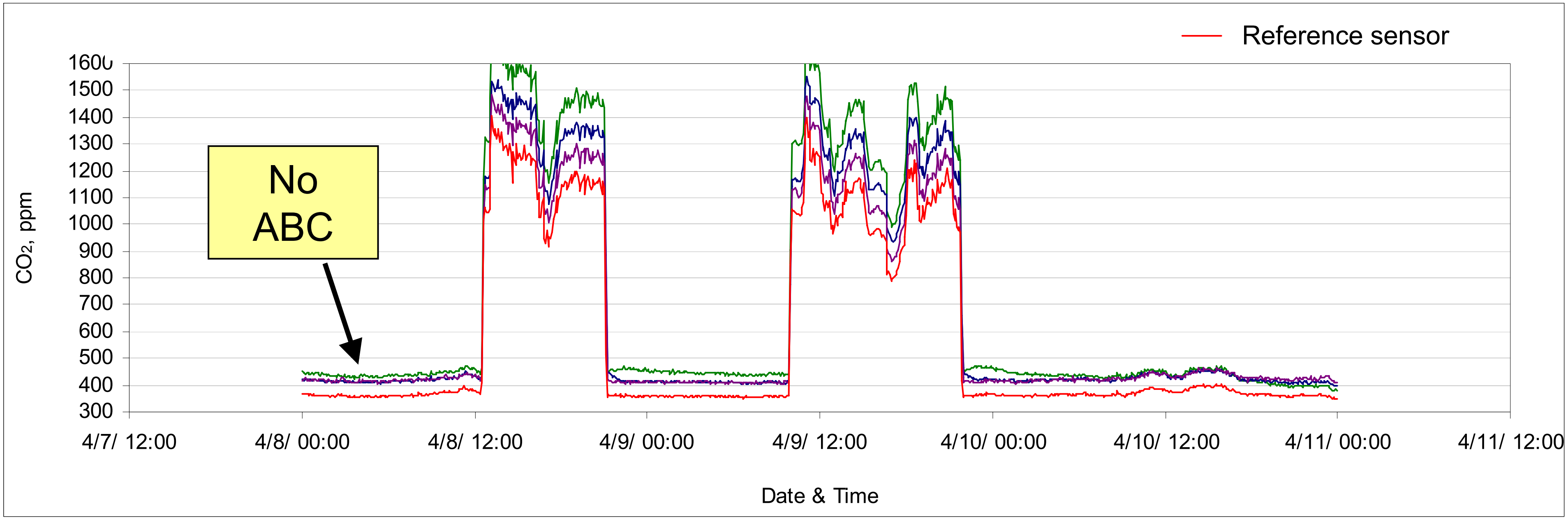
Long-term exercises

Three sensors from another manufacturer



Long-term exercises

Three sensors from another manufacturer



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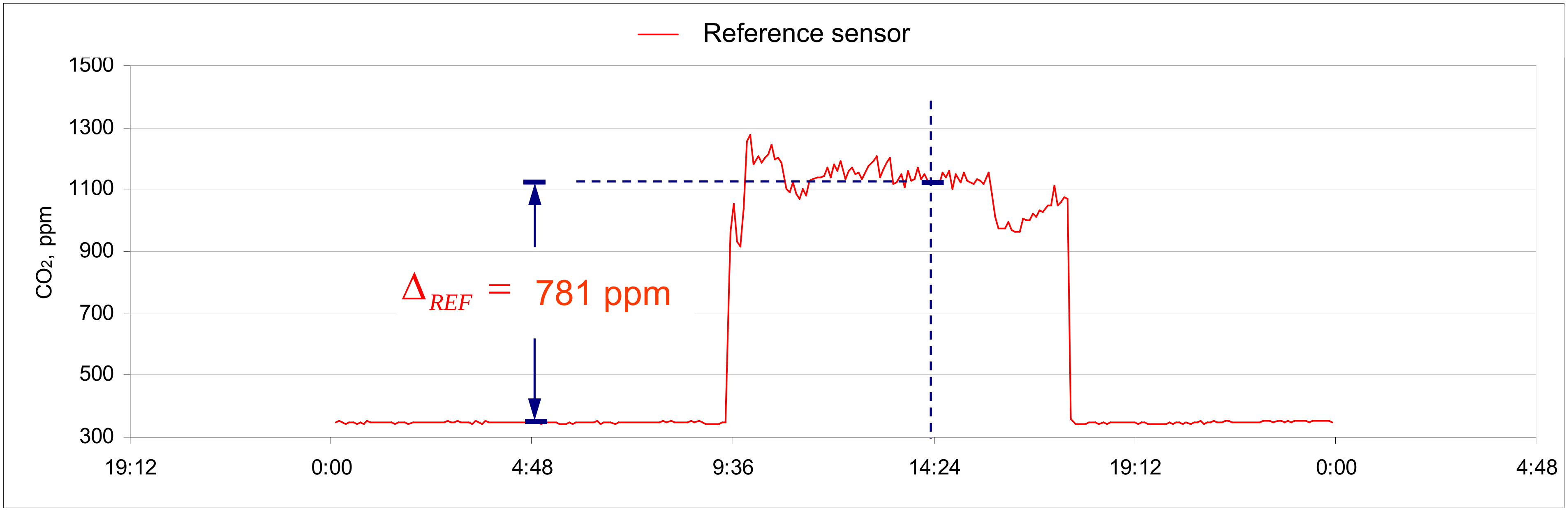
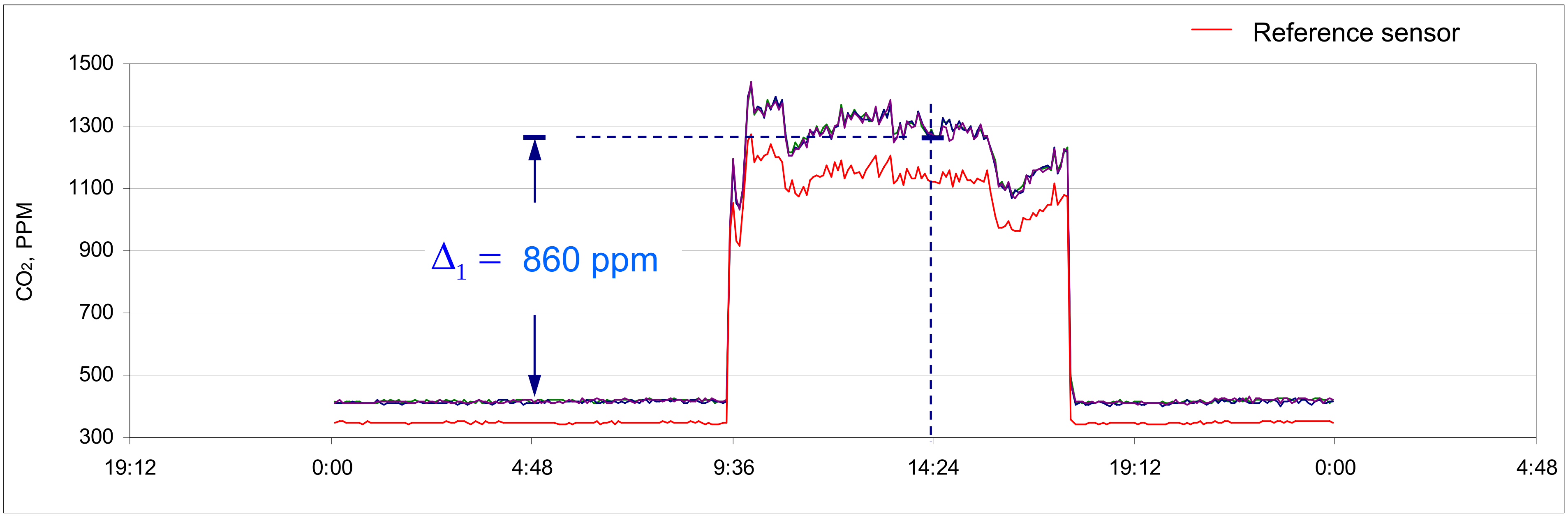
Long-term exercises

Determine the change in concentration for the reference sensor



Long-term exercises

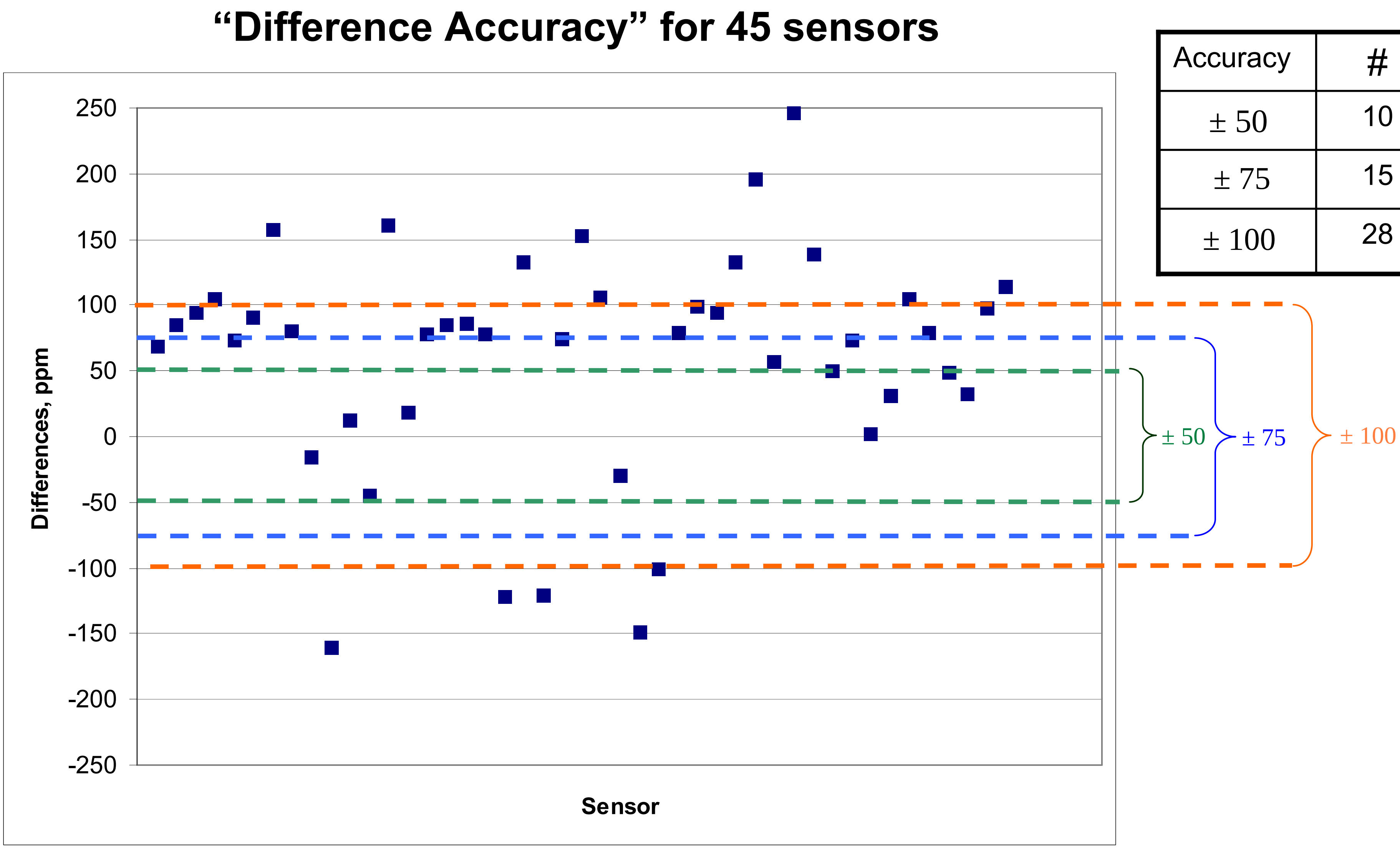
Determine the change in concentration for other sensors (at same point in time)



Compare the difference: 860 ppm - 781 ppm = 79 ppm "difference accuracy"

NBCIP

Long-term exercises



Accuracy	#
± 50	10
± 75	15
± 100	28

Summary

Product information is not always consistent for a given sensor.

“ABC” logic not well documented by most manufacturers.

Wide variation on sensor accuracy for “as received” conditions.

Sensor readings are strongly affected by pressure and to a lesser extent by temperature.

Variations in local barometric pressure does affect the sensor output.

Some sensors are strongly affected by relative humidity.

To date, no conclusive data on long-term stability.