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**A Performance Evaluation of Two Portable Infrared Gas Analyzers for the  
Measurement of Nitrous Oxide Under Laboratory Conditions**

by

Lieutenant Commander Brandon Parker

United States Public Health Service

Indian Health Service

Thesis submitted to the Faculty of the  
Preventive Medicine and Biostatistics Graduate Program  
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In partial fulfillment of the requirements for the degree of  
Master of Science in Public Health, 2021



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## DEDICATION

I dedicate this thesis to the Numunuu. To my nanisuyaketu numuhabinu; to my pia, ahpu, pabi, nami, patsi, tau, petu, kaku, tooko, and ahra. U kamakutu nu.

**Numunaitu!**

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## ABSTRACT

### A Performance Evaluation of Two Portable Infrared Gas Analyzers for the Measurement of Nitrous Oxide Under Laboratory Conditions

LCDR Brandon Parker, MSPH, REHS, 2021

Thesis directed by: Captain Michael E. Stevens Jr., Ph.D., Division Director for Occupational and Environmental Health Sciences, Preventive Medicine and Biostatistics and Commander Edward A. Benchoff, Ph.D., Assistant Professor, Preventive Medicine and Biostatistics

**Objective:** The objective of this study was to investigate the level of agreement between a Bacharach PGM-IR N<sub>2</sub>O 3015-4787 Monitor, Viasensor G200 N<sub>2</sub>O Analyzer, and a Gasmet DX4040 reference instrument across a discrete range of nitrous oxide (N<sub>2</sub>O) concentrations, at 21°C, and at 22% and 80% relative humidity (RH) levels. Agreement acceptable for the study would be  $\pm 25\%$  of the true concentration as monitored by the Gasmet. The study sought to determine if there was a statistically significant difference between the mean measurements of the Bacharach, Viasensor, and the reference instrument. Information regarding the infrared gas analyzer (IGA) with the best agreement with the reference instrument's nitrous oxide measurements would be offered to the IHS to augment their consideration of a replacement instrument.

**Methods:** Controlled and homogenous nitrous oxide gas atmospheres were generated with a dynamic cylinder dilution system where sampling occurred over an evaluation range of 1 to 500 ppm. Three repeated trials occurred. Each trial consisted of four replicate samples at 21°C, and at relative humidity levels of 22% and 80%. Four two-way analysis of variance (ANOVA) analyses were performed to identify statistically

significant differences between the mean measurements of each investigated IGA when compared to the mean measurements of the reference instrument. The level of agreement between the IGAs with the reference instrument was evaluated to determine if it met the  $\pm 25\%$  criteria set forth by the National Institute for Occupational Safety and Health (NIOSH). Twelve Bland-Altman analyses were used to investigate the specific level of agreement between each investigated IGA and the reference instrument.

**Results:** Two-way ANOVA analyses revealed that the mean measurements of both tested instruments were significantly different than the mean measurements of the reference instrument ( $p < .00005$ ). The Bacharach met level of agreement criteria ( $\pm 25\%$ ), at the 95% confidence interval, for 13 of 14 test concentrations at 22% RH and 80% RH. The Viasensor met level of agreement criteria ( $\pm 25\%$ ), at the 95% confidence interval, for 8 of 14 test concentrations at 22% RH and 9 of 14 test concentrations at 80% RH levels. All Bland-Altman results at 22% RH and 80% RH revealed that the Bacharach had better overall agreement with the reference instrument compared to the Viasensor.

**Conclusion:**

The study determined the level of agreement between two IGAs when compared to a reference instrument. The Bacharach fulfilled accuracy criterion specified in NIOSH technical report 95-117 (23), under all study conditions, at test concentrations from 5 to 500 ppm. The Bacharach had the higher overall level of agreement when compared to the Viasensor. The Bacharach is recommended for further consideration by the IHS to determine whether it meets other criteria requirements such as cost, operational characteristics, and field performance standards.

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## **CHAPTER 1: Introduction**

### **1.1 STATEMENT OF PURPOSE**

*“To investigate the level of agreement between two portable infrared gas analyzers (IGA) at discrete nitrous oxide (N<sub>2</sub>O) concentrations and two relative humidity levels so this performance information can be considered by IHS programs to augment their consideration when replacing infrared gas analyzers used in their occupational settings.”*

The Indian Health Service (IHS), a federal agency within the Department of Health and Human Service responsible for providing health care services to American Indians and Alaska Natives, has a Division of Oral Health (DOH) program with 404 dental units with nearly 1,000 dentists, 400 dental hygienists, 2,250 dental assistants, and 500 office staff (21). To meet the oral health and patient care needs of the DOH community, the Division utilizes nitrous oxide-sedation analgesia (N<sub>2</sub>O) for the reduction of fear, anxiety, and pain response during nitrous oxide-sedation analgesia procedures in their dental care (20).

The IHS Oral Health Program Guide (19) requires dental units monitor occupational exposure to waste emissions of nitrous oxide and ensure controls are effective. To accomplish exposure monitoring, the IHS uses two air sampling methods. These two methods are time-integrated diffusive sampling and active sampling with a nondispersive infrared gas analyzer (NDIR). For active sampling, by policy, the IHS has used the Thermo Fisher Scientific Miran Infrared Spectrophotometer (19). Recently the manufacturer of the Miran has stopped production and support of this instrument with no plans to develop a replacement (43).

The primary purpose of the study is to investigate the performance of two infrared gas analyzers (IGA) that have no known published performance evaluations. Information gathered from this study will be conveyed to the IHS for consideration when replacing the Miran. These two IGAs are:

- Viasensor G200 N<sub>2</sub>O Analyzer (Viasensor, Dexter, MI)
- Bacharach PGM-IR N<sub>2</sub>O Monitor 3015-4787 (Bacharach, New Kensington, PA)

## **1.2 BACKGROUND**

Nitrous oxide, also known as dinitrogen monoxide or laughing gas, is a colorless, inorganic gas with a faint sweet odor and taste that is used in hospital and dental operations for inhalational analgesia (31).

Mixtures of nitrous oxide have been used in dentistry as a general anesthetic agent, analgesic, and sedative for more than 100 years (4). Nitrous oxide has demonstrated a proven clinical efficacy and patient safety record in conscious inhalation sedation but for exposed medical personnel, nitrous oxide may pose adverse health risks (18, 50). Starting in the 1950's, a history of suspected acute and chronic adverse health effects began to raise concerns about the drug. Acute exposures (less than eight hours per week) have been related to decrements in psychomotor performance, memory recall, and visual perception (17). For workers with chronic exposure (eight hours or more per week), a number of epidemiological studies implicate health effects related to renal, liver, kidney, neurological, and reproductive disorders (18).

The Occupational Safety and Health Administration (OSHA) has not established a regulatory exposure limit for nitrous oxide. However, organizations such

as the National Institute for Occupational Safety and Health (NIOSH) and the American Conference of Governmental Industrial Hygienists (ACGIH) have established non-regulatory exposure limits. The NIOSH recommended exposure limit (REL) for nitrous oxide is 25 parts per million (ppm) measured as a Time Weighted Average (TWA), as the average exposure to the gas over the duration of anesthetic administration (31). The ACGIH recommends a Threshold Limit Value – Time Weighted Average (TLV-TWA) for worker exposure to be less than 50 ppm over an 8-hour workday and 40-hour work week (1). The ACGIHs pragmatic precautionary “3/5 Rule” reflects rules of thumb for acceptable excursions above their listed nitrous oxide TLV. According to their recommendation, nitrous oxide may exceed three times the TLV-TWA (150 ppm) for more than a total of 15 minutes at one time, on no more than four occasions spaced one hour apart during a workday. Furthermore, using this rule of thumb, under no circumstances should nitrous oxide exceed five times the TLV-TWA (250 ppm) when measured as a 15-minute TWA (1).

According to Chapter 6 of the IHS Oral Health Program Guide, nitrous oxide exposure limits should not exceed the ACGIH TLV-TWA of 50 ppm for a normal 8-hour workday and a 40-hour work week (19). The Guide also cites that short-term exposures should not exceed 150 ppm for no more than 30 minutes during a workday and under no circumstances should exposures exceed 250 ppm.

NIOSH and OSHA have published guidelines recommending the utilization of engineering, administrative, and work practice controls to mitigate occupational exposure to nitrous oxide (27; 38). Both NIOSH and OSHA list two methods for air sampling of nitrous oxide in dental settings: 1) real-time sampling that provide for

immediate and continuous readouts of nitrous oxide concentrations using a portable infrared gas analyzer (IGA); and 2) time-integrated sampling that includes bag sampling or diffusive sampling (using a “passive dosimeter”). Other controls include, but are not limited to, maintaining the anesthetic delivery system (connections, fittings, hoses), prudent use of nitrous oxide to appropriately sedate patients, selecting the appropriate scavenging mask for proper patient fit, using effective waste gas evacuation systems (scavenging systems), and having good general ventilation that can help dilute nitrous oxide emissions to acceptable levels (38).

The IHS program responsible for nitrous oxide exposure monitoring, using real-time sampling methods, is the IHS Division of Environmental Health Service’s (DEHS) Institutional Environmental Health (IEH) Program (19). The IEH Program, which employs approximately 30 staff (n = 21 with a master’s degree; n = 6 with a Certified Industrial Hygiene certificates), is a DEHS specialty program that conducts industrial hygiene surveys, radiation protection assessments, health care accreditation services, and other important occupational health and safety functions (44).

The analytical technique for measuring nitrous oxide by portable infrared (IR) gas analyzers is known as infrared laser-absorption spectrometry. In IR laser-absorption spectrometry, an air sample is pumped into an instrument at a specific IR absorption energy (or wavelength) whereas the IR energy is absorbed by the sample of interest (10). Upon absorption, an IGA instrument will then quantitatively measure the concentration of the sample via the principles of the Beer-Lambert law, which explains that concentration is directly proportional to the absorbance (10). The corresponding analytical wavelength or IR absorption energy for nitrous oxide is 4.48  $\mu\text{m}$  (32). For

nitrous oxide sampling, the IR radiation source of IGAs have an absorption wavelength around the 4  $\mu\text{m}$  range so that the monitors are sensitive to nitrous oxide (41). Per the validated NIOSH Nitrous Oxide 6600 method, no known interferences have been identified at the nitrous oxide wavelength or absorption line in common applications observed in hospital or dental settings. Therefore, it can be assumed that nitrous oxide IGAs are sufficiently specific to their designed compound, provided no other spectral interference occurs (32).

Historically, the IHS has used the Thermo Fisher Scientific Miran SapphIRe (Figure 1) Portable Ambient Analyzer (Miran SapphIRe) for real-time sampling of nitrous oxide. However, recently Thermo Fisher Scientific released a memorandum stating that all servicing and calibration of the Miran SapphIRe will cease at the end of year 2020 (43). Thus, IHS has a need to evaluate and identify a replacement instrument (or instruments) capable of accurately and precisely measuring nitrous oxide in their occupational settings.



Figure 1: California Area Indian Health Service Miran SapphIRe (44).

At present, there are a limited number of portable IGAs capable of replacing the Miran SapphIRe for the IHS. No studies were identified that provided information about the performance of measuring nitrous oxide with currently available portable IGAs. This project aims to evaluate the ability of two IGAs to measure nitrous oxide accurately and precisely in a laboratory environment. The performance of an IGA relative to the NIOSH accuracy criteria (23) of  $\pm 25\%$  of the true concentration (as determined by a reference instrument) will likely provide important information to IHS program decision-makers, assisting them in determining potential replacement instruments for the Miran SapphIRe.

## **1.3 RESEARCH QUESTION AND SPECIFIC AIMS**

### **1.3.1 Research Question**

What are the levels of agreement between two factory-calibrated portable IGAs and a Fourier transform infrared spectroscopy (FTIR) reference instrument across a discrete range of nitrous oxide concentrations at different humidity levels when measuring nitrous oxide?

### **1.3.2 Specific Aims**

1. Use a well-validated method of infrared spectrometry, FTIR, by means of the Gasmet portable gas analyzer (Gasmet, Vantaa, Finland), as a reference method, to analyze and validate concentrations of nitrous oxide in a sealed rigid container under laboratory conditions.
2. Determine if the levels of agreement (accuracy, precision, and agreement) between two factory-calibrated IGAs are outside of or within  $\pm 25\%$  of the true concentration, when measuring nitrous oxide over an evaluation range of 1 to 500 ppm and relative humidity levels of approximately 20% and 80% at a temperature of approximately 21°C, when compared to a user-calibrated Gasmet (as a reference method).
3. Examine if the two IGAs can maintain good agreement ( $\pm 25\%$  of the true concentration) with the reference instrument, over three repeated trials, at the same concentrations, temperature, and humidity levels listed above.
4. Perform two-way analysis of variances (ANOVAs) at 20% and 80% relative humidity, between the reference instrument and each IGA, for a total of four

ANOVAs, to determine if there is a significant difference between IGA mean measurements at different ppm levels.

5. Perform Bland-Altman analyses to determine the level of agreement between each IGA and the reference instrument. For each IGA, six Bland-Altman analyses will be performed for results at 20% and 80% relative humidity levels.

## CHAPTER 2: Literature Review

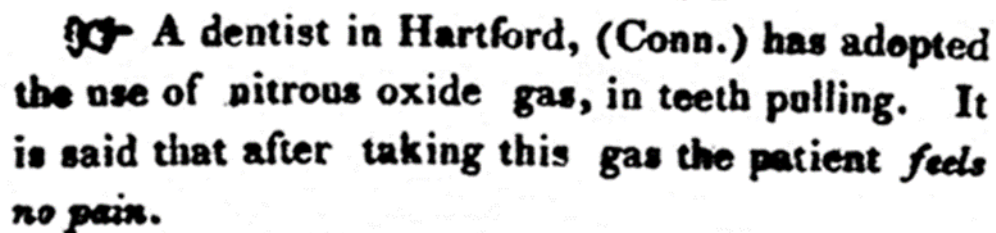
### 2.1 DISCOVERY AND HISTORY OF NITROUS OXIDE

The discovery of nitrous oxide dates to the 1770's and is credited to an English scientist named Sir Joseph Priestley (7). Priestly was experimenting with nitrous air – a mixture of iron filings, sulfur, and water. He called his mixture *dephlogisticated nitrous air*, which is now known as nitrous oxide (46). After its discovery, entrepreneurs such as the famed American firearms manufacturer Samuel Colt (Figure 2) began traveling throughout the nation in the early 1800's to demonstrate the effects of the new drug to mesmerize crowds and pursue profit (48).

**NITROUS OXIDE GAS FOR LADIES AND GENTLEMEN**  
Dr. S. Coult respectfully informs the Ladies and Gentlemen of Portland and vicinity, that he will administer the NITROUS OXIDE, or Exhilarating Gas, on Monday evening at the City Hall. Exhibition to commence at 7 o'clock precisely. The peculiar effects of this singular compound upon the animal system, was first noticed by the English Chemist, Sir Humphry Davy. He observed that when inhaled into the lungs it produced the most astonishing effects upon the nervous system; that some individuals were disposed to laugh, sing, and dance; others, to recitation and declamation, and that the greater number had an irresistible propensity to muscular exertion, such as wrestling, boxing, etc., with numerous fantastic feats. In short, the sensations produced by it are highly pleasurable, and are not followed by debility. . . . Dr. C. has exhibited the extraordinary powers of the gas in many cities of the United States, to audiences composed of Ladies and Gentlemen of the first respectability—and many Ladies have inhaled the gas at select Exhibitions. Those Ladies who may be anxious of witnessing the Exhibition, in this city, may be assured, that the City Hall embraces every accommodation for their comfort, and that not a shadow of impropriety attends the Exhibition,, to shock the most modest. He will attend, on reasonable terms, to any applications for private Exhibitions to select parties of Ladies and Gentlemen .

Figure 2: Samuel Colt Advertisement from October 13, 1832 (45).

On December 10, 1884, in Boston, MA, a nitrous oxide entertainment entrepreneur named Gardner Q. Colton was hosting a show in Hartford, Connecticut (Figure 3). During this event, an audience member, who inhaled nitrous oxide from Colton, became injured when his leg ran into a wooden bench. After becoming injured, the audience member appeared to be unaware of his injuries. In attendance was a dentist named Dr. Horace Wells. Dr. Wells approached the injured individual and reportedly had asked him if he had any felt any pain. It was from this occasion that Dr. Wells, who had been concerned about pain during dental procedures, realized that nitrous oxide may be useful in dentistry thus establishing nitrous oxide for use in dentistry (16).



**A dentist in Hartford, (Conn.) has adopted the use of nitrous oxide gas, in teeth pulling. It is said that after taking this gas the patient feels no pain.**

Figure 3: Announcement in the Boston Bee, January 20, 1845 (16).

## 2.2 Health Concerns from Exposure to Nitrous Oxide

Nitrous oxide has a long and documented history for its safety as an effective drug. In fact, Becker and Rosenberg stated that nitrous oxide could be argued as the safest of all the modalities available for sedation in dentistry (3). Furthermore Gilchrest (2007) states that inhalational sedation with nitrous oxide has a good safety record, with minimal effects on the cardiovascular and respiratory systems, and few reports of adverse reactions have occurred (13).

Wilson et al. (1996) published research which stated practitioners are using nitrous oxide with an increased perception that more pediatric patients need nitrous

oxide (49). With this uptake in use over the course of time, medical professionals began to observe acute and chronic health effects of nitrous oxide exposure on humans. Acute or short term exposure is defined as an exposure to nitrous oxide in the workplace lasting for less than eight hours per week, and chronic or long term exposure is defined as an exposure to nitrous oxide in the workplace where the gas is used eight hours per week or more (47).

### **2.2.1 Acute Exposure**

Nitrous oxide has been found to have acute adverse health effects in healthcare workers and dental personnel who experience acute exposure to the waste anesthetic gas (18). Studies have shown that acute occupational exposure has resulted in a decrease in perceptual, cognitive, and motor skills (5). Dental workers, who are required to perform fine-motor skill tasks, that experience acute health effects may experience a decrease in job performance when providing dental care due to N<sub>2</sub>O exposure. In 1976, a National Institute for Occupational Safety and Health (NIOSH) study exposed 100 male subjects to 25 ppm, 50 ppm, and 500 ppm of nitrous oxide for two hours. The results from that study indicated measurable and statistically significant decrements in audiovisual performance at concentrations of 50 ppm (17).

### **2.2.2 Chronic Exposure**

More recent studies involving chronic occupational exposure to nitrous oxide have reported irreversible adverse health effects to healthcare workers and dental personnel. Howard (18) assessed health risks reported in nine N<sub>2</sub>O exposure studies and found that chronic exposure to nitrous oxide has been associated with reproductive,

hematologic, immunological, neurological, hepatological, and nephrologic disorders. Howard found that exposure effects are both dose and time dependent.

Rowland et.al. (1992) investigated the effects of chronic exposure to nitrous oxide on fertility in over 400 female dental assistants. Their retrospective study found an association between occupational exposure to high levels of nitrous oxide and reduced fertility among female dental assistants (42).

According to a study by the Cohen et al. that investigated dental personnel who were exposed to inhalational anesthetics in dental operatories suggested an association between chronic nitrous oxide exposure and adverse health effects. The study found that dentists and chair-side dental assistants who were chronically exposed experienced an increased incidence of liver disease of 1.7 fold for male dentists and 1.6 fold in female chairside assistants (8). Furthermore, the incidence of kidney disease increased 1.2 fold in male dentists and 1.2 to 1.7 fold in female chair-side dental assistants.

### **2.3 NITROUS OXIDE EXPOSURE LIMITS**

The Occupational Safety and Health Administration (OSHA) or any other federal entity has not established a permissible exposure limit (PEL) for nitrous oxide. However, organizations such as the American Conference of Governmental Industrial Hygienists (ACGIH) and NIOSH have developed non-legally binding recommended exposure limits (RELs) that are intended to represent conditions under which it is believed that nearly all workers may be exposed to without experiencing adverse health effects (2). The ACGIH recommends a Threshold Limit Value Time Weighted Average (TLV-TWA) for worker exposure to be less than 50 parts per million (ppm) over an 8-hour workday and 40-hour work week. The NIOSH REL is 25 ppm measured as a Time

Weighted Average (TWA) which is the average exposure to the gas over the duration of anesthetic administration. This REL is based off a report of decrements in audiovisual tasks following exposure at 50 ppm and is intended to prevent decreases in mental performance, audiovisual ability, and manual dexterity during exposures to nitrous oxide (31).

## **2.4 NITROUS OXIDE EXPOSURE LIMITS IN DENTAL ENVIRONMENTS**

A variety of studies have characterized concentration ranges of exposure to nitrous oxide dental personnel. Gilcrest et al. (13) found 8-hour TWA exposures to nitrous oxide in a pediatric dental unit where patients received restorative dental care that ranged from 16 ppm to 374 ppm, with a mean of 151 ppm. A record review of exposure data from 2015 to 2017 in a dental clinic, as described in a Health Hazard Evaluation report by NIOSH, listed exposures that ranged from 21.4 ppm to 500 ppm (3).

An Indian Health Service (IHS) report by Shelhamer, Lewelling, and Garcia (2017) documented, using a Miran SapphIRe, exposures in a California dental clinic that ranged in concentrations from 73 ppm to 430 ppm (44). More recent studies on nitrous oxide waste emissions in IHS dental clinics by Hansen et. al. (15) described nitrous oxide exposures between 0.9 ppm to 500 ppm. Joplin (2019) listed nitrous oxide concentrations in IHS dental clinics ranging from 1 ppm to 995 ppm (22).

## **2.5 METHODS FOR MONITORING AIR CONCENTRATIONS OF NITROUS OXIDE**

Monitoring of waste emissions of nitrous oxide in dental environments, as published by NIOSH and OSHA, cite the use of direct reading portable infrared gas analyzers (IGA) (27).

Typical nitrous oxide direct reading IGAs use either nondispersive infrared spectrometry (NDIR) or Fourier transform infrared (FTIR) spectrometry (6). Both technologies rely on analyzing a sample of interest by means of a technique known as infrared laser-absorption spectrometry.

### **2.5.1 Nitrous Oxide Detection with Nondispersive Infrared Spectrometry**

The basic nondispersive infrared spectrometer design involves the use of a source of infrared (IR) energy at an analytical wavelength or IR absorption line, a reference cell, and a sample cell. A NDIR will begin its operation by collecting a sample of interest through a sample cell to a detector for signal quantification (Figure 4). Once a sample reaches the detector, the difference in absorbance between the sample cell and the reference cell is converted to an electrical signal. Once this occurs, the NDIR can determine and display the concentration of an analyte on a readout display (10).

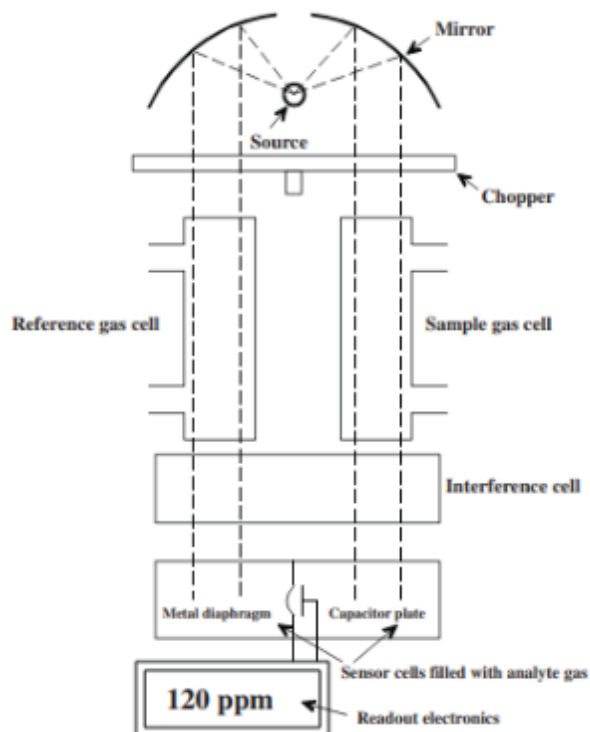


Figure 4: Diagram showing a NDIR spectrometer (10).

### 2.5.2 Nitrous Oxide Detection with Fourier Transform Infrared Spectrometry

Fourier transform infrared spectrometry also involves the use of a source of IR energy, a sample cell, and a detector; however, it differs significantly from NDIR by its use of an interferometer.

Interferometer-based instruments can detect multiple wavelengths over their spectral range simultaneously and have large apertures that allow for high light throughput thus creating high resolution infrared spectrometry (14). The interferometer relies upon a collimated IR radiation beam that is divided into two beams by a beam splitter. One beam is directed to a fixed mirror and the other beam is directed to a moving mirror. The beams are then reunited and directed to a detector. From the detector, the interference resulting from the infrared radiation following different paths

is computed, thus producing an interferogram which displays an absorbance spectrum. A spectrum is a plot of intensity versus wavenumber (10).

## **2.6 CONTROLLED TEST ATMOSPHERES**

To develop, improve, or investigate sampling and analytical methods, a gas generation system is needed (9). A critical aspect of a gas generation system is a controlled test atmosphere.

The two categorical approaches to creating controlled test atmospheres are the static system and the dynamic system. The Static system works by having an appropriate volume of contaminant gas or gases added to a known volume of air in a rigid or nonrigid container. The other type of system for producing gas mixtures is referred to as a dynamic system which works by mixing a concentrated and flowing stream of a contaminant gas or gases with a dilution air stream to continually produce a desired concentration (33).

For the dynamic system, there is no one method of producing gas and vapor mixtures for experimental work; however, major components and processes are similar for all such methods (34). Major components include the introduction of an analyte to the system by means of a compressed cylinder, vapor system, permeation tube, diffusion tube, or syringe. Other major components include a diluent air stream, an independent concentration monitoring system, exposure chamber, laboratory ventilation, and a humidity, temperature, and flow system (9).

In an experimental study by Maughan, Glissmeyer, and Birnbaum, investigating the performance of two antiquated portable infrared analyzers on nitrous oxide gas, they

introduced known concentrations of nitrous oxide from a cylinder into their dynamic dilution system (26).

## **2.7 THERMO FISHER SCIENTIFIC MIRAN SAPPHIRE**

The reference instrument used for monitoring waste emissions of nitrous oxide in dental departments for the IHS has been the Thermo Fisher Scientific Miran SapphIRe Portable Infrared Analyzer. Historically, scientists began to use the Miran SapphIRe in research in the early 2000s and since that time, the Miran has appeared in many scientific articles and journals (24, 42).

Joplin used the Miran SapphIRe in his work to evaluate the agreement of three methods of nitrous oxide samplers (22) in IHS clinics. Shelhamer, Lewelling, and Garcia also utilized the Miran SapphIRe to perform a nitrous oxide exposure assessment in the California Area IHS (44).

## **2.8 STUDY INFRARED GAS ANALYZERS**

With the discontinuation of the manufacture and support of the Miran SapphIRe by Thermo Fisher Scientific, IHS programs need to adopt a new reference instrument to monitor waste emissions of nitrous oxide. In this study, two portable IGAs were selected so performance information can be learned and provided to the IHS to augment their consideration when replacing infrared analyzers. Those instruments are described below. See Table 1 for additional specifications.

### **2.8.1 Viasensor G200 N<sub>2</sub>O Analyzer**

The Viasensor (Viasensor, Dexter, MI) (Figure 5) is a single gas, portable infrared gas analyzer based off NDIR technology. The Viasensor is designed to measure waste emissions of nitrous oxide in health care and dental settings.

A literature review revealed no published performance evaluations for the Viasensor. Additionally, no published studies related to the measuring waste emissions of nitrous oxide in health care and dental settings were found.



Figure 5: Viasensor G200 used in this study.

### **2.8.2 Bacharach PGM-IR N<sub>2</sub>O Monitor 3015-4787**

The Bacharach PGM-IR N<sub>2</sub>O Monitor 3015-4787 (Figure 6) is also a single gas, portable infrared gas analyzer based off NDIR technology. The Bacharach is only designed to measure waste emissions of nitrous oxide in health care and dental settings; however, the device is primarily marketed as a nitrous oxide leak detection instrument for HVAC and healthcare environments.

A study by Mortazavi et. al. utilized an instrument described as a “3015 from Bacharach Company” to actively sample waste emissions of nitrous oxide

concentrations in operating and recovery rooms (29). In this study, reported mean concentrations of nitrous oxide gas in operating rooms ranged from 299 ppm to 325 ppm; and the mean concentration in a recovery room was reported as 51 ppm. Further literature review revealed no published performance evaluations for the Bacharach.



Figure 6: Bacharach PGM-IR N<sub>2</sub>O 3015-4787 analyzer used in this study.

### 2.8.3 Specifications of the Viasensor and Bacharach

Table 1: Instrument characterization.

| Technical Specification <sup>1</sup>            | Viasensor                                                              | Bacharach                                                            |
|-------------------------------------------------|------------------------------------------------------------------------|----------------------------------------------------------------------|
| Accuracy                                        | ± 5 ppm from 0 to 100 ppm<br>± 1.5 % of range for 101 ppm to 1,000 ppm | ± 5% from 0 to 100 ppm<br>± 10 % of reading from 101 to 1,000 ppm    |
| Factory calibrated to <sup>2</sup>              | 0.0, 101.5, 507.5, 913.5 ppm                                           | 50.1 ppm                                                             |
| Sensitivity (minimum contaminant concentration) | 1 ppm                                                                  | 1 ppm                                                                |
| Response time                                   | ≤ 40 seconds                                                           | 90% of response in 3 seconds<br>100% of response in 5 seconds        |
| Nitrous oxide measuring range                   | 0 to 1,000 ppm                                                         | 0 to 1,000 ppm                                                       |
| Pump flow rate                                  | 0.1 to 0.3 L/minute                                                    | ~ 1 L/minute                                                         |
| Operating temperature range                     | 5°C to 40°C (41°F to 104°F)                                            | 0°C to 50°C (32°F to 122°F)                                          |
| Relative humidity range                         | 5% to 95%                                                              | 5% to 90%                                                            |
| Datalogging (TWA operation)                     | Yes                                                                    | Yes <sup>3</sup>                                                     |
| Weight                                          | 1.1 lbs                                                                | 9 lbs                                                                |
| Factory calibration period                      | 12 months                                                              | 12 months                                                            |
| Daily user calibration required                 | Yes <sup>4</sup>                                                       | No                                                                   |
| Filter requirements                             | Yes (external soda lime & external particulate/PTFE water trap filter) | Yes (external particulate & internal particulate/hydrophobic filter) |

<sup>1</sup>All information derived from manufacturer user manual unless stated otherwise.

<sup>2</sup>Derived from instrument's certificate of calibration.

<sup>3</sup>Data downloading requires use of a Microsoft Windows® HyperTerminal, RS-232 cable, and Windows XP Operating System.

<sup>4</sup>Allows for user calibration with calibrant gas or clean room air.

## CHAPTER 3: Materials and Methods

### 3.1 MATERIALS

Materials used in this study:

- Miller-Nelson HCS-501-200 flow, temperature, and humidity control system; serial # 10027 (Miller-Nelson Instruments, Livermore, CA)
- Aalborg GFM57 mass flow meter; serial # 436384-1 (Aalborg, Orangeburg, NY)
- Gasmet FTIR DX4040 portable gas analyzer; # 19657 (Gasmet, Vantaa, Finland)
- Viasensor G200 N<sub>2</sub>O Analyzer; serial # IN12899 (Viasensor, Dexter, MI)
- Bacharach PGM-IR N<sub>2</sub>O Monitor 3015-4787; serial # 20106462 (Bacharach, New Kensington, PA)
- GASCO Nitrous Oxide Calibration Gas, 1000 ppm in 34L Aluminum Cylinder (Cal Gas Direct Incorporated, Huntington Beach CA).
- 99.9% nitrous oxide H cylinder; CAS # 10024-97-2 (Airgas, Radnor, PA)
- Airgas Model N245D High Purity Brass Two-Stage Gas Regulator (Airgas, Radnor, PA)
- Hamilton 2-liter Super Syringe Model S2000 TLL (Hamilton Company, Reno, NV)
- Supelco Model 1062 Bag Sampler Pump Case; 9 in. x 14.6 in. x 21.7 in. (22.9 x 37.1 x 55.1 cm) (Sigma-Aldrich, Darmstadt, Germany)
- Calcmeter Software v12.20 (Gasmet, Vantaa, Finland)
- 24" (L) x 3" (D) cylindrical static mixing chamber

- 10-liter Tedlar® bags
- 3/8” polytetrafluoroethylene (PTFE) tubing
- 1/4” copper tubing
- Swagelok SS-SS4 metering valve, 1/4” (Swagelok, Solon, OH)
- Cole-Palmer Digi-Sense Pre-calibrated Humidity and Temperature Indicator; serial # 200742217 (Cole-Palmer, Vernon Hills, IL)

### **3.2 METHODS**

#### **3.2.1 Sampling Method Overview**

To evaluate the accuracy, precision, and agreement of the Viasensor (Viasensor, Dexter, MI) and the Bacharach (Bacharach, New Kensington, PA), a dynamic (cylinder) dilution system (9) was utilized (Figure 7). A compressed cylinder containing nitrous oxide gas (Airgas, Radnor, PA) at a purity of 99.9% was used.

Fourier transform infrared spectrometry (FTIR), by means of the Gasmeter DX4040 portable gas analyzer (Gasmeter, Vantaa, Finland), was used as the reference instrument to independently validate nitrous oxide concentrations in an exposure chamber prior. Calcmeter software (Gasmeter, Vantaa, Finland) was used to operate the Gasmeter. The Gasmeter was user-calibrated with an eight-point calibration curve with an  $R^2$  above 0.990.

An HCS-501 Air Conditioning System (Miller-Nelson Instruments, Livermore, CA) was connected to compressed house air by polytetrafluoroethylene (PTFE) tubing to create a controlled diluent air stream. Nitrous oxide from the compressed cylinder flowed through copper tubing and fine precision valves to create a controlled nitrous oxide gas stream. To create a controlled continuous test gas stream, the controlled

nitrous oxide gas stream was mixed with the controlled diluent air stream. An in-line static mixing chamber was installed in the continuous test gas air stream to promote a homogenous and controlled test atmosphere. Sampling then occurred within an exposure chamber. To measure temperature and relative humidity inside of the exposure chamber, a Cole-Palmer Digi-Sense Pre-calibrated Temperature and Humidity Indicator (Cole-Palmer, Vernon Hills, IL) was located inside the chamber to record measurements.

A sealed rigid chamber was utilized for the exposure chamber. Desired environmental atmospheric conditions were achieved inside the exposure chamber by manipulating nitrous oxide flow (via valves) and by adjusting temperature, humidity, and air flow rates with the Miller-Nelson HCS-501. The exposure chamber contained three sampling ports on the top of the chamber. The Viasensor, Bacharach, and Gasmeter instruments were each connected to a sampling port where they were simultaneously exposed to well-mixed, humidified, and discrete concentrations of nitrous oxide for sampling and analysis.

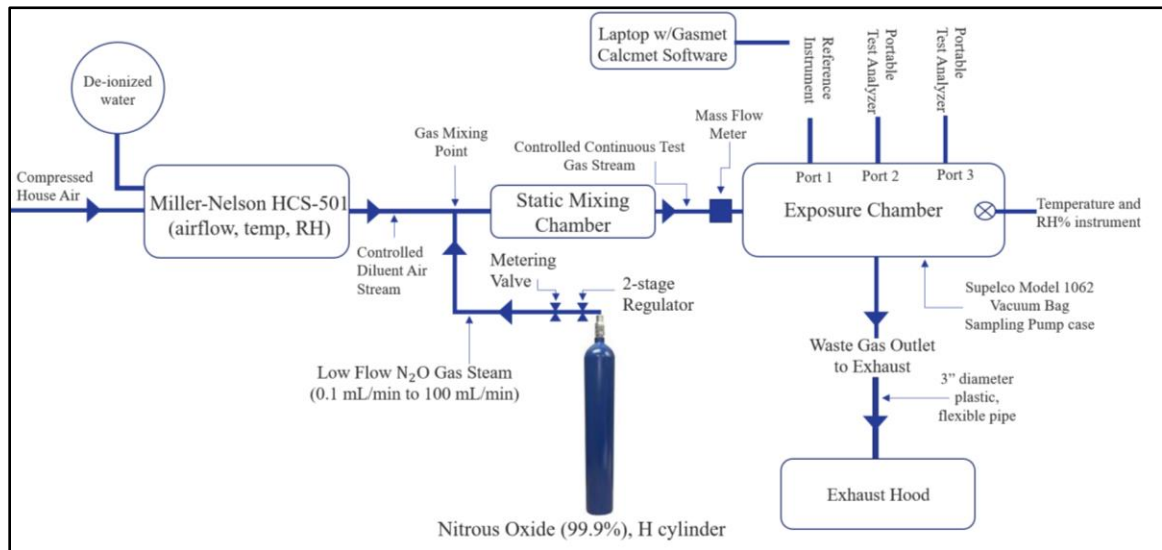


Figure 7: Schematic of the dynamic cylinder dilution system.

### ***3.2.1.1 IGA Calibration and Basic Operations***

The operation of all instruments followed manufacturer instructions to include proper warm-up and shut-down procedures. Daily user-calibrations were conducted on the Gasmet reference instrument and the Viasensor. The Bacharach did not require a daily user-calibration.

All instruments possessed valid National Institute of Standards (NIST) traceable certificates of calibration. All waste gases emitted from all instruments were controlled and safely discharged to a local exhaust ventilation system.

### ***3.2.1.2 Sampling Method***

Laboratory test sampling was designed to quantify ranges of analyzer performance to environmental conditions that may occur in IHS dental settings.

Analyzers under testing were evaluated at concentrations of 1 ppm, 5 ppm, 6 ppm, 7 ppm, 8 ppm, 9 ppm, 10 ppm, 15 ppm, 20 ppm, 25 ppm, 50 ppm, 150 ppm, 250 ppm, and 500 ppm (approximately 0.1, 0.5, 1.0, 3.0, 5.0, and 10.0x the ACGIH TLV-TWA of 50 ppm). Three repeated trials occurred. For each trial, four replicate samples at each concentration were collected for both low and high humidity levels. In total, 336 samples were taken for each IGA.

The above evaluation range was selected with consideration of the following factors:

- The IHS use of the ACGIH TLV-TWA of 50 ppm (19).
- NIOSH Guidelines for Air Sampling and Analytical Method Development and Evaluation document (23).

- Prior laboratory experiments by Fan et al. (11) which compared two analyzers (unknown Miran model, Bacharach 3010) and three passive dosimeters at nitrous oxide concentrations of 10 ppm, 25 ppm, 50 ppm, 125 ppm, 250 ppm, and 500 ppm. Another effort by Maughan et al. (26) that tested two analyzers (Miran SapphIRe 205BXL, Bacharach 3010) at nitrous oxide concentrations of 1 ppm, 25 ppm, 55 ppm, and 100 ppm; and
- Characterized concentration ranges in field dental settings as identified during literature review (3, 13, 15, 22).

Once the controlled test atmosphere attained desired concentrations within the exposure chamber, as validated by the Gasmeter reference instrument, test sampling occurred. While test sampling, nitrous oxide concentrations transitioned from 1 ppm and increased from concentration to concentration sequentially until testing was completed at 500 ppm.

When performing test measurements, analyzers under investigation were exposed to a test atmosphere for 40 seconds to allow for sufficient time for all analyzers to respond. Due to a low flow rate (0.1 to 0.3 L/m), the Viasensor exhibited the longest response time of 40 seconds when compared to the Gasmeter (5 seconds) and the Bacharach (5 seconds). The flowrate for the Gasmeter was ~1.5 L/m, respectively, while the Bacharach flowrate was ~1.0 L/m, respectively.

### 3.2.1.3 Effects of Relative Humidity

To investigate relative humidity effects (23), analyzers were exposed to a temperature of approximately 21°C and relative humidity levels of approximately 22% and 80%, respectively, across all nitrous oxide test concentrations.

### 3.2.2 Static Atmospheres in Non-rigid Container

To calibrate the Gasmeter, static atmospheres (or calibration standards) were made by injecting specific volumes of nitrous oxide and nitrogen into 10-liter Tedlar® bags (Figures 8-9). Static atmospheres were made by using a gastight 2-liter Hamilton Super Syringe, 1,000 ppm nitrous oxide calibration gas from GASCO, and 99.9% nitrogen which is a homonuclear diatomic gas that does not absorb infrared energy (10).

Preparation methods to make static atmospheres are listed in Table 2. To dilute the 1,000 ppm nitrous oxide with 99.9% nitrogen, the following calculation was used:

Equation 1: Dilution

$$V_1C_1 = V_2C_2$$

Where:

$V_1$  = initial volume (ml)

$C_1$  = initial concentration of nitrous oxide (1,000 ppm)

$V_2$  = total volume of static atmosphere of Tedlar® bag (10-liter)

$C_2$  = desired concentration (ppm)

Table 2: Calibration standard preparation method.

|                                                                             |
|-----------------------------------------------------------------------------|
| 1. Inspect Tedlar® bag, valve, and septum for leaks.                        |
| 2. Purge all empty 10-liter Tedlar® bags three times with nitrogen gas.     |
| 3. Utilize house vacuum to remove all dead air from Tedlar® bags.           |
| 4. Fill one 10-liter Tedlar® bag with 10 liters of 1,000 ppm nitrous oxide. |
| 5. Fill one 10-liter Tedlar® bag with 10 liters of 99.9% nitrogen.          |

6. Create calibration standards by filling empty 10-liter Tedlar® bags with appropriate volumes of nitrous oxide and nitrogen, as measured critically with a 2-liter Hamilton gas-tight syringe. A 1.5-inch (L) x 0.125-inch (inside diameter) tube was connected to Tedlar® bag valves and used to transfer all gases from the syringe and Tedlar® bags.

Table 3: Calibration standard dilution volumes.

| Desired concentration (ppm) | Volume of 1,000 ppm nitrous oxide (mL) | Volume of 99.9% nitrogen (mL) |
|-----------------------------|----------------------------------------|-------------------------------|
| 0                           | 0                                      | 10,000                        |
| 25                          | 250                                    | 9,750                         |
| 100                         | 1,000                                  | 9,000                         |
| 200                         | 2,000                                  | 8,000                         |
| 300                         | 3,000                                  | 7,000                         |
| 400                         | 4,000                                  | 6,000                         |
| 500                         | 5,000                                  | 5,000                         |
| 600                         | 6,000                                  | 4,000                         |



Figure 8: Transferring critically measured contents from 2-liter gas tight syringe through a 1.5-inch tube, into a 10-liter Tedlar® bag.

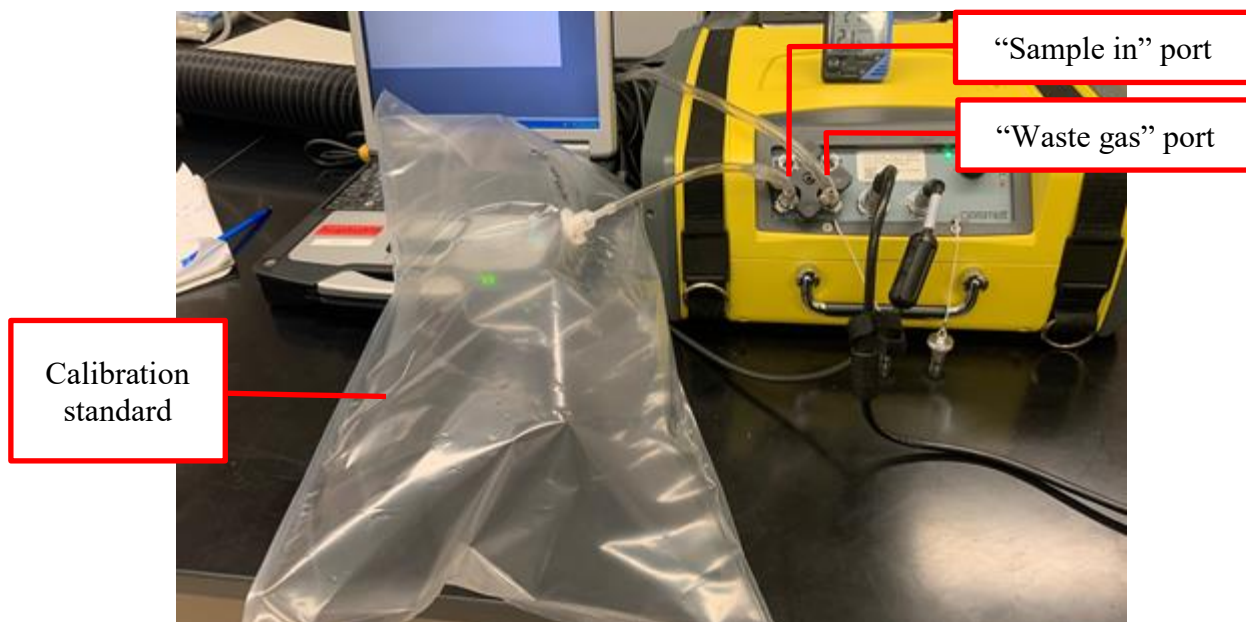


Figure 9: A laboratory prepared static atmosphere in a 10-liter Tedlar® bag shown connected to the "sample in" port on the Gasmeter

### 3.2.3 Calibration of the Gasmeter

The Gasmeter used in this study had received a factory calibration range of 1 to 99.3 ppm for nitrous oxide. Since this study investigated nitrous oxide concentrations from 1 to 500 ppm, a user calibration was performed to create an 8-point calibration curve ranging from 0 to 600 ppm of nitrous oxide. The calibration curve was developed by preparing eight calibration standards of a theoretically known concentration, in 10-liter Tedlar® bags as described in Section 3.2.2. Targeted nitrous oxide concentrations for the calibration standards were 0, 25, 100, 200, 300, 400, 500, and 600 ppm (Table 3). For the calibration procedure, duplicate concentration measurements were recorded at each calibration standard. Each pair of duplicate measurements were averaged to calculate the mean observed instrument response for each calibration standard.

### **3.2.4 Calcmnet Software**

Calcmnet software v12.20 was used to operate and control the Gasmet reference instrument. Through the software, the following analysis settings were established:

- Nitrous oxide measuring range: 0 to 1000 ppm
- Spectral Analysis Area: 1900 to 2233  $\text{cm}^{-1}$
- Measuring time setting during user-calibration: 20 seconds
- Measuring time setting during test sampling: 5 seconds

### **3.2.5 Dynamic Cylinder Dilution System for Producing Homogeneous Nitrous Oxide Gas Atmospheres**

Constantly replenished nitrous oxide mixtures of specific known concentrations were needed for this study. To produce a controlled test atmosphere for testing instruments, a pre-existing dynamic dilution system was modified for this study. Main components of the dynamic cylinder dilution system included a sealed rigid exposure chamber with sampling ports and an exhaust, a static mixing chamber, a diluent air stream, and a nitrous oxide gas stream, which were combined to achieve the nitrous oxide concentrations described in Table 1.

#### ***3.2.5.1 Sealed Rigid Container***

A Supelco Model 1062 Bag Sampler Pump Case (Sigma-Aldrich, Darmstadt, Germany) served as the sealed rigid exposure chamber (Figures 10-12). Within this exposure chamber, dynamic controlled test atmospheres were generated and held approximately in a steady state, which allowed the investigated infrared gas analyzers (IGA) and the reference instrument to simultaneously sample gas within the chamber. Nitrous oxide gas concentrations within the exposure chamber were verified by the

Gasmet portable gas analyzer. Temperature and humidity levels inside the chamber were verified by a Cole-Palmer Digi-Sense Pre-calibrated Humidity and Temperature Indicator.

The chamber consisted of an inlet port (1/4" diameter brass hose barb adapter) for a controlled and continuous test gas stream, a perforated gas dispersion tube (PTFE; 3/8" diameter x 75" long; containing 44 bored 3/32" orifices) located inside the exposure chamber, four test ports (1/4" diameter brass hose barb adapters) for connecting IGAs and the reference instrument to the chamber, and a waste gas outlet tube (3" diameter) to discharge waste gas to an exhaust hood.

To prevent gas leakage from the chamber, all brass test ports were equipped with rubber washers installed within a brass nut, thus, thus producing tight-fitting connections to instrument sampling wands. Additionally, the seam in the exposure chamber was sealed with aluminum foil tape during sampling.

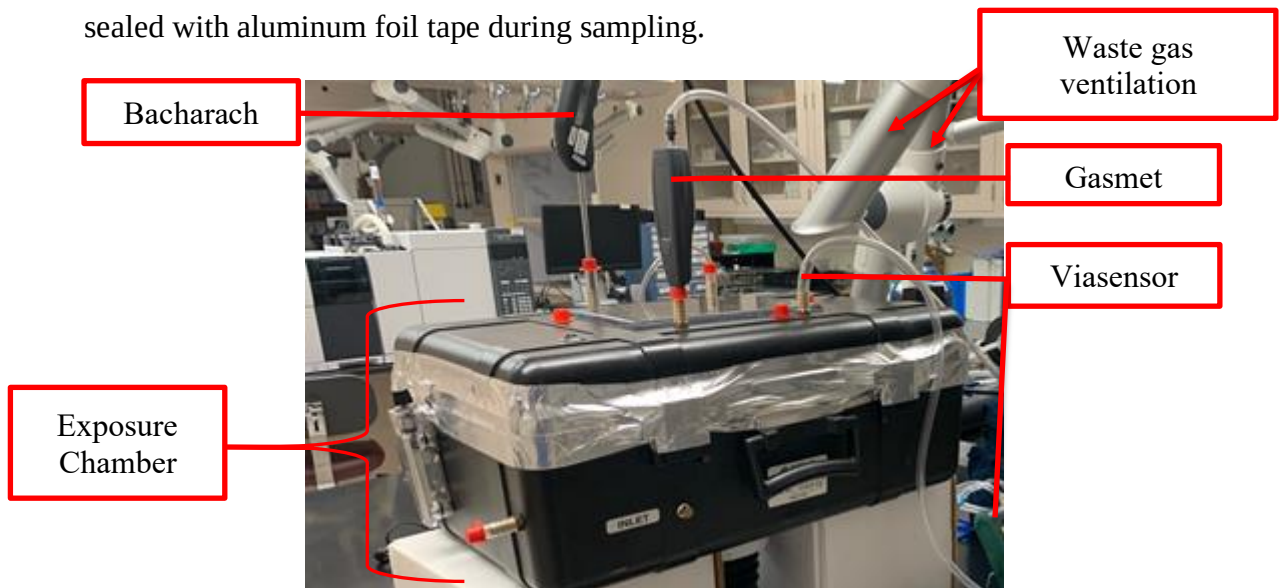


Figure 10: Exposure chamber set up.

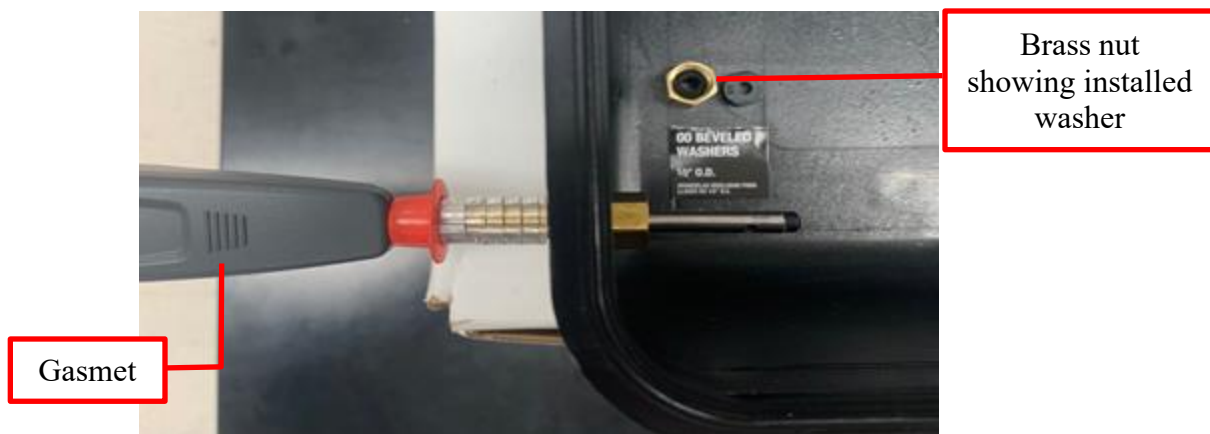


Figure 11: Connection scheme showing brass barbed port, brass nut, and rubber washer.

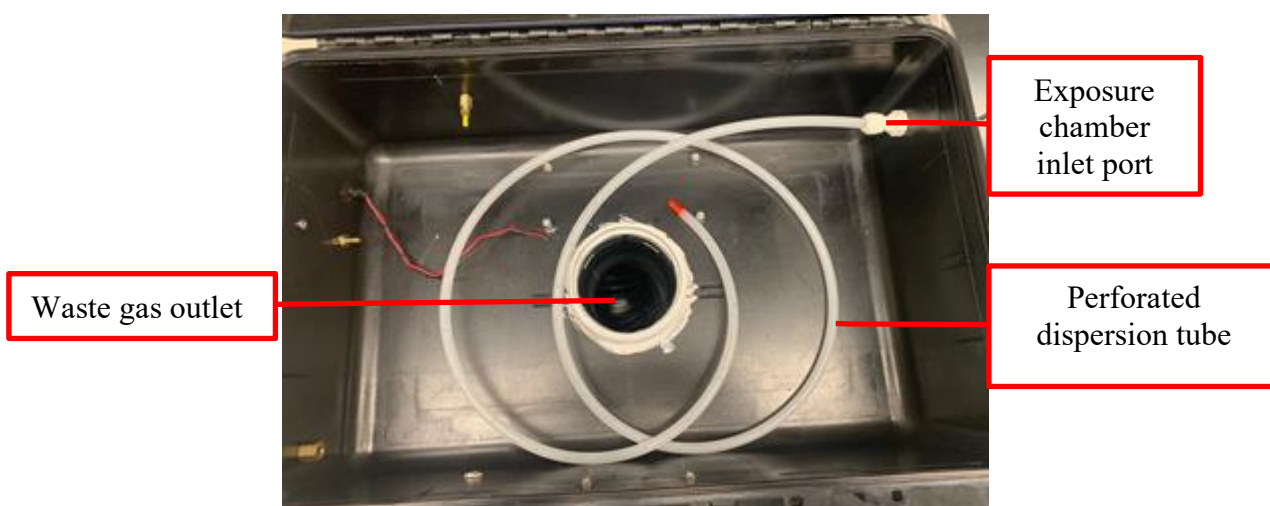


Figure 12: Inlet port, perforated gas dispersion tube, and waste gas outlet to exhaust ventilation hood.

### 3.2.5.2 Controlled Nitrous Oxide Gas Stream

A 300 cubic foot pressurized steel gas cylinder containing a mixture of 99.9% nitrous oxide gas (Airgas, Radnor, PA) was diluted and controlled to generate desired nitrous oxide concentrations. To reduce the 99.9% nitrous oxide gas (999,900 ppm) down to levels ranging from 1 to 500 ppm, a series of precision valves were utilized. An Airgas Model N245D High Purity Brass Two-Stage Gas Regulator (Airgas, Radnor, PA) served as the initial valve component that allowed for the initial reduction of the source

pressure to be reduced to a desired output pressure. Nitrous oxide gas was then routed from the Airgas regulator through a 1/4" copper tube (Figure 13).

For further pressure control and better flow rate control, a Swagelok SS-SS4 low flow metering valve (Swagelok, Solon, OH) capable of creating and accurately controlling low flow gas rates using fine-pitch valve threads and a 0.81 mm orifice was installed on the nitrous oxide gas stream directly downstream of the Airgas regulator (Figure 14).



Figure 13: Airgas regulator, nitrous oxide cylinder, and 1/4" copper tube.

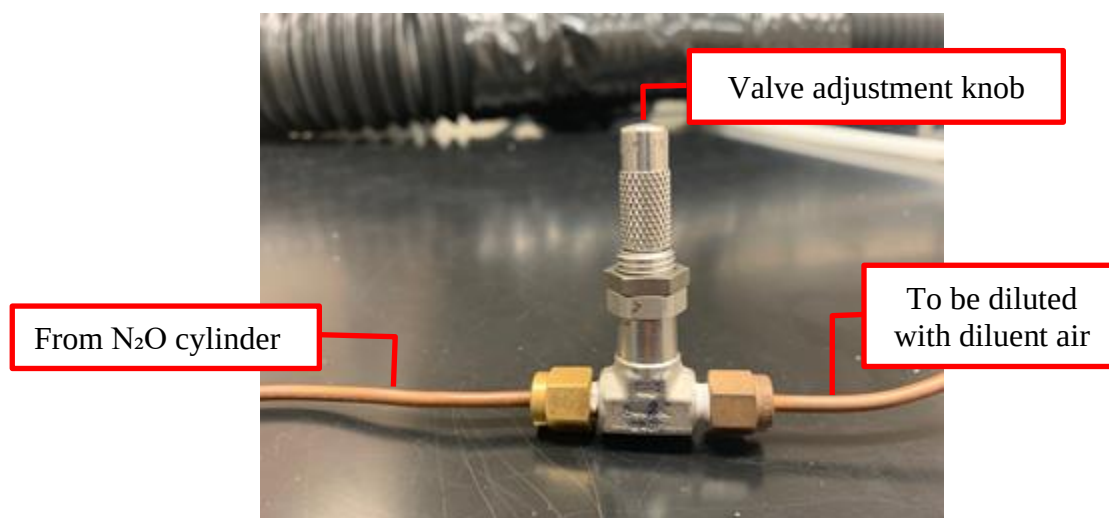


Figure 14: Swagelok SS-SS4 metering valve and 1/4" copper tubing.

#### ***3.2.5.3 Diluent Air Stream***

Compressed house air, which was plumbed to the Miller-Nelson HCS-501 instrument, was used for the diluent air stream that diluted the 99.9% nitrous oxide gas stream.

#### ***3.2.5.4 Controlled Continuous Test Gas Stream***

The nitrous oxide gas stream and the diluent air stream were combined by use of a tee-fitting to create a single continuous test gas stream (Figure 15). The Miller-Nelson HCS-501 temperature, flow rate, and humidity control dials were used to create desired values in the continuous test gas stream. The most important control was the flow rate dial which controlled the flow of air into the continuous test gas stream from 20 LPM to 200 LPM. To attain desired nitrous oxide concentrations, it was necessary to make constant adjustments to air flow.

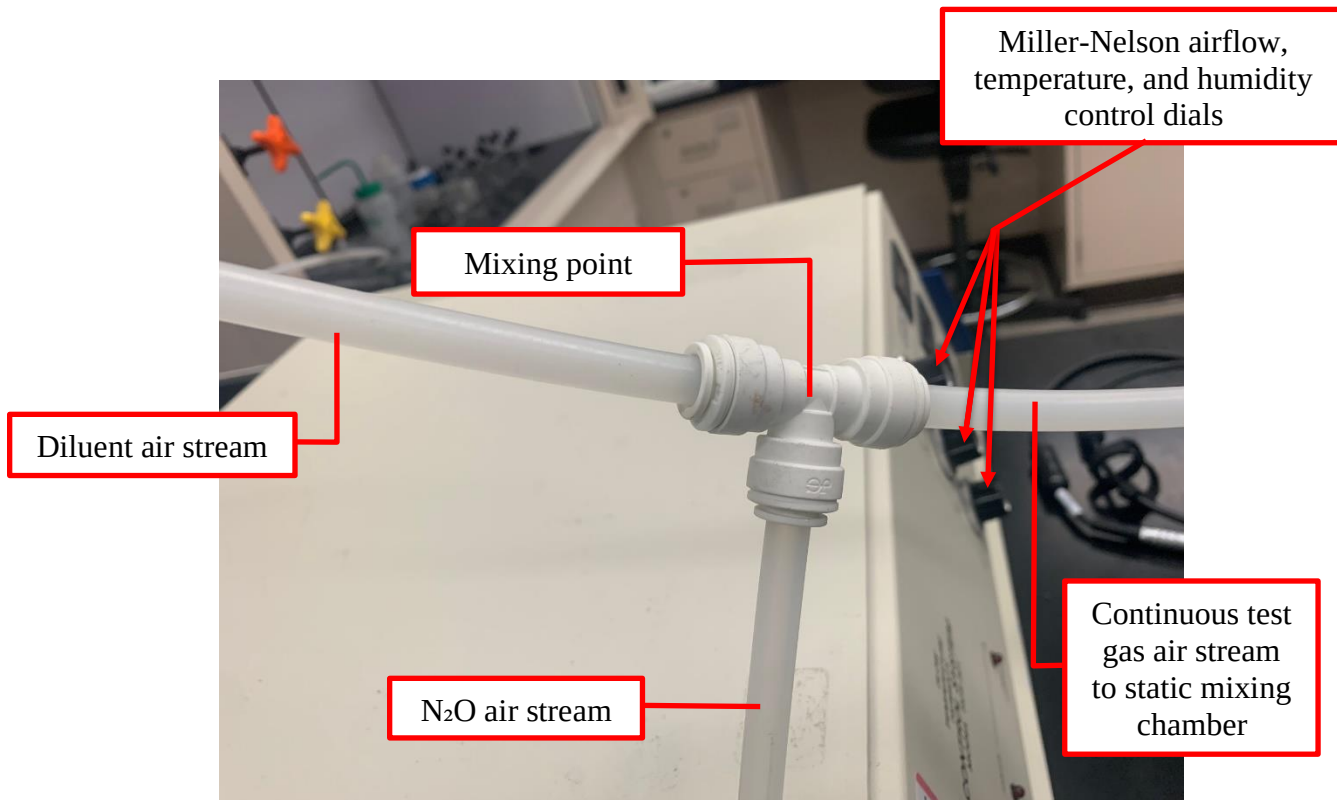


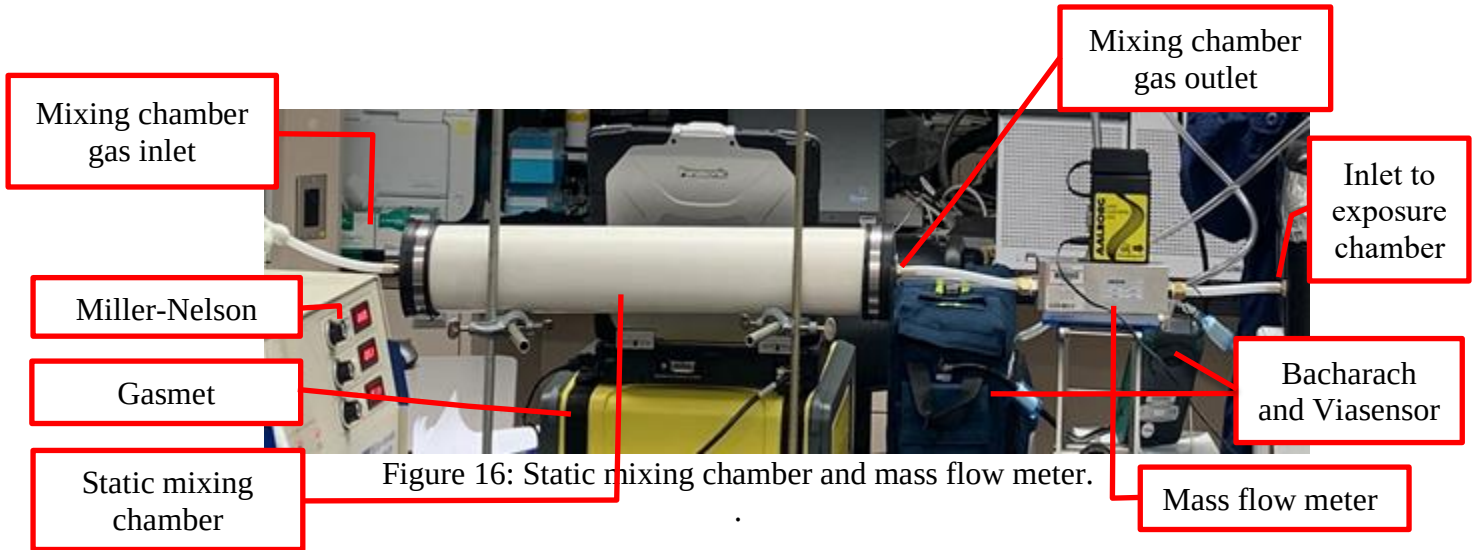
Figure 15: Mixing point showing diluent air stream, Miller-Nelson instrument, nitrous oxide air stream, and continuous test gas air stream to static mixing chamber.

#### 3.2.5.5 Static Mixing Chamber

A cylindrical static mixing chamber was installed directly downstream of the mixing point to promote a homogenous mixture of the continuous test gas stream (Figure 16). The static mixing chamber consisted of a 3" diameter by 24" long tube, with plastic end caps, and inlet and outlet ports (1/4" diameter brass hose barb adapters). Holes were drilled through the end caps to accommodate the inlet and outlet ports. Brass ports were secured in place with brass nuts and rubber washers. Within the mixing chamber, three perforated mixing plates were installed to produce turbulence of the continuous test gas air stream and promote gas mixing. The outlet port on the mixing chamber resulted in a homogeneous mixture of the continuous test gas air stream.

To measure the flow rate of the continuous test gas air stream, an Aalborg GFM57 mass flow meter (Aalborg, Orangeburg, NY) was installed downstream of the

static mixing chamber. All tubing material, from the outlet of the mixing point to the inlet port on the exposure chamber, consisted of 3/8" PTFE tubing.



### 3.2.6. Statistical Methods

Infrared gas analyzer (IGA) precision was assessed by standard deviation and coefficient of variation. Histograms were utilized to assess data for normality. Two-way analysis of variances (ANOVAs) were calculated between the reference instrument and each IGA, for a total of four ANOVAs, to determine if there was a significant difference in the mean measurements between the reference instrument and each IGA.

Bland-Altman analyses, which in part use a plotted graphical approach, were performed to calculate the degree of agreement between the reference instrument and each IGA. A Bland-Altman analysis is a measurement comparison technique (25). The approach quantifies the difference between two paired measurements on the y-axis while the x-axis represents the mean of the two paired measurements. An ideal technique would result in the comparison instruments producing exactly the same measurement

results; therefore, measurement differences (i.e., data points) would be plotted along the “zero” value on the y-axis in such an instance. This would indicate exact agreement (or zero bias) between the comparison instruments’ measurements. Data points plotted below zero on the y-axis would indicate a negative bias or overestimation of the nitrous oxide IGA measurement when compared to the reference instrument. A Bland-Altman analysis can be plotted utilizing absolute differences or they can be plotted as a percent difference (25).

STATA (15, StataCorp LLC, College Station, TX), MedCalc (MedCalc Software Ltd, Oostende, Belgium), and Microsoft Excel Office 365 (Redmond, WA) were used to analyze collected data.

## CHAPTER 4: Results

### 4.1 CALIBRATION OF THE GASMET

The result of the user calibration of the Gasmeter showed an excellent linear response ( $R^2$  0.9993) in the range of 0 to 600 ppm of nitrous oxide. The accuracy of the theoretical nitrous oxide concentrations was also good. The average error (or bias) across the 8-point calibration curve was 1.95%. Figure 17 illustrates the results of the user calibration.

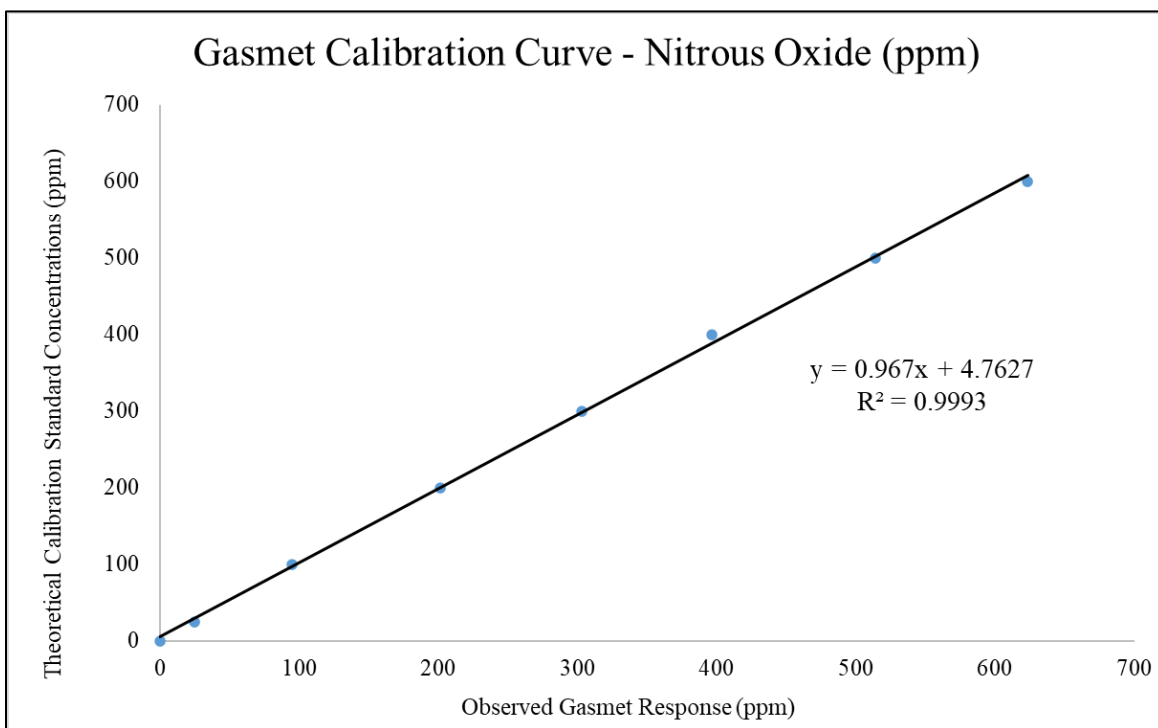


Figure 17: Calibration curve for the Gasmeter.

### 4.2 NORMALITY OF THE INSTRUMENT TEST DATA

The test data were examined to determine whether critical assumptions were met that would allow use of parametric statistics. Results from four histograms indicated that the data was approximately normally distributed. Results can be found in Figures 18-21.

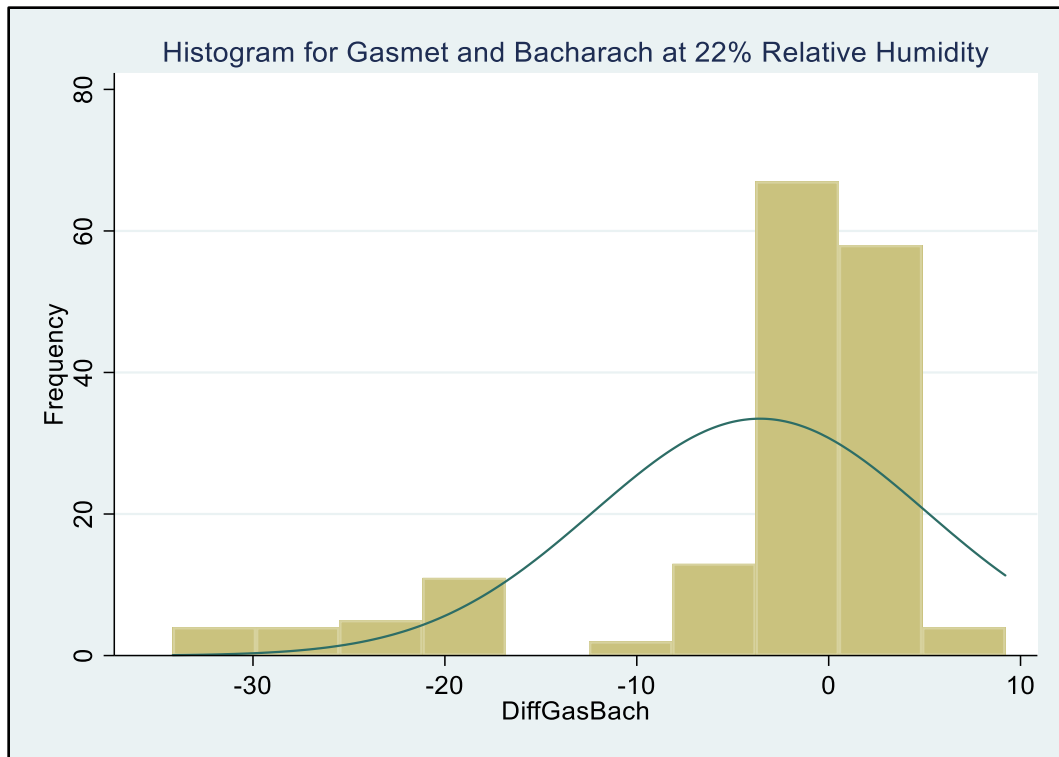


Figure 18: Histogram showing a reasonably normal distribution between the Gasmet and the Bacharach at 22% RH

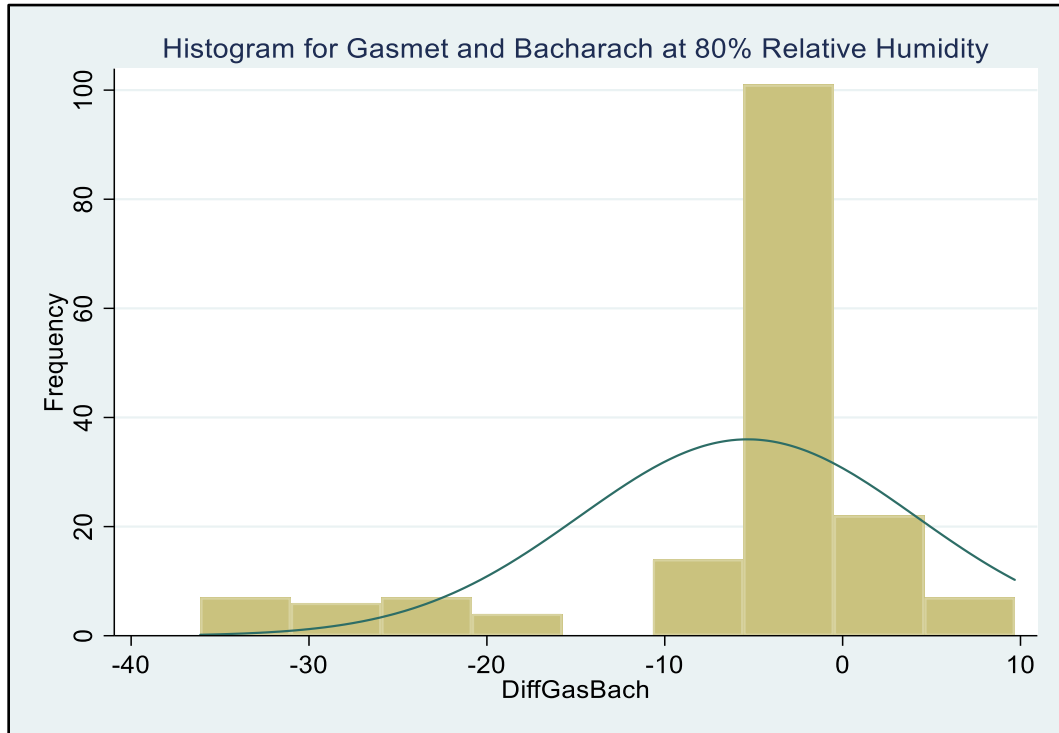


Figure 19: Histogram showing a reasonably normal distribution between the Gasmet and the Bacharach at 80% RH.

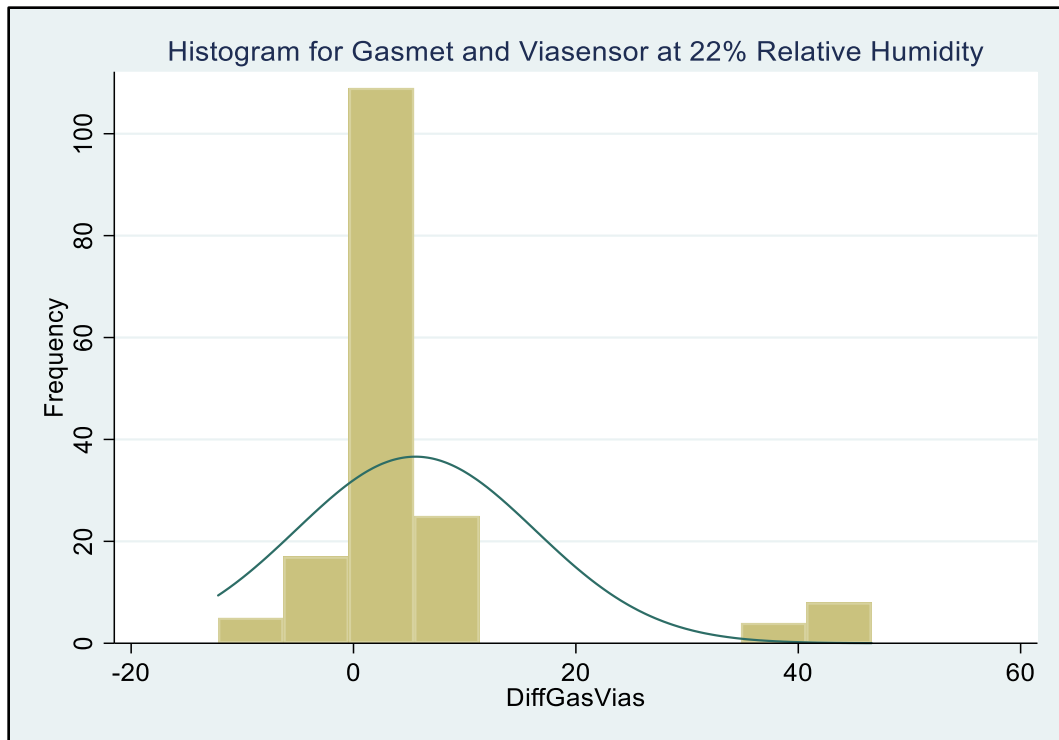


Figure 20: Histogram showing reasonably normal distribution between the Gasmet and the Viasensor at 22% RH.

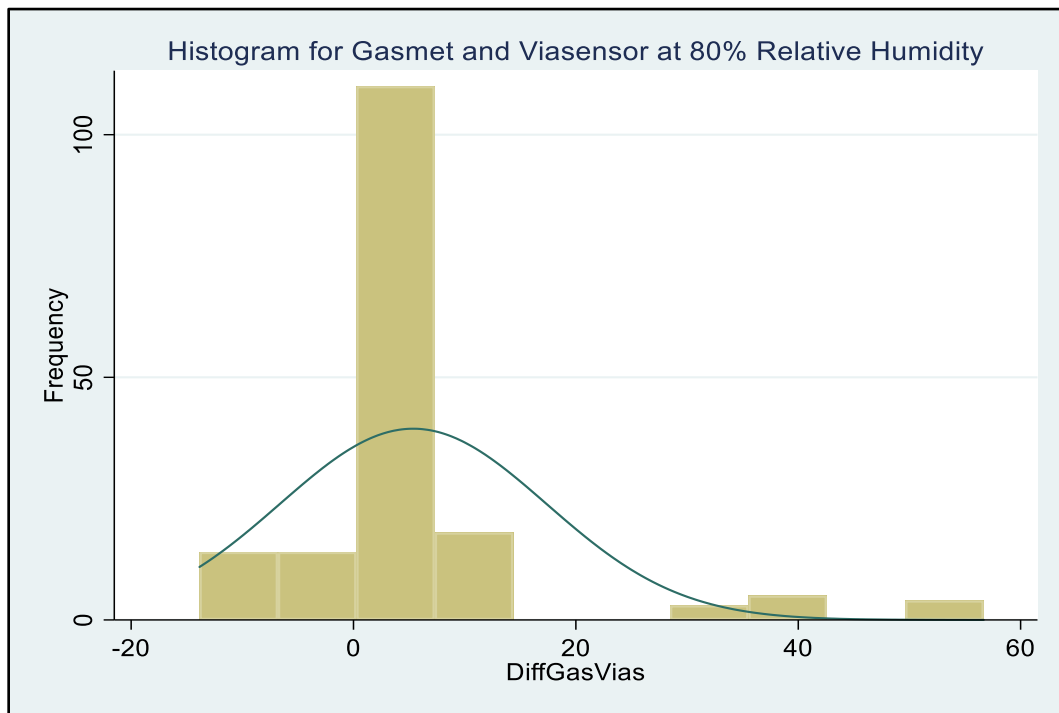


Figure 21: Histogram showing reasonably normal distribution between the Gasmet and the Viasensor at 80% RH.

### 4.3 SAMPLING RESULTS

A total of 1,008 samples were evaluated across an evaluation range of 1 to 500 ppm. Of these, 504 samples were taken at a temperature of 21°C and 22% relative humidity (“low humidity”). Another, 504 samples were taken at a temperature of 21°C and 80% relative humidity (“high humidity”).

Table 4: Size of study population

| Instrument         | 22% RH | 80% RH | Total # of Samples |
|--------------------|--------|--------|--------------------|
| Gasmet             | 168    | 168    | 336                |
| Bacharach          | 168    | 168    | 336                |
| Viasensor          | 168    | 168    | 336                |
| Total # of Samples | 504    | 504    | 1008               |

Tables 7-8 and Figures 22-25 show the mean IGA nitrous oxide concentrations for the Bacharach, Viasensor, and their error relative to the Gasmet (reference instrument) at 22% and 80% relative humidity levels.

For more performance data for the Bacharach and Viasensor, see Appendix A and Appendix B.

#### 4.3.1 Gasmet Performance

The accuracy and precision of the Gasmet was excellent across all nitrous oxide test concentrations with CV values from 0.00 to 0.03 ppm at both 22% and 80% relative humidity levels. Results of the 95% confidence interval achieved excellent values with CIs ranging from  $\pm 0.01$  to  $\pm 0.45$  ppm at both 22% and 80% relative humidity levels.

Results from the reference method which verified concentration in the exposure chamber can be found in Tables 5-6.

Table 5: Gasmet results from 12 replicate samples taken at each concentration, for 22% relative humidity.

| <b>N<sub>2</sub>O Test Concentration (ppm)</b> | <b>1</b> | <b>5</b> | <b>6</b> | <b>7</b> | <b>8</b> | <b>9</b> | <b>10</b> | <b>15</b> | <b>20</b> | <b>25</b> | <b>50</b> | <b>150</b> | <b>250</b> | <b>500</b> |
|------------------------------------------------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|
| Mean (ppm)                                     | 1.00     | 5.02     | 5.99     | 7.02     | 7.98     | 9.03     | 10.01     | 14.99     | 20.01     | 25.00     | 50.03     | 149.94     | 249.98     | 499.78     |
| Standard Deviation                             | 0.01     | 0.02     | 0.03     | 0.04     | 0.04     | 0.04     | 0.05      | 0.06      | 0.06      | 0.07      | 0.11      | 0.12       | 0.36       | 0.50       |
| Coefficient of Variation                       | 0.01     | <0.00    | <0.00    | 0.01     | 0.01     | <0.00    | <0.00     | <0.00     | <0.00     | <0.00     | <0.00     | <0.00      | <0.00      | <0.00      |
| Confidence Interval <sup>1</sup> (95.0%)       | 0.01     | 0.01     | 0.02     | 0.03     | 0.03     | 0.02     | 0.03      | 0.04      | 0.04      | 0.05      | 0.07      | 0.07       | 0.23       | 0.32       |
| Upper CI (95%)                                 | 1.00     | 5.04     | 6.01     | 7.05     | 8.01     | 9.05     | 10.04     | 15.03     | 20.05     | 25.04     | 50.10     | 150.02     | 250.21     | 500.10     |
| Lower CI (95%)                                 | 0.99     | 5.01     | 5.98     | 7.00     | 7.96     | 9.01     | 9.98      | 14.95     | 19.97     | 24.95     | 49.96     | 149.87     | 249.75     | 499.46     |

<sup>1</sup>Confidence interval values are intended to be ( $\pm$ ) to the mean value.

Table 6: Gasmet results from 12 replicate samples taken at each concentration, for 80% relative humidity.

| <b>N<sub>2</sub>O Test Concentration (ppm)</b> | <b>1</b> | <b>5</b> | <b>6</b> | <b>7</b> | <b>8</b> | <b>9</b> | <b>10</b> | <b>15</b> | <b>20</b> | <b>25</b> | <b>50</b> | <b>150</b> | <b>250</b> | <b>500</b> |
|------------------------------------------------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|
| Mean (ppm)                                     | 1.01     | 5.02     | 6.02     | 7.01     | 8.01     | 8.99     | 9.99      | 14.98     | 20.01     | 25.10     | 50.07     | 150.05     | 249.86     | 499.95     |
| Standard Deviation                             | 0.03     | 0.06     | 0.06     | 0.03     | 0.05     | 0.05     | 0.04      | 0.05      | 0.06      | 0.15      | 0.18      | 0.21       | 0.31       | 0.71       |
| Coefficient of Variation                       | 0.03     | 0.01     | 0.01     | <0.00    | 0.01     | 0.01     | <0.00     | <0.00     | <0.00     | 0.01      | <0.00     | <0.00      | <0.00      | <0.00      |
| Confidence Interval <sup>1</sup> (95.0%)       | 0.02     | 0.04     | 0.04     | 0.02     | 0.03     | 0.03     | 0.03      | 0.03      | 0.04      | 0.09      | 0.12      | 0.13       | 0.20       | 0.45       |
| Upper CI (95%)                                 | 1.03     | 5.06     | 6.06     | 7.03     | 8.04     | 9.02     | 10.01     | 15.01     | 20.05     | 25.19     | 50.18     | 150.18     | 250.06     | 500.40     |
| Lower CI (95%)                                 | 0.99     | 4.98     | 5.99     | 6.99     | 7.98     | 8.96     | 9.96      | 14.95     | 19.97     | 25.00     | 49.95     | 149.92     | 249.67     | 499.50     |

<sup>1</sup>Confidence interval values are intended to be ( $\pm$ ) to the mean value.

### 4.3.2 Bacharach and Viasensor $\pm 25\%$ Agreement with Gasmeter at 22% Relative Humidity

At the 95% confidence interval, the Bacharach was able to meet the minimum level of agreement of  $\pm 25\%$  for 13 of 14 test concentrations at 22% relative humidity. Test concentrations that did not maintain good agreement were: 1 ppm. The mean absolute percent error observed for the Bacharach was 15%.

At the 95% confidence interval, the Viasensor was able to meet the minimum level of agreement of  $\pm 25\%$  for 8 of 14 test concentrations. The test concentrations that did not maintain good agreement were: 1, 5, 7, 8, 9, and 10 ppm. The mean absolute percent error observed for the Viasensor was 39%.

Table 7: Mean concentrations, IGA error (from reference instrument), and 95% confidence intervals at 22% relative humidity.

| Test N <sub>2</sub> O (ppm) | Number of Samples per IGA | Gasmeter mean (ppm) | Viasensor mean (ppm) | Viasensor Error (%) | Viasensor CI <sup>1</sup> (95%) | Bacharach mean (ppm) | Bacharach Error (%) | Bacharach CI <sup>1</sup> (95%) |
|-----------------------------|---------------------------|---------------------|----------------------|---------------------|---------------------------------|----------------------|---------------------|---------------------------------|
| 1                           | 12                        | 1                   | 0                    | -92%                | 0.18                            | 0                    | -92%                | 0.18                            |
| 5                           | 12                        | 5.02                | 0                    | -100%               | 0.00                            | 4                    | -20%                | 0.27                            |
| 6                           | 12                        | 5.99                | 4                    | -40%                | 1.31                            | 6                    | -8%                 | 0.33                            |
| 7                           | 12                        | 7.02                | 3                    | -58%                | 1.13                            | 6                    | -9%                 | 0.33                            |
| 8                           | 12                        | 7.98                | 2                    | -70%                | 0.99                            | 7                    | -8%                 | 0.31                            |
| 9                           | 12                        | 9.03                | 6                    | -37%                | 0.87                            | 8                    | -7%                 | 0.33                            |
| 10                          | 12                        | 10.01               | 5                    | -51%                | 1.34                            | 10                   | -3%                 | 0.31                            |
| 15                          | 12                        | 14.99               | 10                   | -35%                | 1.54                            | 16                   | 6%                  | 0.53                            |
| 20                          | 12                        | 20.01               | 16                   | -22%                | 1.16                            | 22                   | 11%                 | 0.37                            |
| 25                          | 12                        | 25                  | 20                   | -18%                | 0.42                            | 27                   | 7%                  | 0.63                            |
| 50                          | 12                        | 50.03               | 47                   | -6%                 | 0.66                            | 55                   | 10%                 | 0.76                            |
| 150                         | 12                        | 149.94              | 153                  | 2%                  | 1.42                            | 169                  | 13%                 | 1.06                            |
| 250                         | 12                        | 249.98              | 254                  | 2%                  | 3.17                            | 277                  | 11%                 | 3.03                            |
| 500                         | 12                        | 499.78              | 458                  | -8%                 | 2.58                            | 498                  | 0%                  | 4.16                            |
| Mean percent error          |                           |                     |                      | 39%                 |                                 |                      | 15%                 |                                 |

<sup>1</sup>Confidence interval values are intended to be ( $\pm$ ) to the IGA mean value.

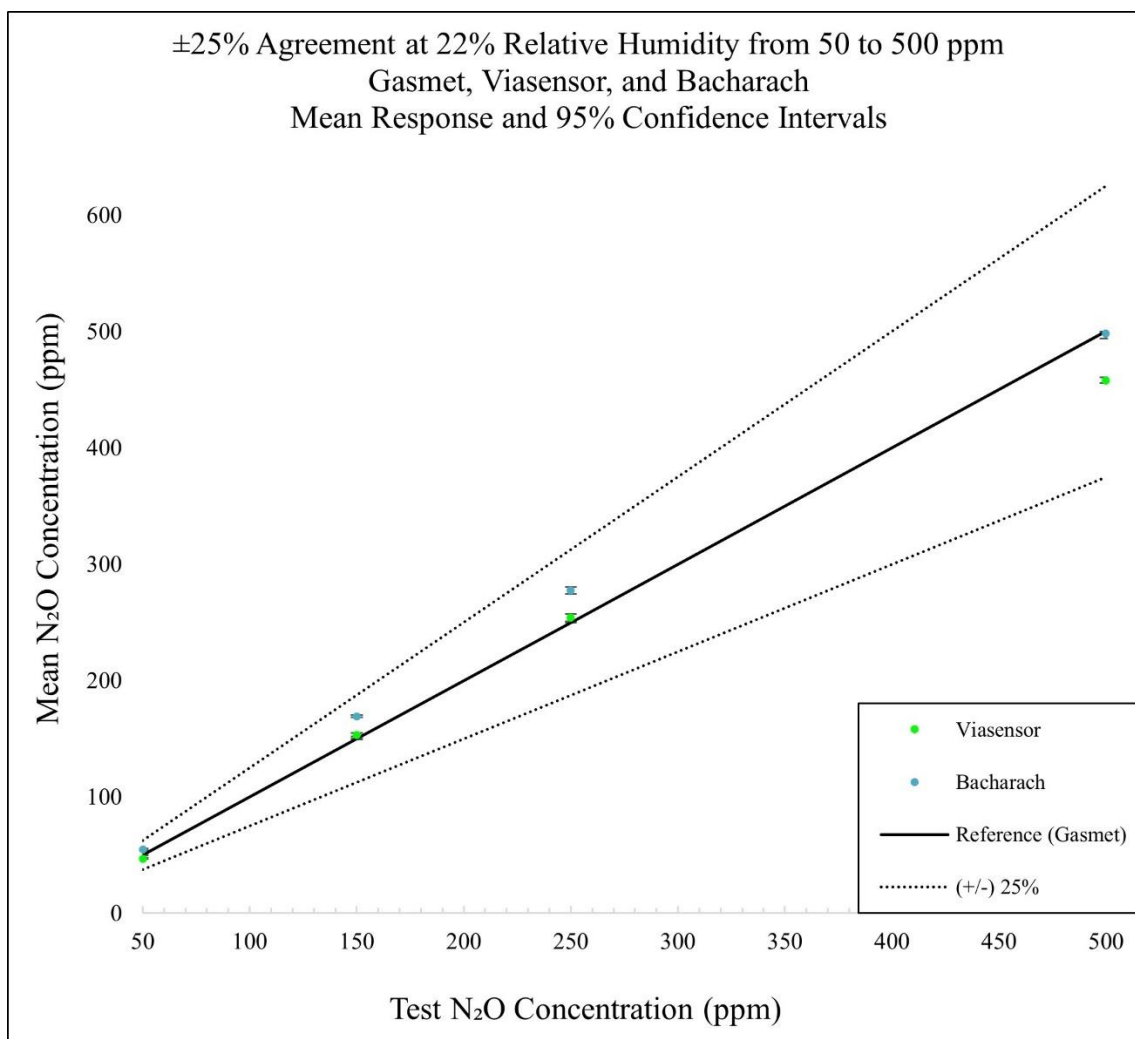


Figure 22 Agreement and 95% confidence intervals from 50 to 500 ppm.

As indicated in Table 7 and seen in Figure 22, for concentrations from 50 to 500 ppm, the Bacharach error ranged from 0% to 13% with 95% CIs ranging from  $\pm 0.76$  to  $\pm 4.16$  ppm. The Viasensor error ranged from -8% to 2% with 95% CIs ranging from  $\pm 0.66$  to  $\pm 2.58$  ppm.

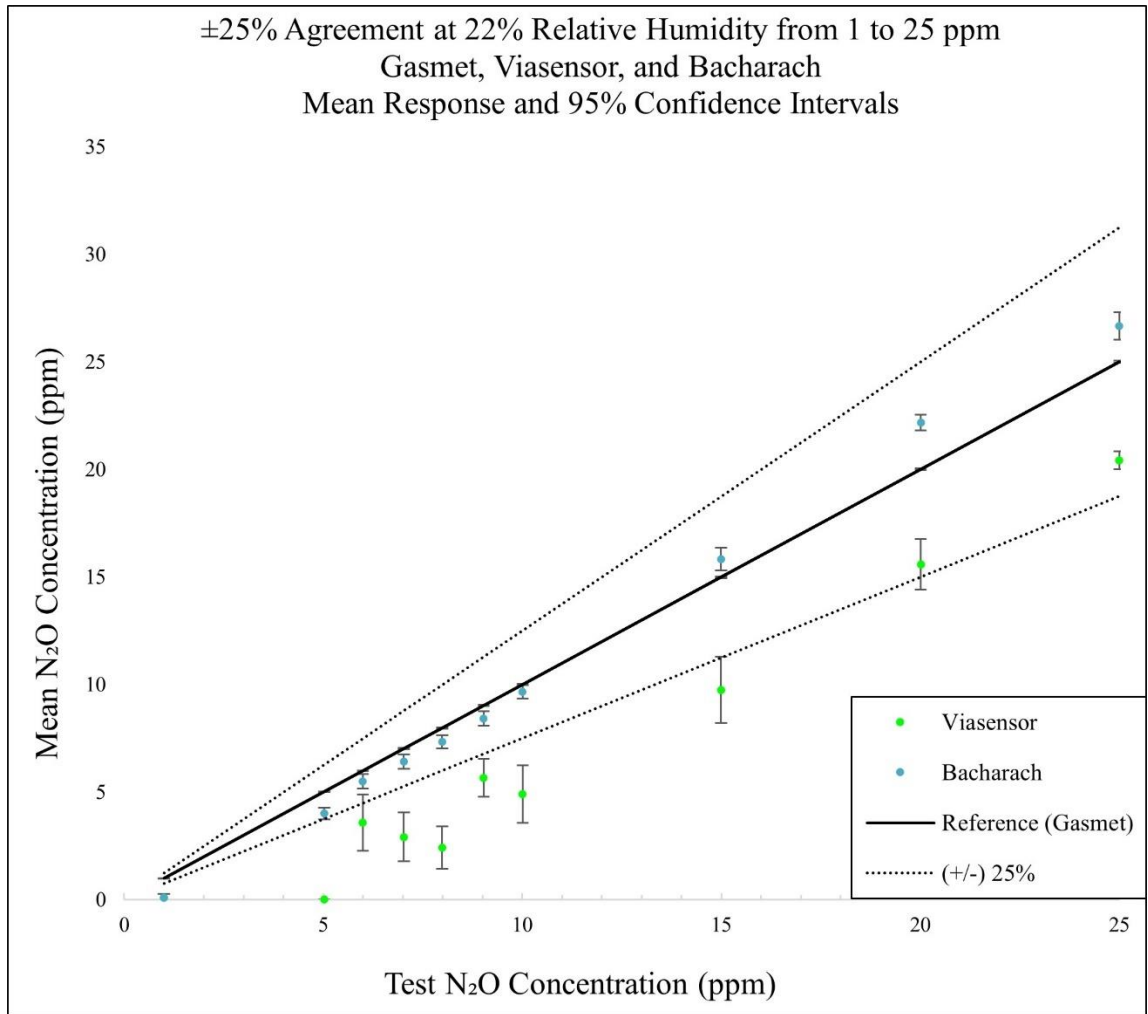


Figure 23: Agreement and 95% confidence intervals from 1 to 25 ppm.

As indicated in Table 7 and seen in Figure 23, for concentrations from 1 to 25 ppm, the Bacharach error ranged from -92% to 11% with 95% CIs ranging from  $\pm 0.18$  to  $\pm 0.63$  ppm. The Viasensor error ranged from -100% to -18% with 95% CIs ranging from  $\pm 0.00$  to  $\pm 1.54$  ppm.

### 4.3.3 Bacharach and Viasensor $\pm 25\%$ Agreement with Gasmet at 80% Relative Humidity

At the 95% confidence interval, the Bacharach was able to meet the minimum level of agreement of  $\pm 25\%$  for 13 of 14 test concentrations at 80% relative humidity. Test concentrations that did not maintain good agreement were: 1 ppm. The mean absolute percent error observed for the Bacharach was 17%.

At the 95% confidence interval, the Viasensor was able to meet the minimum level of agreement of  $\pm 25\%$  for 9 of 14 test concentrations. The test concentrations that did not maintain good agreement were: 1, 7, 8, 10, and 15 ppm. The mean absolute percent error observed for the Viasensor was 34%.

Table 8: Mean concentrations, IGA error (from reference instrument), and 95% confidence intervals at 80% relative humidity.

| Test N <sub>2</sub> O (ppm) | Number of Samples per IGA | Gasmet mean (ppm) | Viasensor mean (ppm) | Viasensor Error (%) | Viasensor CI <sup>1</sup> (95%) | Bacharach mean (ppm) | Bacharach Error (%) | Bacharach CI <sup>1</sup> (95%) |
|-----------------------------|---------------------------|-------------------|----------------------|---------------------|---------------------------------|----------------------|---------------------|---------------------------------|
| 1                           | 12                        | 1.01              | 0                    | -92%                | 0.18                            | 2                    | 57%                 | 0.50                            |
| 5                           | 12                        | 5.02              | 3                    | -38%                | 0.88                            | 6                    | 18%                 | 0.18                            |
| 6                           | 12                        | 6.02              | 4                    | -36%                | 1.11                            | 6                    | 1%                  | 0.33                            |
| 7                           | 12                        | 7.01              | 4                    | -50%                | 1.37                            | 8                    | 13%                 | 0.42                            |
| 8                           | 12                        | 8.01              | 2                    | -74%                | 1.10                            | 9                    | 18%                 | 0.33                            |
| 9                           | 12                        | 8.99              | 6                    | -38%                | 1.31                            | 10                   | 13%                 | 0.60                            |
| 10                          | 12                        | 9.99              | 5                    | -55%                | 1.45                            | 12                   | 20%                 | 0.38                            |
| 15                          | 12                        | 14.98             | 10                   | -35%                | 1.38                            | 17                   | 16%                 | 0.33                            |
| 20                          | 12                        | 20.01             | 15                   | -23%                | 1.31                            | 24                   | 18%                 | 0.33                            |
| 25                          | 12                        | 25.10             | 20                   | -20%                | 2.76                            | 30                   | 20%                 | 0.94                            |
| 50                          | 12                        | 50.07             | 48                   | -5%                 | 2.87                            | 58                   | 16%                 | 1.23                            |
| 150                         | 12                        | 150.05            | 155                  | 3%                  | 3.63                            | 172                  | 15%                 | 1.70                            |
| 250                         | 12                        | 249.86            | 256                  | 2%                  | 5.15                            | 281                  | 12%                 | 2.30                            |
| 500                         | 12                        | 499.95            | 456                  | -9%                 | 6.15                            | 495                  | -1%                 | 3.24                            |
| Mean percent error          |                           |                   |                      | 34%                 |                                 |                      | 17%                 |                                 |

<sup>1</sup>Confidence interval values are intended to be ( $\pm$ ) to the IGA mean value.

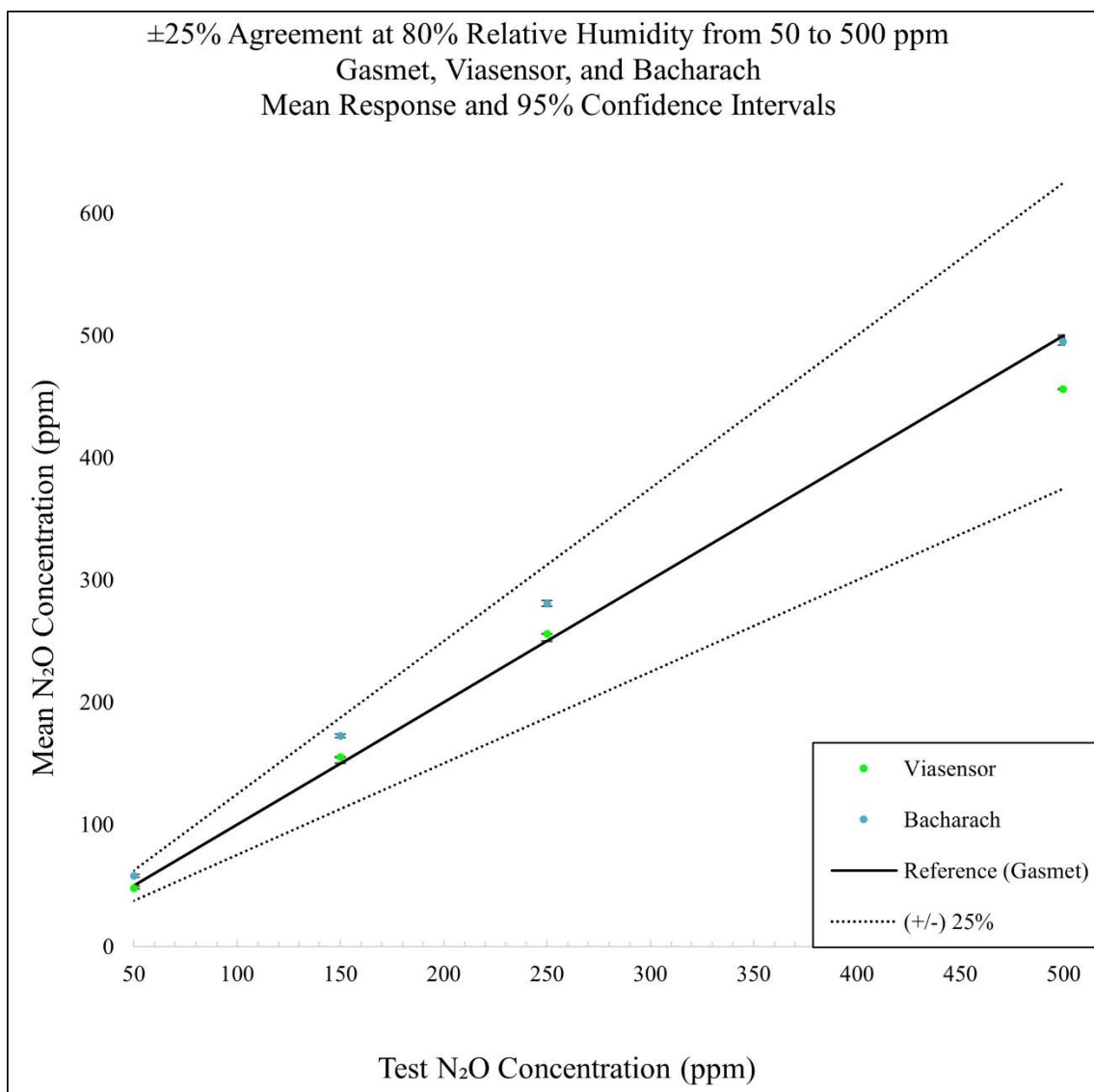


Figure 24: Agreement and 95% confidence intervals from 50 to 500 ppm.

As indicated in Table 8 and seen in Figure 24, for concentrations from 50 to 500 ppm, the Bacharach error ranged from -1% to 16% with 95% CIs ranging from  $\pm 1.23$  to  $\pm 3.24$  ppm. The Viasensor error ranged from -9% to 2% with 95% CIs ranging from  $\pm 2.87$  to  $\pm 6.15$  ppm.

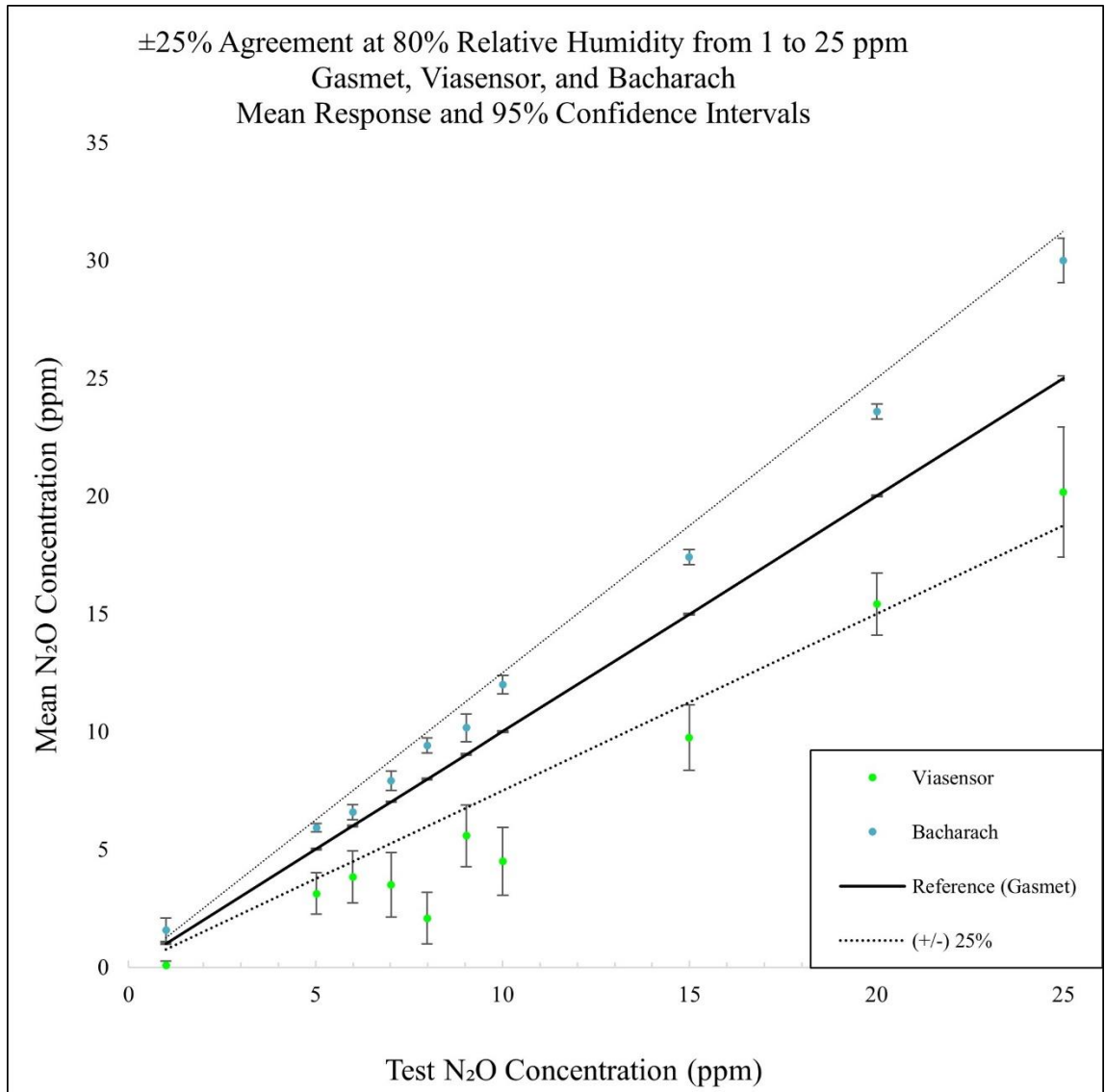


Figure 25: Agreement and 95% confidence intervals from 1 to 25 ppm.

As indicated in Table 8 and seen in Figure 25, for concentrations from 1 to 25 ppm, the Bacharach error ranged from 1% to 57% with 95% CIs ranging from  $\pm 0.18$  to  $\pm 0.94$  ppm. The Viasensor error ranged from -100% to -18% with 95% CIs ranging from  $\pm 0.18$  to  $\pm 2.76$  ppm.

#### 4.4 ANOVA FOR INFRARED GAS ANALYZERS TO REFERENCE INSTRUMENT

Using the Gasmeter portable gas analyzer as the reference, a two-way analysis of variance (ANOVA) was performed, at low and high relative humidity levels, between the reference instrument and each analyzer to determine if there was a significant difference in the sample means of both infrared gas analyzers vs. the mean measurements Gasmeter. A total of four two-way ANOVAs were created. The results of all two-way ANOVA tests indicated that there was a significant difference ( $p = < 0.00005$ ) in the measurement means. Table 9 shows all two-way ANOVA results.

Table 9: Two-way ANOVA results.

| <b>IGA</b> | <b>F</b><br>(22% RH) | <b>P-value</b><br>(22% RH) | <b>F</b><br>(80% RH) | <b>P-value</b><br>(80% RH) |
|------------|----------------------|----------------------------|----------------------|----------------------------|
| Viasensor  | 13440.02             | $< 0.00005$                | 10034.62             | $< 0.00005$                |
| Bacharach  | 21764.13             | $< 0.00005$                | 18567.58             | $< 0.00005$                |

#### 4.5 BLAND-ALTMAN DEGREE OF AGREEMENT PLOTS

To calculate the degree of agreement between each test instrument to the Gasmeter reference instrument, Bland-Altman analyses were performed (Figures 26-37). The plots below show the level of agreement between the reference instrument and the specific instrument under investigation by using percent differences and the mean of the analyzer's response results.

For all plots, the mean percent difference is indicated by the solid line and the 95% confidence limits are indicated by the dashed lines.

#### 4.5.1 Bland-Altman Agreement Plots from 1 to 500 ppm at 22% Relative Humidity

The Bland-Altman plot in Figure 26 shows the mean percent difference (bias), across all measurements taken between the Bacharach and the Gasmeter, from 1 to 500 ppm, was 13.6%. The plot also reports 95% confidence limits of -85.8% to 113.1%. For nitrous oxide concentrations from 50 to 500 ppm, the plot shows the Bacharach overestimated the true nitrous oxide concentration, as such data points are plotted near and below zero on the y-axis.

To better interpret the Bland-Altman results at concentrations below 50 ppm, more resolution is needed.

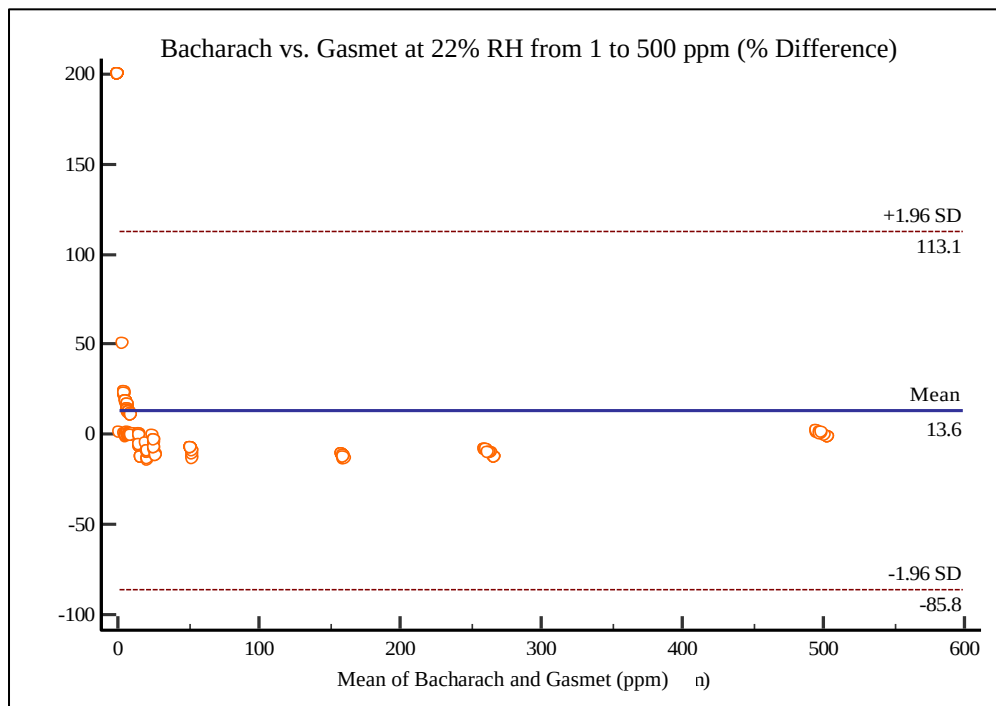


Figure 26: Bacharach vs. Gasmeter from 1 to 500 ppm for 336 samples.

The Bland-Altman plot in Figure 27 shows the mean percent difference (bias), across all measurements taken between the Viasensor and the Gasmeter, from 1 to 500 ppm, was 62.4% with 95% confidence limits of -75.7% to 200.5%. For nitrous oxide concentrations from 150 to 500 ppm, the plot shows Viasensor data points that are plotted near zero on the y-axis, thus indicating good agreement with the Gasmeter. For all other concentrations, the Viasensor underestimated the true concentration, as such data points are plotted near and above zero on the y-axis.

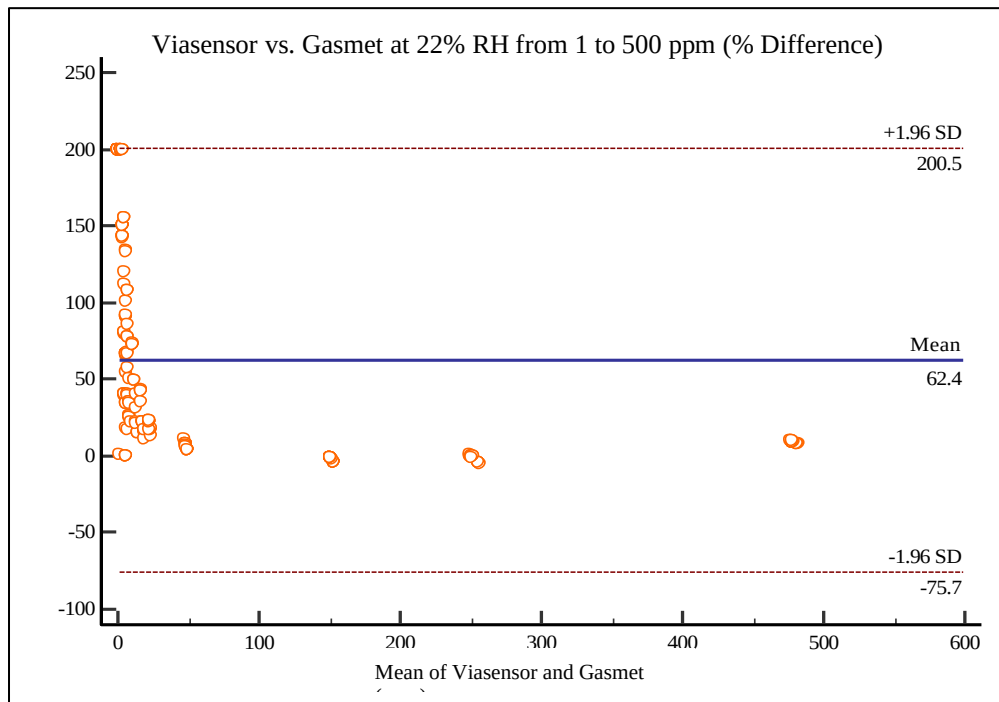


Figure 27: Viasensor vs. Gasmeter from 1 to 500 ppm for 336 samples.

#### 4.5.2 Bland-Altman Agreement Plots from 1 to 50 ppm at 22% Relative Humidity

The Bland-Altman plot in Figure 28 shows the mean percent difference (bias), across all measurements taken between the Bacharach and the Gasmeter, from 1 to 50 ppm, was 19.4% with 95% confidence limits of -90.1% to 128.8%. For nitrous oxide concentrations from 15 to 50 ppm, the plot shows the Bacharach overestimated the true nitrous oxide concentration, as such data points are plotted below zero on the y-axis. For concentrations from 1 to 10, the plot shows Bacharach data points that are plotted at or above zero on the y-axis. This indicates the Bacharach underestimated the true concentration from 1 to 10 ppm, as such data points are plotted near and above zero on the y-axis.

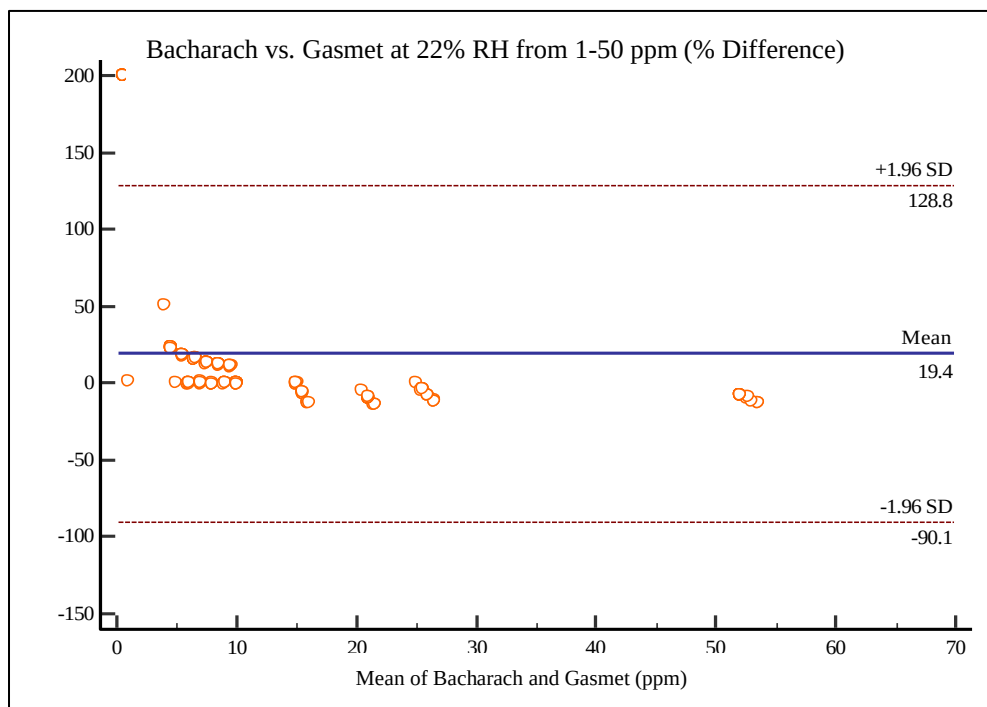


Figure 28: Bacharach vs. Gasmeter from 1 to 50 ppm for 264 samples.

The Bland-Altman plot in Figure 29 shows the mean percent difference (bias), across all measurements taken between the Viasensor and the Gasmeter, from 1 to 50 ppm, was 78.9% with 95% confidence limits of -60.1% to 218.0%. For the nitrous oxide concentration of 50 ppm, the plot shows Viasensor data points that are plotted near zero on the y-axis, thus indicating good agreement with the Gasmeter. For concentrations 0 to 25 ppm, the Viasensor underestimated the true concentration, as such data points are plotted near and above zero on the y-axis.

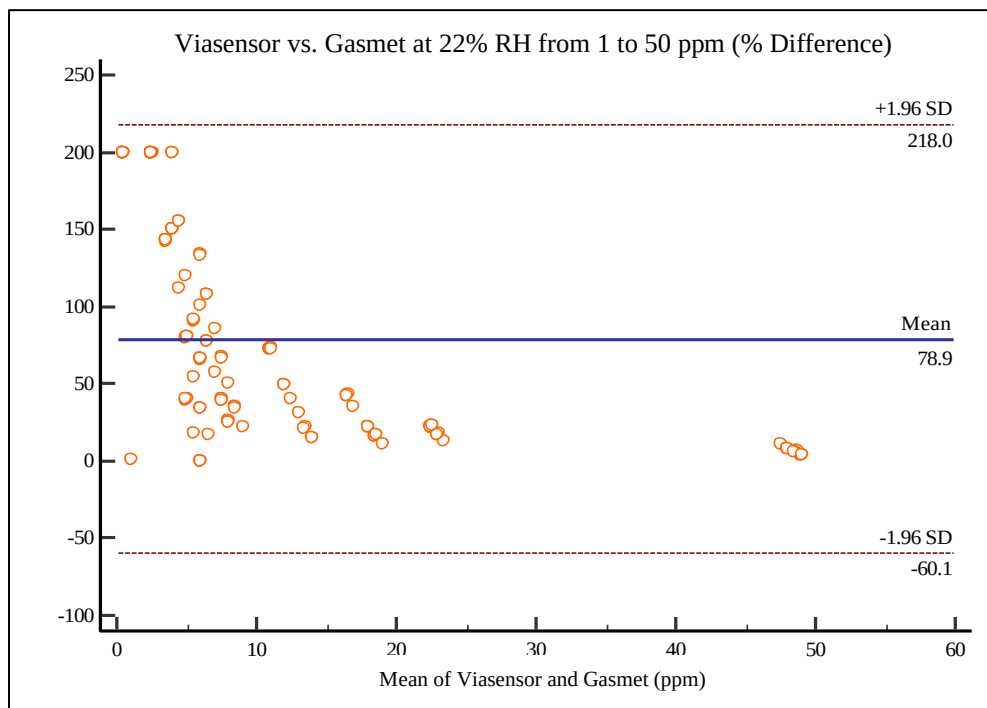


Figure 29: Viasensor vs. Gasmeter from 1 to 50 ppm for 264 samples.

#### 4.5.3 Bland-Altman Agreement Plots from 1 to 25 ppm at 22% Relative Humidity

The Bland-Altman plot in Figure 30 shows the mean percent difference (bias), across all measurements taken between the Bacharach and the Gasmeter, from 1 to 25 ppm, was 22.2% with 95% confidence limits of -91.1% to 135.5%. For nitrous oxide concentrations from 15 to 25 ppm, the plot shows the Bacharach overestimated the true nitrous oxide concentration, as such data points are plotted below zero on the y-axis. For concentrations from 1 to 10, the plot shows Bacharach data points that are plotted at or above zero on the y-axis. This indicates the Bacharach underestimated the true concentration from 0 to 10 ppm, as such data points are plotted near and above zero on the y-axis.

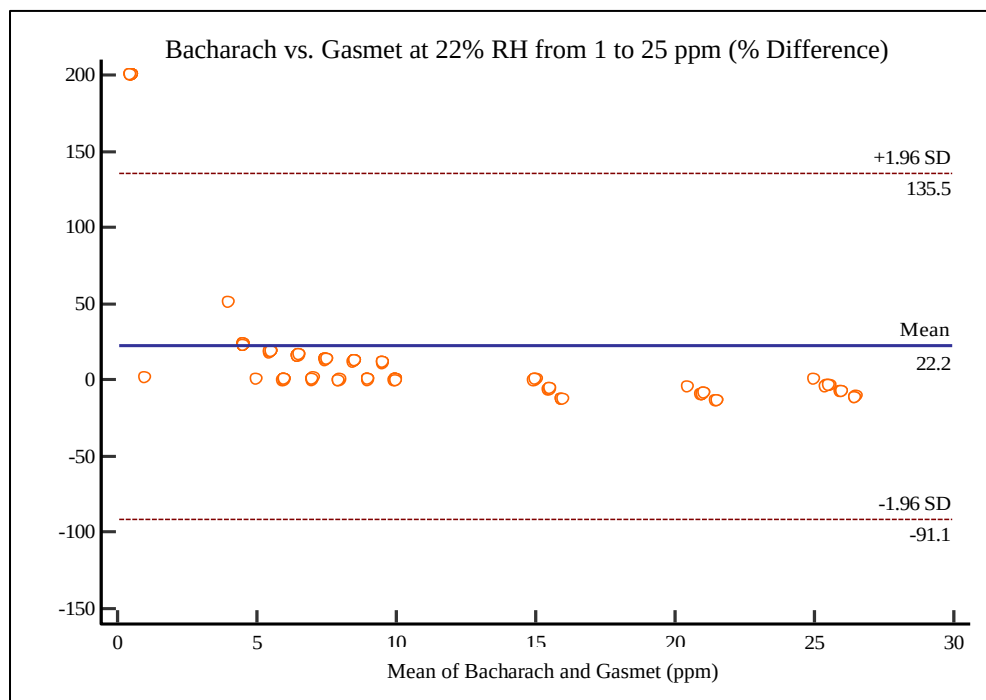


Figure 30: Bacharach vs. Gasmeter from 1 to 25 ppm for 240 samples.

The Bland-Altman plot in Figure 31 shows the mean percent difference (bias), across all measurements taken between the Viasensor and the Gasmeter, from 1 to 25 ppm, was 86.2% with 95% confidence limits of -51.7% to 224.1%. For nitrous oxide concentrations from 1 to 25 ppm, the Viasensor underestimated the true concentration, as such data points are plotted near and above zero on the y-axis.

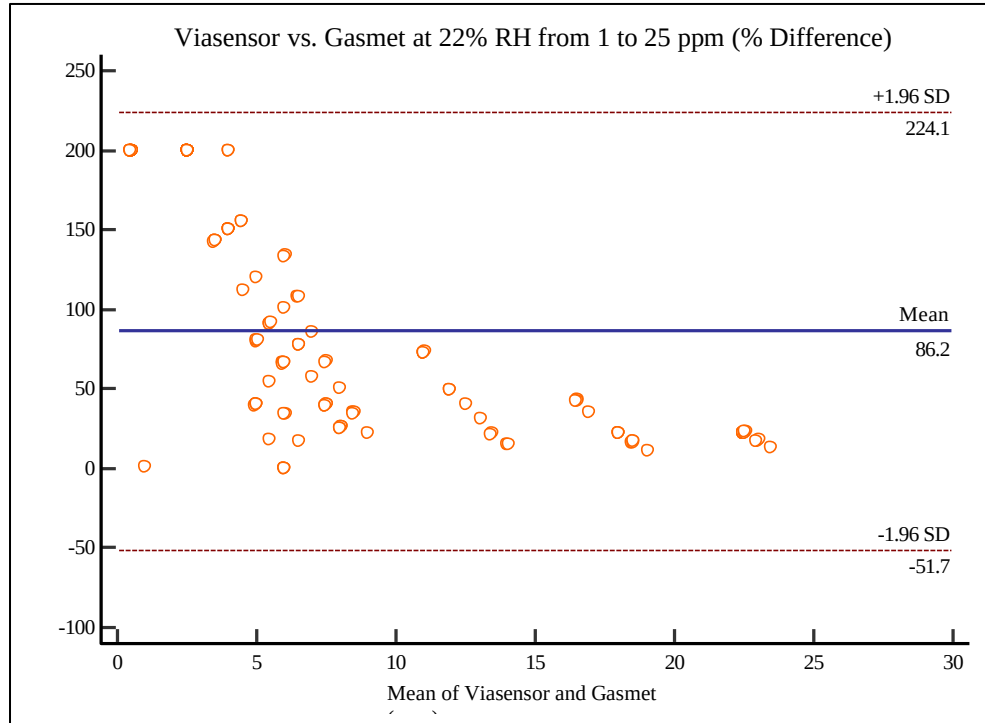


Figure 31: Viasensor vs. Gasmeter from 1 to 25 ppm for 240 samples.

#### 4.5.4 Bland-Altman Agreement Plots from 1 to 500 ppm at 80% Relative Humidity

The Bland-Altman plot in Figure 32 shows the mean percent difference (bias), across all measurements taken between the Bacharach and the Gasmeter, from 1 to 500 ppm, was -14.5%. The plot also reports 95% confidence limits of 13.1% to -42.1%. For nitrous oxide concentrations from 50 to 500 ppm, the plot shows the Bacharach overestimated the true nitrous oxide concentration, as such data points are plotted near or below zero on the y-axis.

To better interpret the Bland-Altman results at concentrations below 50 ppm, more resolution is needed.

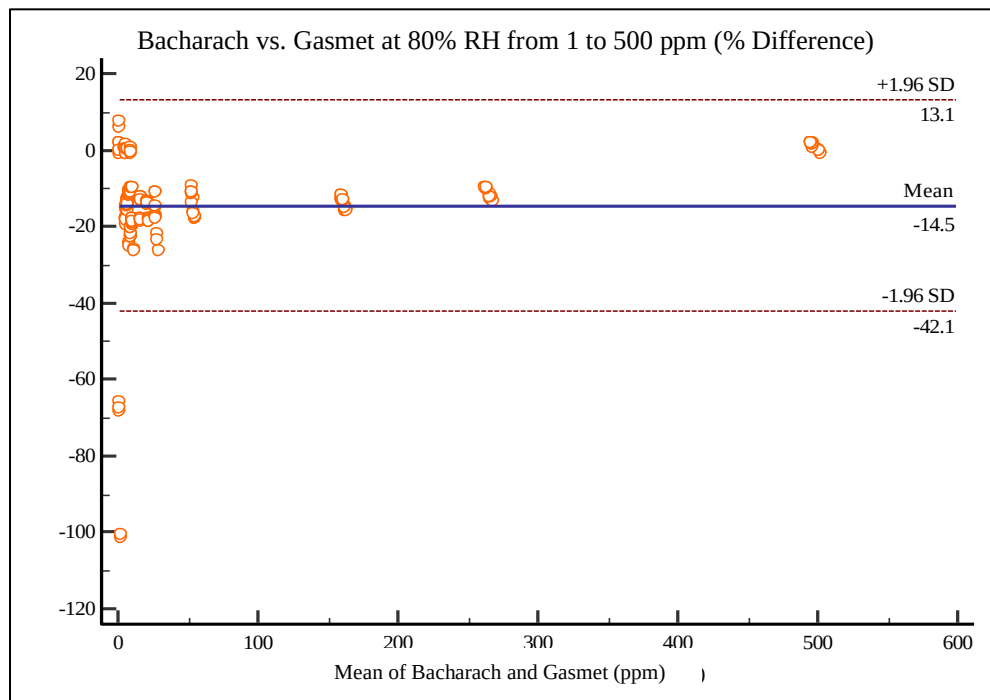


Figure 32: Gasmeter and Bacharach from 1 to 500 ppm for 336 samples.

The Bland-Altman plot in Figure 33 shows the mean percent difference (bias), across all measurements taken between the Viasensor and the Gasmeter, from 1 to 500 ppm, was 59.3% with 95% confidence limits of -75.7% to 193.8%. For the nitrous oxide concentration of 500 ppm, the plot shows Viasensor data points that are plotted above zero on the y-axis, as such indicating an underestimation of the true concentration. For nitrous oxide concentrations from 150 to 250 ppm, the plot shows Viasensor data points that are plotted near zero on the y-axis, thus indicating good agreement with the Gasmeter.

To better interpret the Bland-Altman results at concentrations below 50 ppm, more resolution is needed.

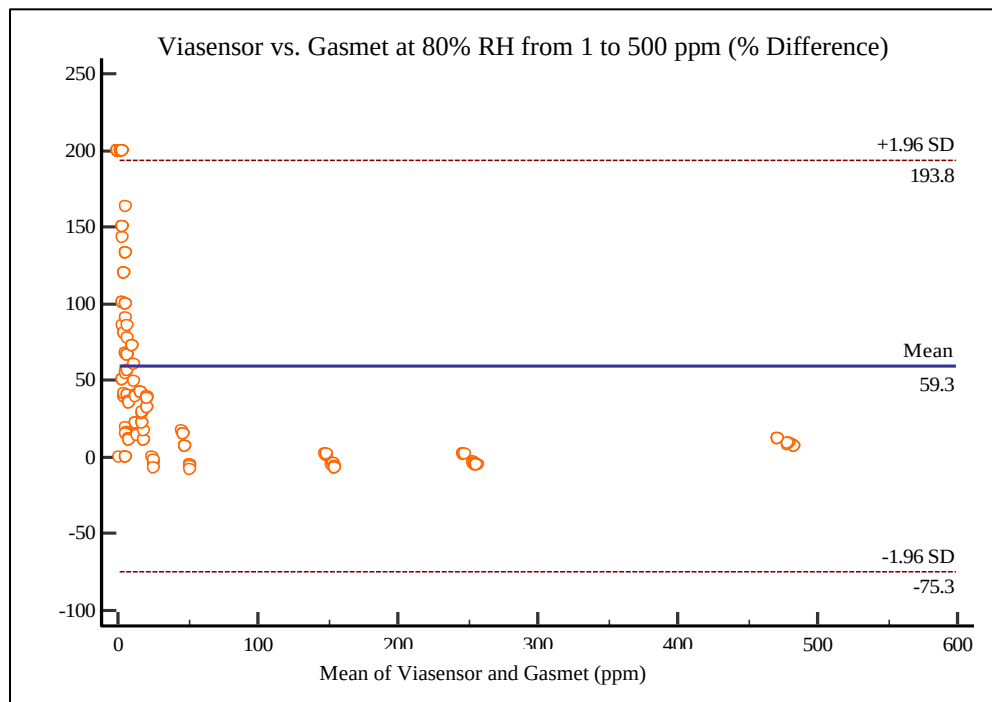


Figure 33: Viasensor vs. Gasmeter from 1 to 500 ppm for 336 samples.

#### 4.5.5 Bland-Altman Agreement Plots from 1 to 50 ppm at 80% Relative Humidity

The Bland-Altman plot in Figure 34 shows the mean percent difference (bias), across all measurements taken between the Bacharach and the Gasmeter, from 1 to 50 ppm, was -16.2% with 95% confidence limits of -45.8% to 13.3%. For nitrous oxide concentrations from 5 to 50 ppm, the plot shows the Bacharach overestimated the true nitrous oxide concentrations, as such data points are plotted at or below zero on the y-axis.

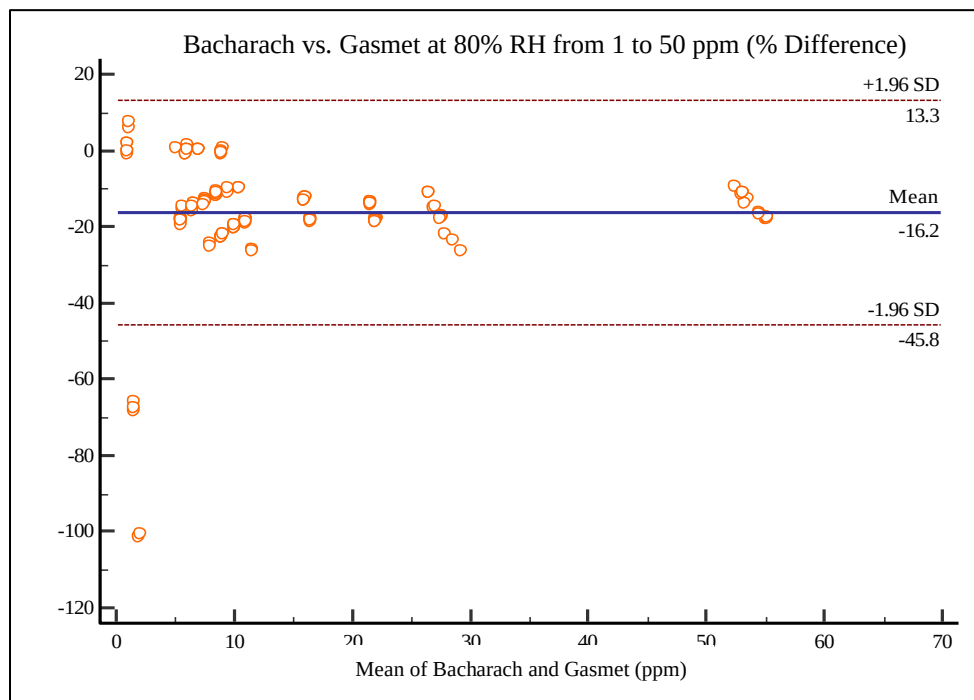


Figure 34: Bacharach vs. Gasmeter from 1 to 50 ppm for 264 samples.

The Bland-Altman plot in Figure 35 shows the mean percent difference (bias), across all measurements taken between the Viasensor and the Gasmet, from 1 to 50 ppm, was 75.1% with 95% confidence limits of -60.9% to 211.1%. For the nitrous oxide concentration from 1 to 50 ppm, the plot shows Viasensor data points that are plotted above zero on the y-axis, as such indicating an underestimation of the true nitrous oxide concentrations.

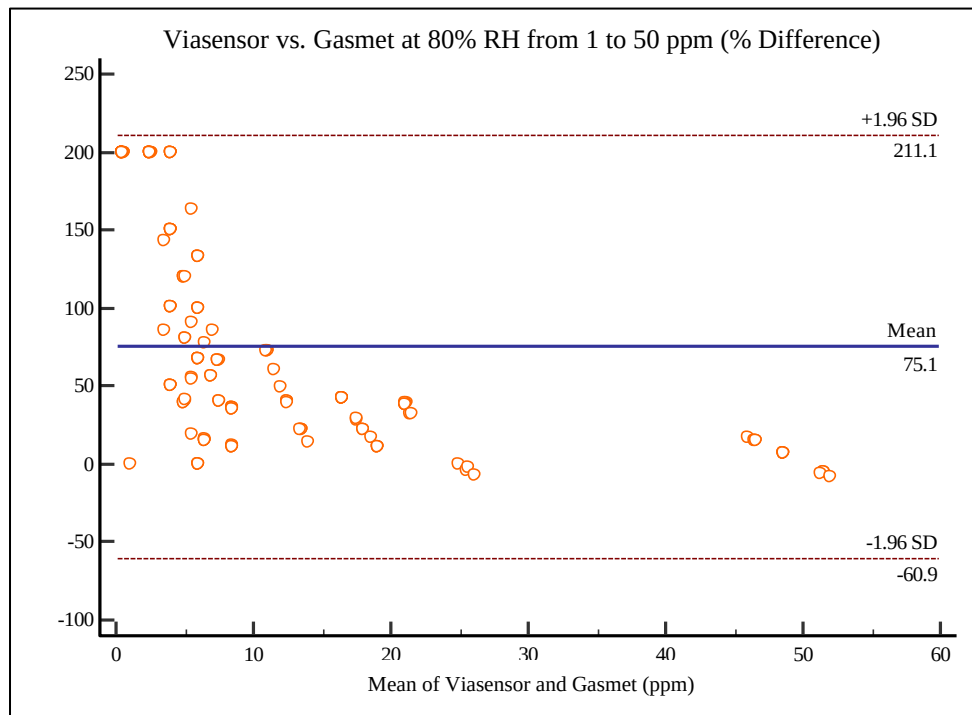


Figure 35: Viasensor vs. Gasmet from 1 to 50 ppm for 264 samples.

#### 4.5.6 Bland-Altman Agreement Plots from 1 to 25 ppm at 80% Relative Humidity

The Bland-Altman plot in Figure 36 shows the mean percent difference (bias), across all measurements taken between the Bacharach and the Gasmeter, from 1 to 25 ppm, was -16.4% with 95% confidence limits of -47.3% to 14.5%. For nitrous oxide concentrations from 5 to 25 ppm, the plot shows the Bacharach overestimated the true nitrous oxide concentration, as such data points are plotted at or below zero on the y-axis.

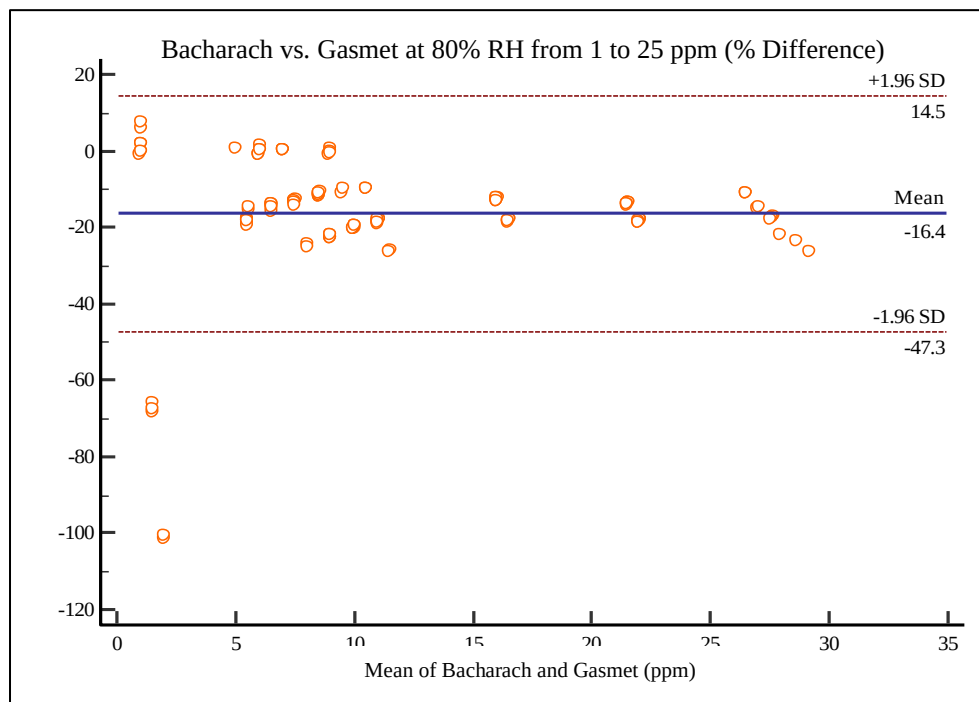


Figure 36: Bacharach vs. Gasmeter from 1 to 25 ppm for 240 samples.

The Bland-Altman plot in Figure 37 shows the mean percent difference (bias), across all measurements taken between the Viasensor and the Gasmet, from 1 to 25 ppm, was 82.1% with 95% confidence limits of -53.0% to 217.2%. For nitrous oxide concentrations from 1 to 25 ppm, the Viasensor underestimated the true concentration, as such data points are plotted near and above zero on the y-axis.

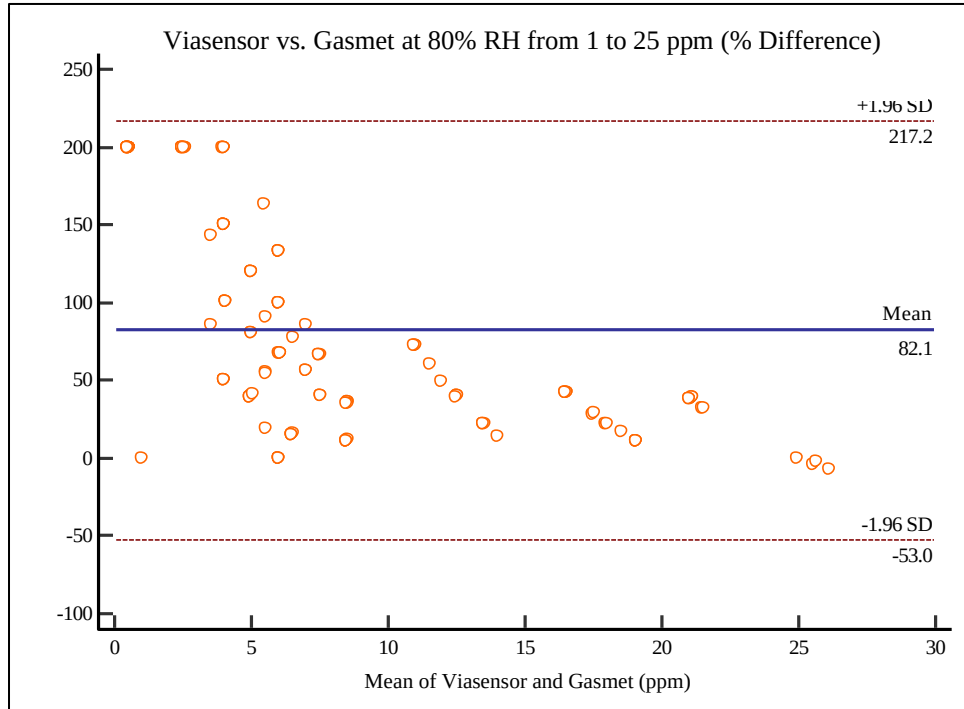


Figure 37: Viasensor vs. Gasmet from 1 to 25 ppm for 240 samples.

## **CHAPTER 5: Discussion**

### **5.1 COMPARISON OF TEST INSTRUMENTS TO REFERENCE INSTRUMENT**

This study investigated the level of agreement between two portable infrared gas analyzers and a reference instrument under environmental conditions that were likely to occur in Indian Health Service dental settings. The Gasmet verified independent nitrous oxide concentrations to which two portable infrared gas analyzers were compared. The study found that there was a significant difference ( $p = <0.00005$ ) in the measurement means of both infrared gas analyzers vs. the measurement means of the Gasmet.

### **5.2 MANUFACTURER ACCURACY STATEMENTS**

Table 1 shows the manufacturer accuracy statements for the Bacharach and Viasensor instruments.

The accuracy statement for the Bacharach is listed as  $\pm 5\%$  of the instrument response for concentrations from 0 to 100 ppm. The accuracy statement for concentrations from 101 to 1,000 ppm is listed as  $\pm 10\%$  of the instrument response. The study showed that at test concentrations from 1 to 500 ppm, at the 95% confidence intervals, the Bacharach met manufacturer accuracy statements at test concentrations of 6, 7, 9, 10, 15, 25, 250, and 500 ppm for 22% RH conditions. At 80% RH test conditions, the Bacharach only met manufacturer accuracy statements, at the 95% confidence intervals, at the single test concentration of 500 ppm.

The accuracy statement for the Viasensor is listed as  $\pm 5$  ppm of the instrument response for concentrations from 0 to 100 ppm. The accuracy statement for concentrations from 101 to 1,000 ppm is listed as  $\pm 1.5\%$  of the instrument response. The study showed that at test concentrations from 1 to 500 ppm, at the 95% confidence

intervals, the Viasensor met all manufacturer accuracy statements at all test concentrations from 1 to 250 ppm at both 22% RH and 80 % RH conditions. The Viasensor did not meet accuracy statements at the 500 ppm test concentration for both 22% RH and 80% RH conditions.

With regard to occupational exposure limits, this accuracy assessment bolsters the importance of thoroughly reviewing and comprehending the listed manufacturer accuracy statements. For example, the action level for nitrous oxide is 25 ppm and, in this study, both instruments met manufacturer accuracy statements at the 25 ppm concentration. However, based off the Bacharach accuracy statement ( $\pm 5\%$  from 0 to 100 ppm), a reading of 25 ppm would result in a manufacturer accuracy range of 23.75 to 26.25 ppm. In comparison, based off the Viasensor accuracy statement ( $\pm 5$  ppm from 0 to 100 ppm), an equivalent reading of 25 ppm would result in a larger manufacturer accuracy range of 20 to 30 ppm, thus permitting a manufacturer error of  $\pm 25\%$  at the 25 ppm concentration. This Viasensor accuracy statement, when applied to 25 ppm, equates to an accuracy statement that is five times larger than the Bacharach accuracy statement of  $\pm 5\%$ . At the 50 ppm occupational exposure limit, the Viasensor accuracy statement would equate to  $\pm 10\%$  of the instrument reading, which is larger and less desirable than the Bacharach accuracy statement of  $\pm 5\%$  at 50 ppm.

Occupational safety and health practitioners should carefully review instrumentation accuracy statements and thoroughly understand how such statements are applied to occupational exposure limits.

More manufacturer accuracy data can be found in Appendix C.

### 5.3 EFFECT OF HUMIDITY

The Bacharach's average percent error of 15%, from the reference instrument, was observed at 20% relative humidity. The average percent error increased to 17% when sampling at 80% relative humidity. The results from a two-ANOVA test indicated that there was a significant difference ( $p = <0.00005$ ) in the measurement means of the Bacharach due to the change in relative humidity.

The Viasensor's average percent error of 39%, from the reference instrument, was observed at 20% relative humidity. The average percent error decreased to 34% when sampling at 80% relative humidity. The results from a two-ANOVA test indicated that the decrease in error was not statistically significant across the measurement means ( $p = <0.545$ ).

A possible explanation for the difference in humidity effects between instruments could be explained by the source of infrared (IR) energy and the range of their analytical wavelengths used in each instrument. The Bacharach could deploy a broader ranged IR source that could cross-interfere (at the lower range) with the IR spectra of water vapor while the Viasensor could deploy a narrower ranged IR source that does not cross-interfere with water vapor's IR spectra. The manufacturer of the Bacharach reported an IR energy source deployed at a wavelength of " $\sim 4.5 \mu\text{m}$ ". The wavelength for the IR energy source of the Viasensor was not provided by the manufacturer. Neither manufacturer provided the range of their IR sources.

#### 5.4 NOTABLE IGA ( $\pm 25\%$ ) ERROR VALUES

This study compared mean measurements of various concentrations from each infrared gas analyzer to the reference instrument using a percent error approach ((IGA measurement – reference measurement)/reference measurement x 100%).

Statistically, for the Bacharach results, the most notable error value, which was an underestimation, for 22% RH, occurred at the 1 ppm test concentration where the Bacharach mean measurement value was 0 ppm (error = -92%). However, this error value, from a practitioner's perspective, is not substantial as it is based off a concentration that is small (1 ppm) and is not expected to place an individual's health at risk. For 22% RH, all remaining error values ranged from -20% to 13%. The most notable error value at 80% RH, which was an overestimation, occurred again at the 1 ppm test concentration. The Bacharach mean measurement value was 2 ppm (error = 57%). However, this error value is based off a small concentration therefore this inaccuracy is not substantial as well. All remaining error values at 80% RH ranged from -1 % to 20%.

For the Viasensor results, the most notable error values, which were underestimations, for 22% RH, occurred at all test concentrations from 1 to 15 ppm. At these test concentrations, error values ranged from -35% to -100% and tended to increase in error as test concentrations decreased in ppm values. Notable error values at 80% RH, which were also underestimations, occurred again at all test concentrations from 1 to 15 ppm. At these test concentrations, error values ranged from -35% to -92% and also tended to increase in error as test concentrations decreased in ppm values.

## **5.5 NITROUS OXIDE CONCENTRATIONS AT THE ACGIH TLV-TWA OF 50 PPM**

With regard to the IHS adopted ACGIH TLV-TWA of 50 ppm, both IGAs met accuracy standards ( $\pm 25\%$ ) with the reference instrument however the Viasensor showed 4% less error than the Bacharach at 22% RH and 11% less error at 80% RH. This indicates the Viasensor displayed more accuracy with the reference instrument than the Bacharach at 50 ppm however the Viasensor showed a bias of underestimating the true concentration, which is not ideal from a practitioner's perspective. The Bacharach showed an acceptable bias toward overestimating the true concentration, as such providing for a more protective response.

Using the Gasmeter as the reference, the Bacharach overestimated this test concentration with a mean response of 55 ppm (error = 10%; 95% CI = 54.088 - 55.59 ppm; at 22% RH) and 58 ppm (error = 16%; 95% CI = 56.69 – 59.14 ppm; at 80% RH).

The Viasensor underestimated this test concentration with a mean response of 47 ppm (error = -6%; 95% CI = 46.34 – 47.66 ppm; at 22% RH) and 48 ppm (error = -5%; 95% CI = 44.80 – 50.54 ppm; at 80% RH).

## **5.6 NITROUS OXIDE CONCENTRATIONS AT AND BELOW THE 25 PPM ACTION LEVEL**

Occupational safety and health practitioners need to measure concentrations of waste anesthetic gases with accurate instrumentation. Real-time direct reading instruments offer near real-time results and feedback. Processes to recognize, evaluate, and control potential hazards are implemented based off results from a direct-reading instrument. Inaccurate instrumentation that underestimates or overestimates the true concentration has the potential to cause adverse health effects to human health by exposing workers to unacceptable exposure conditions.

For the 25 ppm action level, both IGAs met established accuracy standards ( $\pm 25\%$ ) with the reference instrument. However, the Bacharach demonstrated 11% greater accuracy relative to true measurements than the Viasensor, when operated at 22% RH. At 80% RH, the Bacharach's error was 20% (overestimate/protective) and the Viasensor's error was -20% (underestimate/unprotective). This indicates the Bacharach displayed more accuracy with the reference instrument than the Viasensor at 25 ppm when operating at 80% RH. When comparing the Bacharach's response to 25 ppm, the Bacharach error measurement trended in a desirable and protective direction while the Viasensor error measurement trended in an unprotective and undesirable direction.

Using the Gasmet as the reference, the Bacharach overestimated the 25 ppm test concentration with a mean response of 27 ppm (error = 7%; 95% CI = 26.04 – 27.29 ppm; at 22% RH) and 30 ppm (error = 20%; 95% CI = 29.06 – 30.94 ppm; at 80% RH).

The Viasensor underestimated this test concentration with a mean response of 20 ppm (error = -18%; 95% CI = 19.99 – 20.84 ppm; at 22% RH) and 20 ppm (error = -20%; 95% CI = 17.41 – 22.93 ppm; at 80% RH).

For 22% RH, the Bland-Altman mean bias, across all measurements between the Bacharach and reference instrument, for concentrations of 25 ppm and below, was observed as 22.2%; and, as such for the Viasensor, was greater at 86.2%.

For 80% RH, the Bland-Altman mean bias, across all measurements between the Bacharach and reference instrument, for the same concentration range was observed as -16.4%; and, as such for the Viasensor, was greater at 82.1%.

The Bacharach's observed agreement results indicated good agreement between the IGA and the reference instrument. Furthermore, based off the observed humidity

effects, it is expected that as relative humidity conditions increase in values from 22% to 80%, the Bacharach's response to measuring nitrous oxide should trend toward a more protective response, and should overestimate the true concentration with increasing relative humidity yet still maintain good agreement standards.

The same cannot be said for the Viasensor. The observed agreement results indicated poor agreement across all measurement means, at concentrations of 25 ppm and below, between the IGA and reference instrument (at both humidity conditions). These observed Bland-Altman findings for the Viasensor, for this concentration range, indicated response results that were unacceptable. The instrument showed a bias toward underestimating the true concentration which, from a practical perspective, is not satisfactory and could potentially expose workers to hazardous exposure conditions that could lead toward adverse health effects. For example, a field reading of 20 ppm with the Viasensor could provide the practitioner to interpret that airborne concentrations are within acceptable limits when, in actuality, the true concentration is 25 ppm, thus meeting the threshold where actions such as employee medical surveillance or modifications to engineering controls should be implemented.

## **5.7 STUDY LIMITATIONS**

This study utilized a single analyzer from each of the listed manufactures (Bacharach and Viasensor), thus making the reported performance results limited to only those analyzers listed in this study. Certified calibration standards were not used when the user-calibration was performed on the Gasmeter reference instrument. Some degree of unknown error may have occurred when manually making calibration standards in-house. Although both analyzers were capable of continuous monitoring and data

logging, for time-weighted average performance investigative purposes, continuous monitoring performance was not conducted due to limitations of the supply of stock nitrous oxide gas available to the researcher. Furthermore, this study occurred in a laboratory environment which offered a tightly controlled and repeatable research design; therefore, outcomes from this study may not be generalizable to field settings.

## CHAPTER 6: Conclusions

An important part of a health and safety risk assessment is the accurate characterization of exposure. A portable nitrous oxide infrared gas analyzer that can most accurately measure the true concentration, across both low and high concentration levels, is a valuable tool for a health and safety program.

This study determined the level of agreement between two IGAs when compared to a reference instrument. The Bacharach instrument displayed better overall agreement ( $\pm 25\%$ ) at both low and high relative humidity conditions than the Viasensor. The Bacharach fulfilled accuracy criterion specified in NIOSH technical report 95-117 (23), under all study conditions, at test concentrations from 5 to 500 ppm. Additionally, the Bacharach showed a bias toward overestimating test concentrations; which, while not ideal, errors in an acceptable and protective direction.

The Viasensor showed an acceptable level of agreement ( $\pm 25\%$ ) at test concentrations from 50 to 500 ppm but perhaps the most important observation from this study relates to how the instrument performed at lower concentrations. Observed data suggested that at concentrations of 25 ppm and below, the Viasensor did not accurately measure nitrous oxide. The data showed the Viasensor mean error from 1 to 25 ppm was -52% (at 22% RH) and -46% (at 80% RH). The Viasensor's negative bias of underestimating the true concentration was not satisfactory and could potentially lead toward inaccurate exposure characterizations and adverse working conditions.

With the Thermo Fisher Scientific discontinuation of the production of the Miran SapphIRe, to monitor occupational exposure to waste emissions of nitrous oxide in the Indian Health Service (IHS) Oral Health Program, the Bacharach PGM-IR N<sub>2</sub>O 3015-

4787 Monitor is recommended to the IHS for further consideration to determine whether it meets other criteria requirements such as cost, operational characteristics, and field performance standards.

In addition to the Bacharach, the reference instrument used in this study may also be a viable replacement for the Miran SapphIRe. The Gasmeter DX4040 is capable of simultaneously analyzing up to 50 gas compounds with its Fourier transform and interferometer technology (12). The versatility of the instrument can be used in several applications beyond the realm of nitrous oxide monitoring. High compound specificity or identification and quantification can be achieved with the instrument through its unique ability to adjust its “spectral analysis area” or “wave number range” from 900 to 4200  $\text{cm}^{-1}$ . Additionally, the instrument is equipped with a reference library that contains the infrared spectra and concentration information of over 600 gas species. The Gasmeter is a robust, flexible, portable, accurate, and precise instrument that may prove to be beneficial to other occupational safety and health functions within the IHS.

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## Appendix A

### Bacharach Performance Data

Table 10: Bacharach results from 12 replicate samples taken at each concentration, for 22% relative humidity

| N <sub>2</sub> O Test Concentration (ppm) | 1     | 5    | 6    | 7    | 8    | 9    | 10   | 15    | 20    | 25    | 50    | 150    | 250    | 500    |
|-------------------------------------------|-------|------|------|------|------|------|------|-------|-------|-------|-------|--------|--------|--------|
| Mean (ppm)                                | 0     | 4    | 6    | 6    | 7    | 8    | 10   | 16    | 22    | 27    | 55    | 169    | 277    | 498    |
| Standard Deviation                        | 0.29  | 0.43 | 0.52 | 0.51 | 0.49 | 0.51 | 0.49 | 0.83  | 0.58  | 0.98  | 1.19  | 1.67   | 4.77   | 6.56   |
| Coefficient of Variation                  | 3.46  | 0.11 | 0.09 | 0.08 | 0.07 | 0.06 | 0.05 | 0.05  | 0.03  | 0.04  | 0.02  | 0.01   | 0.02   | 0.01   |
| Confidence Interval <sup>1</sup> (95.0%)  | 0.18  | 0.27 | 0.33 | 0.33 | 0.31 | 0.33 | 0.31 | 0.53  | 0.37  | 0.63  | 0.76  | 1.06   | 3.03   | 4.16   |
| Upper CI (95%)                            | 0.27  | 4.27 | 5.83 | 6.74 | 7.65 | 8.74 | 9.98 | 16.36 | 22.53 | 27.29 | 55.59 | 170.39 | 280.37 | 502.50 |
| Lower CI (95%)                            | -0.10 | 3.73 | 5.17 | 6.09 | 7.02 | 8.09 | 9.35 | 15.30 | 21.80 | 26.04 | 54.08 | 168.27 | 274.30 | 494.17 |

<sup>1</sup>Confidence interval values are intended to be (±) to the mean value.

Table 11: Bacharach results from 12 replicate samples taken at each concentration, for 80% relative humidity.

| N <sub>2</sub> O Test Concentration (ppm) | 1    | 5    | 6    | 7    | 8    | 9     | 10    | 15    | 20    | 25    | 50    | 150    | 250    | 500    |
|-------------------------------------------|------|------|------|------|------|-------|-------|-------|-------|-------|-------|--------|--------|--------|
| Mean (ppm)                                | 2    | 6    | 7    | 8    | 9    | 10    | 12    | 17    | 24    | 30    | 58    | 172    | 281    | 495    |
| Standard Deviation                        | 0.79 | 0.29 | 0.51 | 0.67 | 0.51 | 0.94  | 0.60  | 0.51  | 0.51  | 1.48  | 1.93  | 2.68   | 3.61   | 5.11   |
| Coefficient of Variation                  | 0.50 | 0.05 | 0.08 | 0.08 | 0.05 | 0.09  | 0.05  | 0.03  | 0.02  | 0.05  | 0.03  | 0.02   | 0.01   | 0.01   |
| Confidence Interval <sup>1</sup> (95.0%)  | 0.50 | 0.18 | 0.33 | 0.42 | 0.33 | 0.60  | 0.38  | 0.33  | 0.33  | 0.94  | 1.23  | 1.70   | 2.30   | 3.24   |
| Upper CI (95%)                            | 2.09 | 6.10 | 6.91 | 8.34 | 9.74 | 10.76 | 12.38 | 17.74 | 23.91 | 30.94 | 59.14 | 174.12 | 283.13 | 498.33 |
| Lower CI (95%)                            | 1.08 | 5.73 | 6.26 | 7.49 | 9.09 | 9.57  | 11.62 | 17.09 | 23.26 | 29.06 | 56.69 | 170.71 | 278.54 | 491.84 |

<sup>1</sup>Confidence interval values are intended to be (±) to the mean value.

## Appendix B

### Viasensor Performance Data

Table 12: Viasensor results from 12 replicate samples taken at each concentration, for 22% relative humidity.

| <b>N<sub>2</sub>O Test Concentration (ppm)</b> | <b>1</b> | <b>5</b> | <b>6</b> | <b>7</b> | <b>8</b> | <b>9</b> | <b>10</b> | <b>15</b> | <b>20</b> | <b>25</b> | <b>50</b> | <b>150</b> | <b>250</b> | <b>500</b> |
|------------------------------------------------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|
| Mean (ppm)                                     | 0        | 0        | 4        | 3        | 2        | 6        | 5         | 10        | 16        | 20        | 47        | 153        | 254        | 458        |
| Standard Deviation                             | 0.29     | 0.00     | 2.07     | 1.78     | 1.56     | 1.37     | 2.11      | 2.42      | 1.83      | 0.67      | 1.04      | 2.23       | 4.99       | 4.06       |
| Coefficient of Variation                       | 3.46     | 0.00     | 0.58     | 0.61     | 0.65     | 0.24     | 0.43      | 0.25      | 0.12      | 0.03      | 0.02      | 0.01       | 0.02       | 0.01       |
| Confidence Interval <sup>1</sup> (95.0%)       | 0.18     | 0.00     | 1.31     | 1.13     | 0.99     | 0.87     | 1.34      | 1.54      | 1.16      | 0.42      | 0.66      | 1.42       | 3.17       | 2.58       |
| Upper CI (95%)                                 | 0.27     | 0.00     | 4.90     | 4.05     | 3.41     | 6.54     | 6.26      | 11.29     | 16.75     | 20.84     | 47.66     | 154.75     | 257.34     | 460.49     |
| Lower CI (95%)                                 | -0.10    | 0.00     | 2.27     | 1.78     | 1.42     | 4.80     | 3.58      | 8.21      | 14.42     | 19.99     | 46.34     | 151.92     | 251.00     | 455.34     |

<sup>1</sup>Confidence interval values are intended to be (±) to the mean value.

Table 13 Viasensor results from 12 replicate samples taken at each concentration, for 80% relative humidity.

| <b>N<sub>2</sub>O Test Concentration (ppm)</b> | <b>1</b> | <b>5</b> | <b>6</b> | <b>7</b> | <b>8</b> | <b>9</b> | <b>10</b> | <b>15</b> | <b>20</b> | <b>25</b> | <b>50</b> | <b>150</b> | <b>250</b> | <b>500</b> |
|------------------------------------------------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|-----------|------------|------------|------------|
| Mean (ppm)                                     | 0        | 1        | 4        | 4        | 2        | 6        | 5         | 10        | 15        | 20        | 48        | 155        | 256        | 456        |
| Standard Deviation                             | 0.29     | 1.38     | 1.75     | 2.15     | 1.73     | 2.07     | 2.28      | 2.18      | 2.07      | 4.34      | 4.52      | 5.72       | 8.10       | 9.68       |
| Coefficient of Variation                       | 3.46     | 1.50     | 0.46     | 0.62     | 0.83     | 0.37     | 0.51      | 0.22      | 0.13      | 0.22      | 0.09      | 0.04       | 0.03       | 0.02       |
| Confidence Interval <sup>1</sup> (95.0%)       | 0.18     | 0.88     | 1.11     | 1.37     | 1.10     | 1.31     | 1.45      | 1.38      | 1.31      | 2.76      | 2.87      | 3.63       | 5.15       | 6.15       |
| Upper CI (95%)                                 | 0.27     | 1.79     | 4.94     | 4.87     | 3.18     | 6.90     | 5.95      | 11.13     | 16.73     | 22.93     | 50.54     | 158.80     | 261.15     | 462.40     |
| Lower CI (95%)                                 | -0.10    | 0.04     | 2.72     | 2.13     | 0.98     | 4.27     | 3.05      | 8.37      | 14.10     | 17.41     | 44.80     | 151.53     | 250.85     | 450.10     |

<sup>1</sup>Confidence interval values are intended to be (±) to the mean value.

## Appendix C

Table 14: Analysis of manufacturer accuracy<sup>1</sup> statement for the Bacharach.

| N <sub>2</sub> O (ppm) | Lower Accuracy Range (ppm) | Upper Accuracy Range (ppm) | Lower and Upper 95% CI (22% RH) |        | Lower and Upper 95% CI (80% RH) |        |
|------------------------|----------------------------|----------------------------|---------------------------------|--------|---------------------------------|--------|
| 1                      | 0.95                       | 1.05                       | -0.10                           | 0.27   | 1.08                            | 2.09   |
| 5                      | 4.75                       | 5.25                       | 3.73                            | 4.27   | 5.73                            | 6.10   |
| 6                      | 5.70                       | 6.3                        | 5.17                            | 5.83   | 6.26                            | 6.91   |
| 7                      | 6.65                       | 7.35                       | 6.09                            | 6.74   | 7.49                            | 8.34   |
| 8                      | 7.60                       | 8.4                        | 7.02                            | 7.65   | 9.09                            | 9.74   |
| 9                      | 8.55                       | 9.45                       | 8.09                            | 8.74   | 9.57                            | 10.76  |
| 10                     | 9.50                       | 10.5                       | 9.35                            | 9.98   | 11.62                           | 12.38  |
| 15                     | 14.25                      | 15.75                      | 15.30                           | 16.36  | 17.09                           | 17.74  |
| 20                     | 19.00                      | 21                         | 21.80                           | 22.53  | 23.26                           | 23.91  |
| 25                     | 23.75                      | 26.25                      | 26.04                           | 27.29  | 29.06                           | 30.94  |
| 50                     | 47.50                      | 52.5                       | 54.08                           | 55.59  | 56.69                           | 59.14  |
| 150                    | 135.00                     | 165                        | 168.27                          | 170.39 | 170.71                          | 174.12 |
| 250                    | 225.00                     | 275                        | 274.30                          | 280.37 | 278.54                          | 283.13 |
| 500                    | 450.00                     | 550                        | 494.17                          | 502.50 | 491.84                          | 498.33 |

<sup>1</sup> ± 5% of the response from 0 to 100 ppm; ± 10% of response from 101 to 1,000 ppm.

Table 15: Analysis of manufacturer accuracy<sup>1</sup> statement for the Viasensor.

| N <sub>2</sub> O (ppm) | Lower Accuracy Range (ppm) | Upper Accuracy Range (ppm) | Lower and Upper 95% CI (22% RH) |        | Lower and Upper 95% CI (80% RH) |        |
|------------------------|----------------------------|----------------------------|---------------------------------|--------|---------------------------------|--------|
| 1                      | -4                         | 6                          | -0.10                           | 0.27   | -0.10                           | 0.27   |
| 5                      | 0                          | 10                         | 0.00                            | 0.00   | 0.04                            | 1.79   |
| 6                      | 1                          | 11                         | 2.27                            | 4.90   | 2.72                            | 4.94   |
| 7                      | 2                          | 12                         | 1.78                            | 4.05   | 2.13                            | 4.87   |
| 8                      | 3                          | 13                         | 1.42                            | 3.41   | 0.98                            | 3.18   |
| 9                      | 4                          | 14                         | 4.80                            | 6.54   | 4.27                            | 6.90   |
| 10                     | 5                          | 15                         | 3.58                            | 6.26   | 3.05                            | 5.95   |
| 15                     | 10                         | 20                         | 8.21                            | 11.29  | 8.37                            | 11.13  |
| 20                     | 15                         | 25                         | 14.42                           | 16.75  | 14.10                           | 16.73  |
| 25                     | 20                         | 30                         | 19.99                           | 20.84  | 17.41                           | 22.93  |
| 50                     | 45                         | 55                         | 46.34                           | 47.66  | 44.80                           | 50.54  |
| 150                    | 147.75                     | 152.25                     | 151.92                          | 154.75 | 151.53                          | 158.80 |
| 250                    | 246.25                     | 253.75                     | 251.00                          | 257.34 | 250.85                          | 261.15 |
| 500                    | 492.5                      | 507.5                      | 455.34                          | 460.49 | 450.10                          | 462.40 |

<sup>1</sup> ± 5 ppm of the response from 0 to 100 ppm; ±1.5% of response from 101 to 1,000 ppm.

## Appendix D

### Raw Data

Table 16: Raw data.

| Run Number | Test N <sub>2</sub> O Concentration (ppm) | Gasmet Response (ppm) | Viasensor Response (ppm) | Bacharach Response (ppm) | Temp (°C) | Relative Humidity (%) |
|------------|-------------------------------------------|-----------------------|--------------------------|--------------------------|-----------|-----------------------|
| 1          | 1                                         | 0.99                  | 0                        | 0                        | 20.2      | 22                    |
| 2          | 1                                         | 1.01                  | 1                        | 1                        | 20.2      | 22                    |
| 3          | 1                                         | 1.01                  | 0                        | 0                        | 20.2      | 22                    |
| 4          | 1                                         | 1.00                  | 0                        | 0                        | 20.2      | 22                    |
| 5          | 1                                         | 1.00                  | 0                        | 0                        | 20.3      | 22                    |
| 6          | 1                                         | 1.00                  | 0                        | 0                        | 20.3      | 22                    |
| 7          | 1                                         | 0.98                  | 0                        | 0                        | 20.3      | 22                    |
| 8          | 1                                         | 1.00                  | 0                        | 0                        | 20.3      | 22                    |
| 9          | 1                                         | 1.00                  | 0                        | 0                        | 20.5      | 22                    |
| 10         | 1                                         | 1.00                  | 0                        | 0                        | 20.5      | 22                    |
| 11         | 1                                         | 1.00                  | 0                        | 0                        | 20.5      | 22                    |
| 12         | 1                                         | 0.99                  | 0                        | 0                        | 20.5      | 22                    |
| 13         | 5                                         | 5.01                  | 0                        | 4                        | 20.2      | 22                    |
| 14         | 5                                         | 5.07                  | 0                        | 4                        | 20.2      | 22                    |
| 15         | 5                                         | 5.01                  | 0                        | 5                        | 20.2      | 22                    |
| 16         | 5                                         | 5.00                  | 0                        | 4                        | 20.2      | 22                    |
| 17         | 5                                         | 5.02                  | 0                        | 4                        | 20.4      | 22                    |
| 18         | 5                                         | 5.01                  | 0                        | 4                        | 20.5      | 22                    |
| 19         | 5                                         | 5.00                  | 0                        | 4                        | 20.5      | 22                    |
| 20         | 5                                         | 5.00                  | 0                        | 4                        | 20.5      | 22                    |
| 21         | 5                                         | 5.04                  | 0                        | 3                        | 20.4      | 22                    |
| 22         | 5                                         | 5.04                  | 0                        | 4                        | 20.4      | 22                    |
| 23         | 5                                         | 5.05                  | 0                        | 4                        | 20.4      | 22                    |
| 24         | 5                                         | 5.03                  | 0                        | 4                        | 20.4      | 22                    |
| 25         | 6                                         | 6.01                  | 1                        | 5                        | 20.3      | 23                    |
| 26         | 6                                         | 6.02                  | 1                        | 6                        | 20.3      | 23                    |
| 27         | 6                                         | 5.96                  | 1                        | 5                        | 20.3      | 22                    |
| 28         | 6                                         | 6.02                  | 1                        | 5                        | 20.7      | 22                    |
| 29         | 6                                         | 5.93                  | 4                        | 6                        | 20.7      | 22                    |
| 30         | 6                                         | 6.00                  | 4                        | 6                        | 20.7      | 22                    |
| 31         | 6                                         | 6.03                  | 4                        | 5                        | 20.7      | 22                    |
| 32         | 6                                         | 5.99                  | 4                        | 5                        | 20.7      | 22                    |
| 33         | 6                                         | 5.98                  | 5                        | 6                        | 20.7      | 22                    |
| 34         | 6                                         | 5.99                  | 6                        | 6                        | 20.7      | 22                    |

| <b>Run<br/>Number</b> | <b>Test N<sub>2</sub>O<br/>Concentration<br/>(ppm)</b> | <b>Gasmet<br/>Response<br/>(ppm)</b> | <b>Viasensor<br/>Response<br/>(ppm)</b> | <b>Bacharach<br/>Response<br/>(ppm)</b> | <b>Temp<br/>(°C)</b> | <b>Relative<br/>Humidity<br/>(%)</b> |
|-----------------------|--------------------------------------------------------|--------------------------------------|-----------------------------------------|-----------------------------------------|----------------------|--------------------------------------|
| 35                    | 6                                                      | 6.01                                 | 6                                       | 5                                       | 20.7                 | 22                                   |
| 36                    | 6                                                      | 5.99                                 | 6                                       | 6                                       | 20.7                 | 22                                   |
| 37                    | 7                                                      | 7.00                                 | 1                                       | 7                                       | 20.7                 | 22                                   |
| 38                    | 7                                                      | 6.97                                 | 1                                       | 6                                       | 20.7                 | 22                                   |
| 39                    | 7                                                      | 6.98                                 | 1                                       | 7                                       | 20.7                 | 22                                   |
| 40                    | 7                                                      | 7.02                                 | 1                                       | 7                                       | 20.5                 | 22                                   |
| 41                    | 7                                                      | 7.05                                 | 2                                       | 6                                       | 20.7                 | 22                                   |
| 42                    | 7                                                      | 6.99                                 | 3                                       | 6                                       | 20.7                 | 22                                   |
| 43                    | 7                                                      | 7.01                                 | 3                                       | 6                                       | 20.7                 | 22                                   |
| 44                    | 7                                                      | 7.08                                 | 3                                       | 6                                       | 20.7                 | 22                                   |
| 45                    | 7                                                      | 7.06                                 | 5                                       | 7                                       | 20.7                 | 22                                   |
| 46                    | 7                                                      | 6.97                                 | 4                                       | 6                                       | 20.7                 | 22                                   |
| 47                    | 7                                                      | 7.09                                 | 6                                       | 6                                       | 20.7                 | 22                                   |
| 48                    | 7                                                      | 7.05                                 | 5                                       | 7                                       | 20.7                 | 22                                   |
| 49                    | 8                                                      | 7.94                                 | 1                                       | 8                                       | 20.8                 | 22                                   |
| 50                    | 8                                                      | 7.95                                 | 1                                       | 8                                       | 21.1                 | 22                                   |
| 51                    | 8                                                      | 8.04                                 | 0                                       | 8                                       | 21.1                 | 22                                   |
| 52                    | 8                                                      | 8.04                                 | 0                                       | 7                                       | 21.1                 | 22                                   |
| 53                    | 8                                                      | 7.98                                 | 3                                       | 7                                       | 20.5                 | 22                                   |
| 54                    | 8                                                      | 7.97                                 | 3                                       | 7                                       | 20.5                 | 22                                   |
| 55                    | 8                                                      | 8.03                                 | 3                                       | 7                                       | 20.5                 | 22                                   |
| 56                    | 8                                                      | 7.97                                 | 2                                       | 7                                       | 20.5                 | 22                                   |
| 57                    | 8                                                      | 7.94                                 | 4                                       | 8                                       | 20.7                 | 22                                   |
| 58                    | 8                                                      | 7.92                                 | 4                                       | 7                                       | 20.7                 | 22                                   |
| 59                    | 8                                                      | 7.99                                 | 4                                       | 7                                       | 20.7                 | 22                                   |
| 60                    | 8                                                      | 8.02                                 | 4                                       | 7                                       | 20.9                 | 22                                   |
| 61                    | 9                                                      | 9.04                                 | 4                                       | 9                                       | 20.7                 | 22                                   |
| 62                    | 9                                                      | 9.04                                 | 3                                       | 9                                       | 20.7                 | 22                                   |
| 63                    | 9                                                      | 9.04                                 | 4                                       | 8                                       | 20.9                 | 22                                   |
| 64                    | 9                                                      | 9.01                                 | 6                                       | 9                                       | 20.9                 | 22                                   |
| 65                    | 9                                                      | 8.96                                 | 6                                       | 8                                       | 20.9                 | 22                                   |
| 66                    | 9                                                      | 9.06                                 | 6                                       | 8                                       | 20.7                 | 22                                   |
| 67                    | 9                                                      | 8.96                                 | 6                                       | 9                                       | 20.7                 | 22                                   |
| 68                    | 9                                                      | 9.03                                 | 5                                       | 9                                       | 20.9                 | 22                                   |
| 69                    | 9                                                      | 9.08                                 | 7                                       | 8                                       | 20.6                 | 22                                   |
| 70                    | 9                                                      | 9.06                                 | 7                                       | 8                                       | 20.7                 | 22                                   |
| 71                    | 9                                                      | 9.05                                 | 7                                       | 8                                       | 20.6                 | 22                                   |
| 72                    | 9                                                      | 9.03                                 | 7                                       | 8                                       | 20.6                 | 22                                   |
| 73                    | 10                                                     | 9.98                                 | 7                                       | 10                                      | 20.3                 | 22                                   |

| <b>Run<br/>Number</b> | <b>Test N<sub>2</sub>O<br/>Concentration<br/>(ppm)</b> | <b>Gasmet<br/>Response<br/>(ppm)</b> | <b>Viasensor<br/>Response<br/>(ppm)</b> | <b>Bacharach<br/>Response<br/>(ppm)</b> | <b>Temp<br/>(°C)</b> | <b>Relative<br/>Humidity<br/>(%)</b> |
|-----------------------|--------------------------------------------------------|--------------------------------------|-----------------------------------------|-----------------------------------------|----------------------|--------------------------------------|
| 74                    | 10                                                     | 10.03                                | 7                                       | 9                                       | 20.3                 | 22                                   |
| 75                    | 10                                                     | 10.01                                | 8                                       | 10                                      | 20.3                 | 22                                   |
| 76                    | 10                                                     | 9.93                                 | 7                                       | 10                                      | 20.3                 | 22                                   |
| 77                    | 10                                                     | 10.08                                | 2                                       | 9                                       | 20.6                 | 22                                   |
| 78                    | 10                                                     | 9.95                                 | 2                                       | 10                                      | 20.6                 | 22                                   |
| 79                    | 10                                                     | 9.98                                 | 3                                       | 10                                      | 20.6                 | 22                                   |
| 80                    | 10                                                     | 10.04                                | 3                                       | 9                                       | 20.6                 | 22                                   |
| 81                    | 10                                                     | 10.05                                | 5                                       | 10                                      | 20.7                 | 22                                   |
| 82                    | 10                                                     | 10.05                                | 6                                       | 9                                       | 20.7                 | 22                                   |
| 83                    | 10                                                     | 10.03                                | 4                                       | 10                                      | 20.7                 | 22                                   |
| 84                    | 10                                                     | 9.96                                 | 5                                       | 10                                      | 20.7                 | 22                                   |
| 85                    | 15                                                     | 15.04                                | 13                                      | 15                                      | 20.4                 | 22                                   |
| 86                    | 15                                                     | 15.06                                | 13                                      | 15                                      | 20.4                 | 22                                   |
| 87                    | 15                                                     | 14.96                                | 12                                      | 15                                      | 20.4                 | 22                                   |
| 88                    | 15                                                     | 14.87                                | 12                                      | 15                                      | 20.4                 | 22                                   |
| 89                    | 15                                                     | 14.96                                | 7                                       | 16                                      | 20.6                 | 22                                   |
| 90                    | 15                                                     | 14.97                                | 7                                       | 15                                      | 20.6                 | 22                                   |
| 91                    | 15                                                     | 15.06                                | 7                                       | 16                                      | 20.6                 | 22                                   |
| 92                    | 15                                                     | 15.01                                | 7                                       | 16                                      | 20.6                 | 22                                   |
| 93                    | 15                                                     | 14.94                                | 9                                       | 17                                      | 20.5                 | 22                                   |
| 94                    | 15                                                     | 14.93                                | 9                                       | 17                                      | 20.7                 | 22                                   |
| 95                    | 15                                                     | 15.00                                | 10                                      | 17                                      | 20.7                 | 22                                   |
| 96                    | 15                                                     | 15.09                                | 11                                      | 16                                      | 20.4                 | 22                                   |
| 97                    | 20                                                     | 20.08                                | 17                                      | 23                                      | 20.4                 | 22                                   |
| 98                    | 20                                                     | 19.95                                | 17                                      | 23                                      | 20.4                 | 22                                   |
| 99                    | 20                                                     | 20.00                                | 17                                      | 22                                      | 20.4                 | 22                                   |
| 100                   | 20                                                     | 20.06                                | 18                                      | 22                                      | 20.4                 | 22                                   |
| 101                   | 20                                                     | 20.09                                | 13                                      | 23                                      | 20.6                 | 22                                   |
| 102                   | 20                                                     | 20.02                                | 13                                      | 22                                      | 20.6                 | 22                                   |
| 103                   | 20                                                     | 19.95                                | 13                                      | 22                                      | 20.6                 | 22                                   |
| 104                   | 20                                                     | 19.94                                | 14                                      | 22                                      | 20.6                 | 22                                   |
| 105                   | 20                                                     | 20.02                                | 16                                      | 22                                      | 20.3                 | 22                                   |
| 106                   | 20                                                     | 19.96                                | 16                                      | 21                                      | 20.7                 | 22                                   |
| 107                   | 20                                                     | 19.98                                | 16                                      | 22                                      | 20.7                 | 22                                   |
| 108                   | 20                                                     | 20.08                                | 17                                      | 22                                      | 20.7                 | 22                                   |
| 109                   | 25                                                     | 25.01                                | 20                                      | 28                                      | 20.4                 | 22                                   |
| 110                   | 25                                                     | 24.94                                | 22                                      | 27                                      | 20.4                 | 22                                   |
| 111                   | 25                                                     | 24.96                                | 21                                      | 28                                      | 20.4                 | 22                                   |
| 112                   | 25                                                     | 24.98                                | 20                                      | 28                                      | 20.4                 | 22                                   |

| <b>Run<br/>Number</b> | <b>Test N<sub>2</sub>O<br/>Concentration<br/>(ppm)</b> | <b>Gasmet<br/>Response<br/>(ppm)</b> | <b>Viasensor<br/>Response<br/>(ppm)</b> | <b>Bacharach<br/>Response<br/>(ppm)</b> | <b>Temp<br/>(°C)</b> | <b>Relative<br/>Humidity<br/>(%)</b> |
|-----------------------|--------------------------------------------------------|--------------------------------------|-----------------------------------------|-----------------------------------------|----------------------|--------------------------------------|
| 113                   | 25                                                     | 24.95                                | 20                                      | 25                                      | 20.5                 | 22                                   |
| 114                   | 25                                                     | 24.98                                | 20                                      | 26                                      | 20.5                 | 22                                   |
| 115                   | 25                                                     | 25.09                                | 21                                      | 26                                      | 20.5                 | 22                                   |
| 116                   | 25                                                     | 25.12                                | 20                                      | 26                                      | 20.5                 | 22                                   |
| 117                   | 25                                                     | 24.98                                | 20                                      | 27                                      | 20.4                 | 22                                   |
| 118                   | 25                                                     | 24.86                                | 21                                      | 26                                      | 20.4                 | 22                                   |
| 119                   | 25                                                     | 25.00                                | 20                                      | 27                                      | 20.4                 | 22                                   |
| 120                   | 25                                                     | 25.10                                | 20                                      | 26                                      | 20.4                 | 22                                   |
| 121                   | 50                                                     | 50.03                                | 48                                      | 55                                      | 20.6                 | 22                                   |
| 122                   | 50                                                     | 50.02                                | 48                                      | 57                                      | 20.6                 | 22                                   |
| 123                   | 50                                                     | 49.95                                | 48                                      | 57                                      | 20.6                 | 22                                   |
| 124                   | 50                                                     | 49.99                                | 48                                      | 56                                      | 20.6                 | 22                                   |
| 125                   | 50                                                     | 50.03                                | 45                                      | 54                                      | 20.3                 | 22                                   |
| 126                   | 50                                                     | 49.94                                | 46                                      | 54                                      | 20.3                 | 22                                   |
| 127                   | 50                                                     | 50.01                                | 46                                      | 54                                      | 20.3                 | 22                                   |
| 128                   | 50                                                     | 49.94                                | 46                                      | 54                                      | 20.3                 | 22                                   |
| 129                   | 50                                                     | 50.34                                | 47                                      | 55                                      | 20.4                 | 22                                   |
| 130                   | 50                                                     | 50.08                                | 47                                      | 54                                      | 20.4                 | 22                                   |
| 131                   | 50                                                     | 49.96                                | 47                                      | 54                                      | 20.6                 | 22                                   |
| 132                   | 50                                                     | 50.04                                | 48                                      | 54                                      | 20.4                 | 22                                   |
| 133                   | 150                                                    | 149.93                               | 156                                     | 171                                     | 20.6                 | 22                                   |
| 134                   | 150                                                    | 149.78                               | 156                                     | 171                                     | 20.6                 | 22                                   |
| 135                   | 150                                                    | 149.93                               | 156                                     | 172                                     | 20.6                 | 22                                   |
| 136                   | 150                                                    | 150.02                               | 157                                     | 171                                     | 20.6                 | 22                                   |
| 137                   | 150                                                    | 149.85                               | 152                                     | 169                                     | 20.4                 | 22                                   |
| 138                   | 150                                                    | 149.94                               | 151                                     | 167                                     | 20.4                 | 22                                   |
| 139                   | 150                                                    | 150.11                               | 153                                     | 168                                     | 20.4                 | 22                                   |
| 140                   | 150                                                    | 149.82                               | 151                                     | 167                                     | 20.4                 | 22                                   |
| 141                   | 150                                                    | 150.19                               | 152                                     | 168                                     | 20.4                 | 22                                   |
| 142                   | 150                                                    | 149.89                               | 152                                     | 169                                     | 20.4                 | 22                                   |
| 143                   | 150                                                    | 149.91                               | 152                                     | 169                                     | 20.6                 | 22                                   |
| 144                   | 150                                                    | 149.95                               | 152                                     | 170                                     | 20.6                 | 22                                   |
| 145                   | 250                                                    | 249.54                               | 260                                     | 282                                     | 20.6                 | 22                                   |
| 146                   | 250                                                    | 249.95                               | 260                                     | 283                                     | 20.6                 | 22                                   |
| 147                   | 250                                                    | 249.82                               | 262                                     | 284                                     | 20.6                 | 22                                   |
| 148                   | 250                                                    | 250.04                               | 261                                     | 283                                     | 20.6                 | 22                                   |
| 149                   | 250                                                    | 249.41                               | 251                                     | 271                                     | 20.4                 | 22                                   |
| 150                   | 250                                                    | 249.89                               | 249                                     | 271                                     | 20.4                 | 22                                   |
| 151                   | 250                                                    | 250.16                               | 249                                     | 273                                     | 20.4                 | 22                                   |

| <b>Run<br/>Number</b> | <b>Test N<sub>2</sub>O<br/>Concentration<br/>(ppm)</b> | <b>Gasmet<br/>Response<br/>(ppm)</b> | <b>Viasensor<br/>Response<br/>(ppm)</b> | <b>Bacharach<br/>Response<br/>(ppm)</b> | <b>Temp<br/>(°C)</b> | <b>Relative<br/>Humidity<br/>(%)</b> |
|-----------------------|--------------------------------------------------------|--------------------------------------|-----------------------------------------|-----------------------------------------|----------------------|--------------------------------------|
| 152                   | 250                                                    | 250.32                               | 251                                     | 273                                     | 20.6                 | 22                                   |
| 153                   | 250                                                    | 250.64                               | 252                                     | 278                                     | 20.6                 | 22                                   |
| 154                   | 250                                                    | 249.91                               | 251                                     | 277                                     | 20.6                 | 22                                   |
| 155                   | 250                                                    | 250.41                               | 252                                     | 277                                     | 20.6                 | 22                                   |
| 156                   | 250                                                    | 249.65                               | 252                                     | 276                                     | 20.6                 | 22                                   |
| 157                   | 500                                                    | 499.81                               | 464                                     | 507                                     | 20.2                 | 22                                   |
| 158                   | 500                                                    | 499.32                               | 463                                     | 508                                     | 20.2                 | 22                                   |
| 159                   | 500                                                    | 499.75                               | 463                                     | 508                                     | 20.2                 | 22                                   |
| 160                   | 500                                                    | 499.55                               | 463                                     | 503                                     | 20.2                 | 22                                   |
| 161                   | 500                                                    | 499.22                               | 456                                     | 492                                     | 20.7                 | 22                                   |
| 162                   | 500                                                    | 499.12                               | 456                                     | 493                                     | 20.4                 | 22                                   |
| 163                   | 500                                                    | 500.21                               | 457                                     | 491                                     | 20.3                 | 22                                   |
| 164                   | 500                                                    | 500.11                               | 456                                     | 491                                     | 20.4                 | 22                                   |
| 165                   | 500                                                    | 500.50                               | 454                                     | 498                                     | 20.6                 | 22                                   |
| 166                   | 500                                                    | 499.93                               | 454                                     | 496                                     | 20.6                 | 22                                   |
| 167                   | 500                                                    | 499.27                               | 455                                     | 497                                     | 20.6                 | 22                                   |
| 168                   | 500                                                    | 500.60                               | 454                                     | 496                                     | 20.6                 | 22                                   |
| 169                   | 1                                                      | 1.06                                 | 0                                       | 1                                       | 20.8                 | 81                                   |
| 170                   | 1                                                      | 1.01                                 | 0                                       | 2                                       | 20.8                 | 80                                   |
| 171                   | 1                                                      | 1.02                                 | 0                                       | 1                                       | 20.8                 | 80                                   |
| 172                   | 1                                                      | 1.08                                 | 0                                       | 1                                       | 21                   | 80                                   |
| 173                   | 1                                                      | 1.00                                 | 1                                       | 1                                       | 20.8                 | 78                                   |
| 174                   | 1                                                      | 0.99                                 | 0                                       | 1                                       | 20.8                 | 78                                   |
| 175                   | 1                                                      | 1.02                                 | 0                                       | 1                                       | 20.8                 | 79                                   |
| 176                   | 1                                                      | 1.00                                 | 0                                       | 1                                       | 20.6                 | 79                                   |
| 177                   | 1                                                      | 0.98                                 | 0                                       | 2                                       | 20.8                 | 79                                   |
| 178                   | 1                                                      | 0.98                                 | 0                                       | 3                                       | 20.6                 | 78                                   |
| 179                   | 1                                                      | 0.99                                 | 0                                       | 3                                       | 20.6                 | 79                                   |
| 180                   | 1                                                      | 0.99                                 | 0                                       | 2                                       | 20.8                 | 79                                   |
| 181                   | 5                                                      | 5.02                                 | 0                                       | 6                                       | 21                   | 79                                   |
| 182                   | 5                                                      | 5.13                                 | 0                                       | 6                                       | 21                   | 80                                   |
| 183                   | 5                                                      | 4.99                                 | 0                                       | 6                                       | 21                   | 80                                   |
| 184                   | 5                                                      | 5.17                                 | 0                                       | 6                                       | 21                   | 80                                   |
| 185                   | 5                                                      | 5.02                                 | 2                                       | 6                                       | 20.8                 | 82                                   |
| 186                   | 5                                                      | 5.02                                 | 3                                       | 6                                       | 20.8                 | 81                                   |
| 187                   | 5                                                      | 4.99                                 | 3                                       | 6                                       | 20.8                 | 78                                   |
| 188                   | 5                                                      | 5.03                                 | 3                                       | 5                                       | 20.8                 | 80                                   |
| 189                   | 5                                                      | 4.98                                 | 0                                       | 6                                       | 20.8                 | 81                                   |
| 190                   | 5                                                      | 5.00                                 | 0                                       | 6                                       | 20.8                 | 79                                   |

| <b>Run<br/>Number</b> | <b>Test N<sub>2</sub>O<br/>Concentration<br/>(ppm)</b> | <b>Gasmet<br/>Response<br/>(ppm)</b> | <b>Viasensor<br/>Response<br/>(ppm)</b> | <b>Bacharach<br/>Response<br/>(ppm)</b> | <b>Temp<br/>(°C)</b> | <b>Relative<br/>Humidity<br/>(%)</b> |
|-----------------------|--------------------------------------------------------|--------------------------------------|-----------------------------------------|-----------------------------------------|----------------------|--------------------------------------|
| 191                   | 5                                                      | 4.94                                 | 0                                       | 6                                       | 20.8                 | 81                                   |
| 192                   | 5                                                      | 5.00                                 | 0                                       | 6                                       | 20.8                 | 81                                   |
| 193                   | 6                                                      | 6.06                                 | 1                                       | 7                                       | 21                   | 82                                   |
| 194                   | 6                                                      | 6.08                                 | 2                                       | 6                                       | 21                   | 79                                   |
| 195                   | 6                                                      | 6.09                                 | 2                                       | 7                                       | 21                   | 78                                   |
| 196                   | 6                                                      | 6.06                                 | 2                                       | 7                                       | 20.8                 | 78                                   |
| 197                   | 6                                                      | 6.02                                 | 4                                       | 6                                       | 20.8                 | 78                                   |
| 198                   | 6                                                      | 5.93                                 | 4                                       | 6                                       | 20.6                 | 82                                   |
| 199                   | 6                                                      | 5.93                                 | 4                                       | 6                                       | 20.6                 | 82                                   |
| 200                   | 6                                                      | 6.09                                 | 4                                       | 7                                       | 20.8                 | 80                                   |
| 201                   | 6                                                      | 6.02                                 | 6                                       | 7                                       | 20.8                 | 78                                   |
| 202                   | 6                                                      | 6.01                                 | 6                                       | 6                                       | 20.6                 | 82                                   |
| 203                   | 6                                                      | 5.98                                 | 6                                       | 7                                       | 20.6                 | 82                                   |
| 204                   | 6                                                      | 6.03                                 | 5                                       | 7                                       | 20.8                 | 80                                   |
| 205                   | 7                                                      | 7.05                                 | 1                                       | 9                                       | 20.6                 | 80                                   |
| 206                   | 7                                                      | 7.00                                 | 1                                       | 9                                       | 20.8                 | 79                                   |
| 207                   | 7                                                      | 7.02                                 | 1                                       | 8                                       | 20.6                 | 80                                   |
| 208                   | 7                                                      | 7.01                                 | 1                                       | 8                                       | 20.6                 | 80                                   |
| 209                   | 7                                                      | 7.06                                 | 4                                       | 8                                       | 20.8                 | 80                                   |
| 210                   | 7                                                      | 7.03                                 | 3                                       | 7                                       | 20.8                 | 78                                   |
| 211                   | 7                                                      | 7.01                                 | 4                                       | 7                                       | 20.8                 | 81                                   |
| 212                   | 7                                                      | 7.02                                 | 3                                       | 7                                       | 21.1                 | 82                                   |
| 213                   | 7                                                      | 6.99                                 | 6                                       | 8                                       | 20.8                 | 78                                   |
| 214                   | 7                                                      | 7.01                                 | 6                                       | 8                                       | 20.8                 | 78                                   |
| 215                   | 7                                                      | 6.98                                 | 6                                       | 8                                       | 20.8                 | 77                                   |
| 216                   | 7                                                      | 6.94                                 | 6                                       | 8                                       | 20.8                 | 78                                   |
| 217                   | 8                                                      | 7.95                                 | 0                                       | 10                                      | 21                   | 81                                   |
| 218                   | 8                                                      | 7.94                                 | 0                                       | 10                                      | 21                   | 81                                   |
| 219                   | 8                                                      | 8.01                                 | 0                                       | 9                                       | 21                   | 81                                   |
| 220                   | 8                                                      | 7.98                                 | 0                                       | 9                                       | 21                   | 81                                   |
| 221                   | 8                                                      | 7.99                                 | 2                                       | 9                                       | 20.6                 | 79                                   |
| 222                   | 8                                                      | 8.02                                 | 3                                       | 10                                      | 20.6                 | 79                                   |
| 223                   | 8                                                      | 7.97                                 | 2                                       | 10                                      | 20.6                 | 79                                   |
| 224                   | 8                                                      | 8.02                                 | 2                                       | 10                                      | 20.4                 | 79                                   |
| 225                   | 8                                                      | 8.07                                 | 4                                       | 9                                       | 21                   | 81                                   |
| 226                   | 8                                                      | 8.03                                 | 4                                       | 9                                       | 21                   | 81                                   |
| 227                   | 8                                                      | 8.10                                 | 4                                       | 9                                       | 21                   | 80                                   |
| 228                   | 8                                                      | 8.07                                 | 4                                       | 9                                       | 20.8                 | 79                                   |
| 229                   | 9                                                      | 9.03                                 | 4                                       | 11                                      | 20.9                 | 81                                   |

| <b>Run<br/>Number</b> | <b>Test N<sub>2</sub>O<br/>Concentration<br/>(ppm)</b> | <b>Gasmet<br/>Response<br/>(ppm)</b> | <b>Viasensor<br/>Response<br/>(ppm)</b> | <b>Bacharach<br/>Response<br/>(ppm)</b> | <b>Temp<br/>(°C)</b> | <b>Relative<br/>Humidity<br/>(%)</b> |
|-----------------------|--------------------------------------------------------|--------------------------------------|-----------------------------------------|-----------------------------------------|----------------------|--------------------------------------|
| 230                   | 9                                                      | 8.98                                 | 3                                       | 11                                      | 20.4                 | 81                                   |
| 231                   | 9                                                      | 8.95                                 | 3                                       | 10                                      | 20.4                 | 82                                   |
| 232                   | 9                                                      | 9.00                                 | 3                                       | 11                                      | 20.4                 | 82                                   |
| 233                   | 9                                                      | 8.96                                 | 5                                       | 11                                      | 21.1                 | 78                                   |
| 234                   | 9                                                      | 8.97                                 | 5                                       | 11                                      | 21.1                 | 78                                   |
| 235                   | 9                                                      | 9.03                                 | 6                                       | 11                                      | 21.1                 | 81                                   |
| 236                   | 9                                                      | 9.06                                 | 6                                       | 10                                      | 21.1                 | 80                                   |
| 237                   | 9                                                      | 8.91                                 | 8                                       | 9                                       | 20.4                 | 82                                   |
| 238                   | 9                                                      | 9.04                                 | 8                                       | 9                                       | 20.4                 | 82                                   |
| 239                   | 9                                                      | 8.97                                 | 8                                       | 9                                       | 20.6                 | 82                                   |
| 240                   | 9                                                      | 8.94                                 | 8                                       | 9                                       | 20.6                 | 82                                   |
| 241                   | 10                                                     | 10.04                                | 7                                       | 12                                      | 20.8                 | 80                                   |
| 242                   | 10                                                     | 10.04                                | 7                                       | 12                                      | 20.8                 | 81                                   |
| 243                   | 10                                                     | 10.02                                | 7                                       | 13                                      | 21                   | 80                                   |
| 244                   | 10                                                     | 9.98                                 | 7                                       | 13                                      | 20.8                 | 80                                   |
| 245                   | 10                                                     | 9.97                                 | 1                                       | 11                                      | 21                   | 80                                   |
| 246                   | 10                                                     | 9.97                                 | 2                                       | 11                                      | 21                   | 80                                   |
| 247                   | 10                                                     | 9.95                                 | 2                                       | 12                                      | 21                   | 80                                   |
| 248                   | 10                                                     | 10.03                                | 2                                       | 12                                      | 21                   | 80                                   |
| 249                   | 10                                                     | 10.00                                | 4                                       | 12                                      | 20.6                 | 77                                   |
| 250                   | 10                                                     | 10.01                                | 5                                       | 12                                      | 20.9                 | 78                                   |
| 251                   | 10                                                     | 9.92                                 | 5                                       | 12                                      | 20.9                 | 78                                   |
| 252                   | 10                                                     | 9.94                                 | 5                                       | 12                                      | 20.9                 | 78                                   |
| 253                   | 15                                                     | 14.96                                | 12                                      | 17                                      | 21                   | 80                                   |
| 254                   | 15                                                     | 14.95                                | 13                                      | 18                                      | 21                   | 81                                   |
| 255                   | 15                                                     | 15.03                                | 12                                      | 18                                      | 21                   | 80                                   |
| 256                   | 15                                                     | 14.90                                | 12                                      | 18                                      | 21                   | 81                                   |
| 257                   | 15                                                     | 15.03                                | 7                                       | 18                                      | 21                   | 81                                   |
| 258                   | 15                                                     | 15.01                                | 7                                       | 17                                      | 21                   | 80                                   |
| 259                   | 15                                                     | 14.94                                | 7                                       | 17                                      | 21                   | 80                                   |
| 260                   | 15                                                     | 15.00                                | 8                                       | 18                                      | 21                   | 80                                   |
| 261                   | 15                                                     | 14.94                                | 9                                       | 17                                      | 20.6                 | 82                                   |
| 262                   | 15                                                     | 15.05                                | 10                                      | 17                                      | 20.6                 | 80                                   |
| 263                   | 15                                                     | 15.01                                | 10                                      | 17                                      | 20.6                 | 80                                   |
| 264                   | 15                                                     | 14.94                                | 10                                      | 17                                      | 20.9                 | 79                                   |
| 265                   | 20                                                     | 20.08                                | 18                                      | 24                                      | 21                   | 80                                   |
| 266                   | 20                                                     | 20.07                                | 18                                      | 23                                      | 21                   | 80                                   |
| 267                   | 20                                                     | 20.07                                | 18                                      | 23                                      | 21                   | 81                                   |
| 268                   | 20                                                     | 20.06                                | 17                                      | 24                                      | 21                   | 81                                   |

| <b>Run<br/>Number</b> | <b>Test N<sub>2</sub>O<br/>Concentration<br/>(ppm)</b> | <b>Gasmet<br/>Response<br/>(ppm)</b> | <b>Viasensor<br/>Response<br/>(ppm)</b> | <b>Bacharach<br/>Response<br/>(ppm)</b> | <b>Temp<br/>(°C)</b> | <b>Relative<br/>Humidity<br/>(%)</b> |
|-----------------------|--------------------------------------------------------|--------------------------------------|-----------------------------------------|-----------------------------------------|----------------------|--------------------------------------|
| 269                   | 20                                                     | 20.00                                | 13                                      | 24                                      | 21                   | 80                                   |
| 270                   | 20                                                     | 19.91                                | 13                                      | 24                                      | 21                   | 80                                   |
| 271                   | 20                                                     | 20.05                                | 13                                      | 24                                      | 21                   | 80                                   |
| 272                   | 20                                                     | 19.99                                | 13                                      | 24                                      | 21                   | 80                                   |
| 273                   | 20                                                     | 19.91                                | 16                                      | 24                                      | 20.7                 | 79                                   |
| 274                   | 20                                                     | 19.97                                | 16                                      | 23                                      | 20.7                 | 79                                   |
| 275                   | 20                                                     | 19.98                                | 15                                      | 23                                      | 20.9                 | 82                                   |
| 276                   | 20                                                     | 20.01                                | 15                                      | 23                                      | 20.9                 | 82                                   |
| 277                   | 25                                                     | 25.15                                | 17                                      | 30                                      | 21                   | 81                                   |
| 278                   | 25                                                     | 25.25                                | 17                                      | 30                                      | 21                   | 80                                   |
| 279                   | 25                                                     | 25.14                                | 17                                      | 30                                      | 21                   | 81                                   |
| 280                   | 25                                                     | 25.19                                | 17                                      | 30                                      | 21                   | 80                                   |
| 281                   | 25                                                     | 24.84                                | 25                                      | 31                                      | 20.6                 | 81                                   |
| 282                   | 25                                                     | 25.03                                | 26                                      | 30                                      | 20.6                 | 81                                   |
| 283                   | 25                                                     | 25.35                                | 26                                      | 33                                      | 20.8                 | 80                                   |
| 284                   | 25                                                     | 25.23                                | 27                                      | 32                                      | 20.8                 | 78                                   |
| 285                   | 25                                                     | 24.90                                | 18                                      | 29                                      | 20.8                 | 81                                   |
| 286                   | 25                                                     | 25.02                                | 18                                      | 29                                      | 20.8                 | 80                                   |
| 287                   | 25                                                     | 25.02                                | 17                                      | 28                                      | 20.8                 | 80                                   |
| 288                   | 25                                                     | 25.03                                | 17                                      | 28                                      | 20.8                 | 79                                   |
| 289                   | 50                                                     | 50.19                                | 47                                      | 60                                      | 21                   | 81                                   |
| 290                   | 50                                                     | 50.29                                | 47                                      | 60                                      | 21                   | 80                                   |
| 291                   | 50                                                     | 50.22                                | 47                                      | 60                                      | 21                   | 80                                   |
| 292                   | 50                                                     | 50.24                                | 47                                      | 60                                      | 21                   | 80                                   |
| 293                   | 50                                                     | 50.07                                | 53                                      | 59                                      | 20.6                 | 78                                   |
| 294                   | 50                                                     | 50.11                                | 53                                      | 57                                      | 20.6                 | 78                                   |
| 295                   | 50                                                     | 49.62                                | 53                                      | 57                                      | 20.6                 | 80                                   |
| 296                   | 50                                                     | 49.93                                | 54                                      | 59                                      | 20.6                 | 82                                   |
| 297                   | 50                                                     | 49.97                                | 42                                      | 56                                      | 20.8                 | 80                                   |
| 298                   | 50                                                     | 49.95                                | 43                                      | 55                                      | 20.8                 | 81                                   |
| 299                   | 50                                                     | 50.12                                | 43                                      | 56                                      | 20.8                 | 80                                   |
| 300                   | 50                                                     | 50.10                                | 43                                      | 56                                      | 20.8                 | 79                                   |
| 301                   | 150                                                    | 150.45                               | 157                                     | 176                                     | 21                   | 80                                   |
| 302                   | 150                                                    | 149.78                               | 157                                     | 176                                     | 21                   | 80                                   |
| 303                   | 150                                                    | 150.26                               | 157                                     | 176                                     | 21                   | 82                                   |
| 304                   | 150                                                    | 150.13                               | 157                                     | 174                                     | 21                   | 80                                   |
| 305                   | 150                                                    | 149.70                               | 161                                     | 174                                     | 20.6                 | 80                                   |
| 306                   | 150                                                    | 150.02                               | 160                                     | 172                                     | 20.8                 | 78                                   |
| 307                   | 150                                                    | 149.97                               | 161                                     | 171                                     | 20.6                 | 78                                   |

| <b>Run<br/>Number</b> | <b>Test N<sub>2</sub>O<br/>Concentration<br/>(ppm)</b> | <b>Gasmet<br/>Response<br/>(ppm)</b> | <b>Viasensor<br/>Response<br/>(ppm)</b> | <b>Bacharach<br/>Response<br/>(ppm)</b> | <b>Temp<br/>(°C)</b> | <b>Relative<br/>Humidity<br/>(%)</b> |
|-----------------------|--------------------------------------------------------|--------------------------------------|-----------------------------------------|-----------------------------------------|----------------------|--------------------------------------|
| 308                   | 150                                                    | 149.92                               | 161                                     | 171                                     | 20.4                 | 78                                   |
| 309                   | 150                                                    | 150.00                               | 148                                     | 169                                     | 20.8                 | 81                                   |
| 310                   | 150                                                    | 150.00                               | 147                                     | 170                                     | 20.8                 | 81                                   |
| 311                   | 150                                                    | 150.16                               | 148                                     | 169                                     | 20.8                 | 81                                   |
| 312                   | 150                                                    | 150.20                               | 148                                     | 171                                     | 20.8                 | 80                                   |
| 313                   | 250                                                    | 250.19                               | 261                                     | 284                                     | 21                   | 80                                   |
| 314                   | 250                                                    | 249.56                               | 258                                     | 284                                     | 21                   | 80                                   |
| 315                   | 250                                                    | 249.22                               | 260                                     | 283                                     | 21                   | 78                                   |
| 316                   | 250                                                    | 249.89                               | 260                                     | 286                                     | 21                   | 80                                   |
| 317                   | 250                                                    | 249.67                               | 262                                     | 282                                     | 20.6                 | 82                                   |
| 318                   | 250                                                    | 250.23                               | 263                                     | 283                                     | 20.6                 | 82                                   |
| 319                   | 250                                                    | 250.15                               | 264                                     | 281                                     | 20.8                 | 79                                   |
| 320                   | 250                                                    | 249.56                               | 263                                     | 282                                     | 20.6                 | 79                                   |
| 321                   | 250                                                    | 250.11                               | 245                                     | 277                                     | 20.8                 | 80                                   |
| 322                   | 250                                                    | 250.05                               | 245                                     | 276                                     | 20.8                 | 79                                   |
| 323                   | 250                                                    | 249.84                               | 245                                     | 276                                     | 20.8                 | 80                                   |
| 324                   | 250                                                    | 249.90                               | 246                                     | 276                                     | 20.8                 | 80                                   |
| 325                   | 500                                                    | 499.83                               | 464                                     | 504                                     | 27                   | 78                                   |
| 326                   | 500                                                    | 500.14                               | 466                                     | 502                                     | 27                   | 79                                   |
| 327                   | 500                                                    | 500.38                               | 466                                     | 500                                     | 28                   | 81                                   |
| 328                   | 500                                                    | 500.18                               | 467                                     | 501                                     | 28                   | 81                                   |
| 329                   | 500                                                    | 498.09                               | 459                                     | 494                                     | 20.4                 | 82                                   |
| 330                   | 500                                                    | 500.63                               | 460                                     | 492                                     | 20.6                 | 81                                   |
| 331                   | 500                                                    | 500.78                               | 460                                     | 492                                     | 20.6                 | 80                                   |
| 332                   | 500                                                    | 499.81                               | 458                                     | 493                                     | 20.6                 | 79                                   |
| 333                   | 500                                                    | 500.57                               | 444                                     | 491                                     | 20.8                 | 81                                   |
| 334                   | 500                                                    | 499.63                               | 444                                     | 491                                     | 20.8                 | 81                                   |
| 335                   | 500                                                    | 499.68                               | 443                                     | 490                                     | 20.8                 | 80                                   |
| 336                   | 500                                                    | 499.74                               | 444                                     | 491                                     | 20.8                 | 80                                   |