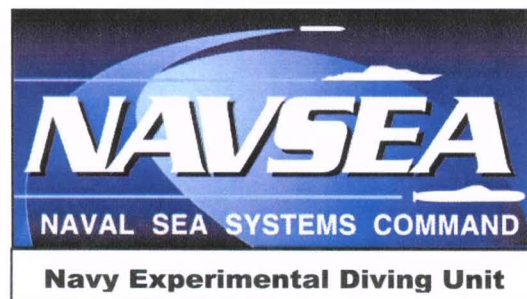


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DEVELOPMENT AND EVALUATION OF AN ONLINE AIR QUALITY MONITOR (DIVEAIR2) FOR DIVING COMPRESSORS



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19. ABSTRACT

The U.S. Navy Diver's Air Sampling Program coordinates the mandatory semiannual air purity testing of compressors used to supply diver's air in the Fleet. Gas sampling kits are sent to the field, where gas samples are taken. These samples are then returned to a contract laboratory for analysis, with the results subsequently reported back to the field. This approach is expensive, cumbersome, and potentially unreliable. Consequently, the U.S. Navy is interested in having a real-time, online air quality monitor to ensure that compressors deliver safe diving air. With the help of the manufacturer, Navy Experimental Diving Unit has developed and extensively tested an online air quality monitor (Anagas Diveair2, model DV 2.0, Geotechnical Instruments, Inc.; Leamington Spa, UK) for compressors supplying diving air for U.S. Navy operations. This monitor simultaneously displays levels of O₂, CO₂, CO, and volatile organic compounds, and it has many features designed specifically for the Navy: (1) an internal gas pump, (2) visual alarms, (3) datalogging capability, (4) a push-button program to automatically record peak gas values during testing, (5) temperature compensation of gas readings, and (6) passcode protection for calibration and other functions. The final version Diveair2 that we have tested should allow reliable real-time screening of diving air — provided that any hardware and procedures adopted for use in the field are verified to produce acceptable results.

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INTRODUCTION

The U.S. Navy Diver's Air Sampling Program coordinates the mandatory semiannual air purity testing of compressors used to supply divers' air in the Fleet. Gas sampling kits supplied by a contract laboratory are sent to the field, where gas samples are taken and then returned to the laboratory for analysis. Analytical results indicating pass or fail levels according to specifications for diving air in the *U.S. Navy Diving Manual*¹ are reported back to the field.

This approach is expensive, cumbersome, and potentially unreliable. Accuracy of results depends partly on gas collection procedures in the field, which can be difficult to perform correctly even under the best conditions. Relying on a contract laboratory also introduces concerns including the ensurance of accurate data and the long time delay between sampling and reporting of results. Consequently, the U.S. Navy is interested in having a real-time, online air quality monitor to ensure that compressors deliver safe diving air.

The benefits of an online air quality monitor for diving compressors might include:

1. providing continuous, credible data immediately to the person in the field;
2. allowing immediate retesting in case of questions and for troubleshooting problems;
3. eliminating potential sampling problems associated with collection of gas for later analysis;
4. eliminating current logistical requirements associated with sampling kit delivery and return;
5. allowing initial screening of ambient air at diving sites having suspect air quality (e.g., fuel-laden salvage sites) before compressor start-ups, followed by subsequent testing of compressor discharge air; and
6. allowing commercially obtained diving air to be tested by forward-deployed personnel.

Thus, use of these monitors could replace or supplement present methods that encompass the U.S. Navy Diver's Air Sampling Program. However, it is important to note that a decision about how any monitor will be used in the Fleet is the responsibility of Naval Sea Systems Command (NAVSEA 00C).

MONITOR DEVELOPMENT

The Navy Experimental Diving Unit (NEDU) has developed, with the help of the manufacturer, an online air quality monitor (Anagas Diveair2, model DV 2.0, Geotechnical Instruments, Inc.; Leamington Spa, UK) for compressors that supply diving air for U.S. Navy operations. This compressor monitor was adapted from an earlier version of the Diveair (model DV 1.1) described and evaluated in two previous reports,^{2,3} and it was designed to measure and simultaneously display levels of O₂, CO₂, CO, and volatile organic compounds (VOCs). Through an iterative process of repeated laboratory testing followed by manufacturer modifications in response to NEDU testing results, the Diveair2 prototypes initially delivered to NEDU were refined over a multiyear period to better meet requirements for air monitoring in the field. This report describes that effort.

MONITOR REQUIREMENTS

Air purity standards defined in the *U.S. Navy Diving Manual*¹ were used as the initial basis for the screening requirements of the compressor monitor:

O₂: 20–22%;

CO₂: 1,000 ppm (max);

CO: 20 ppm (max);

Total hydrocarbons (expressed in CH₄ equivalents, but excluding CH₄): 25 ppm (max);

Oil, mist, particulates: 5 mg/m³ (max); and

Odor: not objectionable,

where ppm = parts per million, and mg/m³ = milligrams per cubic meter.

Initial monitor requirements are listed below as either “essential” or “desired but not essential,” although the feasibility of some of the essential requirements for any prototype monitor was difficult to predict in advance. Thus, we anticipated that our early testing of the prototype monitors would help refine these requirements by suggesting which requirements could be easily met, which could be possibly met only with some effort, and which could not easily be met. Comments listed below some of the requirements indicate either (1) our initial level of expectation for meeting the requirement or (2) some of the rationale for these requirements.

Essential requirements

1. Gases measured, measurement range, and units:

O₂: 0 to 25%

CO₂: 0 to 2500 ppm

CO: 0 to 50 ppm

VOCs: 0 to 20 ppm, expressed in isobutylene (or other species) equivalents

All four gases in balance N₂ are displayed simultaneously with indicated measurement units.

The measurement ranges for O₂, CO₂, and CO bracket the current *U.S. Navy Diving Manual* limits, which were expected to be the same as those used with the monitor. We chose to replace the total hydrocarbon measurement of the *Diving Manual* with the measurement of VOCs, which is a broader category including all hydrocarbons as well as other nonhydrocarbon species such as freons. However, any "total contaminant" measurement such as that for VOCs depends on the relative response factors of the VOC sensor being used for the contaminants in the air as well as the reference species used for calibration and quantification.

Isobutylene, one possible calibration gas to quantify VOCs, is nontoxic and currently used for calibrating photoionization detectors (PIDs) for other gas screening procedures in the Fleet and in the industrial workplace, and produces an intermediate PID response compared to many common VOCs. Sharing commonality with calibration standards for different applications in the Fleet may have added benefits, including (1) simplified Navy purchasing of gas standards, (2) a reduction in the number of different standards on hand, and (3) increased chances that a replacement calibration gas can be found at a dive site if the existing standard runs out. Although the VOC limit for any online compressor monitor could not initially be precisely defined, we expected that the 0–20 ppm isobutylene range would bracket any VOC limit chosen in the future.

We chose to exclude the measurement of oil, mist, and particulates from our requirements for the monitor. Our experience with measuring oil, mist, and particulates in diving gas in the field³ suggested that attempting to accurately make such measurements with any online analyzer would be difficult, if not impossible. NAVSEA 00C agreed with this decision and believed that, even without an ability to measure oil, mist, and particulates, the air quality monitor would still be a valuable tool for the Fleet. One assumption behind using a monitor with this limitation might be that proper maintenance of the particulate filters in any compressor system should minimize the chances for significant particulate contamination to occur. However, we emphasize that the decision to delete that particulate requirement from the monitor was neither a recommendation to change any current U.S. Navy air standards nor an argument that particulate measurements were unimportant.

2. Display resolution (minimal):

O₂: 0.1%
CO₂: 10 ppm
CO: 1 ppm
VOCs: 0.1 ppm

3. Single unit requirement: all four components monitored with a single analyzer.

4. Operating and storage conditions:

Pressure: ~1 ATA (atmosphere absolute)
Temperature: 0 to 50 °C
Relative humidity (RH): dry to ~90 to 100% (noncondensing)

The temperature requirement is expected to bracket the range of ambient air temperatures of many but not all diving operations and to be achievable in view of current technology for portable gas analyzers. However, our experience suggests that portable gas analyzers commonly have problems compensating for changes in ambient temperatures. Thus, when used at ambient temperature extremes, such analyzers may be less accurate than they otherwise are.

The compressor discharge air is expected to have a relatively low water vapor pressure (and thus low RH) unless a failure occurs in the driers. However, in locations where suspect ambient air quality may exist, such as at accident sites during salvage operations in fuel-laden water, the compressor monitor may also be used to sample the ambient air before the compressor starts up. For such ambient air, the entire range of relative humidities is possible, as reflected in the requirement. The capability to sample the ambient air, and thus the compressor intake air, may prevent contamination of the compressor and its hardware that could occur if it is operated when high VOC levels exist.

5. Gas sampling pump: to allow sampling of ambient air, as described in requirement #4.

6. Water resistance: When not in use, analyzers will be stored inside, but they may commonly be operated outdoors. Although they will not be expected to tolerate direct exposure to inclement weather (e.g., rain and wind) and should be sheltered from such conditions, some exposure to precipitation will undoubtedly occur.

7. Portability: fixed in place at the compressor but easily removed and connected to another compressor.

At sites with several or more compressors, portability should significantly reduce the number of monitors required, as monitors would be connected only to those compressors in operation.

8. Electrical power: powered by rechargeable batteries, capable of continuous operation without recharging for periods greater than eight hours.

Batteries are expected to be recharged before use. The desire is to be able to leave the monitor attached to the battery charger, when convenient, until the next use; this will ensure that the batteries are fully charged when the monitor is needed. However, in situations where the monitor may be stored, batteries will need to be checked and recharged immediately before use.

9. Alarms: visual and audible, with selectable limits.

To alert the compressor operator of a possible problem, a visual alarm should be visible from at least 50 ft away in all directions. An audio alarm was initially also desired, but it was decided that such an alarm would be difficult, if not impossible, to be reliably heard in the noisy environment of an operating compressor.

10. Backlight for display: to allow a display to be read in low-light areas.

11. Simplicity of operation: a standalone unit (e.g., one that does not require a computer or other type of controller) to be operated by Navy diving personnel. The only exception to this requirement would be that any datalogging capability would presumably require a computer for downloading data.

12. Ruggedness: stable electronic and mechanical operation under the field conditions expected at compressor sites, including shipboard use.

Desired but not essential requirements

1. Calibration in field: zero and one-point span for all four sensors together at ambient temperatures of 19–25 °C (66–77 °F), “normal room temperatures.”

Zero: hydrocarbon-free, CO₂-free N₂

Span: nominal mixture of 21% O₂, 1000 ppm CO₂, 20 ppm CO, 10 ppm isobutylene or other VOC, balance N₂

A single zeroing and a single spanning step will be the most efficient calibration procedure. Spanning sensors with one gas standard containing O₂, CO₂, CO, and a selected VOC, with all four gases at concentrations approximating the screening limits, will minimize measurement errors about these concentrations. The isobutylene concentration is expected to be close to the VOC limit finally chosen.

Calibration at “normal room temperatures,” followed by use of the monitor at more extreme temperatures, would be desired, as this procedure can be evaluated easily in the laboratory. Such evaluation is important, as requirement #4 of the **Essential requirements** section notes that the monitors are expected to be less accurate at ambient temperature extremes than at nonextreme levels. However, our experience with field testing has shown that the temperatures of work spaces commonly used for instrument setup and calibration in the field is often minimally controlled. Because of such differences between lab testing and field use of the monitors, predicting instrument performance in the field may be difficult, a fact emphasizing the need for field testing.

2. Precision, defined as repeatability of short-term (within 10 min) test results, as determined by sampling the calibration span gas in the laboratory:

O₂: ±0.2% absolute (1% relative of 21% O₂)
CO₂: ±50 ppm absolute (5% relative of 1000 ppm CO₂)
CO: ±2 ppm absolute (10% relative of 20 ppm CO)
VOC: ±0.5 ppm absolute (5% relative of 10 ppm isobutylene)

A well-designed analyzer should be expected to meet these levels of precision.

3. Short-term accuracy over measurement and temperature ranges within eight hours of calibration, as determined in the laboratory:

O₂: ±1% (5% relative of 21% O₂)
CO₂: ±100 ppm (10% relative of 1000 ppm CO₂)
CO: ±2 ppm (10% relative of 20 ppm CO)
VOC: ±1 ppm (10% relative of 10 ppm isobutylene)

Even if we assume some increase in error in the field, this level of accuracy in the laboratory should meet the need for reliably monitoring diving air. However, until laboratory testing is done, it is unknown whether such accuracy can be achieved at the extremes of the temperature range.

4. Sensor life: more than one year for all four components.

5. Response time: less than 60 seconds to 95% of reading.

This response time should be more than adequate, as gas concentrations in compressor air should not change quickly.

6. Weight: 10 lb or less.

Some flexibility exists with the weight requirement — although the lighter, the better.

7. Dimension limits: 30 cm X 30 cm X 30 cm (1' X 1' X 1').

Although a large, bulky monitor would be undesirable, some flexibility exists for this requirement.

8. Chemical interferences: accuracy limits of all four components met with sample concentrations of CO₂, CO, and VOCs (isobutylene and other VOCs that might be expected to commonly occur in diving air) at expected screening limits.

Laboratory testing will determine whether this requirement can be met.

INITIAL PROTOTYPE MONITORS

Three prototype Diveair2s — serial numbers N0255, N0256, and N0257 (which will be noted in this report as #255, #256, and #257) — were initially delivered to NEDU in February 2003. These analyzers displayed levels of O₂, CO₂, CO, and VOCs with all four readings updated every second. The displayed readings represented the actual readings at that time for O₂, CO, and VOCs, whereas the CO₂ reading was a 20-second moving average. Display resolution was 0.1% O₂, 10 ppm CO₂, 1 ppm CO, and 0.1 ppm VOC. A small internal pump drew a gas sample into the unit, where O₂ and CO were measured with separate electrochemical detectors. CO₂ was measured with a nondispersive infrared detector, and VOCs were measured with a PID.

The biggest difference between the new Diveair2 and the previous Diveair was the addition of a VOC sensor in the new model. The PID selected for monitoring VOCs contained an internally sealed light source emitting at an energy level (10.6 eV) that can ionize some, but not all, gases. The total ion current detected by the PID during gas sampling is used to quantify the VOCs. Small, usually nontoxic gases (e.g., CO₂, CO, methane, many freons) give little or no response by the PID. However, many toxic gases such as aromatic hydrocarbons can be detected down to 1 ppm. The PID also responds to many inorganic gases. The energy of the PID in the Diveair2 is slightly greater than the 10.2 eV of the shipboard PID (a trace gas analyzer) used routinely to screen the submarine atmosphere, so both sensors should have similar responses to VOCs.

Upon our request, the Diveair2 manufacturer added a VOC filter, external to the analyzer case, in the gas pathway to the CO sensor. This filter was designed to remove the VOCs to prevent them from possibly affecting the CO sensor: such an effect can be a common problem with these sensors. Although most CO sensors generally contain filter material designed to reduce cross sensitivity to VOCs, our experience with the early Diveair2 instruments suggested that such filters may deteriorate over time, a deterioration causing the CO sensor to develop an undesired sensitivity to VOCs.

Both audio and visual alarms of the Diveair2 were triggered when the concentration of one or more of the four gases was below (O₂) or above (CO₂, CO, and VOCs) the alarm limits, which could be set by the user. The alarms consisted of a relatively soft beeping

and blinking of the display components that are outside their limits. The audio alarm could be muted (and reversed to audio) by a single keystroke. Once activated, both alarms were configured to stop as soon as the gas concentrations returned to acceptable levels.

Preliminary testing of the Diveair2s revealed a CO₂ drift problem and the need for a datalogging function for our evaluation. Thus, all three Diveair2s were returned to the manufacturer in late March 2003 to correct this problem and to allow Geotechnical Instruments to develop and install datalogging software. All three monitors were returned to us in June 2003 after these tasks were completed, and detailed testing then began.

The added datalogging function of the Diveair2 allowed logging of readings at intervals of every 1 to 60 min. The data could then be downloaded by using the Diveair2 software, after the air monitor had been connected to the RS232 serial port of a personal computer with the supplied lead. In addition, the Diveair2 was equipped with a special program that displayed the highest ("peak") values of three of the gases (CO₂, CO, and VOCs) and the lowest value of O₂ during any specified time period; this function could be started and stopped with single keystrokes on the monitor's keypad. In this report we will refer to this function as the "peak program."

Two additional Diveair2s, serial numbers N0294 and N0295 (noted in this report as #294 and #295), were delivered to NEDU in September 2005; a third unit, serial number N0296 (#296), was received in January 2006. These three monitors were obtained in preparation for field testing and were tested in the laboratory in a fashion similar to that of the original three units.

SUBSEQUENT MODIFICATIONS TO MONITORS

As laboratory testing proceeded, the initial Diveair2 prototypes were refined to better meet NEDU requirements through an iterative process of repeated testing followed by manufacturer modifications. We list directly below the significant modifications that were made to the initial prototype monitors.

1. Alarms

In response to our request, an external alarm light was added in 2004 to the outside of the instrument, so that this flashing light would be visible at a distance (e.g., 50 yards) from all directions. Two alarm modes that were user selectable were also provided. In addition to the original "nonlatching" mode in which the audio and visual alarms stopped once the gas concentrations became acceptable, the user could select an alternative "latching" mode so that, once triggered, the alarms would continue even if the gas concentrations returned to acceptable levels. The latter mode would be useful during compressor testing to ensure that even when test personnel were briefly away from the immediate area, they would not miss a transient alarm.

2. VOC filter

The VOC filter was originally located on the outside of the instrument case and connected to tubing in line with the gas flow to the CO sensor. However, the filter was exposed and unprotected, and the external tubing to which it was connected potentially could become kinked if it were accidentally bumped. Furthermore, the analyzers with these VOC filters would not fit into their soft carry case for ease of transport and added protection. To expedite the project at the start of testing, NEDU and Geotechnical Instruments acknowledged this VOC filter arrangement to be a temporary one. No problems appeared, as NEDU carefully handled the instruments during its initial laboratory testing. However, harsher treatment — potentially resulting in filter and tubing damage — would undoubtedly occur in the field.

In 2006 the manufacturer thus introduced an additionally protective and rugged VOC filter arrangement. With sturdy plastic supports permanently mounted on the monitor case to hold the filter, this modification eliminated the external tubing leading to it. When replacing the filter became necessary, the new design allowed it to be easily removed by unscrewing the two end-caps in the filter holder and then gently pushing the filter out of the holder. The soft carrying case was also modified to accommodate the monitor with its new filter arrangement.

3. Temperature compensation

Early versions of the monitor contained manufacturer-developed temperature compensation of the CO₂ sensor to reduce measurement error in cold and hot conditions. No such factory-added compensation for changes in ambient temperature existed for the other three sensors. Our laboratory testing at different ambient temperatures revealed significant effects of cold and heat on some of the sensor readings: details are described below in **LABORATORY TESTING**. As a result, the manufacturer subsequently developed and installed additional temperature compensation of the O₂ and CO sensors in 2006, and NEDU tested these in the laboratory. We were told that the correction to the CO monitor involved an engineering design change, whereas the O₂ readings were corrected for temperature by use of a mathematical model derived from some of our previous data.

LABORATORY TESTING OF PROTOTYPE MONITORS

TEST SUMMARY

The Diveair2s were evaluated in the laboratory for

1. precision (in terms of repeatability of test results over a 10-minute period);
2. accuracy (immediately after calibration, short-term [up to approximately five hours after calibration], and long-term [up to one month after calibration]);

3. effects of ambient temperature inside a chamber at 5, 25, and 42 °C;
4. instrument stabilization and signal noise;
5. cross sensitivity of sensors to the components of the calibration gas;
6. effectiveness of the VOC filter;
7. battery duration;
8. effects of RH from ~0 to ~95%; and
9. overall performance, including ease of use.

In addition, operating procedures based on the manufacturer's recommendations were developed and revised where necessary.

METHODS

Instruments were stored, calibrated, and tested (except for the temperature testing) at laboratory temperatures between 22 and 26 °C. During periods when instruments were not being tested, the analyzers were turned off, connected to their battery chargers, and stored on the laboratory bench. Analyzers were tested in two laboratory locations: on the laboratory bench and inside a temperature-controlled test chamber. During bench testing, analyzers were either connected or not connected to their battery chargers, according to the test protocol. To evaluate the effect of temperature on performance, the instruments were disconnected from their chargers to allow testing inside the test chamber.

During all use of analyzers — including warm-up, calibration, and testing — the internal gas sampling pump was always turned on. To prevent the instrument alarms (both audible and visual) from triggering during calibration and testing, analyzer software was used to reset the alarm limits at <0.0% for O₂, >5000 ppm for CO₂, >100 ppm for CO, and >50 ppm for VOCs. This procedure was effective, except for cases when the O₂ readings were <0.0%.

At the beginning of and at frequent intervals throughout each test day, ambient temperatures were recorded within one foot of the analyzers with a digital Thermanen thermometer (model 211076, Electronic Temperature Instruments; West Sussex, UK). Barometric pressures in the laboratory were recorded with a digital barometer (model AG400, Sensotec; Columbus, OH) that had been calibrated within the year by the manufacturer. When analyzers were inside the chamber, ambient temperatures outside but close to the chamber were recorded. In addition, the battery status was recorded at

the beginning of each test day approximately five minutes after instrument start-up, as well as at other times throughout the day.

The following gases were used during testing:

1. 100% N₂: CO₂-free, hydrocarbon-free (will be referred to as “zero N₂” or “zero gas”). This was used for zeroing all four sensors during calibration and as a diluent for testing with the precision gas divider, as described in paragraphs following this listing.
2. Span gas: a gravimetric standard of a nominal concentration of 21% O₂, 1000 ppm CO₂, 20 ppm CO, and 10 ppm isobutylene, balance N₂. This was used for spanning all four sensors during calibration and for evaluating instrument performance.
3. A gravimetric standard of a nominal concentration of 2500 ppm CO₂, balance air: this was used to check other sensors for sensitivity to CO₂.
4. A gravimetric standard of a nominal concentration of 50 ppm CO, balance air: this was used to check other sensors for sensitivity to CO.
5. A gravimetric standard of a nominal concentration of 20 ppm isobutylene, balance air: this was used to check other sensors for sensitivity to VOCs and to test the VOC filter upstream of the CO sensor.

All standards were obtained commercially and certified to $\pm 1\%$ relative or better. Measurement results necessarily reflect the error associated with the reported concentrations of the gas standards.

The span gas concentrations for O₂, CO₂, and CO were chosen to approximate the expected limits that would be used to judge the safety of the air, limits based on current *U.S. Navy Diving Manual* guidance. This approach should minimize measurement errors about these limits. For our initial evaluation, the manufacturer fixed the values of the four components of the span gas in the software at 21.0% O₂, 1000 ppm CO₂, 20 ppm CO, and 10 ppm isobutylene. These span values would be expected to be slightly different from the actual values of any calibration gas. However, this discrepancy should not affect our testing results, since we were concerned not with the absolute concentrations but rather with the instrument performance in terms of precision, linearity, and the effects of other factors. A later version of the instrument software allowed actual span gas concentrations to be entered by the user.

Up to three analyzers were tested together at a time. During calibration and testing, gas was delivered to all of them simultaneously through a branching circuit of Teflon tubing with a precision gas divider (STEC Model SGD-701, Horiba Instruments, Inc.; Ann Arbor, MI; Fig. 1). This branching circuit was joined together by stainless steel and chrome-plated connections and included a side branch with an attached flowmeter — to allow a slight overflow that ensured adequate but not excessive gas supply to the analyzers while it minimized back pressure (<1 psi). A short (~2 cm) piece of Tygon

tubing was used as a butt connector to join the branching circuit to the metal tube connector serving as the inlet of the analyzer. Contact of gas with the Tygon was carefully minimized. Our gas delivery system will be referred to as an “open-split” system.

For both bench and chamber testing, gas flow from the STEC device to the three analyzers was adjusted to produce an overflow of ~400 mL/min, although much higher overflows were demonstrated to have little effect on instrument readings. The only bench testing that did not use the STEC was that evaluating the effect of humidity, when the delivery gases were directly routed through a water bubbler and then to the instruments (see **Relative humidity** below).

The STEC device allowed blending of the four-component span gas standard with a diluent gas (here, zero N₂) in 10 equal steps of 10% each, from 0 to 100% of the standard concentrations. Using low ppm levels of VOCs and up to 25% of fixed gases (e.g., O₂, CO₂), we have previously shown this gas divider to be linear to within the manufacturer’s specification of $\pm 0.5\%$ of full scale.⁴ With the STEC, an entire response curve could be generated from the 10 concentrations produced from a single gas standard. For this work, however, the actual STEC tests usually consisted of going from 0 to 100 and back to 0%, in five equal steps of 20% to reduce the total test time.

After each step change in the STEC, at least five minutes was allowed until readings were stable before the STEC was then adjusted to the next concentration. After reaching 100% and recording the first set of readings, we commonly left the STEC unchanged and made a second set of measurements 10 min later. The STEC was then stepped back down in 20% intervals to 0%, where again often two sets of measurements, 10 min apart, were collected. These repeated tests at 0% and 100% after five and fifteen minutes of gas flow were used to check the stability of readings over these time periods. The complete test, as just described, will be referred to as a “STEC test” in the remainder of this report.

The only significant change to this test was made partway through our testing, when the manufacturer recommended that we minimize the O₂ sensor’s exposure time to the O₂-free test gas to avoid the known effects of O₂ depletion on this sensor. As a result, we tried to limit all exposures to N₂ (STEC = 0%) to no more than approximately five minutes, and we thus began recording only one reading after five minutes at 0% at the end of all STEC tests.

During most testing on the laboratory bench, instrument readings were recorded manually on a data sheet after they had stabilized. However, datalogging (using a one-minute recording interval, the shortest available) was used to monitor the variability in readings over several hours. Unfortunately, it was not possible to log the data at shorter intervals (e.g., one second), which would have been useful to evaluate signal noise. Datalogging was also used when instruments were being tested inside the temperature-

controlled chamber, as poor visibility through the chamber ports prevented reliable viewing of instrument displays.

Start-up and calibration

Analyzers were commonly calibrated at the start of each test day, after instruments had been turned on and allowed to warm up for at least 30 min. However, for some protocols instruments were not calibrated daily but, after they had been turned on, were always allowed at least 30 min to warm up at the beginning of the day before any testing. The 30-minute warm-up was conservatively chosen to facilitate instrument stabilization for our testing, although we have successfully operated and tested other versions of these Geotechnical Instruments analyzers with only a five-minute warm-up.

Analyzers were calibrated on the bench, with the STEC delivering zero N₂ or span gas to all the instruments simultaneously. Before most calibrations, the calibration status of the instruments was checked by first supplying the span gas for five minutes, recording the stabilized readings, and then supplying the zero gas and again recording stabilized readings after five minutes. This test provided data on instrument stability since the last calibration.

Immediately after the precalibration checks, calibration was performed as described in the Diveair2 manufacturer's operating manual: all four sensors were first zeroed together following five minutes on zero N₂, and the post-zero readings were recorded immediately afterward. All four sensors were then spanned together after five minutes on the span gas, and the postspan readings were recorded. Zero gas was delivered by adjusting the STEC to 0, and span gas was delivered by changing the STEC to 100 while N₂ was used as the STEC diluent. The four-component calibration gas was used as the STEC standard.

Because of its poor performance observed with past Geotechnical Instruments analyzers, the factory calibration function (i.e., stored calibration parameters based on factory testing) on the monitor was not used or tested during our evaluation and is not recommended for Navy use.

Precision and accuracy

Short-term repeatability of results was determined by observing the range in monitor readings over a 10-minute period on the bench, while the monitor was sampling calibration span gas after first being allowed at least five minutes to equilibrate with that span gas.

We assessed accuracy by performing STEC tests on the bench at room temperature (between 22 and 26 °C) and inside the test chamber held within 1 °C at one of three temperatures: 5, 25, and 42 °C. Testing commonly involved first performing a morning STEC test on the bench or in the chamber at 25 °C, immediately after calibration and

precision testing (if done); this testing determined postcalibration error. A second STEC test was then done several hours later in the afternoon, either again on the bench or in the chamber at one of the three temperatures. For chamber tests, analyzers were allowed 30 min for temperature equilibration inside the already equilibrated chamber before the testing began.

The STEC tests determined not only short-term variability between repeated tests at ~25 °C during one day but also the effect of ambient temperature on instrument accuracy. Although our lower and upper test temperatures do not fully span the manufacturer's specification for the range in operating temperatures (0 to 50 °C),⁵ the range of test temperatures represents the extremes in those at which our chamber could be reliably maintained. We also performed one series of STEC tests over a nearly month-long period without recalibration to assess analyzer stability over time.

Instrument stabilization and signal noise

Following initial start-up, we evaluated how long it took for instruments to stabilize on the laboratory bench while they were sampling the span gas. For this testing we used datalogging at one-minute intervals over one to two hours. This testing also allowed signal noise to be evaluated, although it was not possible to log the data at shorter intervals (e.g., one second) that would have been useful to evaluate such noise.

Interfering gases

We also used the individual CO₂, CO, and or isobutylene gas standards (balance air) with the STEC at various settings to examine cross sensitivity of the analyzer sensors.

VOC filter

The effectiveness of the VOC filter upstream from the CO sensor was checked by delivering the isobutylene standard to the analyzers and observing the effect on the CO readings. To provide an unfiltered comparison, the CO response to VOCs was subsequently checked by a similar isobutylene challenge after the VOC filter was removed and replaced with a small piece of Teflon tubing.

Battery duration

Battery duration was tested frequently during this project by turning on the monitors, disconnecting them from the chargers, and recording battery capacity at regular intervals (e.g., every one or two hours) during the day.

Relative humidity

The effect of water vapor (i.e., RH) on instrument readings was examined by humidifying the span gas to varying degrees and sampling it with the analyzers. Water

vapor was added to the span gas by using two water bubblers connected in series and held at 35–45 °C in a water bath. The humidified gas was then blended with a flow of dry span gas to adjust to the desired RH.

For these tests, adjustment to a precise RH was not necessary and would have required time to achieve by using fairly coarse valves to repeatedly adjust and readjust the flows of the dry and wet gas. Instead, a dry (~0% RH), a wet (~95%, which was a humidity as high as we could achieve with our setup), and several in-between humidity levels were produced and delivered to the analyzers via the same branching circuit of tubing used with the STEC device. When stable, the temperature and RH readings of the gas delivered to the analyzers was measured from the overflow site on the gas delivery circuit just upstream from the analyzers by using a hand-held humidity and temperature meter (model HM70; Vaisala Oyj, Finland), with calibration traceable to the National Institute of Standards and Technology. Analyzer readings were recorded simultaneously with these measurements. Because of the potential for water in the bubbler to partially remove some components of the span gas, gas from the overflow was also analyzed by gas chromatography (GC; as in Lillo, Caldwell, and Porter³) to determine the actual concentrations of CO₂, CO, and isobutylene delivered to the analyzer. In this case the overflow line was connected with several feet of Teflon tubing to the sample introduction line of the GC gas sample valve.

Data collection and analysis

During calibration and some testing on the laboratory bench, instrument readings were recorded manually from the display after we had waited at least five minutes for values to stabilize following the switch to a new gas. However, as with any gas analyzer, the displayed values varied to some degree (i.e., the levels of precision), as they were updated every second. Thus, all data recorded manually in this way should be viewed as being within the range of precision reported in the **RESULTS AND DISCUSSION** section.

Datalogging with a one-minute recording interval (the shortest available) was used for most of the testing and was required when instruments were being tested inside the temperature-controlled chamber, since the chamber ports prevented reliable viewing of instrument displays. During workup of the logged data and before further analysis, the analyzer-generated data files were edited by deleting much of the data to produce one set of stabilized readings for each set of conditions (e.g., each STEC setting). As the logged data were recorded every minute directly from the displayed values, those data should also be viewed within the same level of precision as the displayed data.

All data were used to calculate absolute error:

$$\text{Error} = \text{observed reading} - \text{expected reading},$$

where the expected reading was equal to the product of the gas standard concentration and the STEC setting.

RESULTS AND DISCUSSION

We conducted formal testing of the prototype monitors in the laboratory from 2003 to 2007, with much of the data collected from interim versions of the monitor. Rather than present all the data we collected during the entire development and evaluation period, we will present only (1) some of the data demonstrating monitor performance problems that required modifications by the manufacturer and (2) sufficient data documenting the performance of the final prototype version.

General performance

During the development and evaluation periods, the six monitors were tested for hundreds of hours in the laboratory. Analyzers generally worked well without incident during most of the testing — although, as with any electrical instrument, especially unproven prototypes, occasional problems resulted. The display menu was easy to follow and simple to use, even with little training. Calibration by first zeroing and then spanning all four sensors together was efficient and without error in nearly all instances. Datalogging and downloading were easy to accomplish and invaluable for our laboratory evaluation.

Miscellaneous problems

In view of the amount of testing the six monitors underwent, the laboratory problems we encountered were relatively few but deserving of mention. We expect that many of these problems (particularly those related to the printed circuit boards [PCBs]) were probably symptomatic of our aging and repeatedly “tinkered-with” monitor inventory. Three units were nearly four years old by the end of the lab testing phase, and all our units had been sent back and forth multiple times to the manufacturer so that the factory could perform routine preventive maintenance and make minor repairs as well as modifications found necessary by our testing. Many of these modifications required changes to the PCBs.

1. Batteries

When disconnected from the charger and operated off fully charged batteries, analyzers normally operated for at least eight hours. When any monitor was found to operate for significantly fewer than eight hours following recharging and not to have been used within several weeks, the batteries of that monitor were given several cycles of charging followed by discharging — which often restored the battery to acceptable operation. These cases of shortened operating times undoubtedly resulted from the development of “battery memory” characteristic of nickel cadmium (NiCad) batteries. If battery operating time was still found unacceptable after battery cycling, we replaced the

batteries with new ones and conditioned the new batteries by several cycles of charging and discharging.

During all our testing, we observed only one set of batteries actually failing and preventing the instrument from being turned on. Because the monitors are powered by the battery and, even with the charger attached, will not turn on if the battery is dead or missing, our laboratory testing readily revealed failed batteries. We suspect that the low battery failure rate may at least partly reflect our policies of changing the batteries when battery life was found to be unacceptable as well as having the manufacturer replace them during the preventive maintenance that was performed several times on the six monitors during this multiyear project.

We experienced only one apparent failure with the battery charging system: one monitor required repair of the PCB by the manufacturer.

2. Alarms.

Other than occasionally confirming that the external alarm light would flash and the display would blink when the monitor was in the alarm mode, most of our laboratory testing was conducted with the monitor alarm limits set to prevent the alarms from triggering (as discussed above in the **METHODS** section). We therefore did not have much opportunity to determine whether any problems occurred with the alarms. However, we did observe that the external alarm light of one monitor stopped working early in 2007, and we returned this monitor to the manufacturer, where it was repaired.

3. PCB components.

In addition to the battery charging failure already described (see subsection 1. Batteries), we experienced a few other monitor problems requiring repair or replacement of PCB components. One instance (unit #256) involved an unstable CO sensor that was fixed. In another case, the monitor's liquid crystal display (LCD) "locked up" and thus left the monitor unresponsive to the keypad. This display problem reoccurred following an initial repair; the manufacturer then replaced the microprocessor, LCD, and backlight.

4. Display darkening.

We commonly observed LCD darkening in several monitors during laboratory testing in the heat (at 42 °C). Unfortunately, adjusting the contrast in these situations often did not produce a satisfactory result: the displayed information (gas readings or menu items) was still difficult, if not impossible at times, to read.

Precision

Precision is important to determine first, since any accuracy testing is affected by short-term changes in measurements. As determined by the range in monitor readings over a 10-minute period while span gas was sampled, short-term repeatability for the final version monitors was $\pm 0.2\%$ O₂, ± 20 ppm CO₂, ± 2 ppm CO, and 0.2 ppm VOCs.

Accuracy

Based on four instruments tested in the chamber at 25 °C immediately after calibration and plotted in Figs. 2A, 3A, 4A, and 5A, measurement error for the final monitor prototype version was on average

for O₂: $\pm 0.5\%$ absolute across the test range of 0 to 21%, but $\pm 0.3\%$ O₂ at the span value of 21%;

for CO₂: ± 60 ppm across the test range of 0 to 1000 ppm, but ± 40 ppm at the span value of 1000 ppm;

for CO: ≤ 2 ppm low across the test range of 0 to 20 ppm; and

for VOCs: ± 0.5 ppm across the test range of 0 to 20 ppm.

Test results show good consistency among analyzers (as shown by the overlap of their three plots) and over test days (as shown by the generally small standard deviations). These plots contain, as do all the STEC plots in this report, the two consecutive readings at 100% of the span gas for each test, as described in the **METHODS** section. The small amount of hysteresis with the VOC plots probably results from the monitor's relatively slow equilibration with isobutylene during periods of increasing and decreasing concentrations of the test gas. Because we did not round off the plotted averages in Figs. 2–5 (or any later figures) to the level of the monitor's resolution (i.e., 0.1% O₂, 10 ppm CO₂, 1 ppm CO, and 0.1 VOC for all displayed and logged readings), all estimates of instrument accuracy should be made only down to these levels of resolution, as our discussion has done.

Without recalibration between tests, short-term variability between two repeated STEC tests (the first in the morning, followed by a second in the afternoon) of three interim prototype units was low and, with the exception of that for VOCs, was equal to the resolution of the monitors. Based on five days of testing, the difference between morning and afternoon tests was on average

for O₂: $\pm 0.1\%$ absolute,
for CO₂: ± 10 ppm,
for CO: ± 1 ppm, and
for VOCs: ≤ 0.2 ppm lower in the afternoon.

The three monitors were tested for short-term variability before the changes discussed in the **SUBSEQUENT MODIFICATIONS TO MONITORS** subsection. The only subsequent change that might affect accuracy was the CO sensor's correction for ambient temperature.

Before reviewing the temperature testing data from the final version monitors, we will discuss the factory-added temperature compensation for the CO and O₂ sensors. Regarding the CO compensation, we present some data comparing the three monitors' responses to temperature during chamber testing before and after they received the CO temperature modification. The 25 °C tests were made in the morning immediately after calibration; a second STEC test then followed several hours later in the afternoon, at either 5 or 42 °C. On each of the three graphs in Figs. 6A–C, the premodified data are presented as solid symbols in the plots and denoted as "PRE" in the graph legends; the postmodified data are presented as symbols with crosshairs and denoted as "MOD" in the legends. For these three monitors, premodified CO readings ranged up to ~10 ppm low at 42 °C and up to ~10 ppm high at 5 °C. Even greater effects of temperature resulted in another monitor not shown here. Although the CO modification had no obvious effect on CO measurement at 25 °C, the modification greatly reduced, or even eliminated in some cases, the effect of heat and cold applied during testing on the CO readings, a reduction resulting in substantial improvements in accuracy. On the basis of our results, we adopted the CO modification in going forward with this project. Unfortunately, other testing showed that the temperature compensation of the O₂ sensor that the manufacturer had developed and initially installed in two monitors for our evaluation seemed to increase the effect of temperature on O₂ readings. Therefore, the O₂ correction was removed from these two analyzers and not adopted as testing went forward.

Figs. 2–5 present some results from STEC tests performed in the chamber on four of the final version monitors at the three test temperatures. The 25 °C tests were done in the morning immediately after calibration, with second tests in the afternoon at either 5 or 42 °C. All three monitors contained the factory-added temperature compensation of the CO monitor adopted for the final Navy unit. Testing showed that monitor readings on average were affected by ambient temperature as follows:

1. O₂ error increased from $\pm 0.5\%$ absolute at 25 °C up to $\pm 1\%$ absolute at both 42 and 5 °C across the test range of 0 to 21%.
2. Whereas CO₂ error was ± 60 ppm at 25 °C, at 42 and 5 °C CO₂ readings were up to 150 ppm higher than expected across the test range of 0 to 1000 ppm.
3. CO readings were ≤ 2 ppm lower than expected at both 25 and 42 °C, and ≤ 4 ppm lower than expected at 5 °C, across the test range of 0 to 20 ppm.
4. Whereas VOC error at 25 °C was ± 0.5 ppm across the test range of 0 to 20 ppm, at 42 and 5 °C VOC error tended to be somewhat greater than that at 25

°C, especially at the higher VOC concentrations.

Overall, heat and cold generally increased the variability of response among the monitors for all four gases.

Beginning on the afternoon of the first day and repeated on four additional days up to 26 days thereafter in July 2003, one long-term accuracy test was conducted with three early version monitors to compare the differences between monitor postcalibration readings taken during the first STEC test in the morning and subsequent readings taken without recalibration. These results should indicate calibration stability over the test period, and any significant change in monitor readings from the initial postcalibration measurements should reflect a change in calibration status. Results from the three monitors over the nearly month-long testing show that

1. Subsequent readings for O₂ varied $\pm 0.2\%$ absolute from postcalibration values.
2. Subsequent readings for CO₂ were from 20 ppm higher to 60 ppm lower than postcalibration values.
3. Subsequent readings for CO varied ± 1 ppm from postcalibration values.
4. Subsequent readings for VOCs were from 0.3 ppm higher to 0.5 ppm lower than postcalibration values.

For each of the four gases, the variability between postcalibration values and subsequent readings during the test period appeared to be similar among the three monitors.

Instrument stabilization and signal noise

Stabilization tests, each lasting up to two hours with three final version monitors, were conducted in January 2007 with datalogging at one-minute intervals (the most frequent logging possible). Results showed that O₂, CO₂, and CO readings generally stabilized nearly immediately upon start-up of the monitors, with most of the short-term changes occurring thereafter within the level of precision reported above in the **Precision** subsection: $\pm 0.2\%$ O₂, ± 20 ppm CO₂, and ± 2 ppm CO.

For VOCs, monitor #294 immediately following start-up exhibited an initial period of approximately eight minutes when both the displayed and logged VOC values were 0.0 ppm. This monitor then began displaying expected span gas readings and quickly stabilized for the remainder of the test, again within the previously reported levels of precision: ± 0.2 ppm VOC. This delay phenomenon was observed other times during our start-up testing. For example, in a similar test on another day, monitor #255 showed a delay of approximately four minutes before it displayed VOC readings. Although we

routinely did not closely observe monitor displays immediately after start-up during most of our other testing, we suspect that such delays in VOC function may be common and may result from differences in monitor electronics warm-up times that affect when the PID sensor is activated.

Due to the minimum one-minute datalogging intervals, we were unable to evaluate signal noise of the sensors, other than to observe second-to-second changes in the display, as reported in the **Precision** subsection above.

Individual cal gas testing

We never observed cross sensitivity of the four sensors when tested with the individual CO₂, CO, or isobutylene gas standards (nominally 2500 ppm CO₂, 50 ppm CO, and 20 ppm isobutylene) at various STEC settings and with the VOC filter in line upstream from the CO sensor.

VOC filter

As noted in the **Interfering gases** subsection, challenging the CO sensor with isobutylene gas and the VOC filter in place was never observed to produce a response. However, following removal of the VOC filter from three of the interim prototype units during testing in December 2003, exposure to 21 ppm isobutylene produced readings of up to 7 ppm CO in two of the monitors (#256 and #257), but no CO response in monitor #255. We suspect that these results in the first two monitors indicate a deterioration of the filter material commonly incorporated in the CO sensors and in the third monitor a sensor filter still effectively operating. Although this testing was done less than one year from initial delivery of these monitors to NEDU, the sensors had been subjected to many hours of exposure to test gases containing isobutylene, which should decrease the lifetime effectiveness of the filters. Therefore, the external VOC filter should be expected to perform a useful backup function, particularly when monitors are frequently exposed to span gas containing isobutylene during calibrations.

Relative humidity

When sampling span gas over a range of RHs from ~0 to ~95%, we observed that instrument readings differed from the span gas concentrations only within the level of precision (reported above in the **Precision** subsection; see Table 1). Results from GC analysis showed that wet test gas (95% RH) contained ~97% of the CO₂, CO, and isobutylene of dry test gas, a reduction in these gases explained by the estimated water vapor pressure in the sample gas and based on the RH and temperature measured in the overflow gas at the time of the GC analysis. As these reductions in gas constituents are likewise within the level of precision, it is not surprising that we did not observe obvious effects in the monitors' readings when we sampled the wet gas. Although the components of the span gas, particularly CO₂, would be expected to dissolve readily in water, the GC data suggest that saturation of the water in the bubbler of the humidifying

system had occurred before testing started: no additional reduction was evident in the components of the span gas due to gas solution in the bubbler.

When compressor discharge air is sampled, concern about the effect of humidity on a monitor's readings should be minimal, as this air is expected to be very dry unless the drier system fails or another hardware problem occurs. A more likely concern about humidity is with sampling ambient air — for example, at a salvage site — to confirm the air quality before the compressor system is activated. Despite reassuring results from our humidity testing, we are unsure of what the most appropriate laboratory test(s) might be for using the monitor in the field. One issue is that any potential humidity effect on the monitor might be altered if condensation were to occur within the instrument (e.g., possibly when warm humid gas is sampled with a cold instrument) or if the RH of the test gas were to decrease as the gas flows through the monitor (e.g., possibly when gas is sampled at ambient temperatures below the monitor's internal temperature). Of these two scenarios, we believe the latter is more likely, as the heat generated by the monitor's electronics should elevate its internal temperature above the ambient level.

CONCLUSIONS

1. Our extensive testing showed that the monitors generally worked well, were easy to use, and had many useful features including datalogging and visible alarms.
2. Laboratory testing demonstrated that the final version prototypes met or came close to meeting many of the important requirements identified in the **MONITOR REQUIREMENTS** section.
3. As reported from our laboratory testing, the few significant miscellaneous problems (e.g., PCB component failures) are expected to decrease in frequency or to go away (e.g., display darkening in the heat) in the final production version (see the **"REBOXING" OF MONITORS** section below).
4. Immediately following calibration, the accuracy of all four sensors was good at 25 °C and remained so during short- (three- to five-hour) and long-term (up to one month) testing.
5. Accuracy of the monitors in the cold (5 °C) and heat (42 °C) was not as good as we liked, although the temperature modification for the CO sensor greatly improved performance at temperature extremes. However, our experience suggests that the accuracy of many, if not all, portable gas analyzers are affected to some degree by ambient temperatures, and further reduction in the effect of temperature on these monitors probably would require substantially more effort and cost than we have expended so far. Nevertheless, one strategy for field use might be to allow the monitor to equilibrate to the ambient temperature near the compressor before it is calibrated and used.

6. The VOC filter in line with the CO sensor appeared to remain effective during the entire testing period, although we did not test its operating duration, and this filter should provide a useful backup in case of a sensor-filter compromise.

7. From limited data, we find that instruments stabilize nearly immediately upon start-up — except for the VOC sensor (as shown via PID readings), which may experience a delay in turn-on. Once the PID has turned on, however, the VOC readings also quickly stabilize. These laboratory data suggest that at least following monitor storage at room temperatures, little or no warm-up is needed before monitor use.

8. Although we were unable to fully evaluate signal noise of the sensors in the laboratory, by updating displayed gas values at one-second intervals, the monitor does not require high-speed sampling, where noise could cause problems.

9. Although humidity was shown to have negligible effects on the monitors in the laboratory, we are unsure whether water vapor will be a problem during ambient air sampling in the field.

FIELD TESTING OF PROTOTYPE MONITORS

TEST SUMMARY

Field testing consisted of using the monitor to screen the output air from one or more compressors at each of three on-shore sites at weekly (recommended) intervals over an approximately six-month period. The three sites were the Navy Diving and Salvage Training Center (NDSTC), Panama City, FL; the Mobile Diving and Salvage Unit One (MDSU-1), Pearl Harbor, HI; and the Mobile Diving and Salvage Unit Two (MDSU-2), Norfolk, VA.

Test procedures (including data sheets) were defined in a written test plan, which was slightly different for each site to accommodate hardware differences among them. Testing evaluated (1) measurement stability over time, (2) measurement accuracy, (3) operational reliability of the monitor and the air-sampling device (which, along with its associated hardware, will be identified as the “air-sampler”) used to connect the monitor to the compressor, (4) needs for any changes to the procedures or the monitor, and (5) ability to train on-site personnel to use the monitor.

EQUIPMENT

The equipment supplied by NEDU and delivered to each test site was as follows:

1. Two Diveair2 monitors with
 - a. two extra VOC filters and two extra pairs of battery sticks (one battery pair needed for monitor operation),

b. two battery chargers, and

c. one copy of downloading software on CD and one downloading cable.

2. Two identical air-samplers (including associated hardware) — used to screen compressor air with the air monitor. Two versions of the air-sampler were custom made by the Navy and tested. One version incorporated all the hardware into a small pelican-type case that was opened and placed near the compressor during sampling: this version was used at NDSTC and MDSU-2. The other version incorporated the sampling hardware on a sheet of stainless steel hung near the compressor during sampling: this was used at MDSU-1. Both air samplers were designed to deliver both the calibration gases and compressor samples in the same “open-split” manner as in the laboratory, with an overflow of ~400 mL/min out a side branch in the gas delivery circuit. No other discussion of the differences between the two air-samplers will be given in this report.

3. Two high-pressure whips — 10,000 psi, stainless steel, Teflon core; one 10-foot whip and one 22-foot whip. These were used for connecting the air-sampler to the compressor sampling site. The shorter whip was preferred for ease of use, but a longer whip was included in case compressor location made it necessary.

4. Special connecting hardware (if any were needed) to connect a high-pressure whip to the compressor sampling site — this hardware was specific to the test site.

5. One set of Teflon tubing used for analyzer calibration and sampling, and several short (<1-inch) pieces of Tygon tubing “butt connectors” — these were used to connect the Teflon tubing to the monitor sampling port.

6. Three (two as spares) gas cylinders of zero N₂ (CO₂-free, hydrocarbon-free) — these were used for zeroing all four sensors and additional testing of the monitor.

7. Three (two as spares) calibration gas cylinders (span gas; primary gravimetric standard) containing four components in balance N₂: nominally 21% O₂, 1,000 ppm CO₂, 20 ppm CO, and 10 ppm isobutylene — these were used for spanning all four sensors and additional testing of the monitors. Copies of cylinder certificates were also included.

8. Three (two as spares) cylinders of isobutylene in air (~10 ppm; primary gravimetric standard). These were used for checking the status of the external VOC filter upstream of the monitor's CO sensor. Copies of cylinder certificates were included.

9. One high-purity regulator (CGA-580) for the zero N₂ cylinder.

10. One high-purity regulator (CGA-590) for both the calibration gas cylinder and isobutylene-only gas standard.

11. At least six high-pressure gas collection cylinders, previously evacuated — used for taking compressor air samples for subsequent analysis at NEDU — and cardboard tags for labeling cylinders. Two of these cylinders were used for initial training; additional cylinders were left for taking samples during actual testing.

12. One high-purity regulator configured with a high-pressure whip — 10,000 psi, stainless steel, Teflon core — and attachment hardware to take compressor air samples with the gas collection cylinders.

13. Teflon tape, used to wrap the pipethread end of the gas collection cylinders during their attachment to the gas sampling whip while air samples are collected.

14. Two digital thermometers, for measuring ambient air temperatures at compressor sites, and extra batteries.

All test equipment, except gases, was delivered to those involved with testing during a training visit (see the **TRAINING** subsection below) at the start of testing. All gases (zero N₂, span gas, and isobutylene) were delivered by commercial shipping before the training visit. The gas cylinders were returned to the vendor when testing was completed. Following the field test, all equipment was returned to NEDU.

The only equipment needed for testing and not supplied by NEDU was a personal computer, with a 9-pin RS232 serial port, to download data via the monitor's datalogging function.

TRAINING

All equipment (except gases) and copies of procedures and data sheets were distributed during an on-site training visit before the start of the testing. The two-day hands-on training consisted of

1. review of the test plan to detail exactly how the test was to be performed and data recorded;
2. instruction on using the compressor monitor and air-sampler — including having the on-site personnel step through the test plan, perform all the test procedures, and download the data to a personal computer; and
3. instruction on collecting air samples by using evacuated high-pressure cylinders.

At NDSTC, where field testing was first conducted, NEDU presented the training. At the other two sites, NDSTC personnel who had participated in the testing at their facility performed the training.

TESTING

Following the training, the actual testing by the on-site personnel began on a recommended weekly basis. During the testing, NEDU maintained communication with the testing personnel via visits (to NDSTC only, due to its proximity) or phone calls, FAX, and E-mail correspondence for the purposes of

1. discussing testing progress and problems,
2. transmitting data sheets and electronic data files, and
3. determining needs to adjust the test plan or procedures.

Testing recommendations

1. Appropriate hearing and vision protective devices were to be worn during testing.
2. The same people were to perform all procedures during a given test day.
3. To avoid exposing equipment to weather that might damage it (e.g., high wind, heavy precipitation), testing was to be postponed to another day if weather was inclement.
4. To minimize the risk of damaging the monitor, anytime gas was being hooked up and initially adjusted to the air-sampler, the monitor tubing was to be disconnected from the air-sampler.

Test procedures

1. When testing was not being done, all equipment was stored inside at the test location. At the start of each test day, the temperature of this storage area was recorded.
2. We recommended that air be tested via the air-sampler and the monitor at least one day every week from one or more compressors, at the sampling location given in Volume 1 of the *U.S. Navy Diving Manual*. On each test day, each compressor was to be monitored for at least one hour.
3. We recommended that, if possible, testing should be alternated between the two monitors and between the two air-samplers, so that on each test day a different monitor and different air-sampler were used from those that had been used during the previous test day. This procedure was to result in the testing of all the equipment.
4. If the monitor or any of the other test equipment did not appear to operate correctly, details of the problem were recorded on the data sheet. If the monitor or the air-sampler was suspected to have a problem, another monitor or air-sampler was substituted — to

determine whether the problem was resolved. If the problem could not be easily resolved, the testers were to contact NEDU immediately for help; if necessary, NEDU supplied a replacement monitor or other equipment.

5. All screening results and air collection information were either recorded on the data sheet provided or collected via the datalogging function of the monitor. When completed, all data sheets and datalog computer files were sent to NEDU via FAX (data sheets) or E-mail (data files).

6. The current U.S. Navy Diver's Air Program and its contract laboratory remained the standard for pass/fail assessments of diver's air during this testing period. The results from this testing were considered to be research data and not data to determine whether the compressor met the *Diving Manual* specifications for diving air.

7. At all three test sites, duplicate air samples were to be collected from the compressor in gas collection cylinders whenever unusual monitor readings were observed or an objectionable odor was detected, as these were situations when an ability to detect problems was important. In addition, during the first half of the testing at the first test site (NDSTC), cylinder samples were taken during each test day at the end of the compressor sampling period. All air samples were sent back to NEDU to be analyzed and compared to the measurements made in the laboratory. These samples were compared to the monitor readings to determine the accuracy of the monitor in the field, with the assumption that the lab analysis results from the cylinders were the true gas readings.

8. When not being used, the monitor was left connected to its charger. The monitor was disconnected from the charger at the beginning of each test day and turned on; the pump was turned on, and batteries were checked. Generally, all testing was done with the monitor operating off its batteries. However, if battery capacities were less than 90% after the batteries had been on the charger at least overnight, the testers were advised to contact NEDU, as the batteries might need to be replaced. If the charge was insufficient (<50%) at the beginning of the test day due to a human failure to have the monitor connected to the charger or due to some unknown problem, the testers were advised that the monitor could be used with line power via the battery charger if testing was inside and not exposed to the weather. Alternatively, the other monitor could be used, after its battery status had been checked.

9. To begin the test, the monitor and test gear were moved to an indoor location (one different from where the gear was stored), where calibration was done. Span gas settings of the monitor were checked to ensure that they agreed with the actual span gas concentrations, and alarm settings were checked to ensure that latching was off, so that if any alarms were triggered, they would stop once the gas concentrations were acceptable. Alarm levels for calibration were set to avoid triggering the alarms: <00.0% O₂, >5000 ppm CO₂, >100 ppm CO, and >050 ppm VOCs — with all concentrations listed in the format as typed into the monitor. The datalogging interval of the monitor was then set at one minute.

10. After the monitor had warmed up at least 15 minutes, monitor readings were recorded while first the span gas and then the zero N₂ gas were sampled just before calibration. Following initial zeroing, zero N₂ readings were again checked, and if any zero N₂ reading were greater than 0.2% O₂, 40 ppm CO₂, 1 ppm CO, or 0.2 ppm VOC, the monitor was rezeroed. Span gas readings were again checked, the monitor then spanned, and span gas readings again checked. If any gas reading were different from the span gas concentration by more than 0.2% O₂, 40 ppm CO₂, 3 ppm CO, or 0.3 ppm VOC, the monitor was respanded. Following complete calibration, zero N₂ readings were again checked.

11. The following procedures were then done to confirm the correct operation of the alarm function. The alarm levels were changed to <20.0% O₂, >1,000 ppm CO₂, >20 ppm CO, and >10 ppm VOCs, and span gas was again delivered to the monitor. These settings should have allowed the normal variation in the monitor's readings of the span gas to cause one or more of the gases to go into the alarm mode. When this occurred, the monitor tubing was disconnected from the air-sampler and, with the alarm latching still off, the alarm(s) should stop, as ambient air was sampled.

12. If the monitor's VOC filter had not been tested during the last three test days, the isobutylene test gas was delivered to the monitor and the CO reading recorded. If the CO were >1 ppm, the external VOC filter was replaced (as personnel had been shown to do during training), and the monitor was again checked with isobutylene.

13. The monitor and air-sampler were then moved to the sampling location to prepare to monitor the compressor discharge air.

14. Before sampling, each compressor was operated for at least 10 min to warm up. During the warm-up time, the compressor line was blown out through the sample site to remove any water and to equilibrate the line with the gas.

15. The air-sampler was then attached via its whip to the compressor line, the air-sampler purged with sample gas, and the monitor attached to the air-sampler.

16. The monitor's data memory was then cleared and datalogging started; the peak program, to collect the highest gas concentrations observed, was also started.

17. The compressor was run for at least one hour, and any information relevant to the test was recorded. This information included any procedures performed on the compressor, monitor alarms going off, monitor malfunctions, or the presence of objectionable odor in the sample gas.

18. If unusual gas readings were noted or an unusual odor were detected in the compressor area, monitor readings were recorded and duplicate air samples were taken from the compressor via the gas sample cylinders.

19. At the end of the testing period, the peak program was stopped and peak data recorded. Datalogging was then stopped, and the monitor was disconnected from the air-sampler.

20. The valve on the compressor line where the air-sampler was attached was shut, the whip connecting the air-sampler to the compressor line was bled down, and the air-sampler and whip were removed. The compressor was shut off or left running, as the testers desired.

21. The air-sampler and monitor were moved back to the calibration area, and the monitor's responses to span gas and then to N₂ were tested.

22. When testing was finished for the day, the battery status and ambient temperature were recorded, and the monitor was turned off.

23. The data was then downloaded from the monitor, which had been connected to a PC via the downloading cable and software supplied by the manufacturer.

24. Finally, all the gear was returned inside to the storage locations, and the monitor was connected to its battery charger until the next test day.

25. As soon as convenient, the data sheets were faxed to NEDU, and data files were sent by E-mail.

RESULTS AND DISCUSSION

Test summary

At NDSTC, a total of 24 test days was completed over a six-month period, April to October 2006. Three Navy personnel participated in the field test; all three participated for the entire test. Two people worked together during most of the test days. A total of three compressors were used during the test, although only one compressor was tested on any test day. Ambient temperatures ranged from 17 to 23 °C (mean = 20 °C) at the calibration site at the start of calibration, and from 21 to 30 °C (mean = 27 °C) at the end of testing.

At MDSU-2, a total of 12 test days was completed over a four-month period, February to June 2007. Six Navy personnel participated in the field test, although several participated for only one test day. One or two people worked together during each test day. Five compressors were used during the test, although only one compressor was tested on any test day. Ambient temperatures ranged from 5 to 28 °C (mean = 17 °C) at the calibration site at the start of calibration, and from 8 to 35 °C (mean = 22 °C) at the end of testing.

At MDSU-1, a total of 14 test days was completed over a five-month period, May to October 2007. Ten Navy personnel participated in the field test, although many participated for only one test day. Most of the testing was supervised by one person. One or two people worked together during each test day. At least eight compressors were used during the test, although with one exception only one compressor was tested on any test day. Ambient temperatures ranged from 18 to 28 °C (mean = 23 °C) at the calibration site at the start of calibration, and from 24 to 40 °C (mean = 33 °C) at the end of testing.

As we were interested to learn how well the equipment and procedures worked under less than optimal conditions, we also encouraged participants to conduct field tests when possible during deployments. However, this was not done at any of the three sites.

Calibration

Tables 2A–2C present calibration effectiveness and stability data during testing at the three sites. Monitor readings while zero N₂ and span gas were sampled are given (1) before the monitor was zeroed (“Pre-Zero”) at the beginning of each test day, (2) immediately following the zeroing procedure (“Post-Zero”) during calibration, (3) immediately following the spanning procedure (“Postspan”) during calibration, and (4) immediately at the end of the compressor testing. The one exception is that span gas was not tested before initial zeroing at NDSTC, and so those values are not listed in Table 2A. We give ranges, and not standard deviations, for the zero N₂ readings, since the monitor restricts the minimal displayed values (except for O₂) to “0” and thus confounds any attempt to calculate a meaningful standard deviation.

As judged by the postspan values for N₂ and span gas (and the small standard deviations for the latter), results from Tables 2A–2C suggest that calibration was generally done correctly. While sampling N₂, NDSTC reported some negative O₂ values that in all cases came from monitors that had been modified, partway through the field test, with an O₂ temperature correction described in **SUBSEQUENT MODIFICATIONS TO MONITORS**. After six days of field testing, this temperature correction was removed when the laboratory found that the correction seemed to increase the effect of temperature on the O₂ readings.

Since we recommended that the two monitors used for testing be alternated every test day (i.e., approximately every week), monitor readings of N₂ and span gas before initial zeroing of the instruments indicate the calibration status generally after at least a week following the last calibration of a monitor. Although the mean readings of the four span gases did not change much following complete calibration (when pre-zero are compared to postspan values), the standard deviations for O₂ and CO₂ decreased after the zeroing procedure and then again after the spanning, a result suggesting that changes in both zero and span settings were necessary since the last calibration.

Accuracy

Duplicate air samples were collected for subsequent laboratory analysis only at NDSTC, and only during the first half of the testing period under routine conditions. No samples were collected at the other two test sites. The NDSTC monitor readings agreed with the laboratory values for the fourteen sets of samples to within 0.3% for O₂ (with one exception) and within 60 ppm for CO₂. Monitor readings and laboratory results for CO and VOC showed very low (or nondetectable) levels of both constituents present. This level of monitor accuracy for O₂ and CO₂ is encouraging if we consider the number of potential errors associated with these tests, including those associated with gas collection in the field and analysis in the laboratory, and those associated with air screening the field. However, due to the relatively normal levels of the four constituents measured in all the samples, there is limited value of these accuracy tests for evaluating monitor performance under conditions where concern about air purity could occur.

Batteries

Although our experience has shown that battery readings may not be an extremely accurate gauge for judging remaining battery life for operating monitors, Table 3 shows that after testing lasting up to seven hours at the three sites, battery readings (maximum: 100) ranged from 10 to 80. Although batteries were sometimes reported to be low at the start of testing, this problem often was later attributed to failures to charge the batteries before testing. Overall, problems with operating the monitors on batteries did not appear for the duration of the test.

Peak gas values

Peak values in Table 3 did not reveal any significant problems with O₂, CO₂, and CO during the time the air was being monitored at any test sites. However, during three test days at MDSU-1, peak VOC readings approached or exceeded 10 ppm. One of these days occurred just after the compressor being tested had been rebuilt, and the logged data from this and one of the other two days showed that the VOC readings were close to peak values during most, if not all, of the one-hour test. Unfortunately, the data file was not available for the third day with a reported high VOC peak value.

Other problems reported during testing

1. The air-sampler's high-pressure regulator failed once at NDSTC.
2. When challenged with span gas, one monitor shut off on several different test days at the end of MDSU-2 testing. This gas test caused the alarm light to start flashing and soon caused the monitor to shut off. We attributed this shutoff to possible low batteries, although we could not duplicate this event with the same monitor in the laboratory.

3. The display of some of the monitors was observed to darken in the heat, an effect confirming in the field what we had already observed in the laboratory.

Tester comments

On-site test personnel were overwhelmingly enthusiastic about the monitor, found the procedures easy to perform, and commonly asked when the monitor would be available for Fleet use.

CONCLUSIONS

1. Field testing overall went well, with good comments from the testers about the monitor and procedures.
2. Field testing revealed no surprises about the reliability and performance of monitor and testing hardware.

“REBOXING” OF MONITORS

As laboratory testing was being completed, NEDU, NAVSEA 00C, and Geotechnical Instruments agreed that, based on testing results, additional modifications to the prototype monitor should be implemented before any monitor transition to the Fleet occurred. However, in the interest of not unnecessarily delaying the project, field testing as described was conducted with the latest version of the monitor before such additional modifications were made.

The most obvious and significant of the proposed changes was that of installing the monitor into a more rugged pelican-type case for better protection and transport. Consequently, the complete set of modifications accompanying the new case was designated “reboxing”; this term will also be used in this report.

In addition to putting the monitor into a different case, Geotechnical Instruments included the following modifications in its reboxing:

1. Updating the electronic boards and some other components. The original PCBs had been repeatedly altered during the development phase, and Geotechnical Instruments wanted to simplify their layout to improve its ability to manufacture and service them; however, the design of the circuitry was not changed.
2. Improving some software and fixing some software bugs. These changes included: displaying “LOGGING” on the main menu when logging is activated, and requiring a passcode to access important setup and calibration functions. However, a user without passcode access could turn on the instrument and its pump, check the battery, and monitor the four gases. The passcode was also

not needed to start and stop the peak program to display the highest (or for O₂, the lowest) values of the four components during a specific time period.

3. Replacing the existing pair of NiCad batteries with a nickel metal hydride battery. This change was to address new regulations governing use of heavy metals, which discouraged use of NiCad batteries, and to reduce common memory problems with NiCad batteries and extend the operating time following a single battery charge.
4. Providing a power cord that would be weather resistant and capable of powering the monitor continuously without a battery present.
5. Replacing the existing LCD with one more heat resistant. The darkening of the original LCD in the heat had been a common problem during laboratory and field testing.
6. Updating the keypad.
7. Installing the VOC filter inside, rather than outside, the monitor case for better protection.
8. Eliminating the original audio alarm of soft beeping. Since even an extremely loud alarm might not always be heard when compressors were being operated, there would now be no audio alarm.
9. Installing a different alarm light for the new case, a light better protected from physical damage than the original.
10. Changing the range of CO₂ measurements from 0 to 2500 ppm to a range of 0 to 5000 ppm, to accommodate other uses expected of the monitor — such as as screening air for ballast tank diving.

Although the original downloading software was DOS-based, old, and inefficient, no improvement or update to this software (such as a change to a Windows-based version) was implemented during the reboxing. The DOS-based version had proved adequate for our purposes during both laboratory and field testing, and a future need for downloading during actual compressor monitoring by Fleet personnel was uncertain. If improvement in the downloading software were later desired, Geotechnical Instruments would then have to spend what could be considerable time performing the upgrade.

Another downloading issue was the Navy's desire to change the original RS232 downloading connection to the newer USB connection. Unfortunately, Geotechnical Instruments indicated that this change was not possible with the current electronics, but it indicated that it could supply a downloading cable that would convert RS232 to USB.

REBOXED PROTOTYPES

Geotechnical Instruments sent NEDU the first reboxed monitor in August 2007 to review, comment on, and determine what additional changes (if any) would be desired. Following discussions with NAVSEA and Geotechnical Instruments, NEDU then returned this first reboxed monitor to Geotechnical Instruments to incorporate some agreed-upon changes and to build two additional identical units. The additional changes to be implemented included:

1. Installing cable ties to secure the two latches on the monitor case to discourage anyone from opening it. The date when these ties were installed was noted on them, to show when the case had last been opened.
2. Installing a more rugged battery holder, as Geotechnical Instruments acknowledged the battery holder in the first unit to be a temporary arrangement. The final battery holder used two screws (rather than only one, as in the initial unit) to secure the battery.
3. Installing a label with the monitor's serial number on the outside of the case, to allow it to be viewed without opening the case.

The three units delivered to NEDU in October 2007 for initial testing had most of the agreed-upon features. Due to a delay in obtaining new, more heat-resistant LCDs, Geotechnical Instruments provided units that still had the old LCDs.

INITIAL LABORATORY TESTING AND PROBLEMS

The goal of laboratory testing was to ensure that the performance of the new reboxed monitors at least matched that of the final version prototype. However, initial testing of the three reboxed units revealed the following problems, which delayed the start of final testing.

1. Drift in the O₂ readings. Following calibration, testing during the day often produced O₂ readings for span gas (21.0%) and lab air up to 0.7% higher than expected. Generally before calibration at the start of testing the next day, O₂ readings for span gas and lab air were back to normal. At the time, this drift was thought to possibly result from the heat of the new nickel metal hydride batteries on the O₂ cell and on the operational amplifier (op-amp) in the O₂ circuit. The new batteries were expected to create additional warmth during the faster charging in the reboxed units. Furthermore, this heating was more likely to affect the monitor electronics: the batteries were now in the same compartment with the electronics, whereas they had been in a separate compartment.

Solution: Geotechnical Instruments changed the O₂ op-amp to one less responsive to temperature.

2. Effect of battery charging. Following Geotechnical Instruments' changeout of the O₂ op-amp as reported in the preceding paragraph, we examined how connecting and disconnecting the battery charger affected gas readings for previously warmed-up instruments. In one of the two reboxed monitors we tested, O₂ and VOC readings instantly increased up to ~0.3% and ~0.4 ppm, respectively, when the charger was first connected. When the charger was disconnected either immediately or up to 25 min thereafter, these changes were instantly reversed, with readings returning to initial values. No such responses were seen with the second monitor. However, after being hooked to the charger, both monitors also displayed a gradual decrease of 0.5–2.5 ppm in their VOC readings over 15–20 min. When the batteries were disconnected, VOC readings slowly returned to the initial values observed prior to battery attachment. Without doing much additional testing, we hypothesize that during charging, (1) gas readings immediately respond to direct electrical effects, and (2) slower responses are due to battery heating.

Solution: It is probably best to avoid using the monitor when it is being recharged. Any final procedures for monitor use in the field should be based on our test procedures that have worked well during our laboratory evaluation. These procedures include: (1) charging the battery overnight, (2) disconnecting the monitor from the charger before start-up, (3) allowing an adequate warm-up time after the monitor is turned on for use (adequate warm-up time will be discussed in the **FINAL LABORATORY TESTING OF REBOXED MONITORS** section), and (4) calibrating the monitor (if required) and then testing it.

3. Battery display. The charge status displayed on the LCD of the new nickel metal hydride battery was found to be inaccurate and misleading in indicating the amount of useful battery life remaining.

Solution: Geotechnical Instruments subsequently tried to improve the accuracy of the battery display, but it acknowledged that achieving this goal would be difficult. The plot of battery use left vs. battery voltage is very flat, a plot which indicates a desired property of batteries for many applications.

4. Power supply. Geotechnical Instruments provided a "waterproof" AC/DC power supply and cord (model 2122 with an IP67 rating, Mascot Electronics; Fredrikstad, Norway) designed to plug into line power (110 VAC) and run the monitor with or without working batteries in place. Our testing confirmed that this power supply allowed the monitor to be operated in this manner. However, we felt that the configuration of the power supply — with its ~2 m long cord connecting the high-voltage side of the power supply to line power and another cord of similar length connecting the low-voltage side of the power supply to the monitor — introduced potential water/electrical safety problems. Since the waterproof IP67 rating, to the best of our knowledge, applies only to the power supply box, we are concerned about the likelihood that the high-voltage

cord could be easily exposed to the weather even if it were plugged into an electrical outlet located in a safe, weather-sheltered area.

Solution: We recommended changing the power supply from the Mascot model 2122 that comes with a line power cord to that of model 2123 — which instead incorporates an AC plug into the power box — and adding an ~10 m long low-voltage cord from the power box to the monitor. These changes would allow the box to be directly plugged into the AC power supply in a sheltered area, while the low-voltage power cord to the monitor would be the electrical component exposed to the weather. The 10 m length should meet the needs for most (if not all) anticipated field uses for the monitor. Of course, the monitor could always be operated off its battery, if needed. Geotechnical Instruments supplied one of these model 2123 power cords from Mascot for us to test.

5. Temperature performance of the PID sensors. Due to the O₂ drift problem, we delayed starting final testing of the three monitors, as well as examining how ambient temperatures affect monitor performance. However, while investigating the O₂ drift problem in #299, Geotechnical Instruments determined that the temperature performance of the PID sensors was worse than both its technicians and NEDU had observed in the final version prototypes. After contacting the supplier of the PID sensors, Geotechnical Instruments learned that the supplier had made changes to them — changes resulting in a new PID with an apparently greater response to changing ambient temperatures than that of the sensors in the Diveair2 prototypes before they had been reboxed.

Solution: On the basis of Geotechnical Instruments testing of #299, the company fitted it with temperature correction coefficients for the PID, something not required by the earlier version PIDs. Although the sensor supplier had told Geotechnical Instruments that all its PIDs performed similarly and therefore could be corrected for temperature in an identical fashion, subsequent NEDU and Geotechnical Instruments testing of units #263 and #298 after both monitors had been modified with temperature corrections from #299 suggested that temperature performance can vary among PIDs. This observation, which was subsequently confirmed by the sensor supplier, meant that each PID needed to be temperature tested to have its own coefficient determined.

Results in Fig. 7 summarize part of NEDU's considerable testing to investigate how temperature affected VOC readings of the initial reboxed units before formal testing began. Results for only #298 are displayed at the three test temperatures both before and after the PID temperature modification specific for #298 had been completed. As usual, the 25 °C tests were done in the morning immediately after calibration; a second STEC test was then done in the afternoon at either 5 °C or 42 °C.

As in Fig. 6 with the CO modification, the premodified data are presented in Fig. 7 as solid symbols in the plots and denoted as "PRE" in the graph legends; the postmodified data are presented as symbols with crosshairs and denoted as "MOD" in the legends. For #298, premodified VOC readings were significantly affected by heat: they ranged up to ~5 ppm high at 42 °C at the highest test concentrations. Although the VOC

modification caused minimal effects on measurement at 25 and 5 °C, the modification specific for the #298 PID sensor appeared to eliminate the effect of heat at 42 °C and thus to result in substantial improvements in accuracy.

6. Miscellaneous problems.

- a. During shipping that was required during testing, we found on one occasion that after we had received #263, this monitor did not turn on. After we manipulated the battery wires, we did get the instrument to operate — but we immediately returned #263 to Geotechnical Instruments to examine.

Solution: Geotechnical Instruments subsequently corrected the problem by replacing the microprocessor.

- b. The CO sensor in unit #299 failed. Symptoms were readings of 0 ppm for all test gases, including the span gas.

Solution: Geotechnical Instruments replaced the sensor.

Modifications before final testing

Unit #299 was modified with the O₂ and PID changes, a new LCD was installed, and this monitor was returned to us. We then completed some limited testing, which confirmed that #299's performance had been improved. Geotechnical Instruments then modified the other two reboxed units in an identical fashion, with the exception of the PID correction for #263 as discussed directly below, and returned them to us.

To expedite testing of the reboxed monitors, unique temperature corrections for the PID were developed for #298 (as they had been for #299) but not for #263, which showed temperature responses much less extreme than both other monitors. However, our conclusions in this report acknowledge that the PID response of #263 is not optimal, since that response was not based on its own PID.

FINAL LABORATORY TESTING OF REBOXED MONITORS

METHODS

The completed modifications discussed in the **Modifications before final testing** subsection gave us three nearly identical reboxed units to test in the laboratory. Testing of these monitors from May to July 2008 was similar to that done with the earlier prototype monitors described in the **LABORATORY TESTING** section, although repetitive testing in the 2008 studies was more limited. A few additional tests were also performed:

1. Two series of tests examined battery issues. The first series measured how

long the monitors operated on their fully charged nickel metal hydride batteries until shutoff, as indicated in the logged file by the last data entry using a five-minute datalogging interval. The second series compared the performance of the new power cord to the standard battery charger: comparisons were made for operating the monitor with a charged battery, a discharged battery, or a battery disconnected from the PCB.

2. In addition to examining the monitors' responses to individual CO₂, CO, and isobutylene gas standards to determine possible cross sensitivity of the analyzer sensors as we had done before, we tested a few VOC gas standards other than isobutylene to calculate relative PID response values for these VOCs.
3. We briefly checked the function of the three monitors' visual alarms when they were exposed to gases that should set the alarms off.
4. Following normal calibration, with two of the monitors we performed one test checking the accuracy of sampling the span gas from a 10 L Tedlar gas sample bag (catalog #231-08, SKC Inc.; Eighty Four, PA). The bag was purged two times with span gas and then filled partially, and span gas was allowed to flow into the bag via Teflon tubing from the supply cylinder. Each monitor was then separately attached to the bag via a second Teflon line that allowed the monitor to draw gas by its sample pump. This test was designed to approximate sampling ambient air — a procedure which, as discussed in the **INTRODUCTION** section, may be useful at suspect field locations (such as fuel-laden salvage sites) to confirm the suitability of such air for diving before compressors are started.

As with the prototype monitors, we do not present all the data we collected during final testing of the reboxed monitors. Rather, we provide sufficient data that documents the performance of the reboxed monitors in comparison to that of the final version prototype monitors, which NEDU (by using NEDU-designed sampling hardware) viewed as acceptable to the Navy.

RESULTS AND DISCUSSION

General performance

Tested for many hours in the laboratory, the three reboxed monitors generally worked well, although testing was much less extensive than it had been with the prototype monitors, and no reboxed monitor was field tested.

Miscellaneous problem

CO₂ sensor instability. During testing, the CO₂ readings in unit #299 were observed to occasionally fluctuate in large steps. For example, when span gas of nominally 1000 ppm CO₂ was sampled, CO₂ readings sometimes quickly decreased ~50% and remained so for up to several hours before returning to normal. When we attempted recalibration during these times, the CO₂ sensor failed calibration. Geotechnical Instruments traced the problem to the looseness of part of the optical bench that holds the CO₂ detector. Geotechnical Instruments repaired it, although the problem seemed to persist when the monitor was retested at NEDU. During a subsequent attempt by Geotechnical Instruments to repair it, the CO₂ instability could not be reproduced at the factory.

Precision

As determined by the range in monitor readings over a 10-minute period while span gas was being sampled, short-term repeatability for the final three reboxed monitors was

±0.2% O₂,
±20 ppm CO₂,
±2 ppm CO, and
±0.2 ppm VOCs.

This level of precision is identical to that for the final version prototypes.

Accuracy

Based on chamber testing at 25 °C immediately following calibration, measurement error for the final three reboxed monitors is plotted in Figs. 8–11 (A graphs only) and was, on average,

for O₂: ±0.2% absolute across the test range of 0 to 21%, but ±0.1% O₂ at the span value of 21%;

for CO₂: ±40 ppm across the test range of 0 to 1000 ppm, but ±30 ppm at the span value of 1000 ppm;

for CO: ≤2 ppm low across the test range of 0 to 20 ppm; and

for VOCs: ≤0.4 ppm low across the test range of 0 to 20 ppm.

As was the case with the final version prototypes, these test results show good consistency among analyzers (a consistency shown by the overlap of their three plots) and over test days (a consistency shown by the generally small standard deviations). Except for CO readings (where the accuracy of the prototype and reboxed monitors was similar), the accuracy of the final reboxed monitors was better than that of the final

version prototypes, and no hysteresis was obvious with the VOC plots, as it had been observed with the prototypes.

Between two repeated STEC tests (the first test performed in the morning, followed by a second in the afternoon) and without recalibration between tests, short-term variability of the three reboxed units was low (Fig. 12) and similar to that of the prototype monitors. The difference between morning and afternoon tests was, on average,

for O₂: $\pm 0.1\%$ absolute,
for CO₂: ± 20 ppm,
for CO: ± 1 ppm, and
for VOCs: ± 0.1 ppm.

Figs. 8–11 present some results from STEC tests performed in the chamber with the final reboxed monitors at the three test temperatures. Again, the 25 °C tests were in the morning immediately after calibration, with second tests in the afternoon at either 5 or 42 °C. Testing showed that ambient temperatures affected monitor readings, on average, as follows:

1. Whereas O₂ error was $\pm 0.2\%$ absolute at 25 °C across the test range of 0 to 21%, O₂ readings were $\leq 1\%$ low at 42 °C and $\leq 1\%$ high at 5 °C, readings similar to the temperature responses by the prototype monitors.
2. Whereas CO₂ error was ± 40 ppm at 25 °C across the test range of 0 to 1000 ppm, CO₂ readings were ≤ 100 ppm low at 42 °C and ≤ 100 ppm high at 5 °C, readings slightly better than the temperature responses by the prototype monitors.
3. Whereas CO readings were ≤ 2 ppm low at 25 °C across the test range of 0 to 20 ppm, these readings were ≤ 3 ppm high at 42 °C and ≤ 4 ppm low at 5 °C, readings similar to the temperature responses by the prototype monitors.
4. Whereas VOC error was ≤ 0.4 ppm low at 25 °C across the test range of 0 to 20 ppm, this error was ± 0.5 ppm at 42 and 5 °C for monitors #298 and #299, both of which received temperature corrections for the PID specific to each sensor. These temperature responses were similar to those by the prototype monitors. However, this relatively low VOC error contrasts with the considerably greater error at 42 and 5 °C for #263 — an error which incorporated the temperature correction that had been developed for #299 and thus was not be expected to be optimized for #263.

Overall, heat and cold generally increased the monitors' response variability for all four gases. During testing at 42 °C, we did not observe any new LCD darkening that had been observed with the original LCD in the prototype monitors.

Fig. 13 presents results from the longest accuracy test without recalibration (up to twelve days postcalibration) conducted for two of the reboxed monitors. We plot the error in monitor readings taken both seven and twelve days following the last calibration, and for comparison we include the mean error plots from earlier testing for the same two monitors immediately following calibration. These latter plots are taken directly from Figs. 8–11 (A graphs only) and are distinguished in Fig. 13 by the larger symbols on the graphs (and are labeled “Day0 Post-Cal Means” in the legend). All data are based on chamber testing at 25 °C.

Comparing the seven- and twelve-day results with the error immediately following calibration suggests excellent calibration stability for O₂, CO₂, and CO over the test period. For VOC readings, some minor differences appeared between the error found on Days 7 and 12 and that right after calibration. However, all VOC data are still approximately ±0.5 ppm of the expected readings. This stability for all four gases agrees well with the results reported from the nearly month-long testing of the prototype monitors.

Instrument start-up and stabilization

Using one-minute datalogging, Figs. 14 and 15 plot results for two reboxed monitors from the following seven start-up tests over seven days: two tests on Day 1 postcalibration, two tests on Day 4, two tests on Day 5, and one test on Day 7. Because the plots are generated from logged data, the smallest changes in monitor readings that can be shown in these plots are equal to the logging resolution (which is the same as the display resolution): ±0.1% O₂, ±10 ppm CO₂, ±1 ppm CO, and ±0.1 ppm VOC. As noted in the legends, the line thickness of some plots has been increased to help distinguish individual tests.

In some of these tests, stabilization of O₂ and CO readings was observed to occur nearly immediately upon start-up, whereas CO₂ and VOC readings generally took longer to equilibrate. However, most readings appeared to stabilize within 20 min following start-up, with most of the short-term changes occurring thereafter within the level of precision reported in the **Precision** subsection above: ±0.2% O₂, ±20 ppm CO₂, and ±2 ppm CO. These results agree well with those from the prototype monitors.

Agreeing with results from Fig. 13, the generally close overlap of the plots from a seven-day period in Figs. 14–15 suggests excellent calibration stability for all four gases over the test period.

Individual cal gas testing

As with the final version prototype monitors, we never observed cross sensitivity of the four sensors in the reboxed monitors when these were tested with the individual CO₂, CO, or isobutylene gas standards (nominally 2500 ppm CO₂, 50 ppm CO, and 20 ppm

isobutylene) at various STEC settings and with the VOC filter in line upstream from the CO sensor.

Individual VOC testing

Monitor response was tested when gas standards containing ~10 ppm (balance air) of one of the following VOC species were delivered: toluene, xylenes, n-hexane, and n-octane. Because the response to the 10 ppm xylene gas exceeded the monitor display range, the xylene concentration during the test was reduced to 50%, with the STEC used to allow monitor readings to be recorded.

Relative response factors were calculated as follows:

$$\text{Relative response factor} = \text{monitor reading} / \text{ppm VOC.}$$

Relative response factors expressed as the range in values for the three reboxed monitors were

toluene, 1.90–1.94;
xylenes, 1.95–1.98;
n-hexane, 0.22–0.25; and
n-octane, 0.48–0.54.

These response factors agree closely with those reported for the portable Toxic Vapor Analyzer with a 10.6 eV PID (model TVA-1000, Thermo Environmental Instruments, Inc.; Franklin, MA),⁶ which is the same energy (10.6 eV) as the PID in the Diveair2. This agreement suggests that published information on PID sensitivities may be useful in estimating the Diveair2's relative response to various VOCs.

VOC filter

No testing of the VOC filter was done with the reboxed monitors.

Relative humidity

When sampling wet span gas with ~95% RH compared to dry span gas with ~1% RH (see Table 4), we observed that instrument readings, with the exception of VOCs, varied only within the level of precision reported above in the **Precision** subsection. In contrast to the readings from the final version prototype monitors, we observed that VOC readings of wet test gas, sampled immediately after the dry gas had been sampled, were up to ~2 ppm lower than expected. Although we did not analyze the wet test gas by GC, we assume that the small reduction in wet test gas constituents seen during testing of the final version prototype monitors was similar to that which occurred here, a reduction that again was within the precision level of the instruments and therefore was not observable. The reduction in VOC readings with the new PID in the

reboxed monitors agrees with previous reports that PID measurements can be influenced by high humidity, although water vapor itself is not detected.⁷

Operating time and recharging of batteries

Operating times until shutoff for the three monitors were observed to be

16 h, 9 min to 16 h, 30 min (#263, from three tests over a nineteen-day interval);

14 h, 21 min (#298, from one test); and

15 h, 32 min to 15 h, 55 min (#299, from three tests, again over a nineteen-day interval).

As these times are based on a start-up time recorded to the nearest minute and a shutoff time based a five-minute datalogging interval, the actual operating times could be up to ~5 min longer than reported. Such operating times are approximately two times longer than those observed with the NiCad batteries. Two tests with each of two monitors showed that recharging the batteries after the preceding shutoff tests required three to three and one-half hours before the charger light changed from constant (charging) to blinking (trickle charging). Using this as a gauge to estimate charging time suggests that the reboxed monitors' batteries require less than 50% of the time needed for recharging the batteries of the final prototype monitor.

Battery charger and power cord

Following complete discharge of their batteries so that all three monitors would not turn on, the power cord was plugged into line power and then connected sequentially to each monitor. Each monitor would then turn on and operate for the allowed test time (~10 min). The battery display read 100 when the cord was attached, and it returned to 0 when the cord was disconnected. We did not test the accuracy of the monitor readings when the power cord was used, either with or without batteries.

When the battery was disconnected from the PCB in one unit (#298), the power cord again allowed the monitor to operate. However, when the battery charger was connected to the same monitor with the battery disconnected, the monitor initially turned on but then shut off less than one minute later. This test with the charger was repeated many times with the same result. We interpret this observation to indicate the electrical requirements of the battery charger: being a "smart" charger that adjusts its output according to battery status, it needs a battery to provide appropriate electrical resistance to control the charger's output. Without the battery, the charger shuts off.

Tedlar bag testing

While span gas was sampled from the Tedlar bag during the one test conducted, each of the two monitors displayed gas readings that differed from the span gas concentrations only within the level of precision reported. These results suggest that, following calibration according to our procedures, the monitors can be used to accurately sample ambient air.

Visual alarms

Limited testing confirmed that the external alarm light flashed and the correct gases in the display blinked when the monitor was exposed to various challenge gases that triggered the alarms.

CONCLUSIONS

1. Our testing showed that the laboratory performance of the reboxed monitors was overall at least as good as, and in many cases better than, the performance of the final version prototypes, which met or came close to meeting many important requirements given in the **MONITOR REQUIREMENTS** subsection.
2. Unfortunately, before beginning final testing of the reboxed monitors, we had to address unexpected problems found during our initial evaluation of those units. These problems included drift in O₂ readings, battery charging effects, and temperature effects on the new PID. However, after resolving these and other problems, we believe that the reboxed Diveair2 — with its new pelican-type case, longer-lasting battery, new power cord option, software modifications, and other added features — should be useful and easy to operate in screening diving air.
3. We summarize below a few important differences between the laboratory performances of the reboxed monitor and the final version prototype monitor:
 - a. Based on limited data, instrument readings of the reboxed monitors stabilize within 20 min following start-up, a period which may be slightly longer than that observed with the final version prototypes. These laboratory data suggest that, following monitor storage at room temperatures, a warm-up of ~20 min is needed before a monitor is used.
 - b. Humidity was shown to significantly affect the VOC readings of the reboxed monitors; no such effect occurred with the final version prototype monitors. As diving air is normally expected to be very dry, water vapor effects are expected to be problems only when ambient air is sampled in suspect situations (e.g., at salvage diving sites) to confirm the suitability of such air for diving before compressors are started up.

c. Between charges, the reboxed monitor with its new nickel metal hydride battery can be operated for approximately two times longer than the final prototype monitor with the NiCad batteries. Limited testing suggests that the reboxed monitor's batteries require less than 50% of the recharging time that the final prototype monitor's require.

d. The new power cord allows the reboxed monitor to operate with or without batteries, although the effect of the power cord on gas readings has not been evaluated.

FINAL CONCLUSIONS AND RECOMMENDATIONS

1. The final version reboxed Diveair2 that we tested should allow reliable real-time screening of diving air in the field (see Appendix A). However, nearly all our testing used an NEDU-designed open-split gas delivery system that allowed the monitor, with its pump turned on, to freely draw sample gas through its inlet while the excess gas delivered was discharged into the atmosphere via an overflow tube. Since differences in gas delivery procedures may significantly affect monitor performance, we urge caution in applying our results to other gas sampling situations.
2. For now, we recommend that only the procedures given in Appendix B — those using an open-split gas delivery system for calibration and sampling of diving air — be followed when the Diveair2 is operated, since these are the only procedures that we have fully tested. Using alternative operating procedures in the field or in the laboratory will first need to be verified as procedures producing acceptable results. The Diveair2 has not been evaluated by NEDU for screening gases other than air.
3. When the Diveair2 is used to screen diving air in the field, we recommend that the limits for O₂, CO₂, and CO remain the same as the current U.S. Navy limits in the *U.S. Navy Diving Manual*.¹ On the basis of our discussion in Appendix C, we also recommend that an interim limit for VOCs, expressed in isobutylene equivalents, be set at 10 ppm — but that the VOC limit be subject to change, depending on experience with actual field testing.
4. Before any monitors are delivered to the Fleet for field use, we recommend that the following steps as well as any required Authorized for Navy Use procedures be completed:
 - a. To ensure that the monitors operate correctly, perform limited laboratory testing of a significant fraction (e.g., ~25%, up to a maximum of five units) of the initial batch of production monitors procured by the Navy.
 - b. Evaluate fully in the laboratory any proposed testing kit (i.e., all the hardware and calibration gases necessary to use the monitor) for reliability in screening air in the field.
 - c. Develop operating procedures for any proposed field testing kit/air monitor combination, and test these procedures in the laboratory to ensure that they are easy and foolproof.
5. After the three steps in Recommendation 4 above are completed (steps which, combined, should take no more than two months), we recommend that two additional steps be taken during transitioning of the monitors and field testing kits to the Fleet. These steps are essential for successful transition, as the final reboxed monitor has undergone only limited testing in the laboratory and no testing in the field:

a. Maintain a detailed accounting of all problems that emerge during at least the first year of the transition period, as the Fleet begins to use the monitors for air screening.

b. For at least the first year, identify at least one field site as a participant in a "relaxed field test" of the first Fleet monitors, a site where calibration data and other measurements including battery durations and range in ambient temperatures during testing will be collected and evaluated. These data should help determine the need for changes in the field calibration frequency.

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Table 1. Humidity Testing – Prototype Monitors.
Gas temperatures and relative humidities are those measured
from test gas immediately upstream of monitors.

Test Date	Test Time	Temperature: test gas / ambient (°C)	Relative Humidity (%)	Monitor #	Monitor Readings			
					O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOC (ppm)
25 Nov 2003	1056	23.9 / 24.4	0.5	#255	21.0	1010	19	9.4
				#256	21.0	1000	23	9.8
				#257	20.9	1020	19	9.8
	1108	23.9 / -	95.0	#255	20.9	1000	19	9.2
				#256	20.9	990	23	9.4
				#257	20.9	1000	19	9.9
	1137	24.0 / 24.3	0.8	#255	20.9	1030	19	9.3
				#256	20.9	1000	22	9.6
				#257	20.9	1010	19	9.6
4 Nov 2003	1129	25.0 / 25.7	1.1	#255	20.8	970	19	9.8
				#256	20.6	970	21	9.8
				#257	21.0	980	22	10.1
	1204	25.2 / -	50.0	#255	20.8	970	20	9.4
				#256	20.7	970	23	9.8
				#257	21.0	980	21	9.8
	1330	25.0 / 25.2	0.9	#255	20.9	970	20	9.7
				#256	20.9	980	21	10.1
				#257	21.0	990	20	10.0

Table 2A. Calibration Results from Field Testing — NDSTC.

Test Condition	Monitor Readings							
	N ₂ Test Gas: Mean (range)				Span Gas: Mean (SD)			
	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs (ppm)	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs ppm)
Actual Gas	0.0	0	0	0.0	21.0	1000	21	10.6
Pre-Zero	0.0 (-0.9- 0.2)	0 (0-30)	0 (0-2)	0.0				
Post-Zero	0.0 (0.0-0.1)	0 (0-10)	0 (0-1)	0.0	21.1 (0.6)	1010 (40)	20 (1)	10.6 (0.5)
Postspan	0.0	0 (0-10)	0 (0-2)	0.0 (0.0-0.2)	20.9 (0.1)	1000 (10)	20 (1)	10.9 (0.3)
Posttest	0.3 (0.0-0.7)	40 (0-90)	0 (0-1)	0.0 (0.0-0.1)	20.8 (0.3)	1040 (50)	18 (2)	10.9 (0.4)

Table 2B. Calibration Results from Field Testing — MDSU-1.

Test Condition	Monitor Readings							
	N ₂ Test Gas: Mean (range)				Span Gas: Mean (SD)			
	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOC (ppm)	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs (ppm)
Actual Gas	0.0	0	0	0.0	21.0	1000	20	10.0
Pre-Zero	0.2 (0.0-0.8)	30 (0-100)	0 (0-3)	0.5 (0-1.8)	20.8 (0.3)	1030 (70)	20 (1)	10.0 (0.4)
Post-Zero	0.0 (0.0-0.1)	0	0	0.0	20.7 (0.3)	990 (30)	19 (1)	10.0 (1.0)
Postspan	0.1 (0.0-0.7)	10 (0-30)	0	0.2 (0.0-1.5)	20.9 (0.1)	1000 (10)	19 (1)	9.9 (0.4)
Posttest	0.4 (0.2-0.7)	60 (0-110)	0 (0-1)	0.3 (0.0-1.4)	21.2 (0.5)	1060 (50)	22 (2)	9.9 (0.7)

Table 2C. Calibration Results from Field Testing — MDSU-2.

Test Condition	Monitor Readings							
	N ₂ Test Gas: Mean (range)				Span Gas: Mean (SD)			
	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs (ppm)	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs (ppm)
Actual Gas	0.0	0	0	0.0	21.0	1000	21	10.6
Pre-Zero	0.1 (0.0-0.2)	10 (0-40)	0 (0-1)	0.0 (0-0.2)	20.9 (0.3)	990 (40)	21 (1)	10.9 (0.3)
Post-Zero	0.0	0 (0-10)	0	0.0	20.9 (0.3)	1000 (20)	20 (1)	10.9 (0.4)
Postspan	0.0 (0.0-0.1)	0 (0-10)	0	0.1 (0.0-0.2)	20.9 (0.1)	1000 (10)	20 (1)	10.7 (0.4)
Posttest	0.0 (0.0-0.1)	40 (0-120)	0 (0-2)	0.1 (0.0-0.5)	20.8 (0.2)	1020 (30)	21 (1)	10.7 (0.5)

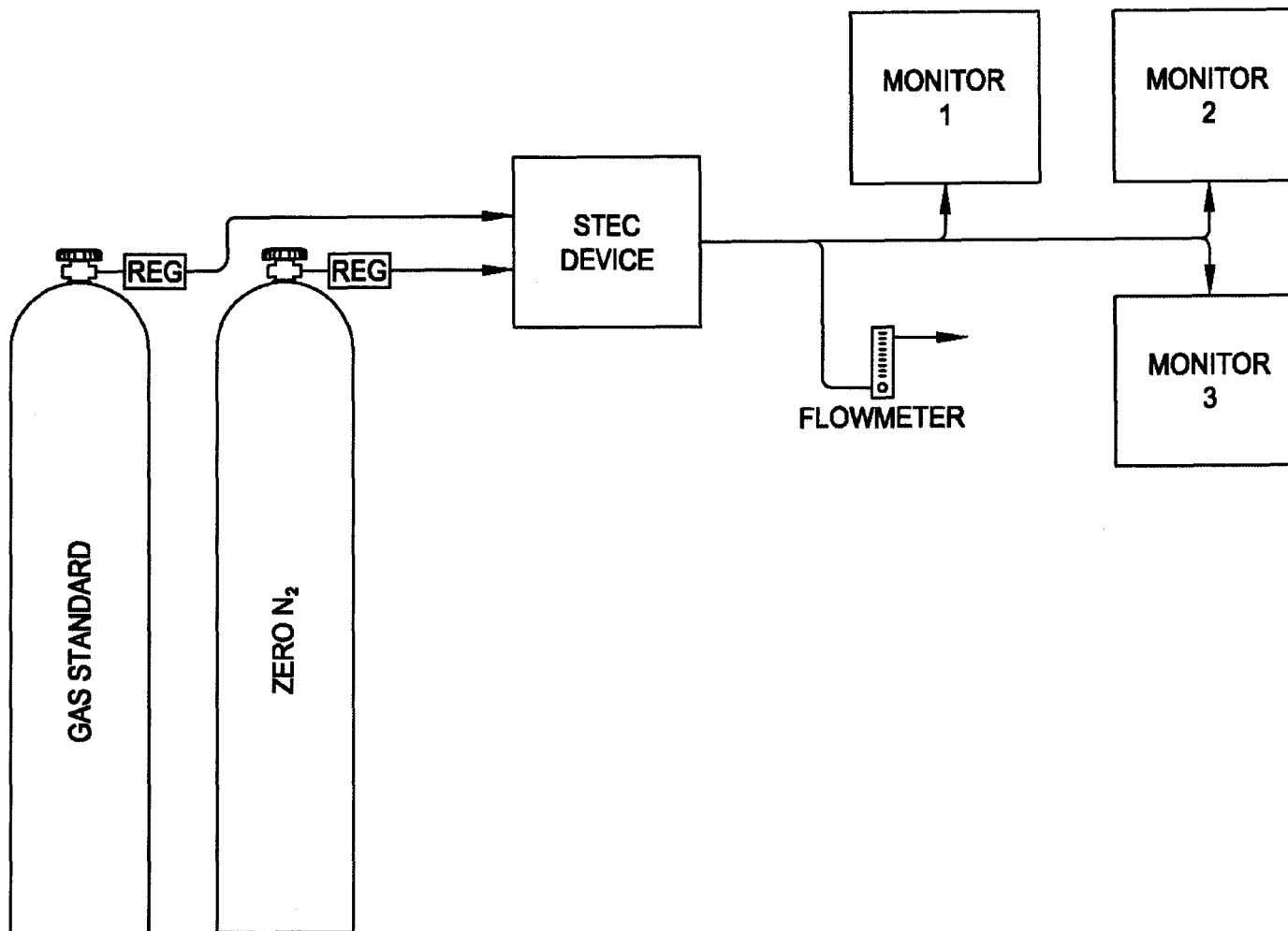
Table 3. Field Testing Results.

Test Site	Test Length: Range (Hours)	Battery Reading: Range		Peak Values: Range			
		Start	End	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs (ppm)
NDSTC	2.7-6.1	70-100	30-60	20.5-20.9	280-500	0-2	0.0-3.3
MDSU-1	2.3-7.0	75-100	10-80	19.9-21.1	320-530	0-6	0.0-10.7
MDSU-2	1.7-6.5	50-100	25-65	20.0-21.0	260-790	0-4	0.0-1.0

Table 4. Humidity Testing — Reboxed Monitors.
Gas temperatures and relative humidities are those measured
from test gas immediately upstream of monitors.

Test Date	Temperature: test gas / ambient (°C)	Relative Humidity (%)	Monitor #	Monitor Readings			
				O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOC (ppm)
22 July 2008	24.5 / 24.5	0.7-1.6	#263	20.9	1000	19	10.0
			#298	21.0	990	20	10.0
			#299	20.9	1000	19	10.0
	24.5 / 24.5	98.4-99.0	#263	20.8	980	20	8.4
			#298	20.9	970	20	8.8
			#299	20.8	970	20	7.8

FIGURE 1. Testing setup showing open-split gas delivery.



FIGURES 2A-C. O₂ accuracy – final version prototype.

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Table 1. Humidity Testing – Prototype Monitors.
Gas temperatures and relative humidities are those measured
from test gas immediately upstream of monitors.

Test Date	Test Time	Temperature: test gas / ambient (°C)	Relative Humidity (%)	Monitor #	Monitor Readings			
					O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOC (ppm)
25 Nov 2003	1056	23.9 / 24.4	0.5	#255	21.0	1010	19	9.4
				#256	21.0	1000	23	9.8
				#257	20.9	1020	19	9.8
	1108	23.9 / -	95.0	#255	20.9	1000	19	9.2
				#256	20.9	990	23	9.4
				#257	20.9	1000	19	9.9
	1137	24.0 / 24.3	0.8	#255	20.9	1030	19	9.3
				#256	20.9	1000	22	9.6
				#257	20.9	1010	19	9.6
4 Nov 2003	1129	25.0 / 25.7	1.1	#255	20.8	970	19	9.8
				#256	20.6	970	21	9.8
				#257	21.0	980	22	10.1
	1204	25.2 / -	50.0	#255	20.8	970	20	9.4
				#256	20.7	970	23	9.8
				#257	21.0	980	21	9.8
	1330	25.0 / 25.2	0.9	#255	20.9	970	20	9.7
				#256	20.9	980	21	10.1
				#257	21.0	990	20	10.0

Table 2A. Calibration Results from Field Testing — NDSTC.

Test Condition	Monitor Readings							
	N ₂ Test Gas: Mean (range)				Span Gas: Mean (SD)			
	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs (ppm)	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs ppm
Actual Gas	0.0	0	0	0.0	21.0	1000	21	10.6
Pre-Zero	0.0 (-0.9- 0.2)	0 (0-30)	0 (0-2)	0.0				
Post-Zero	0.0 (0.0-0.1)	0 (0-10)	0 (0-1)	0.0	21.1 (0.6)	1010 (40)	20 (1)	10.6 (0.5)
Postspan	0.0	0 (0-10)	0 (0-2)	0.0 (0.0-0.2)	20.9 (0.1)	1000 (10)	20 (1)	10.9 (0.3)
Posttest	0.3 (0.0-0.7)	40 (0-90)	0 (0-1)	0.0 (0.0-0.1)	20.8 (0.3)	1040 (50)	18 (2)	10.9 (0.4)

Table 2B. Calibration Results from Field Testing — MDSU-1.

Test Condition	Monitor Readings							
	N ₂ Test Gas: Mean (range)				Span Gas: Mean (SD)			
	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOC (ppm)	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs (ppm)
Actual Gas	0.0	0	0	0.0	21.0	1000	20	10.0
Pre-Zero	0.2 (0.0-0.8)	30 (0-100)	0 (0-3)	0.5 (0-1.8)	20.8 (0.3)	1030 (70)	20 (1)	10.0 (0.4)
Post-Zero	0.0 (0.0-0.1)	0	0	0.0	20.7 (0.3)	990 (30)	19 (1)	10.0 (1.0)
Postspan	0.1 (0.0-0.7)	10 (0-30)	0	0.2 (0.0-1.5)	20.9 (0.1)	1000 (10)	19 (1)	9.9 (0.4)
Posttest	0.4 (0.2-0.7)	60 (0-110)	0 (0-1)	0.3 (0.0-1.4)	21.2 (0.5)	1060 (50)	22 (2)	9.9 (0.7)

Table 2C. Calibration Results from Field Testing — MDSU-2.

Test Condition	Monitor Readings							
	N ₂ Test Gas: Mean (range)				Span Gas: Mean (SD)			
	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs (ppm)	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs (ppm)
Actual Gas	0.0	0	0	0.0	21.0	1000	21	10.6
Pre-Zero	0.1 (0.0-0.2)	10 (0-40)	0 (0-1)	0.0 (0-0.2)	20.9 (0.3)	990 (40)	21 (1)	10.9 (0.3)
Post-Zero	0.0	0 (0-10)	0	0.0	20.9 (0.3)	1000 (20)	20 (1)	10.9 (0.4)
Postspan	0.0 (0.0-0.1)	0 (0-10)	0	0.1 (0.0-0.2)	20.9 (0.1)	1000 (10)	20 (1)	10.7 (0.4)
Posttest	0.0 (0.0-0.1)	40 (0-120)	0 (0-2)	0.1 (0.0-0.5)	20.8 (0.2)	1020 (30)	21 (1)	10.7 (0.5)

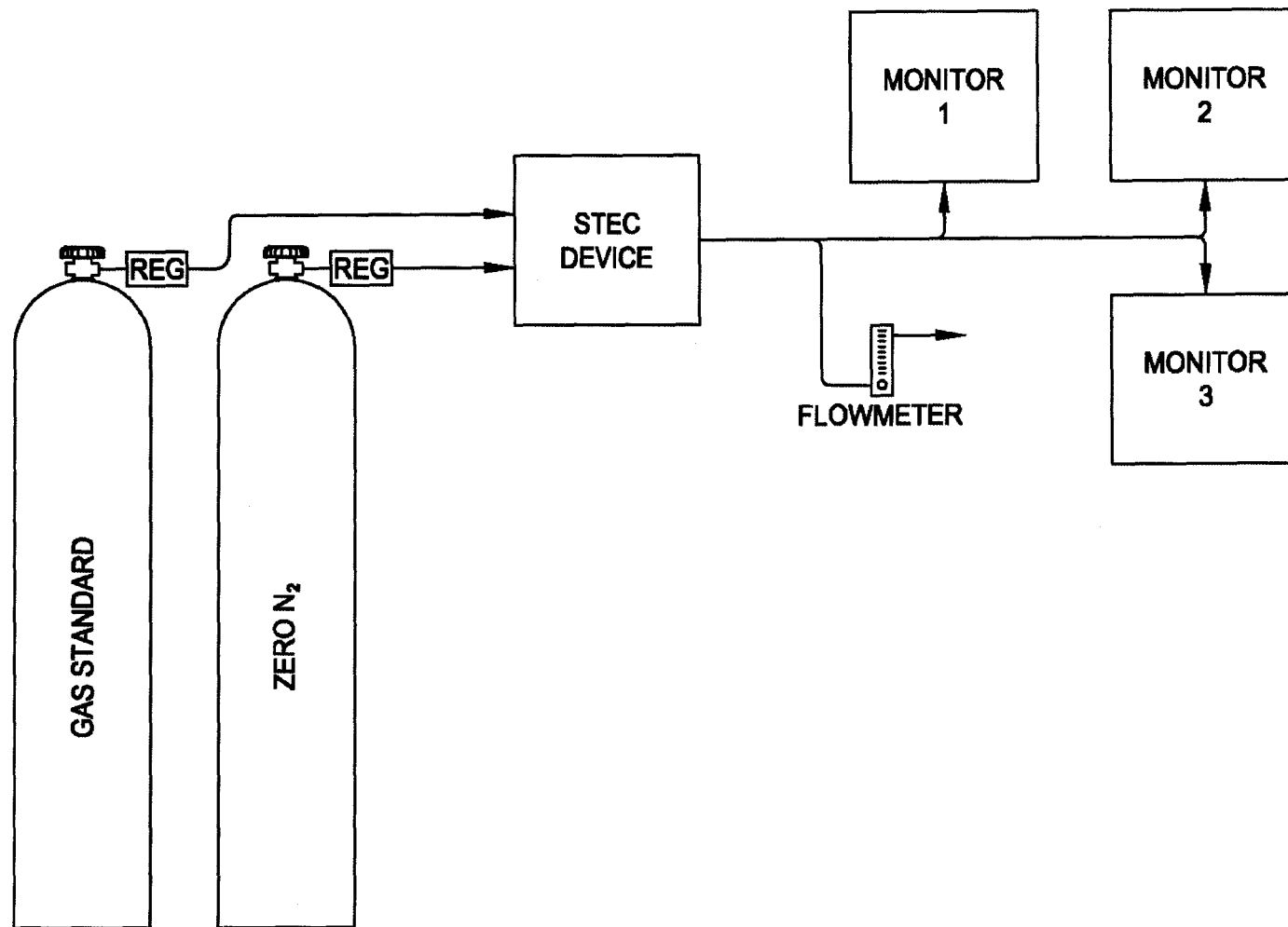
Table 3. Field Testing Results.

Test Site	Test Length: Range (Hours)	Battery Reading: Range		Peak Values: Range			
		Start	End	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOCs (ppm)
NDSTC	2.7-6.1	70-100	30-60	20.5-20.9	280-500	0-2	0.0-3.3
MDSU-1	2.3-7.0	75-100	10-80	19.9-21.1	320-530	0-6	0.0-10.7
MDSU-2	1.7-6.5	50-100	25-65	20.0-21.0	260-790	0-4	0.0-1.0

Table 4. Humidity Testing — Reboxed Monitors.
Gas temperatures and relative humidities are those measured
from test gas immediately upstream of monitors.

Test Date	Temperature: test gas / ambient (°C)	Relative Humidity (%)	Monitor #	Monitor Readings			
				O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOC (ppm)
22 July 2008	24.5 / 24.5	0.7-1.6	#263	20.9	1000	19	10.0
			#298	21.0	990	20	10.0
			#299	20.9	1000	19	10.0
	24.5 / 24.5	98.4-99.0	#263	20.8	980	20	8.4
			#298	20.9	970	20	8.8
			#299	20.8	970	20	7.8

FIGURE 1. Testing setup showing open-split gas delivery.



FIGURES 2A-C. O₂ accuracy – final version prototype.

FIGURE 2A.
O₂ Accuracy: 25C
Final Prototype Monitor
Means and SDs, N=6,4

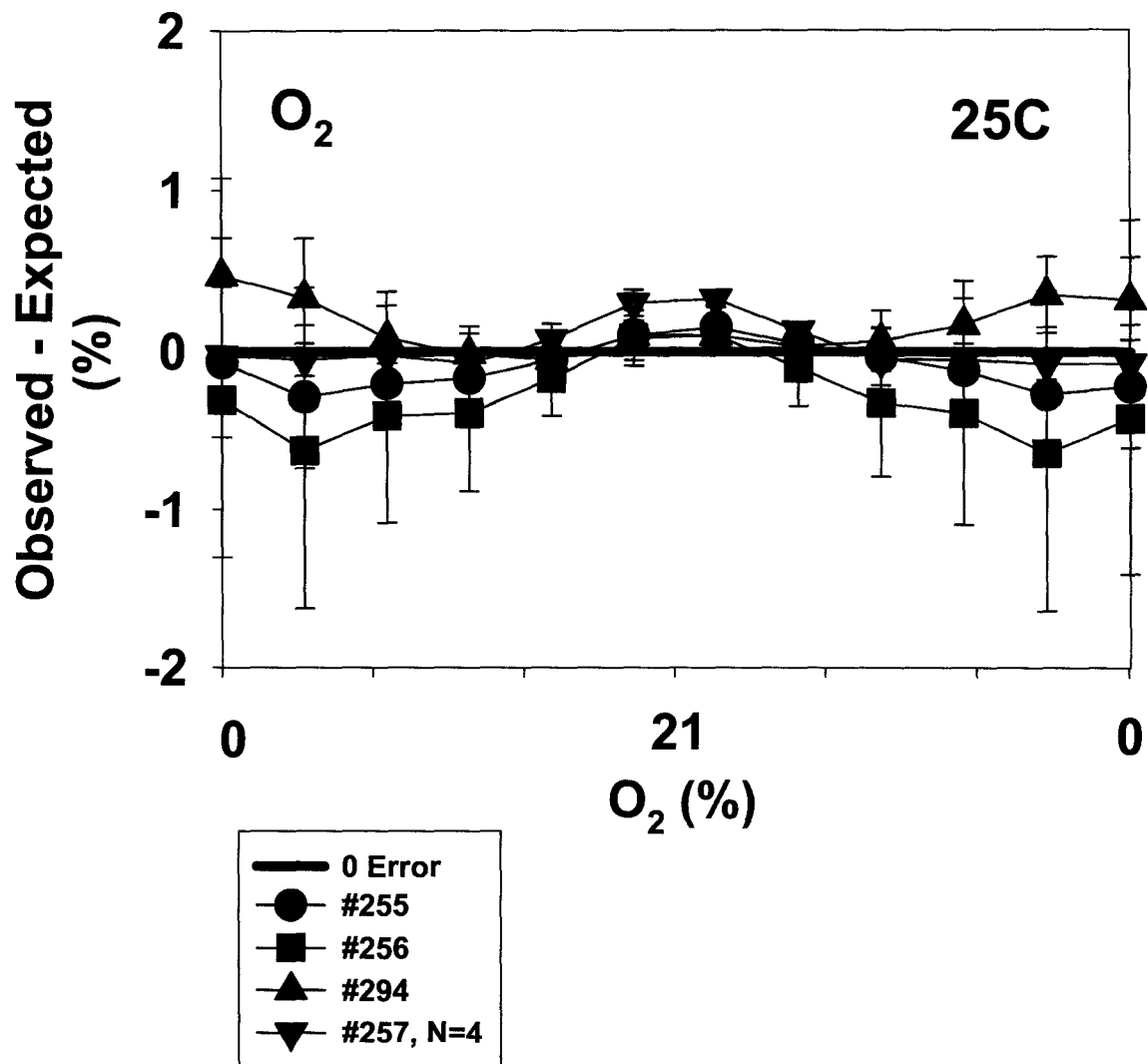


FIGURE 2B.
O₂ Accuracy: 42C
Final Prototype Monitor
Means and SDs, N=3,2

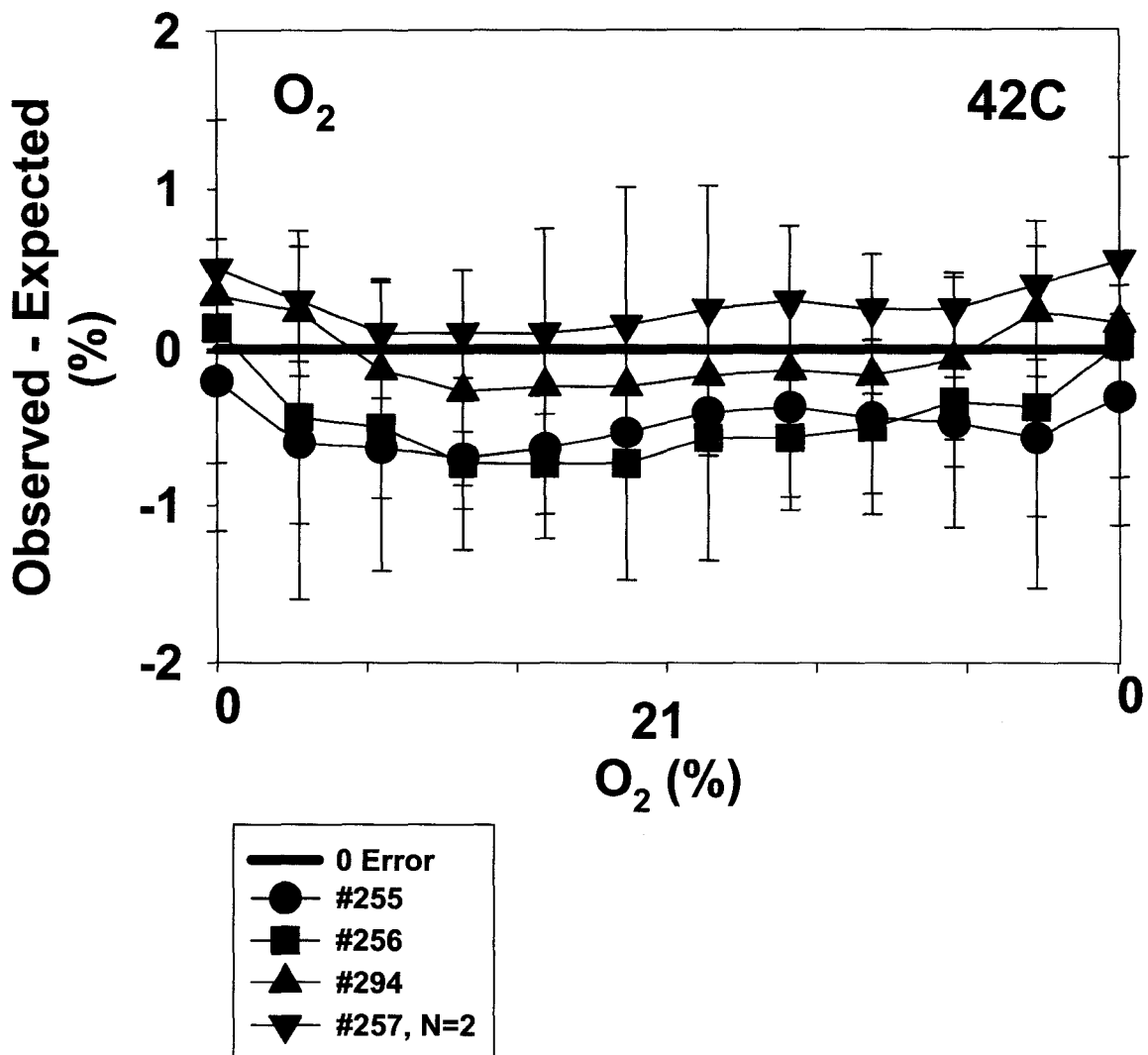
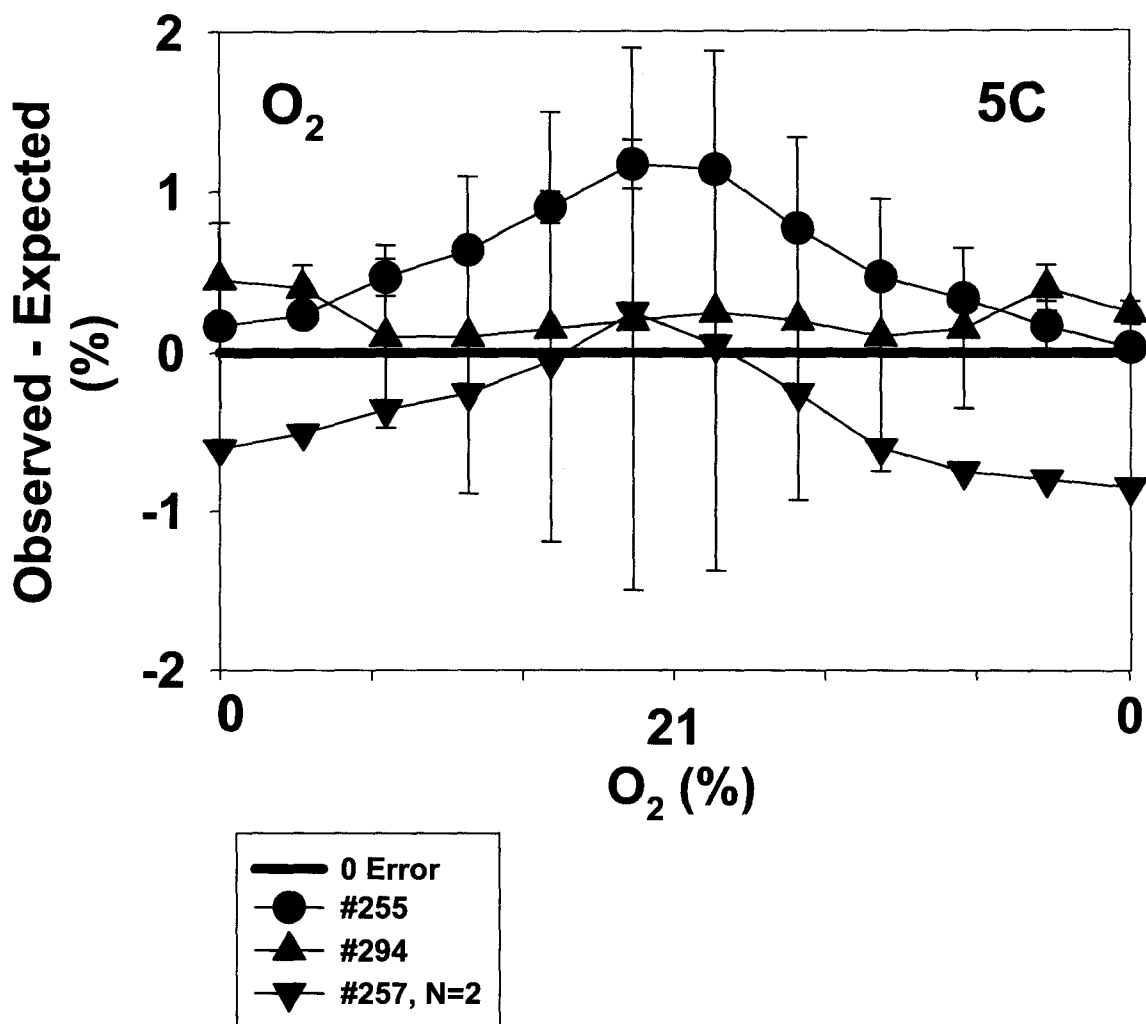


FIGURE 2C.
O₂ Accuracy: 5C
Final Prototype Monitor
Means and SDs, N=3,2



FIGURES 3A-C. CO₂ accuracy – final version prototype.

FIGURE 3A.
CO₂ Accuracy: 25C
Final Prototype Monitor
Means and SDs, N=6,4

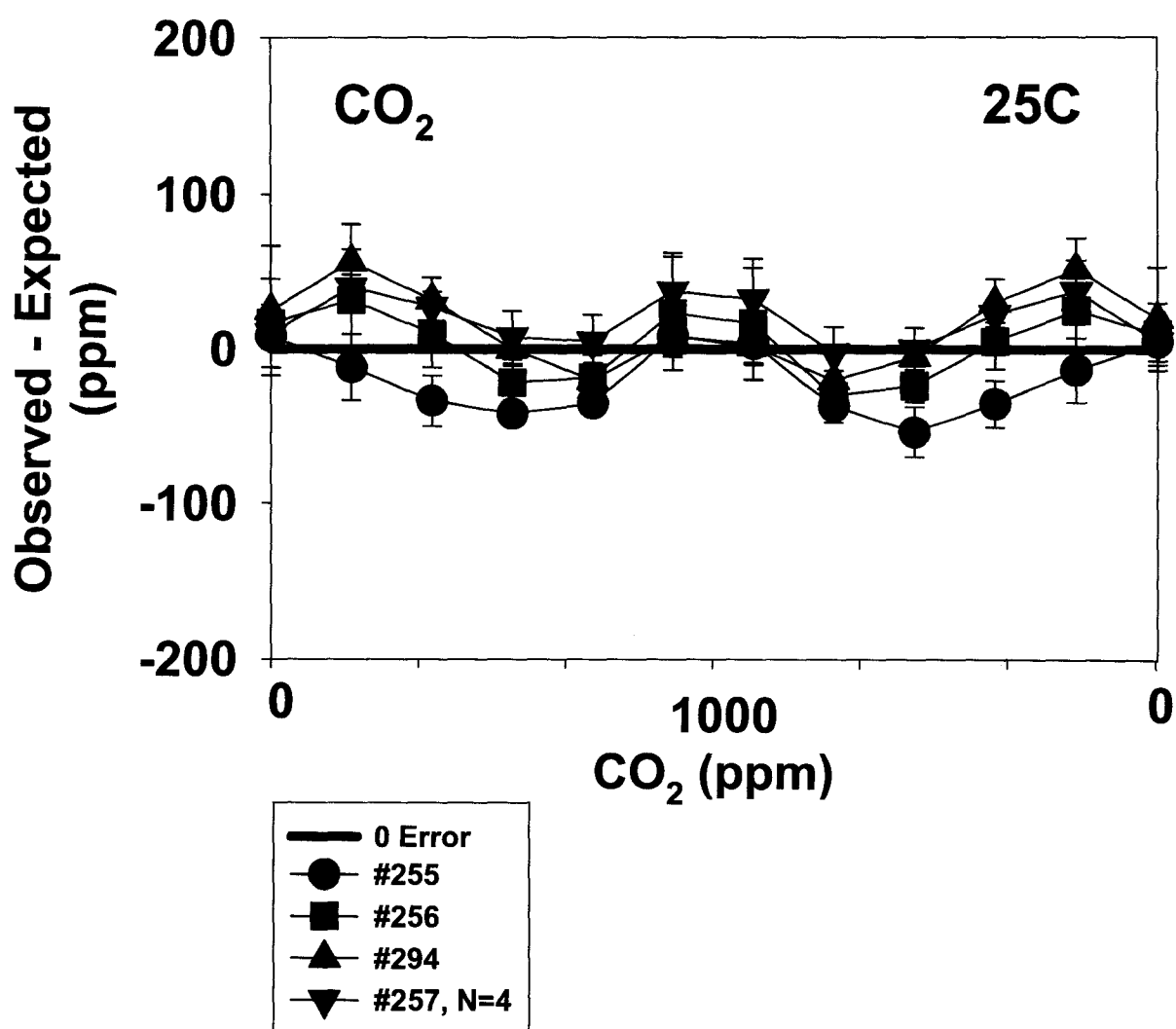


FIGURE 3B.
CO₂ Accuracy: 42C
Final Prototype Monitor
Means and SDs, N=3,2

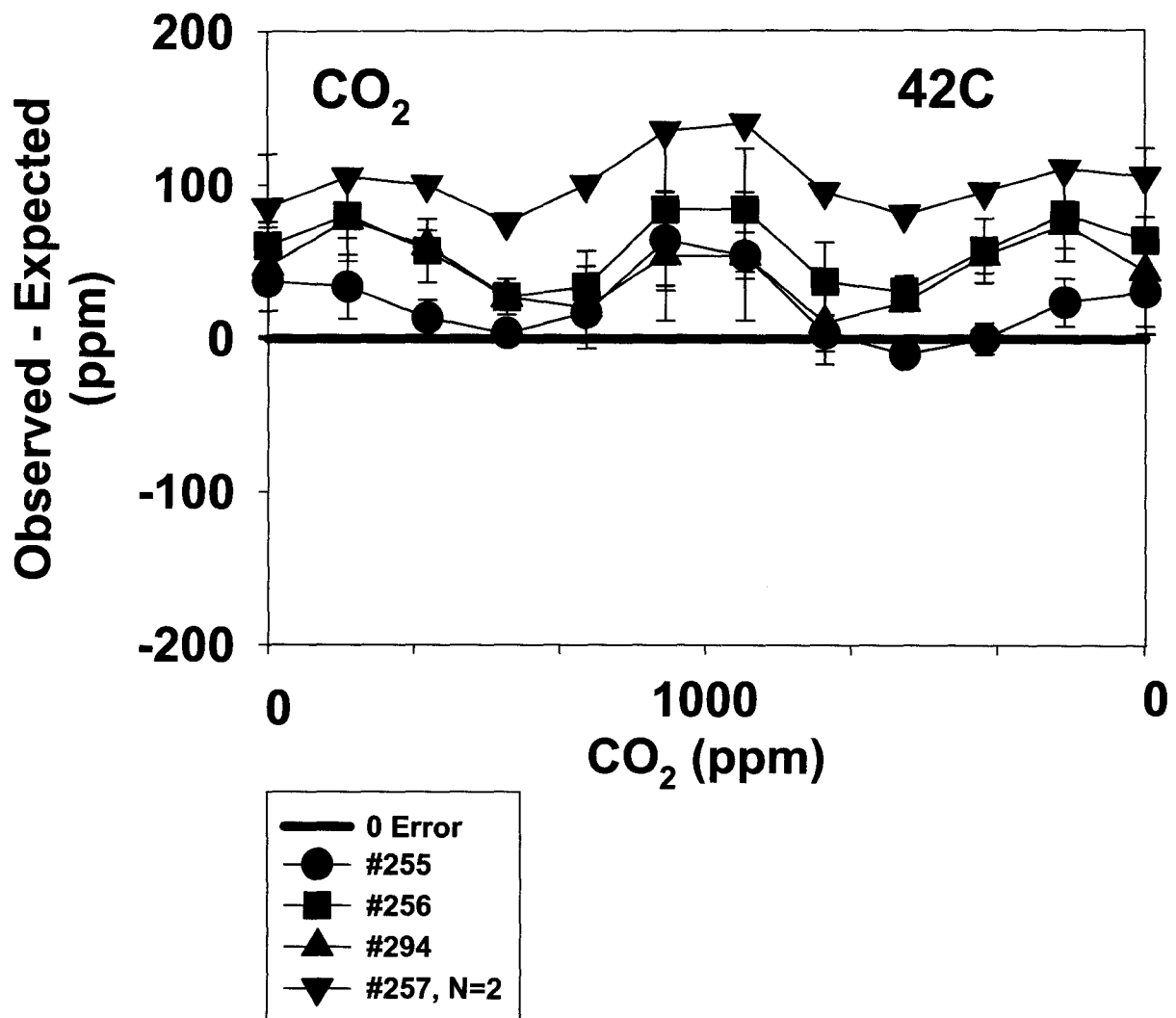
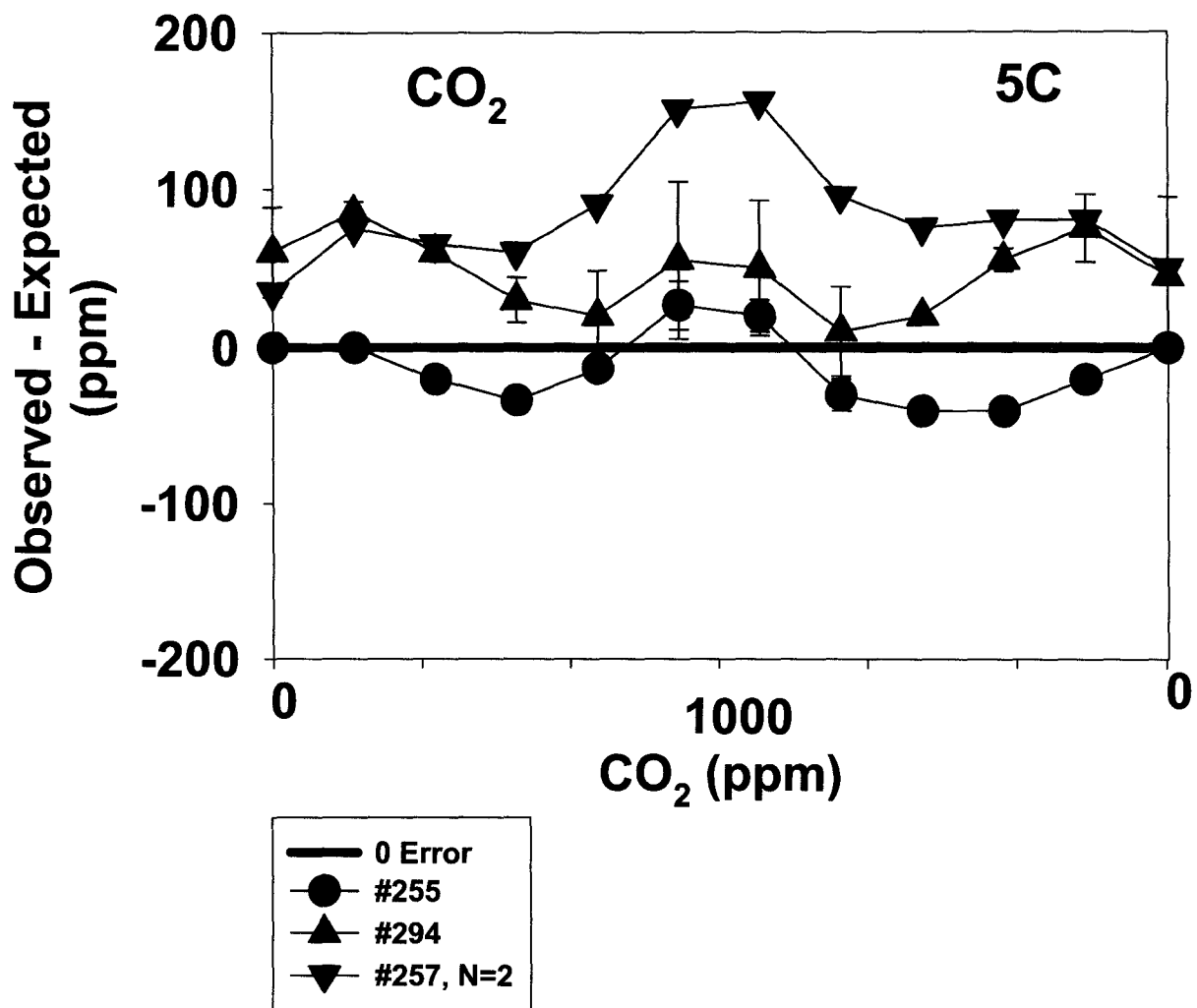


FIGURE 3C.
CO₂ Accuracy: 5C
Final Prototype Monitor
Means and SDs, N=3,2



FIGURES 4A-C. CO accuracy – final version prototype.

FIGURE 4A.
CO Accuracy: 25C
Final Prototype Monitor
Means and SDs, N=6,4

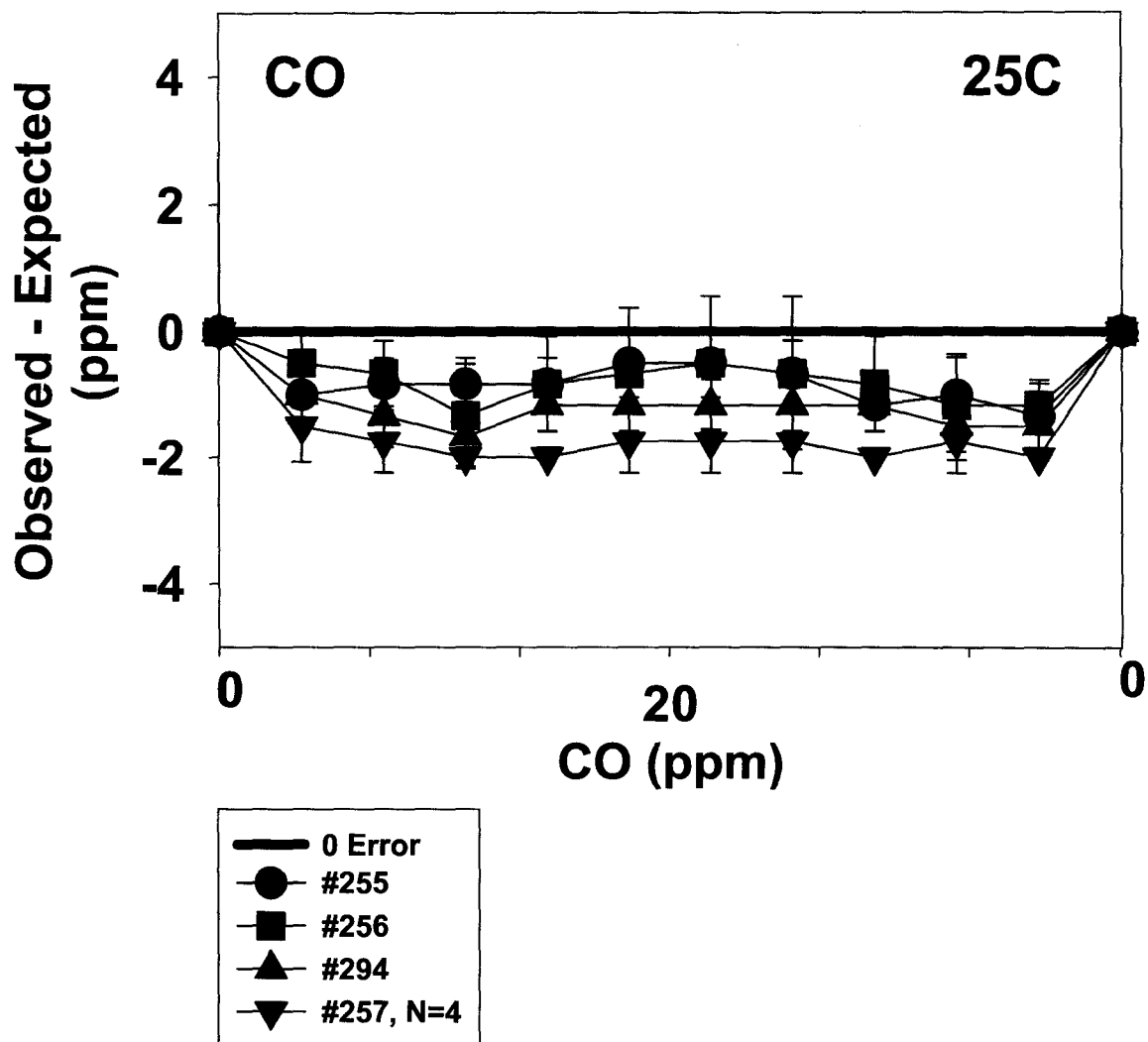


FIGURE 4B.
CO Accuracy: 42C
Final Prototype Monitor
Means and SDs, N=6,2

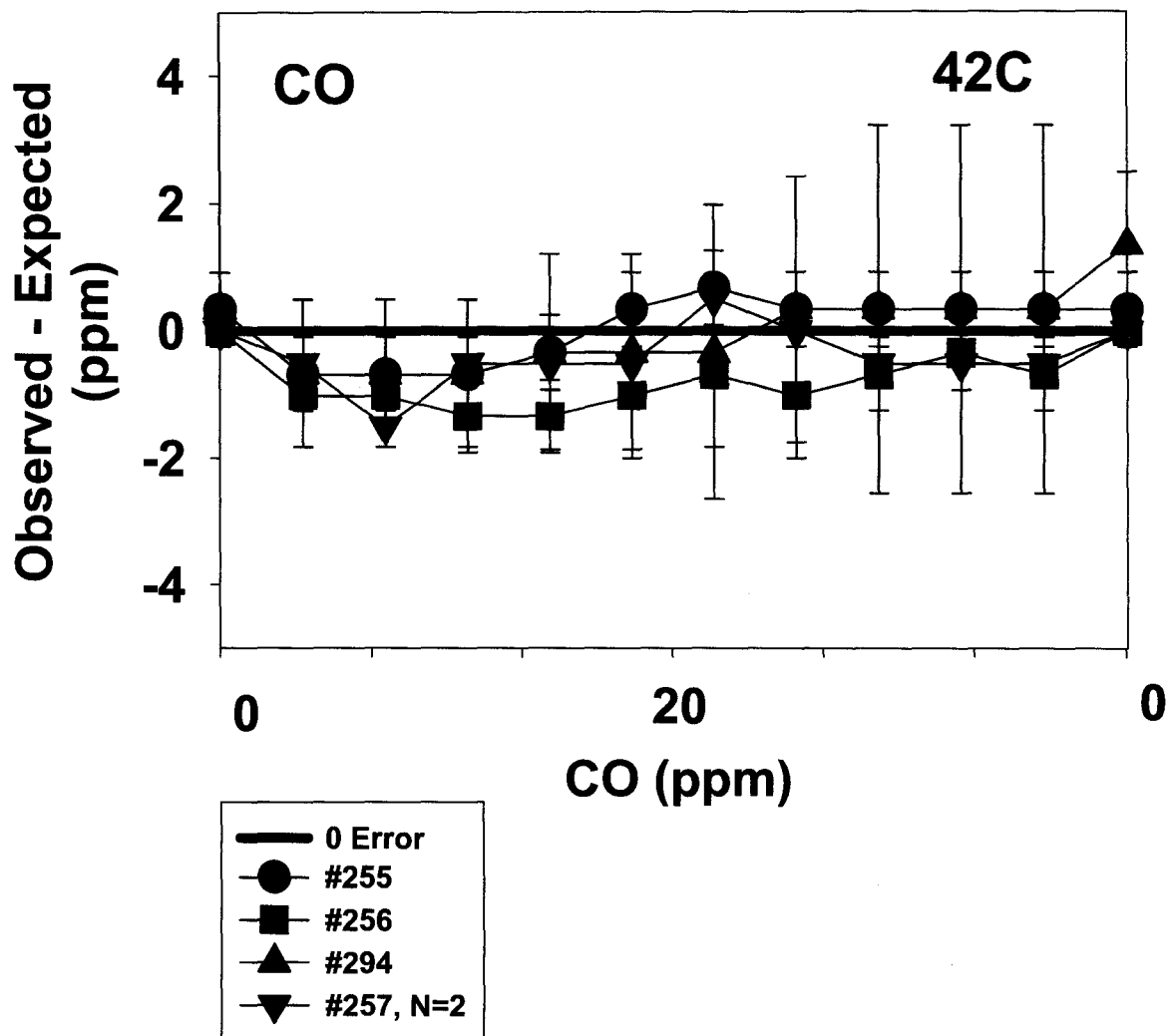
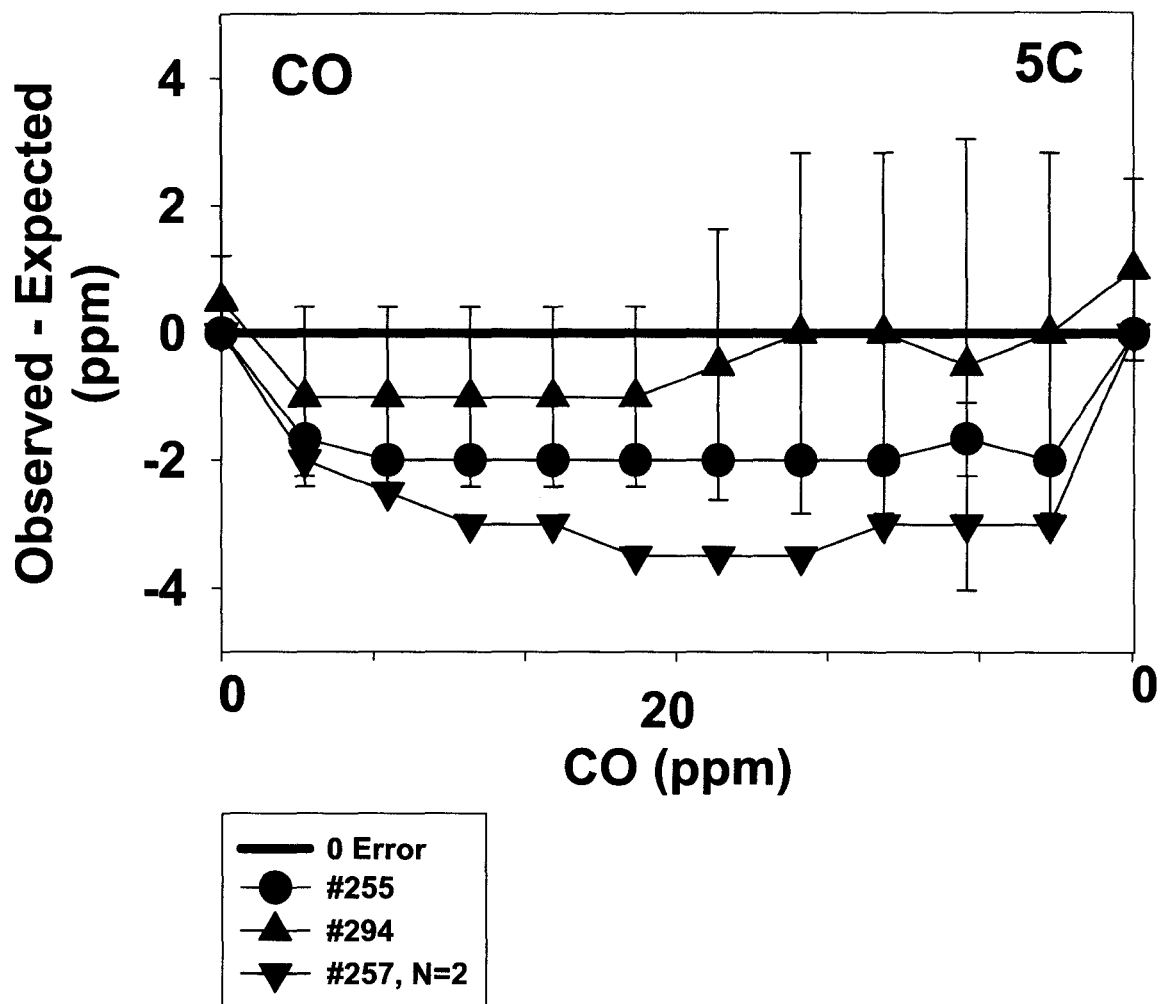


FIGURE 4C.
CO Accuracy: 5C
Final Prototype Monitor
Means and SDs, N=6,2



FIGURES 5A-C. VOC accuracy – final version prototype.

FIGURE 5A.
VOC Accuracy: 25C
Final Prototype Monitor
Means and SDs, N=6,4

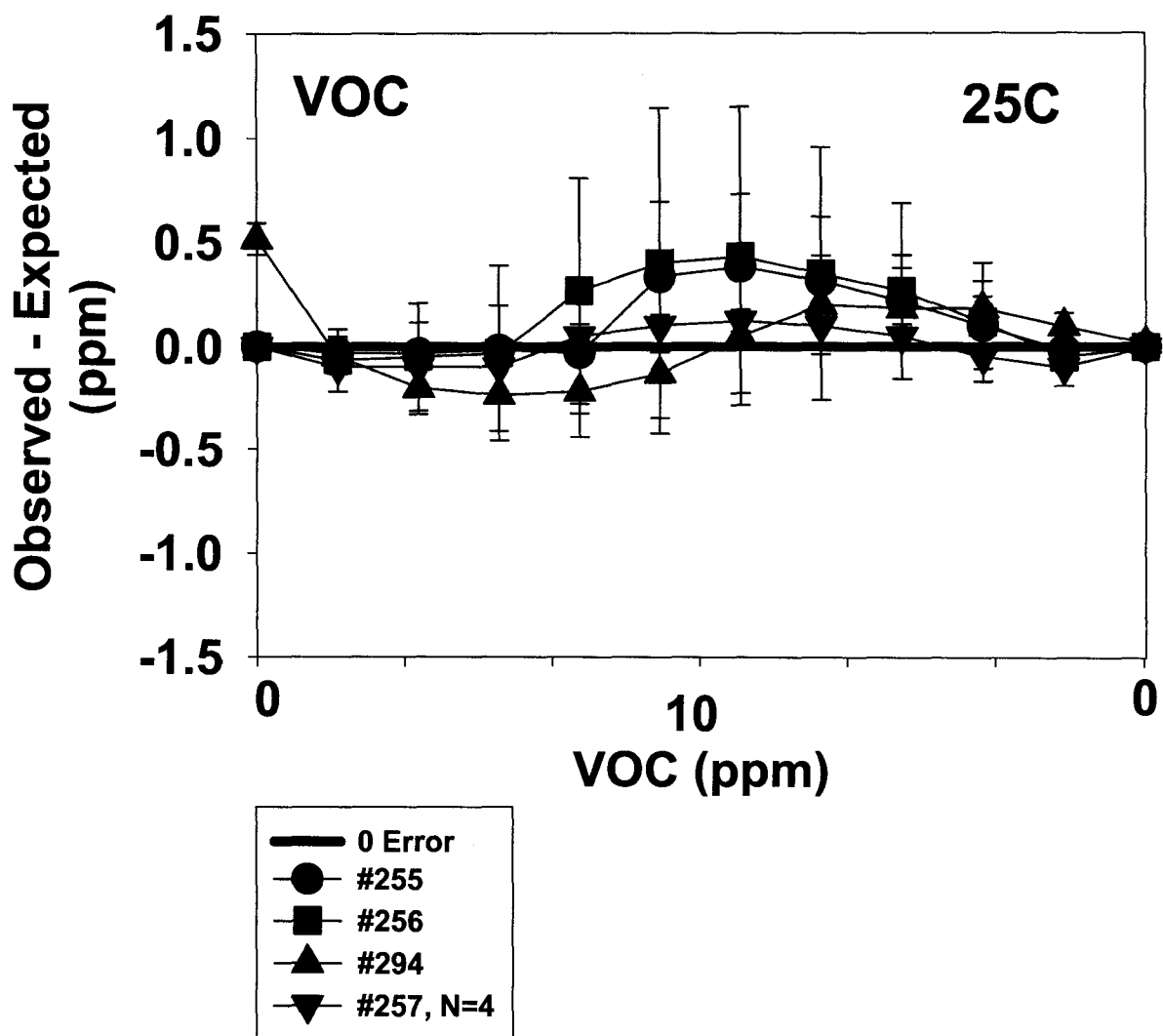


FIGURE 5B.
VOC Accuracy: 42C
Final Prototype Monitor
Means and SDs, N=6,2

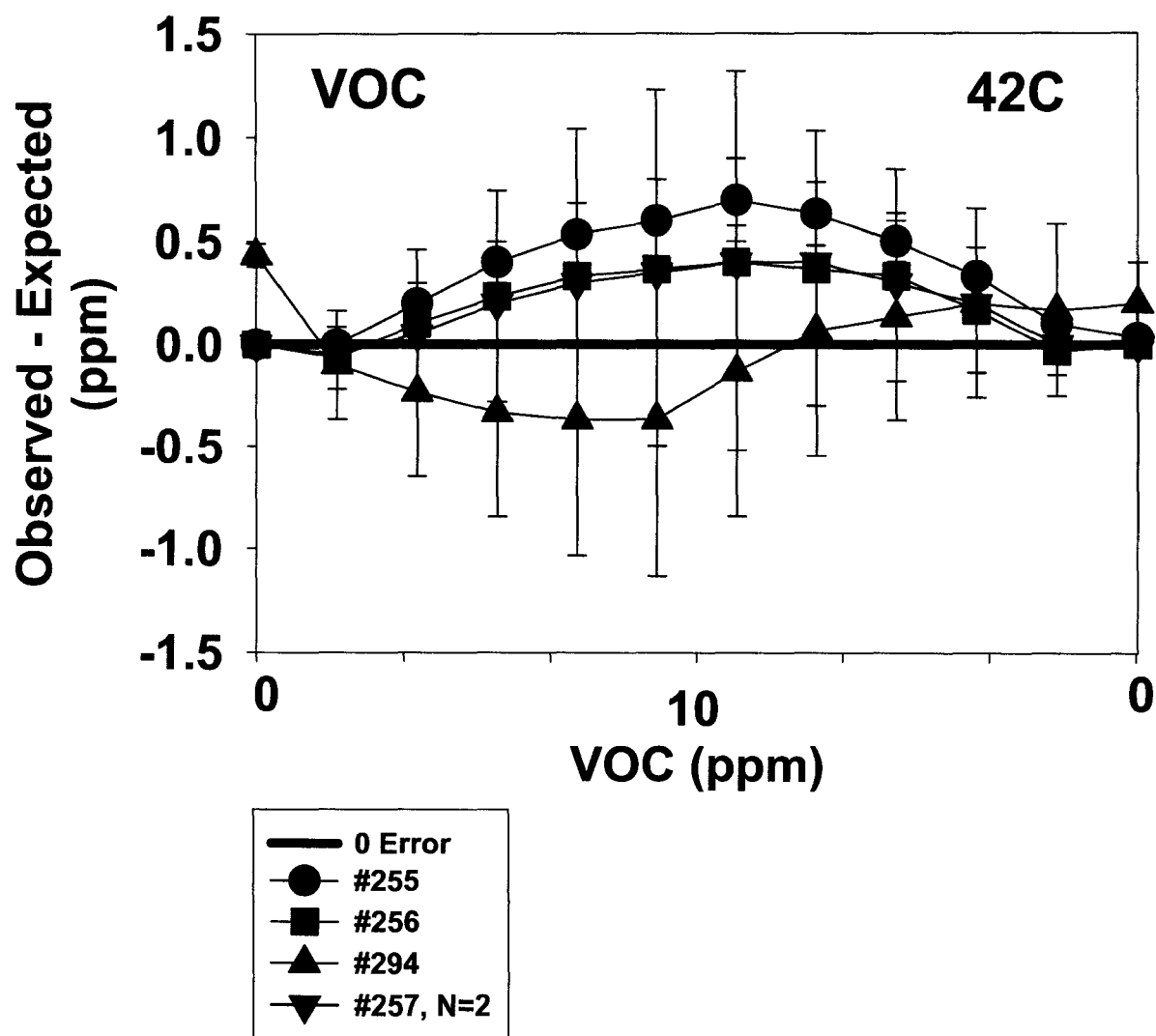
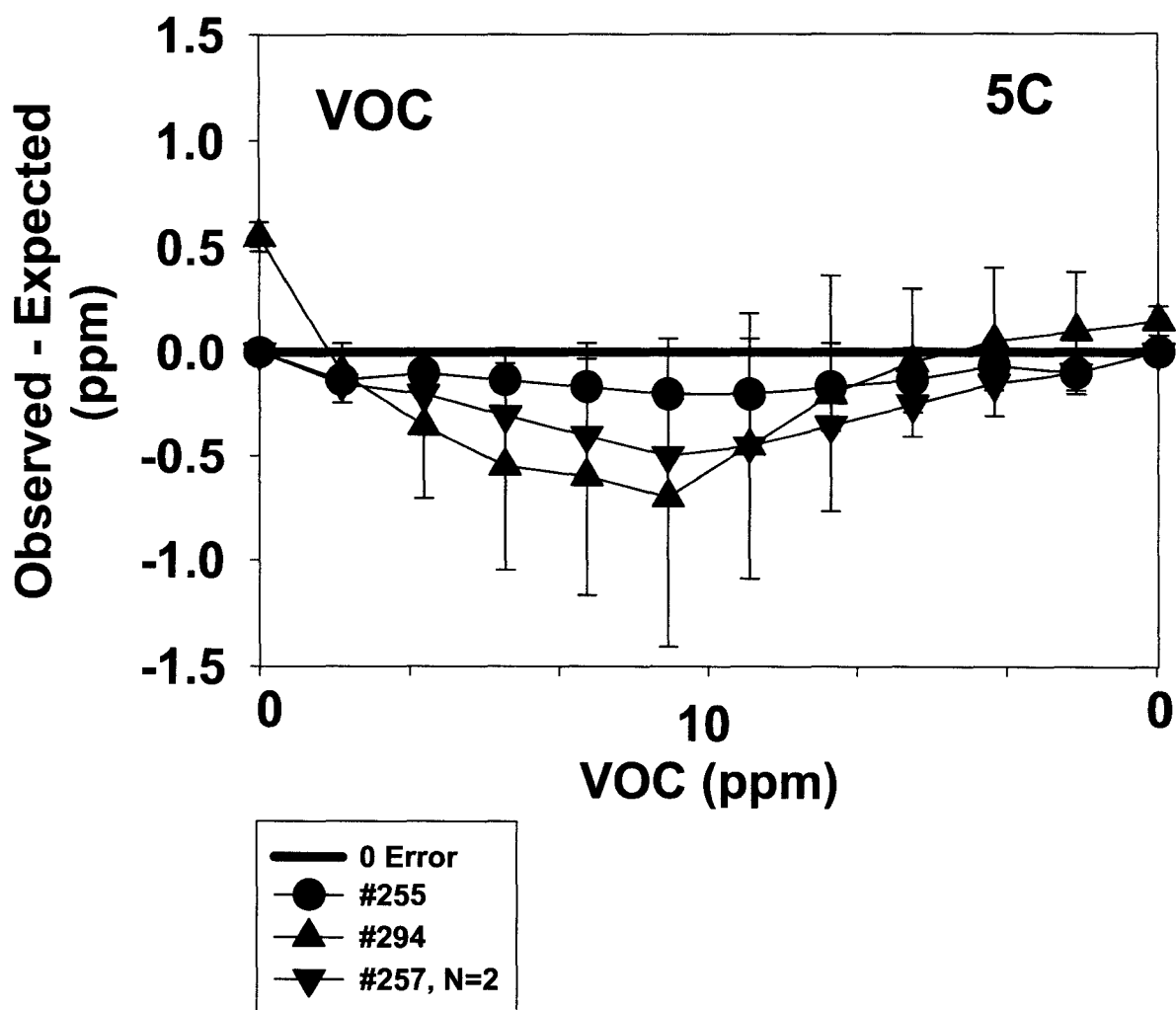


FIGURE 5C.
VOC Temperature: 5C
Final Prototype Monitor
Means and SDs, N=6,2



FIGURES 6A-C. CO temperature testing: before and after CO sensor temperature modification.

FIGURE 6A.
CO Temperature Testing: 25C
Pre/Post CO Temp MOD
Means and SDs, N=6,4

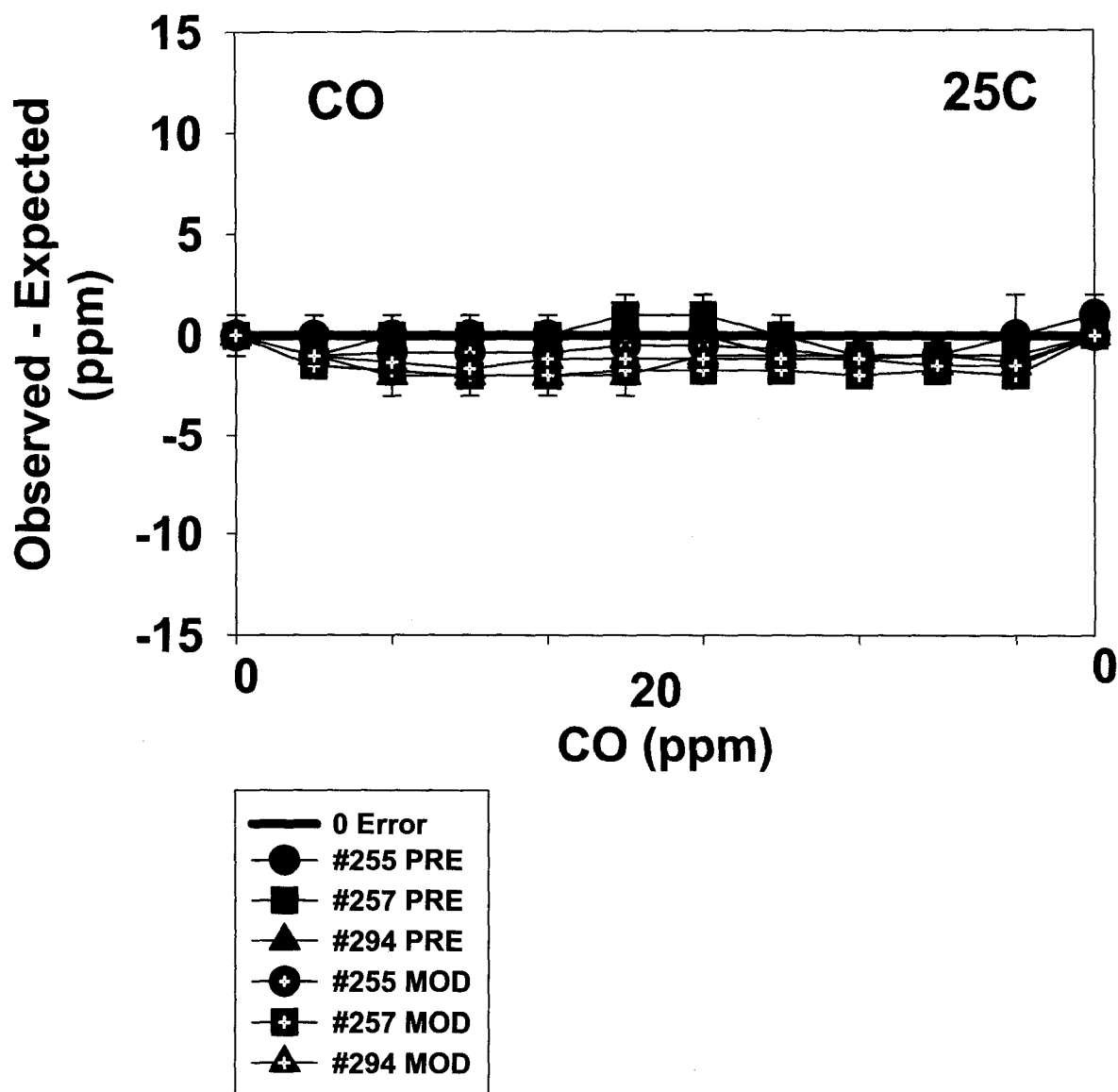


FIGURE 6B.
CO Temperature Testing: 42C
Pre/Post CO Temp MOD
Means and SDs, N=3,2

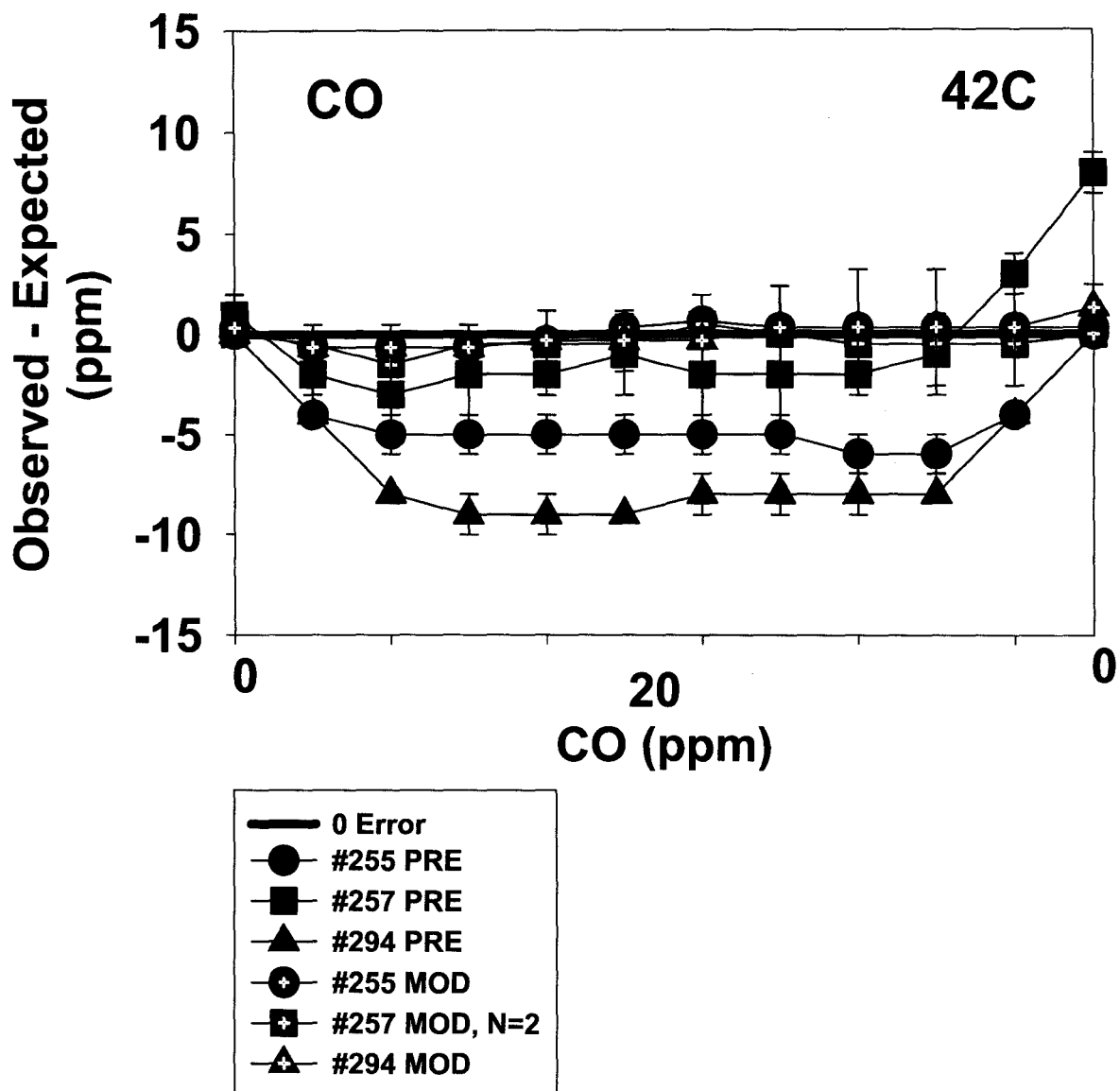


FIGURE 6C.
CO Temperature Testing: 5C
Pre/Post CO Temp MOD
Means and SDs, N=3,2

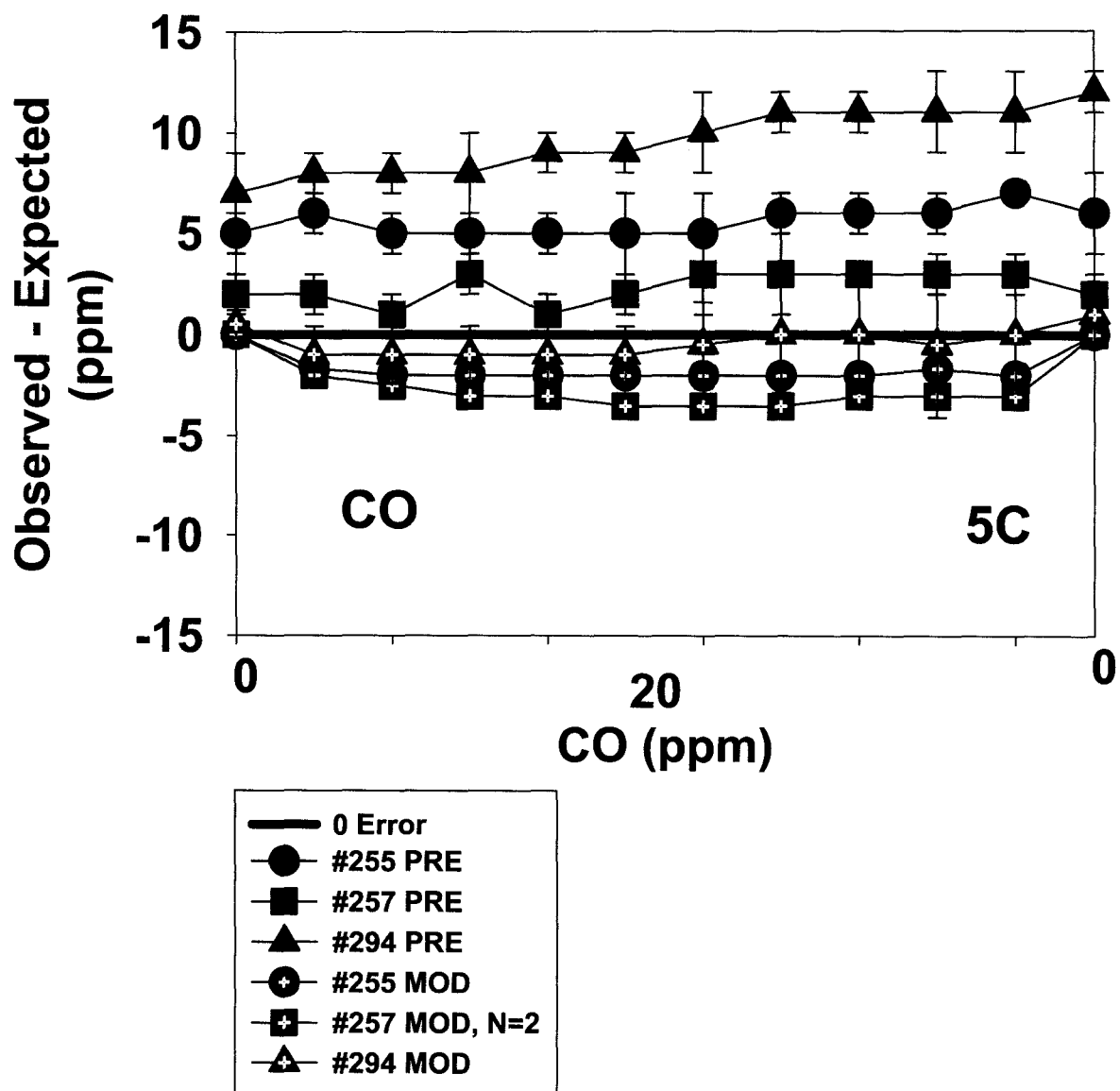
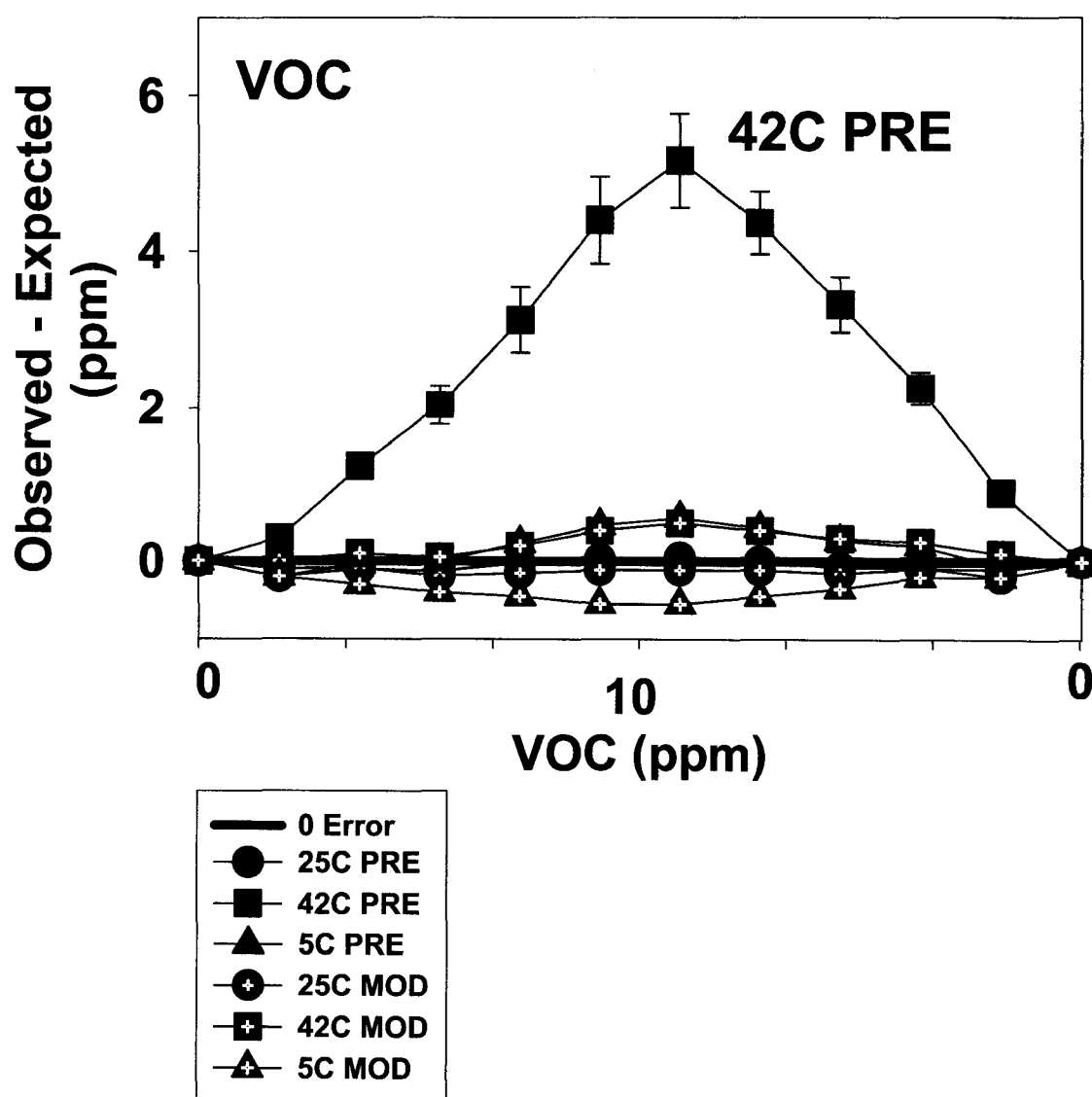


FIGURE 7. VOC temperature testing: before and after PID temperature compensation.

FIGURE 7.
VOC Temperature Testing
Reboxed Monitor #298
Pre/Post PID Temp MOD
Means and SDs, N=3-8



FIGURES 8A-C. O₂ accuracy — final reboxed monitor.

FIGURE 8A.
O₂ Accuracy: 25C
Final Reboxed Monitor
Means and SDs, N=8

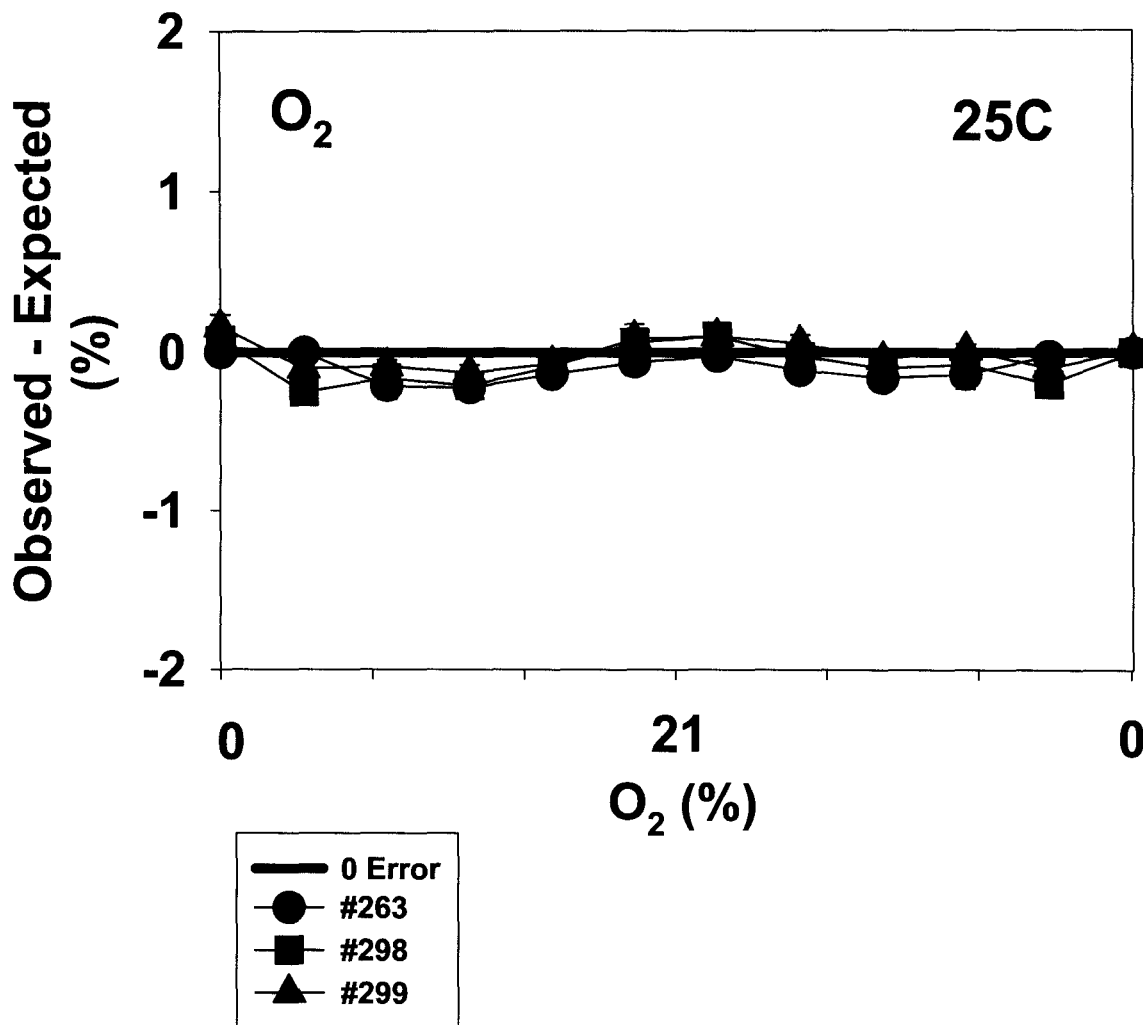


FIGURE 8B.
O₂ Accuracy: 42C
Final Reboxed Monitor
Means and SDs, N=4-8

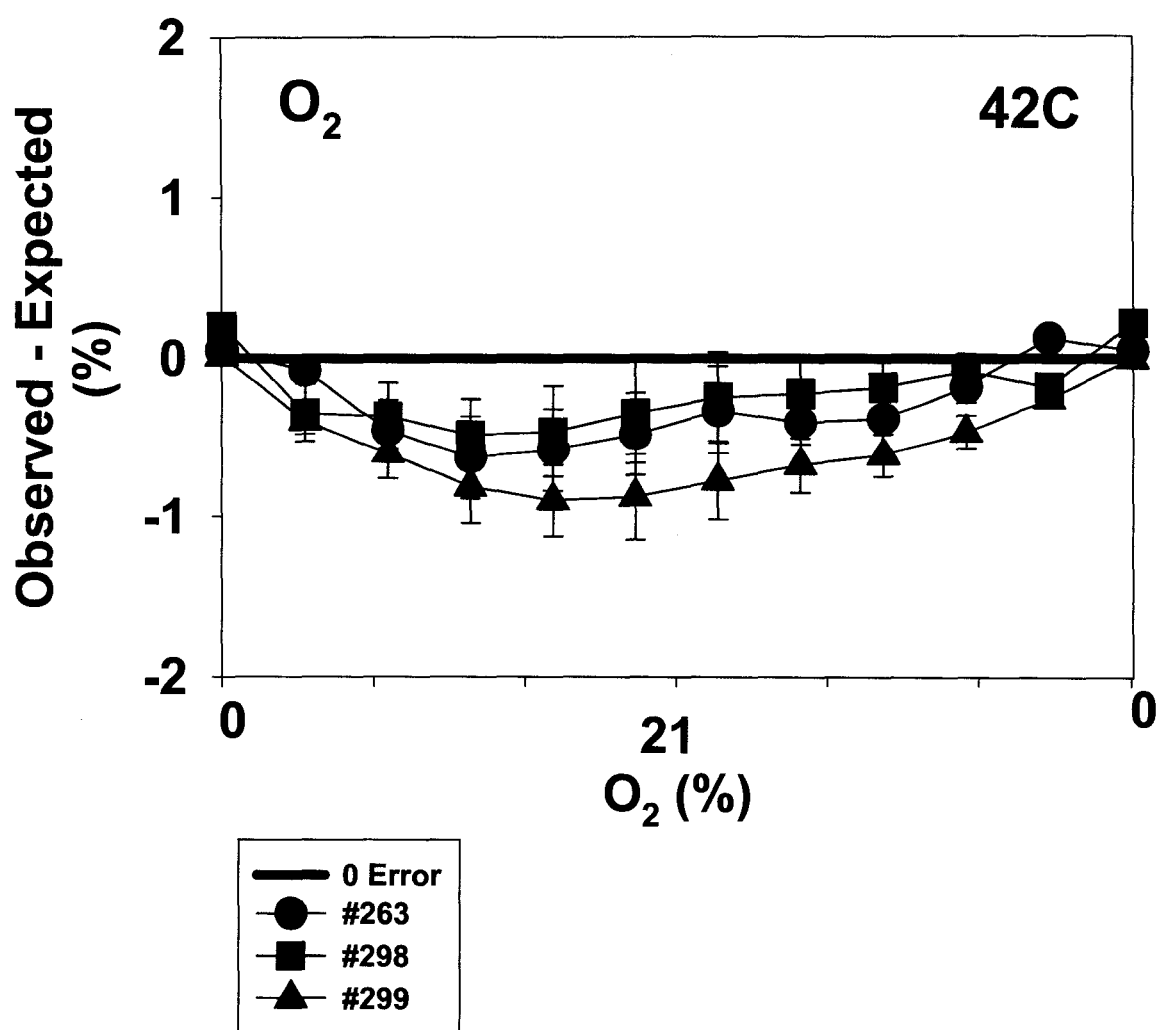
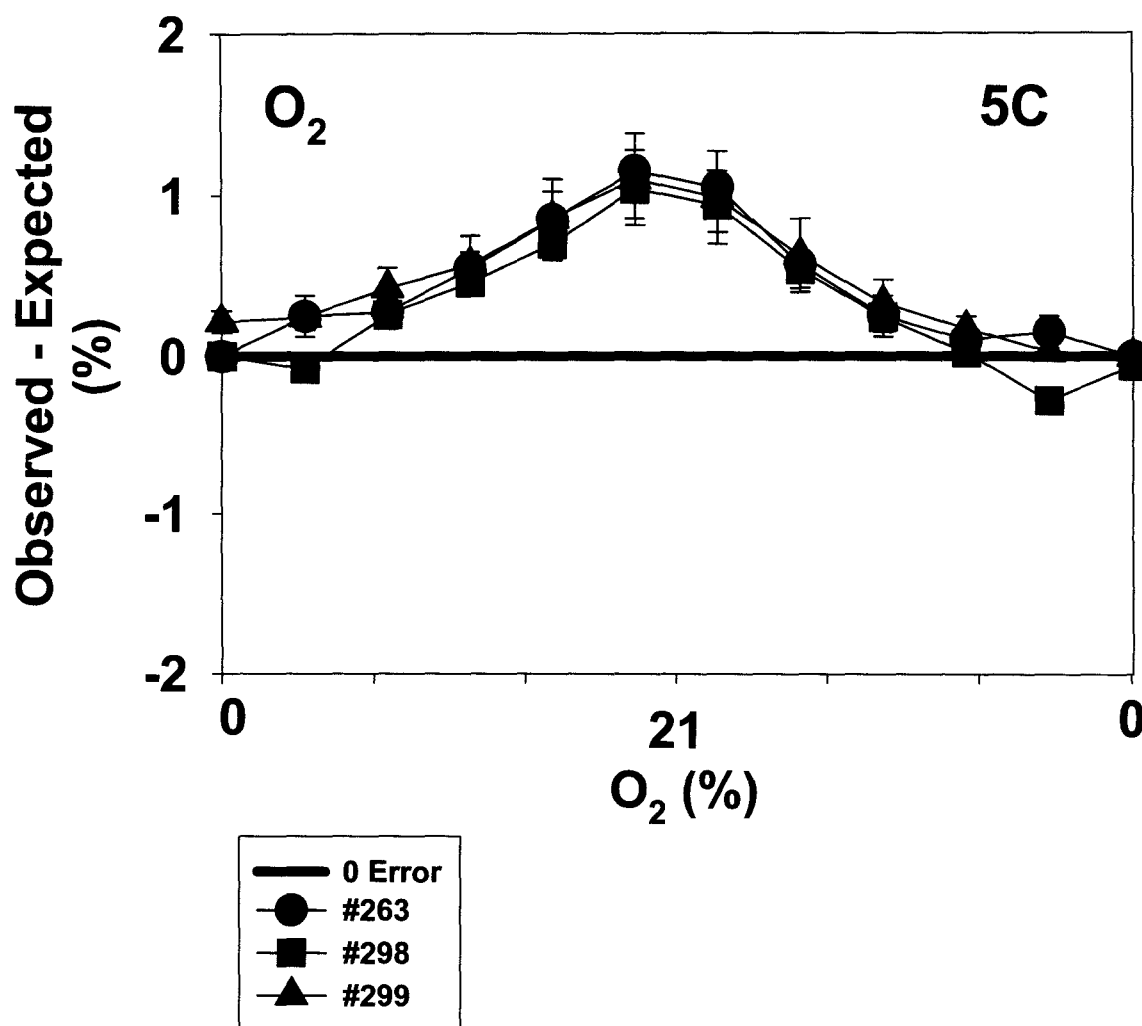


FIGURE 8C.
O₂ Accuracy: 5C
Final Reboxed Monitor
Means and SDs, N=4-7



FIGURES 9A-C. CO₂ accuracy — final reboxed monitor.

FIGURE 9A.
CO₂ Accuracy: 25C
Final Reboxed Monitor
Means and SDs, N=8

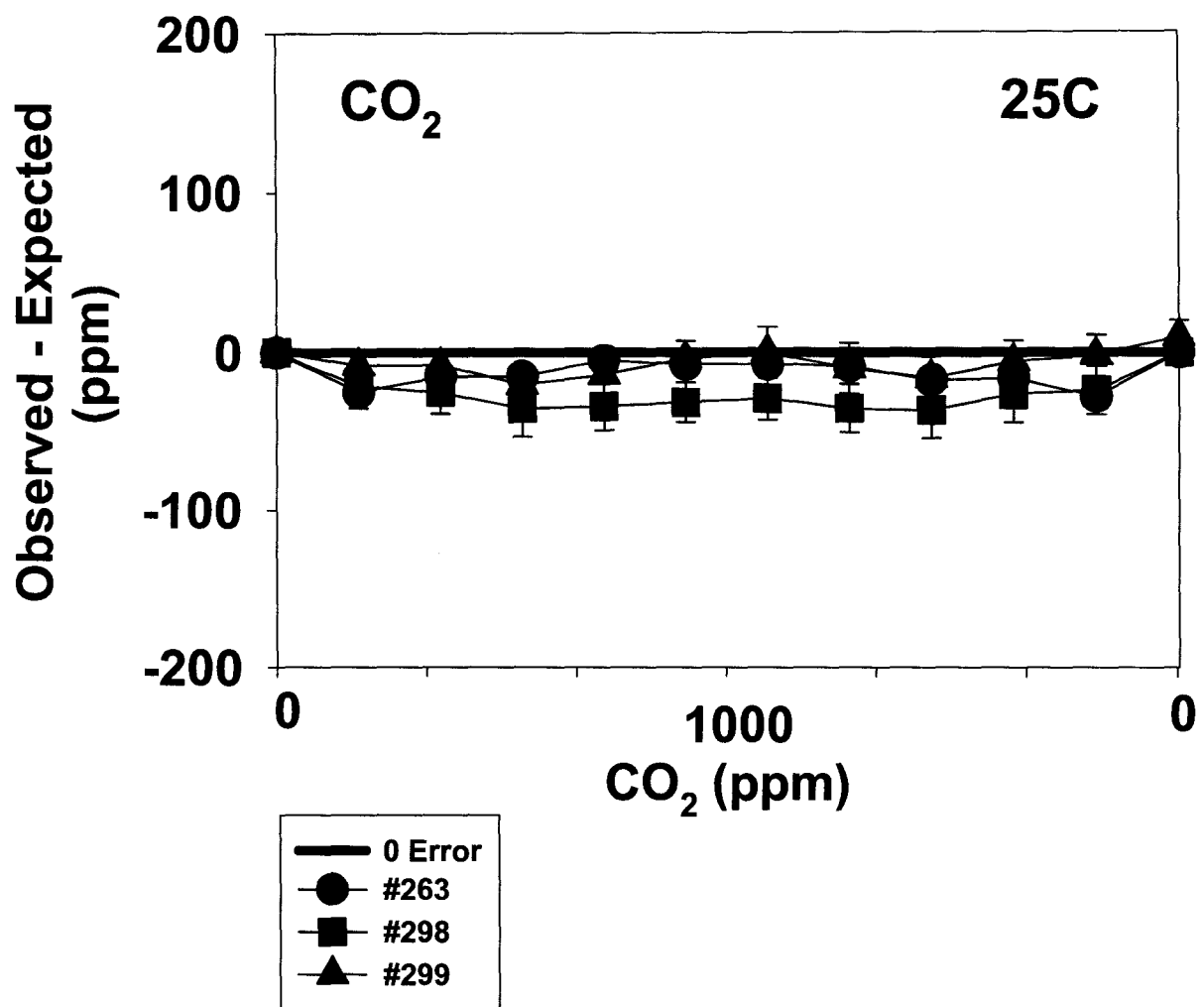


FIGURE 9B.
CO₂ Accuracy: 42C
Final Reboxed Monitor
Means and SDs, N=4-8

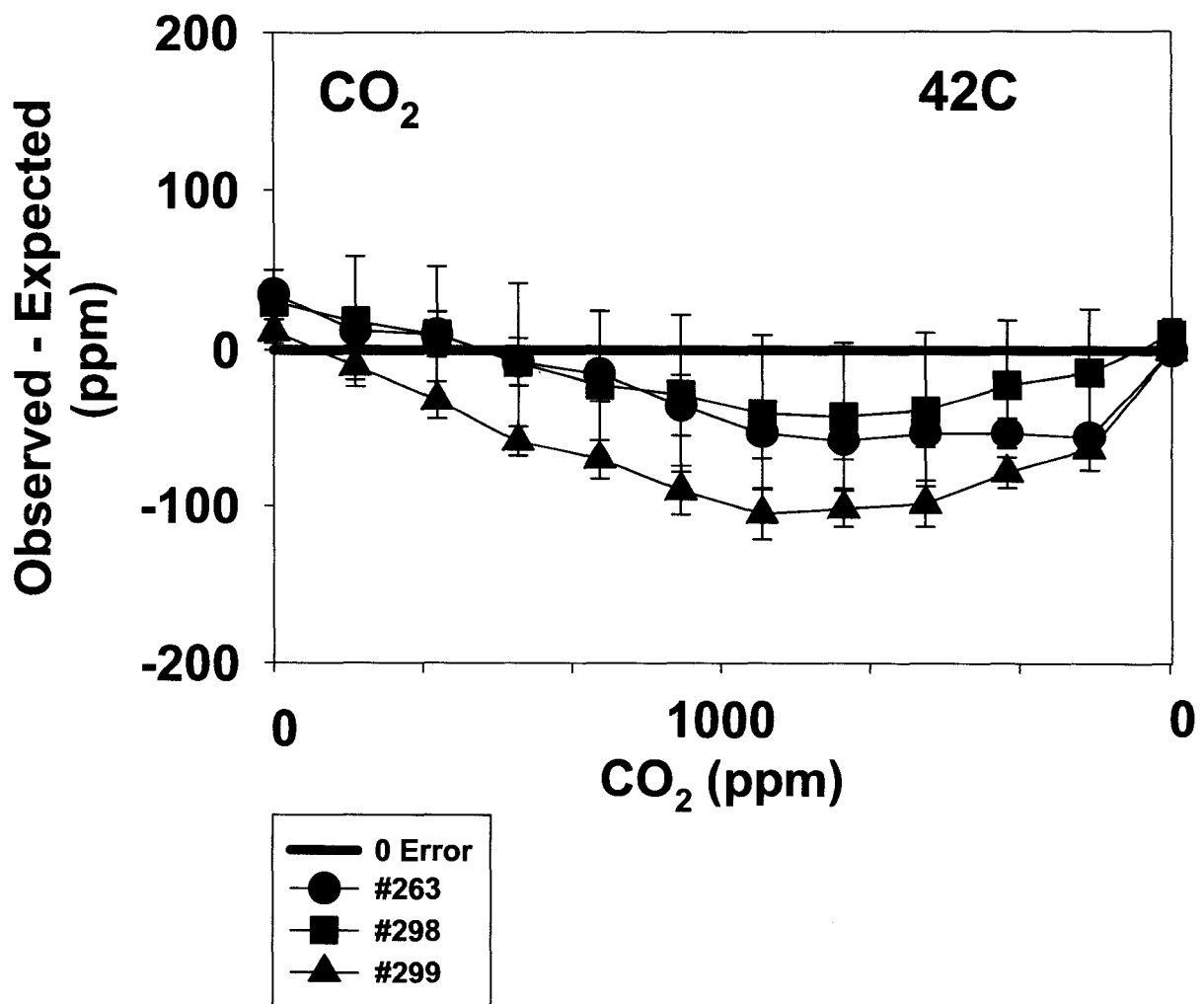
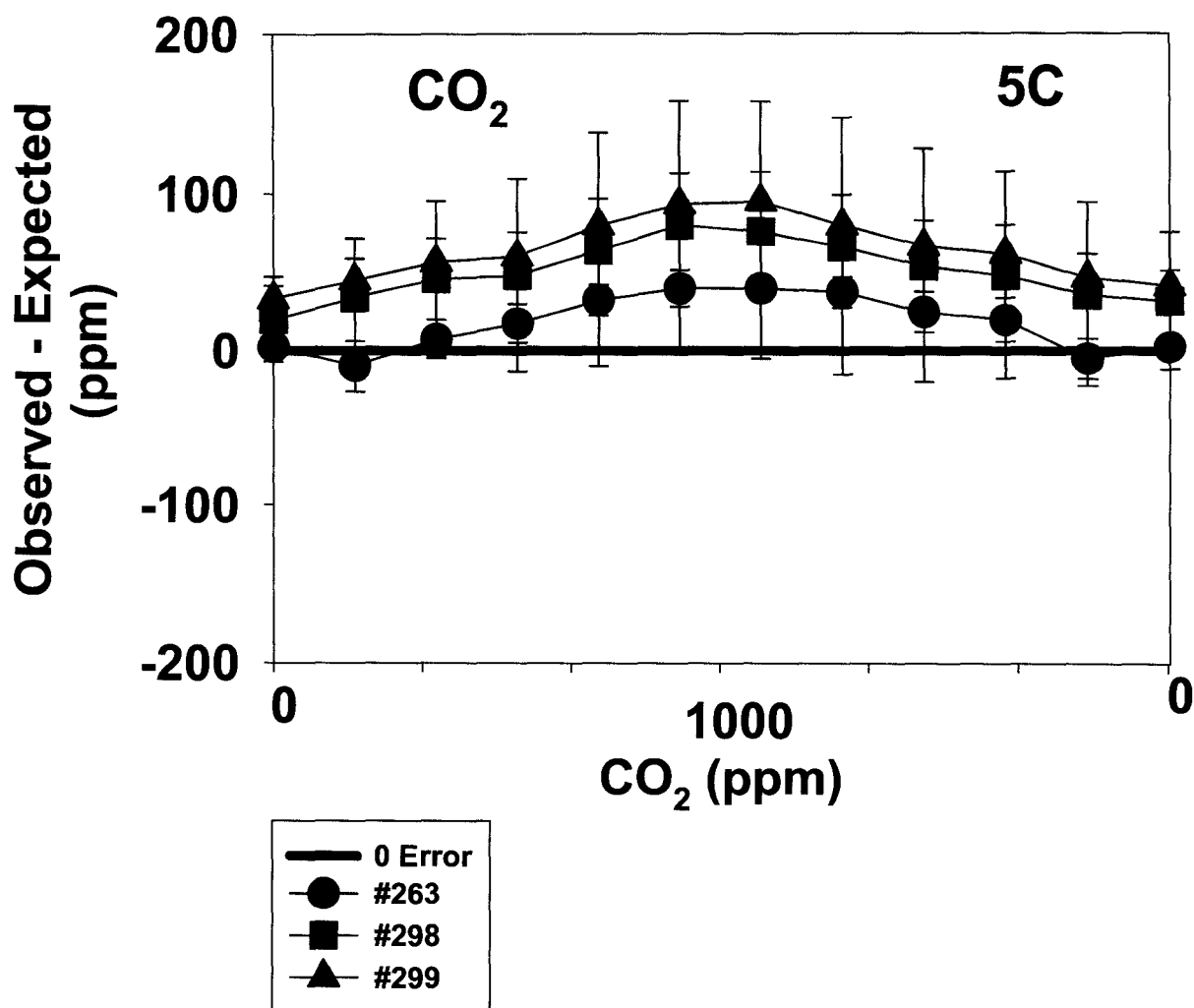


FIGURE 9C.
CO₂ Accuracy: 5C
Final Reboxed Monitor
Means and SDs, N=4-7



FIGURES 10A-C. CO accuracy – final reboxed monitor.

FIGURE 10A.
CO Accuracy: 25C
Final Reboxed Monitor
Means and SDs, N=8

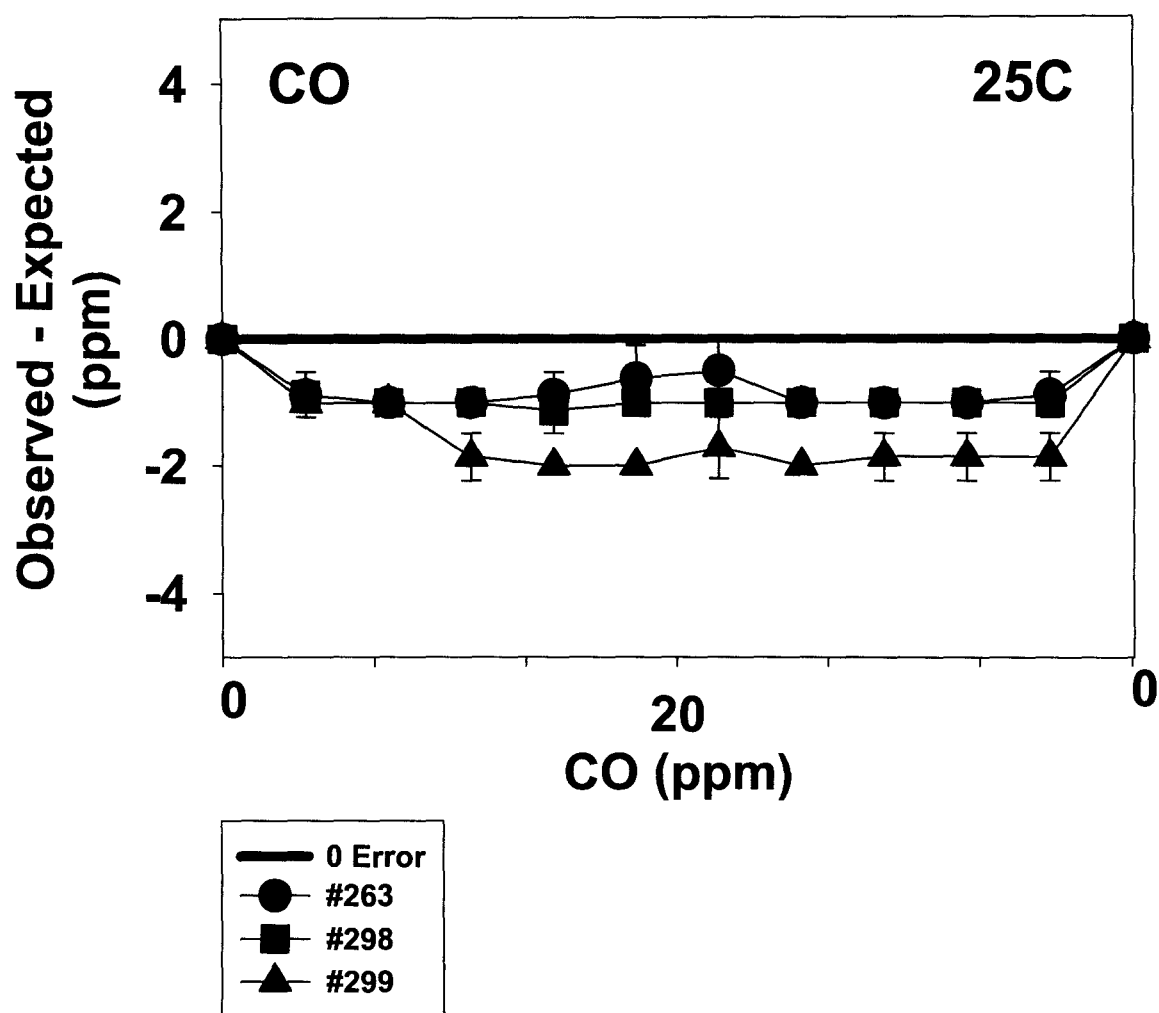


FIGURE 10B.
CO Accuracy: 42C
Final Reboxed Monitor
Means and SDs, N=4-8

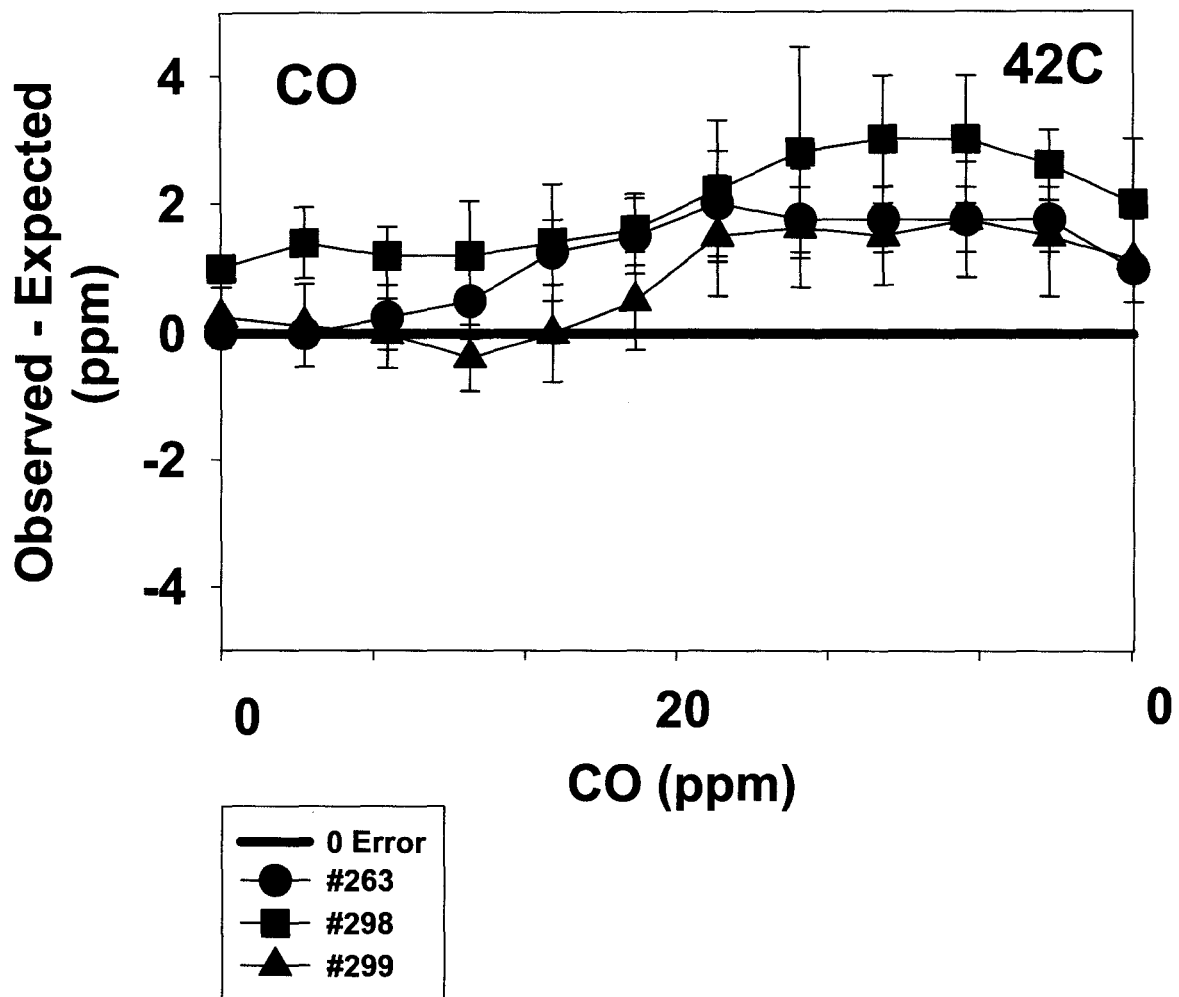
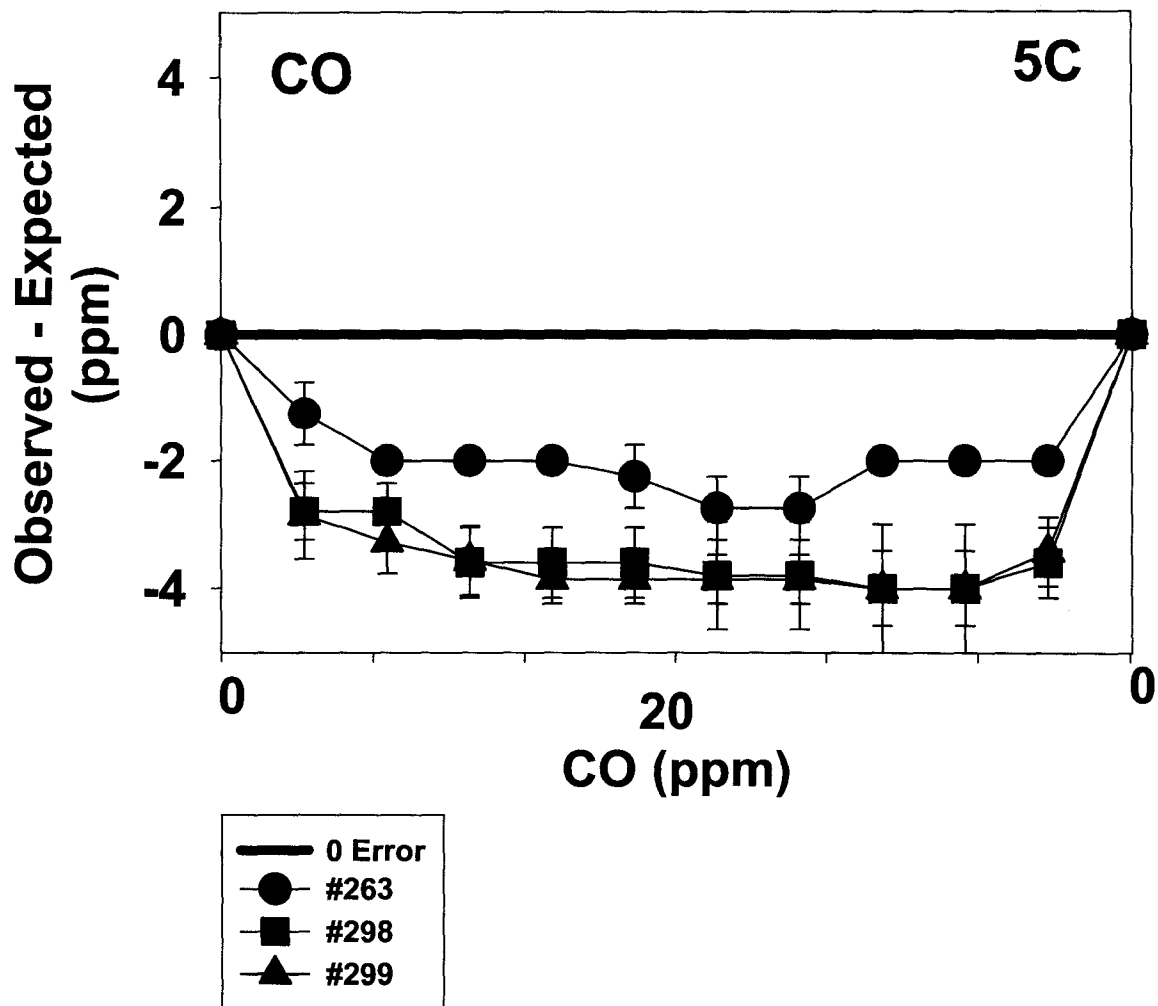


FIGURE 10C.
CO Accuracy: 5C
Final Reboxed Monitor
Means and SDs, N=4-7



FIGURES 11A-C. VOC testing – final reboxed monitor.

FIGURE 11A.
VOC Accuracy: 25C
Final Reboxed Monitor
Means and SDs, N=8

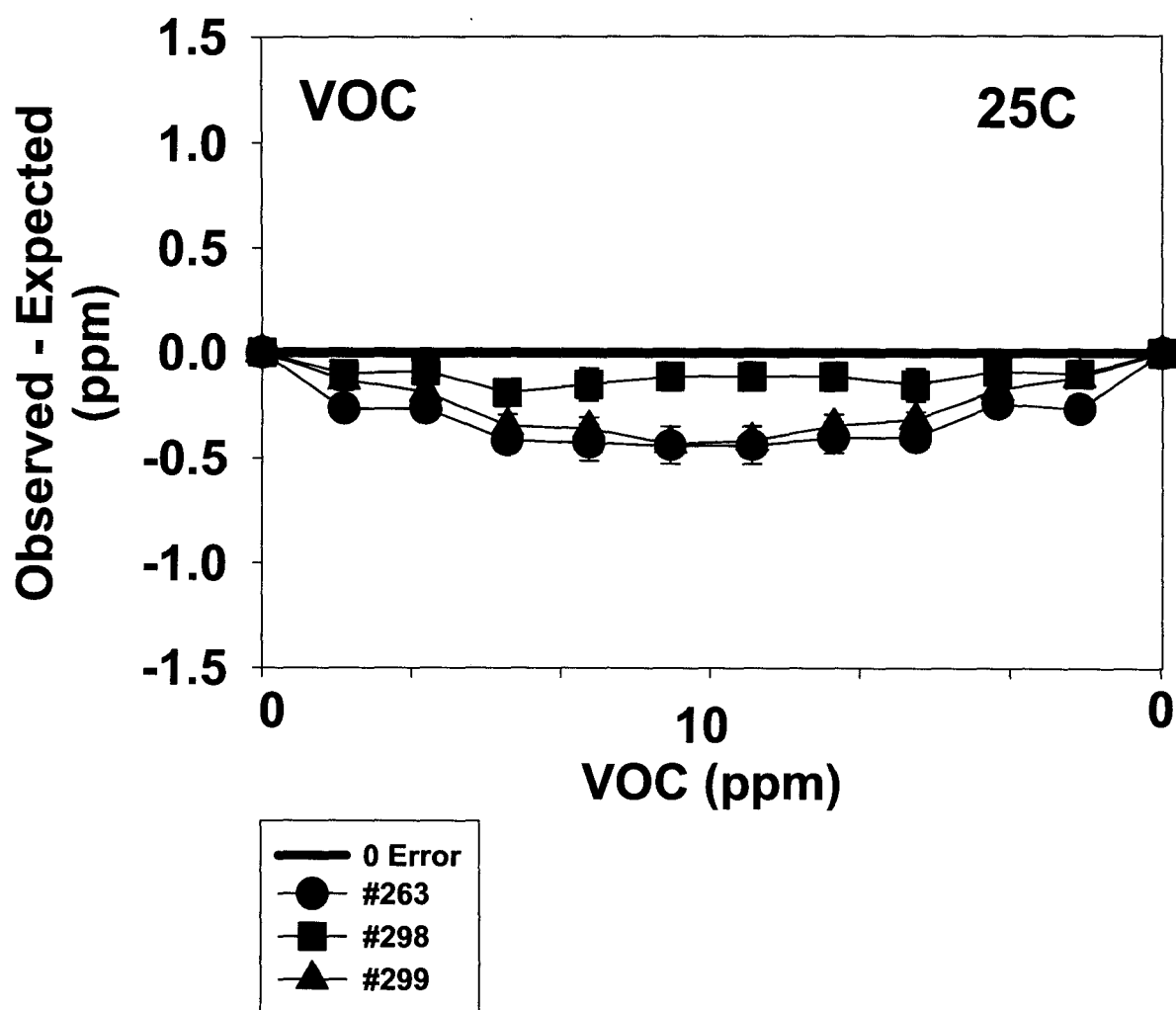


FIGURE 11B.
VOC Accuracy: 42C
Final Reboxed Monitor
Means and SDs, N=2-8

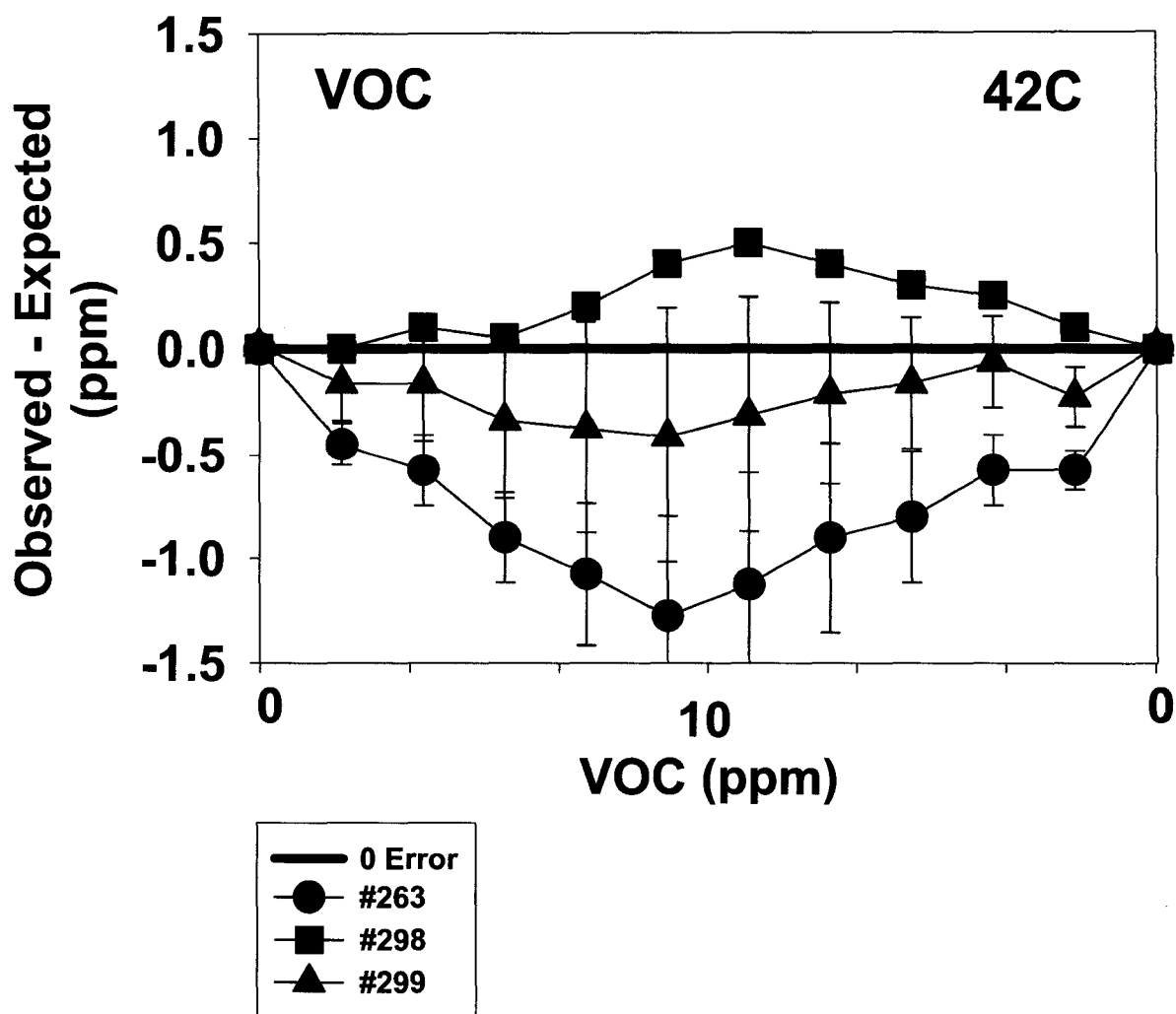
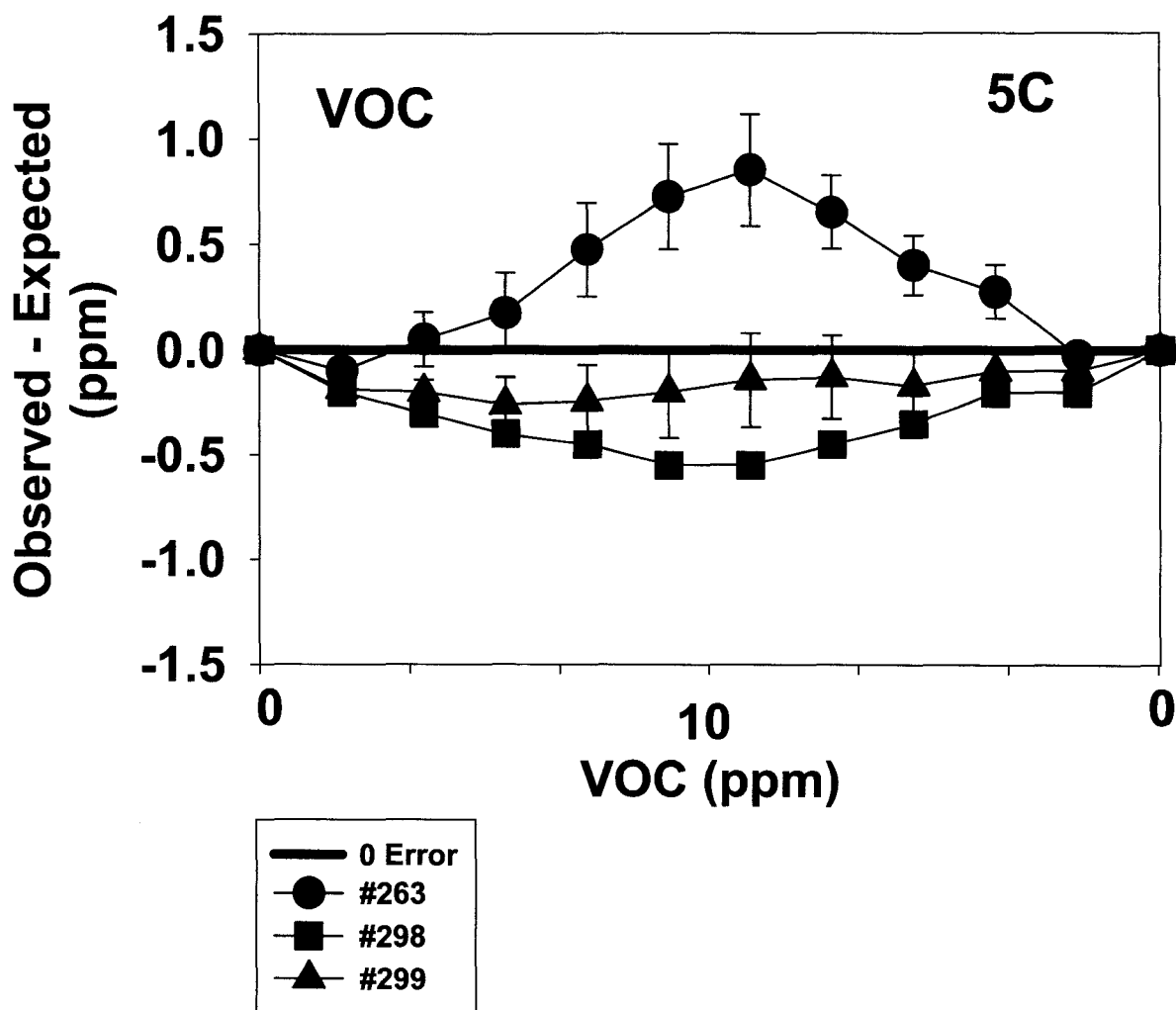


FIGURE 11C.
VOC Accuracy: 5C
Final Reboxed Monitor
Means and SDs, N=2-7



FIGURES 12A-D. Short-term stability – final reboxed monitor.

FIGURE 12A.
O₂ Short-term Stability: 25C
Final Reboxed Monitor
Means and SDs, N=4

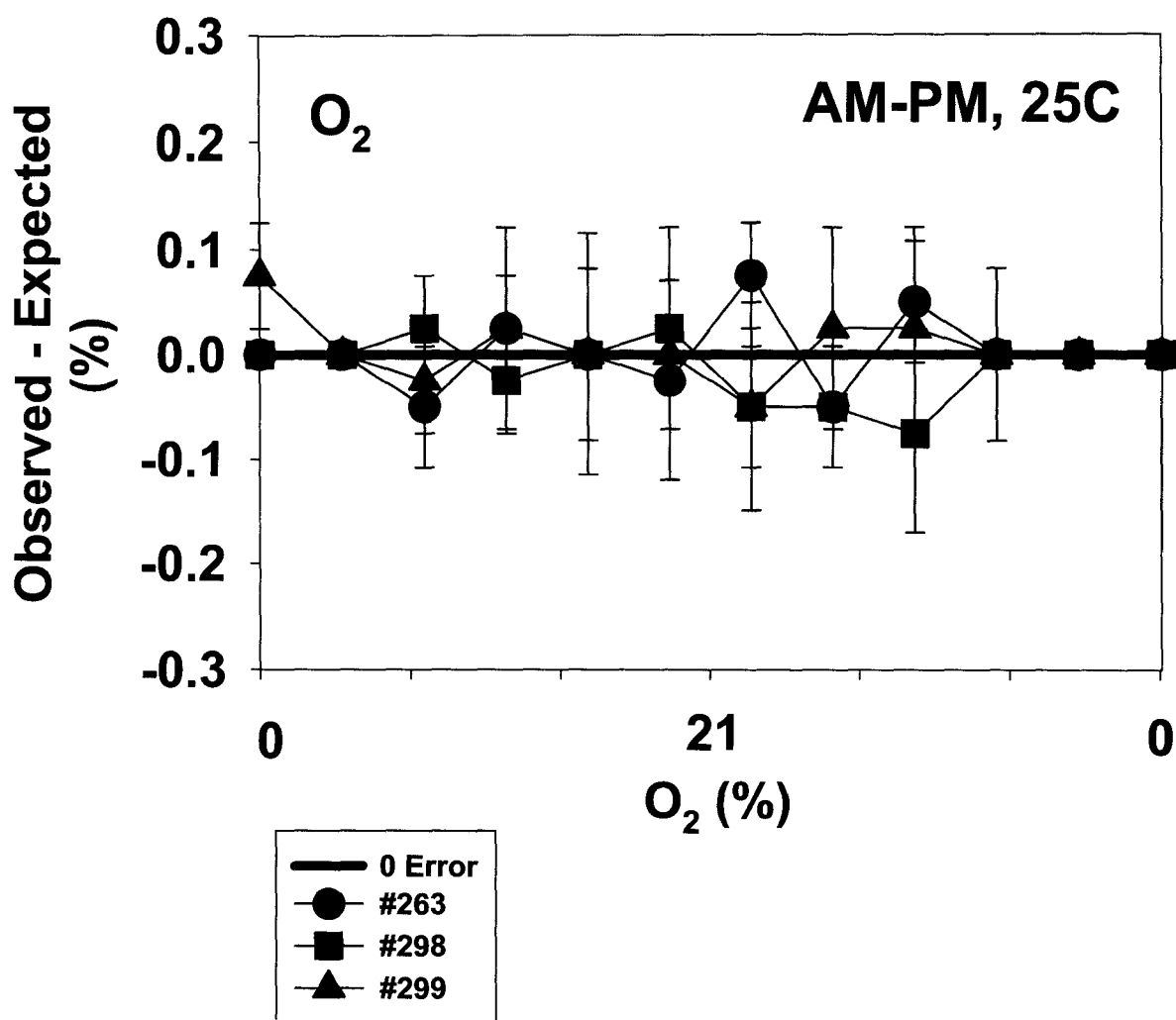


FIGURE 12B.
CO₂ Short-term Stability: 25C
Final Reboxed Monitor
Means and SDs, N=4

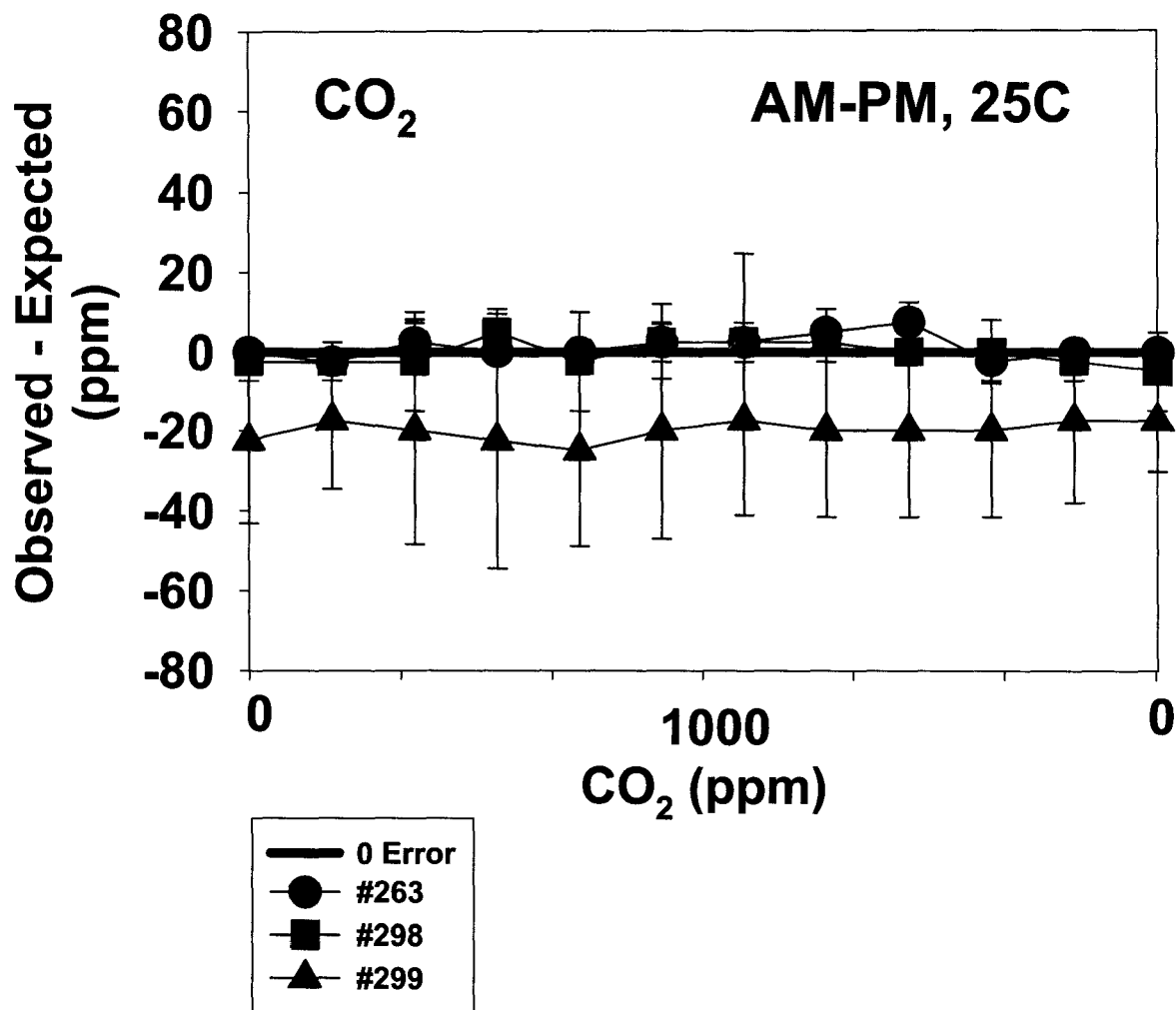


FIGURE 12C.
CO Short-term Stability: 25C
Final Reboxed Monitor
Means and SDs, N=4

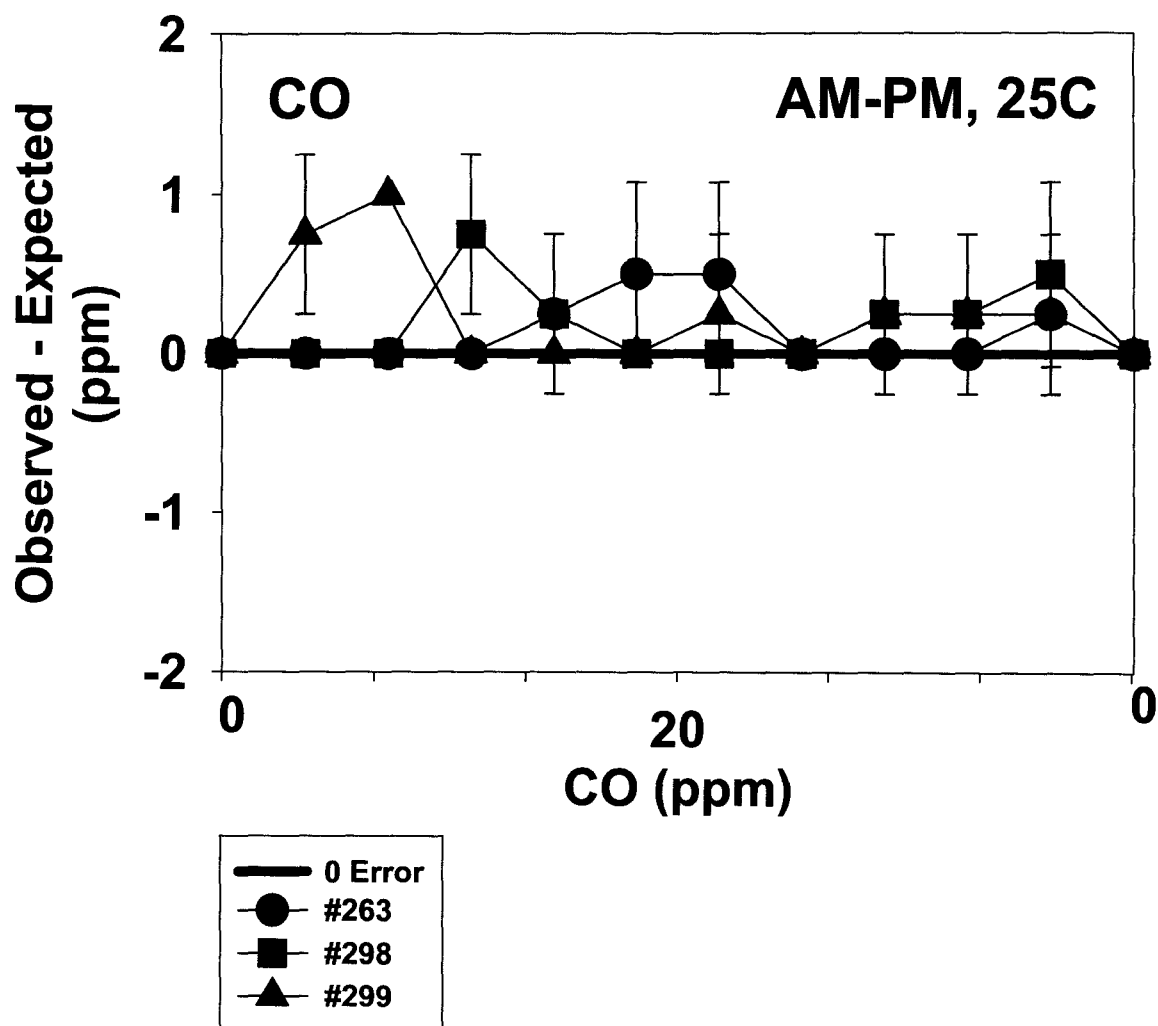
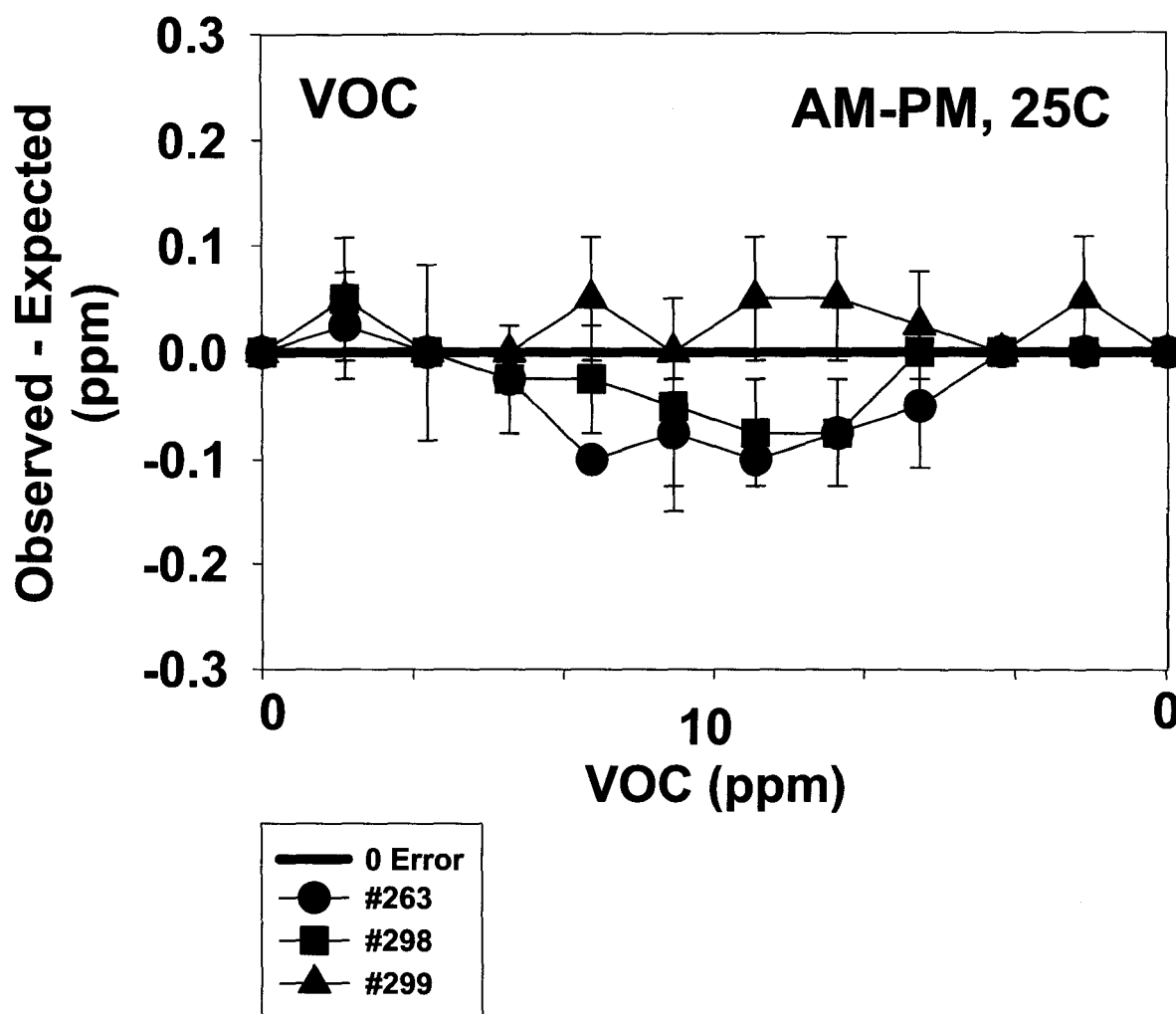


FIGURE 12D.
VOC Short-term Stability: 25C
Final Reboxed Monitor
Means and SDs, N=4



FIGURES 13A-D. Long-term stability – final reboxed monitors.

FIGURE 13A.
O₂ Long-term Stability: 25C
Final Reboxed Monitor
Raw Data and Means Plotted

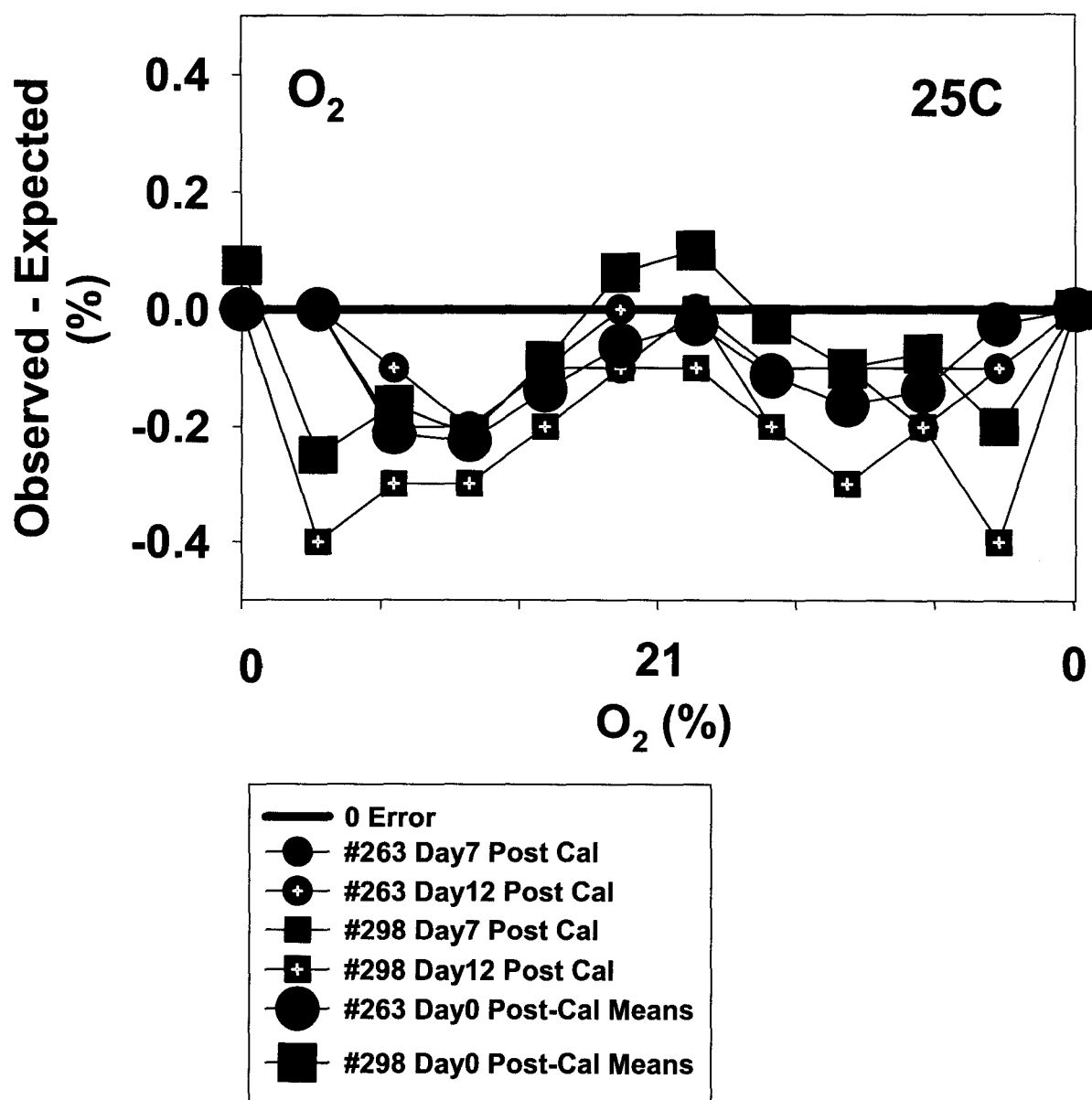


FIGURE 13B.
CO₂ Long-term Stability: 25C
Final Reboxed Monitor
Raw Data and Means Plotted

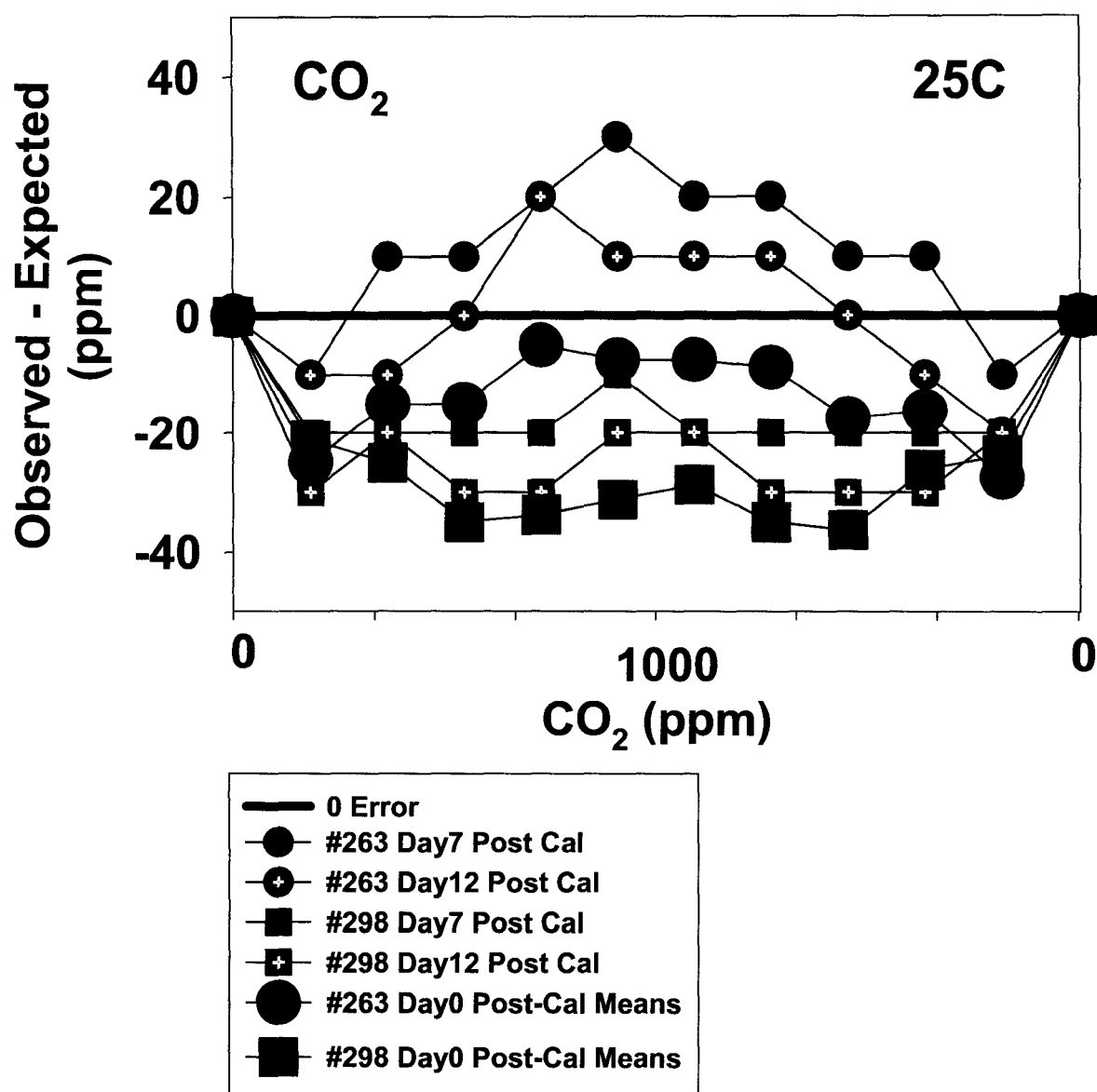


FIGURE 13C.
CO Long-term Stability: 25C
Final Reboxed Monitor
Raw Data and Means Plotted

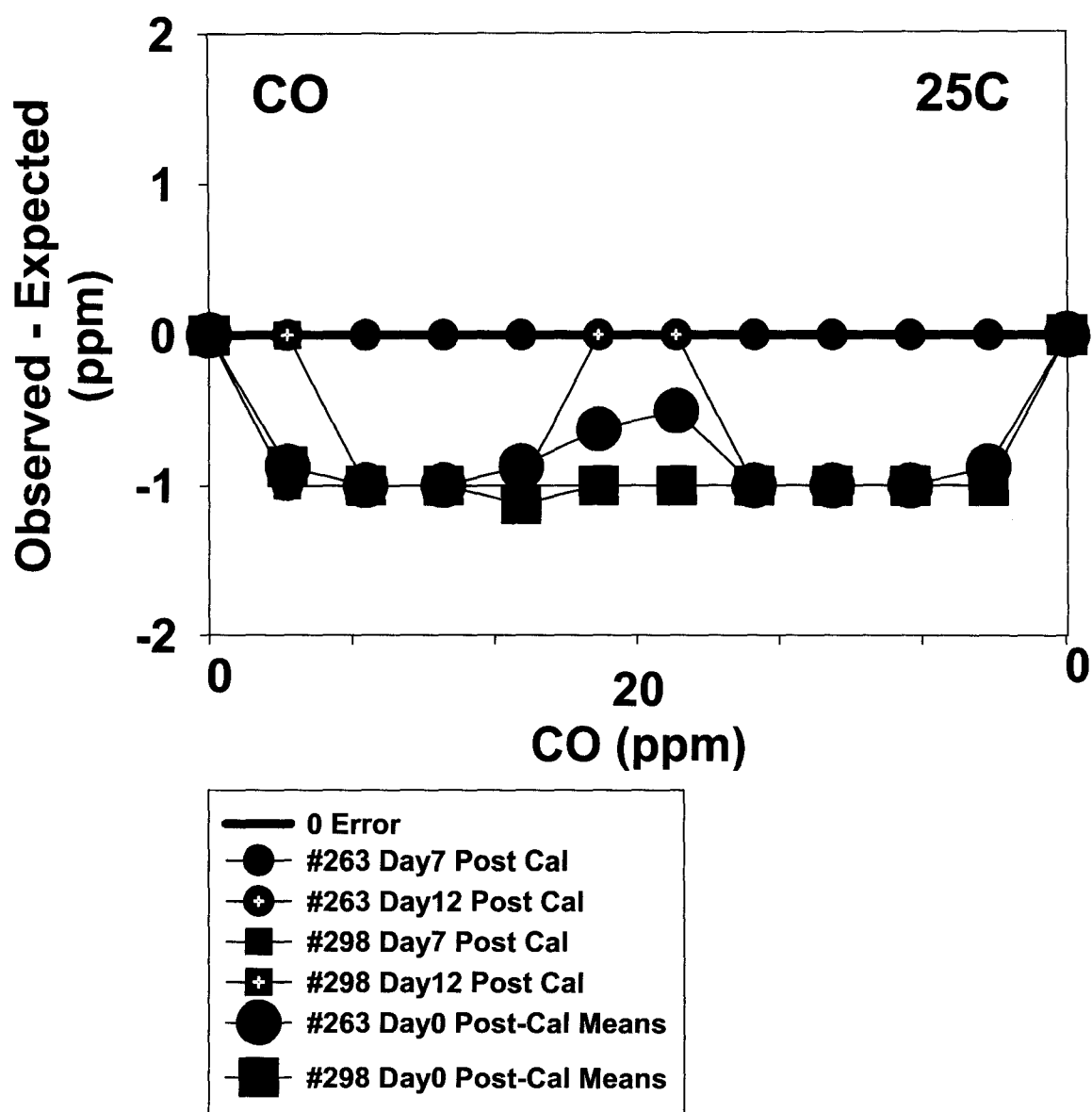
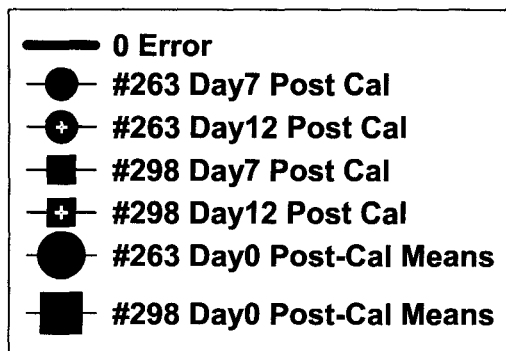
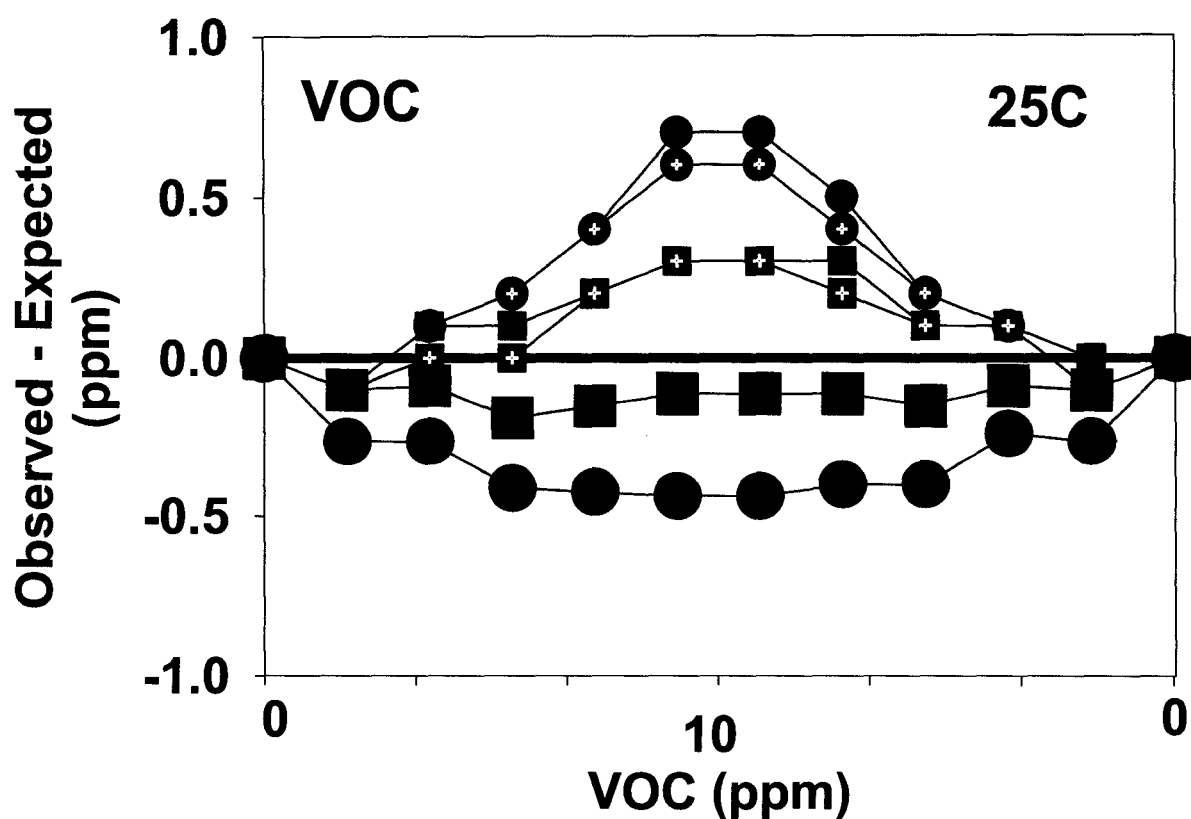


FIGURE 13D.
VOC Long-term Stability: 25C
Final Reboxed Monitor
Raw Data and Means Plotted



FIGURES 14A-D. Start-up and week-long stability – final reboxed monitor #263.

FIGURE 14A.
Start-up and Week-long Accuracy: O₂
Final Reboxed Monitor #263
7 Tests over 7 days - No Recal

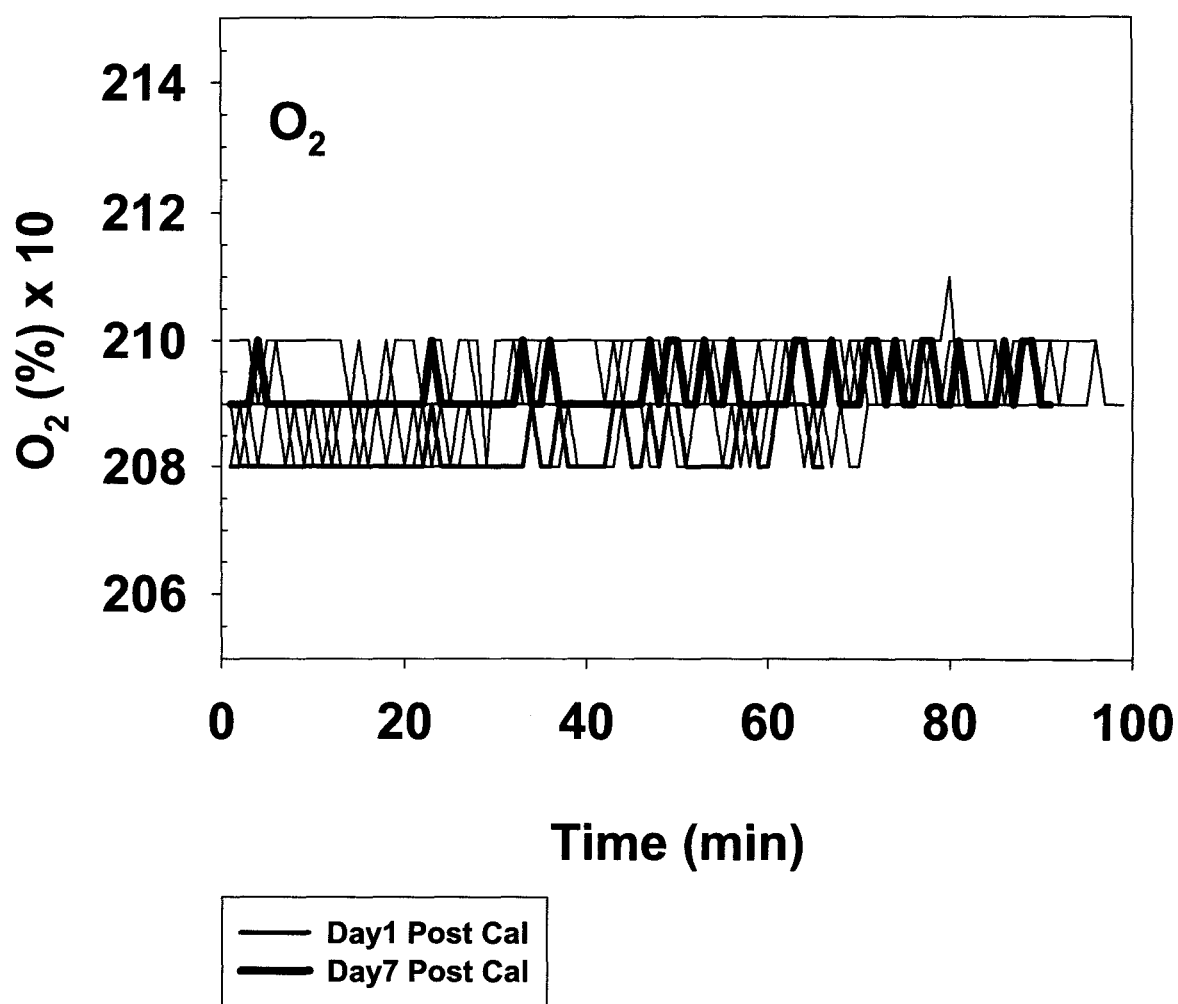


FIGURE 14B.
Start-up and Week-long Accuracy: CO₂
Final Reboxed Monitor #263
7 Tests over 7 days - No Recal

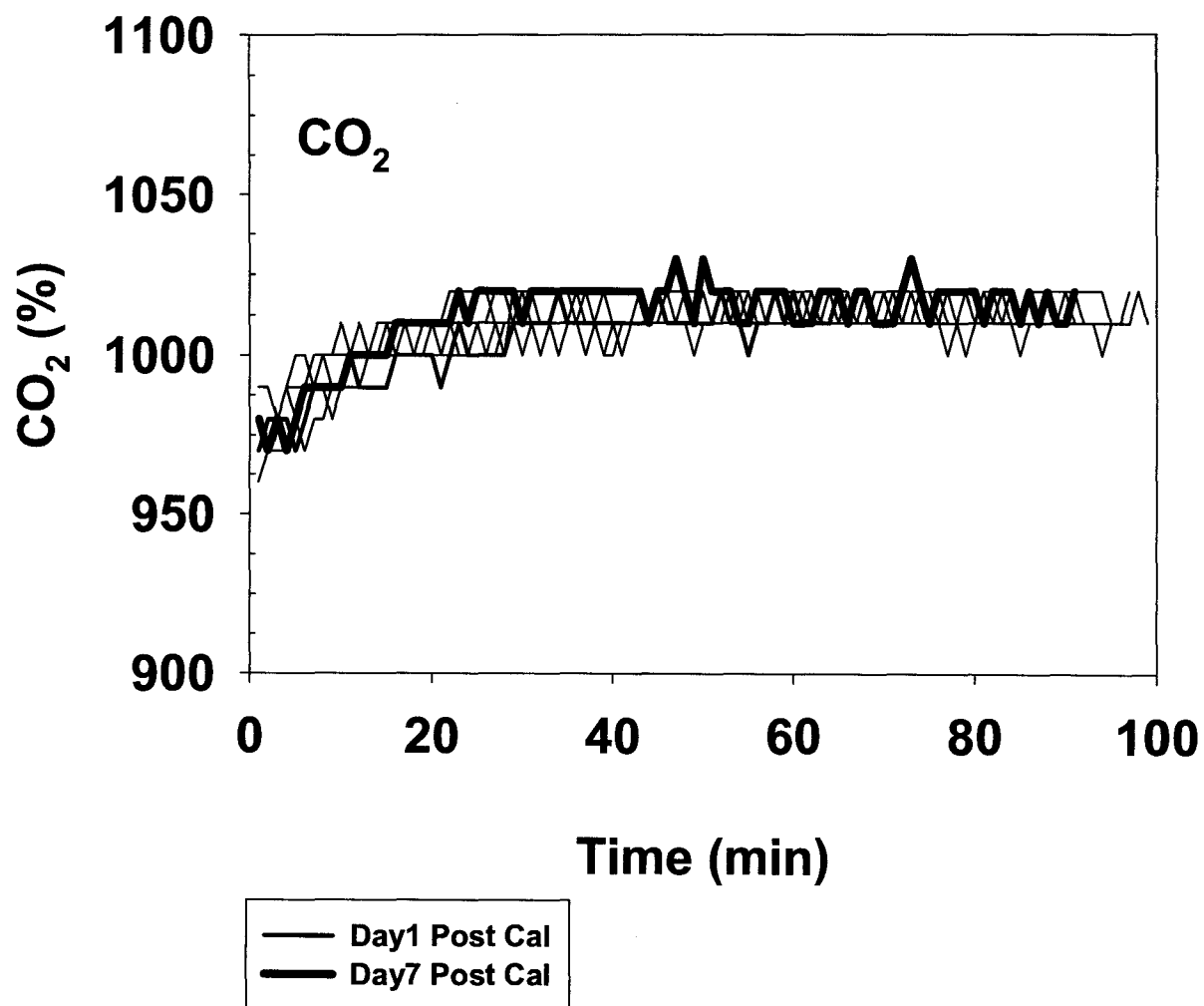


FIGURE 14C.
Start-up and Week-long Accuracy: CO
Final Reboxed Monitor #263
7 Tests over 7 days - No Recal

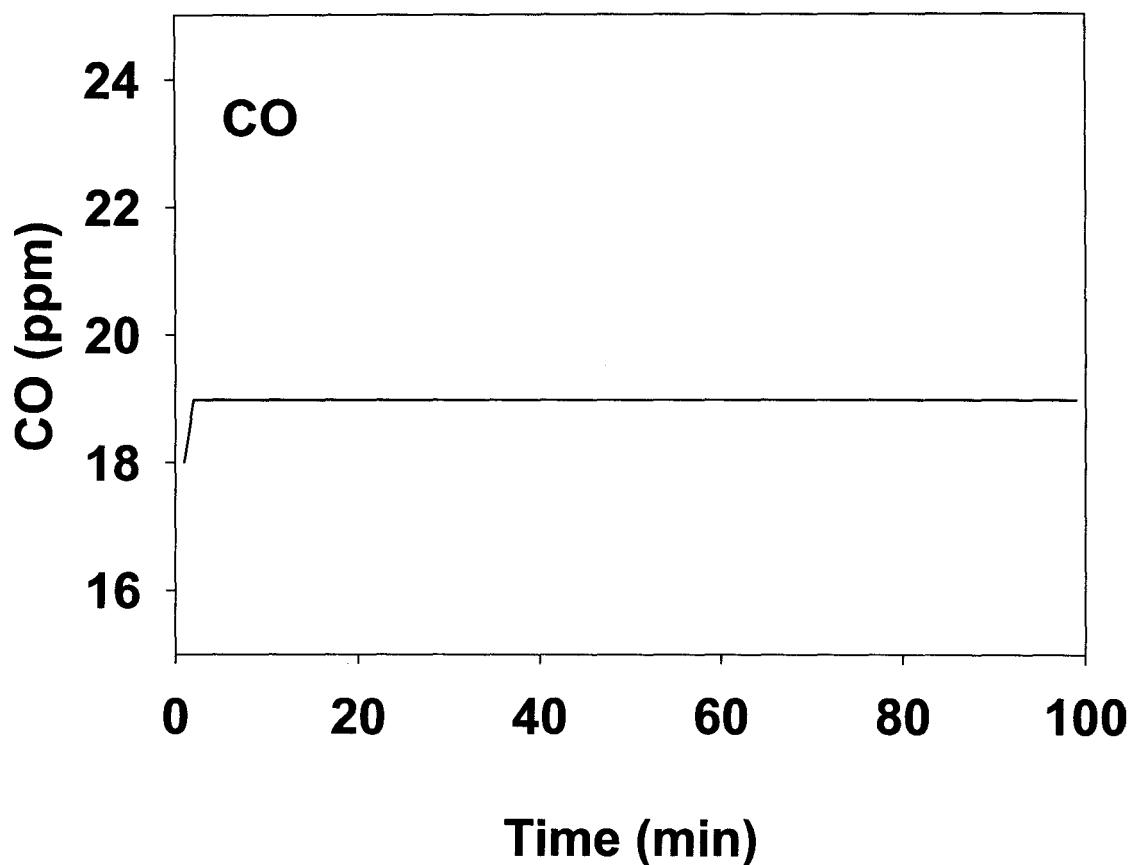
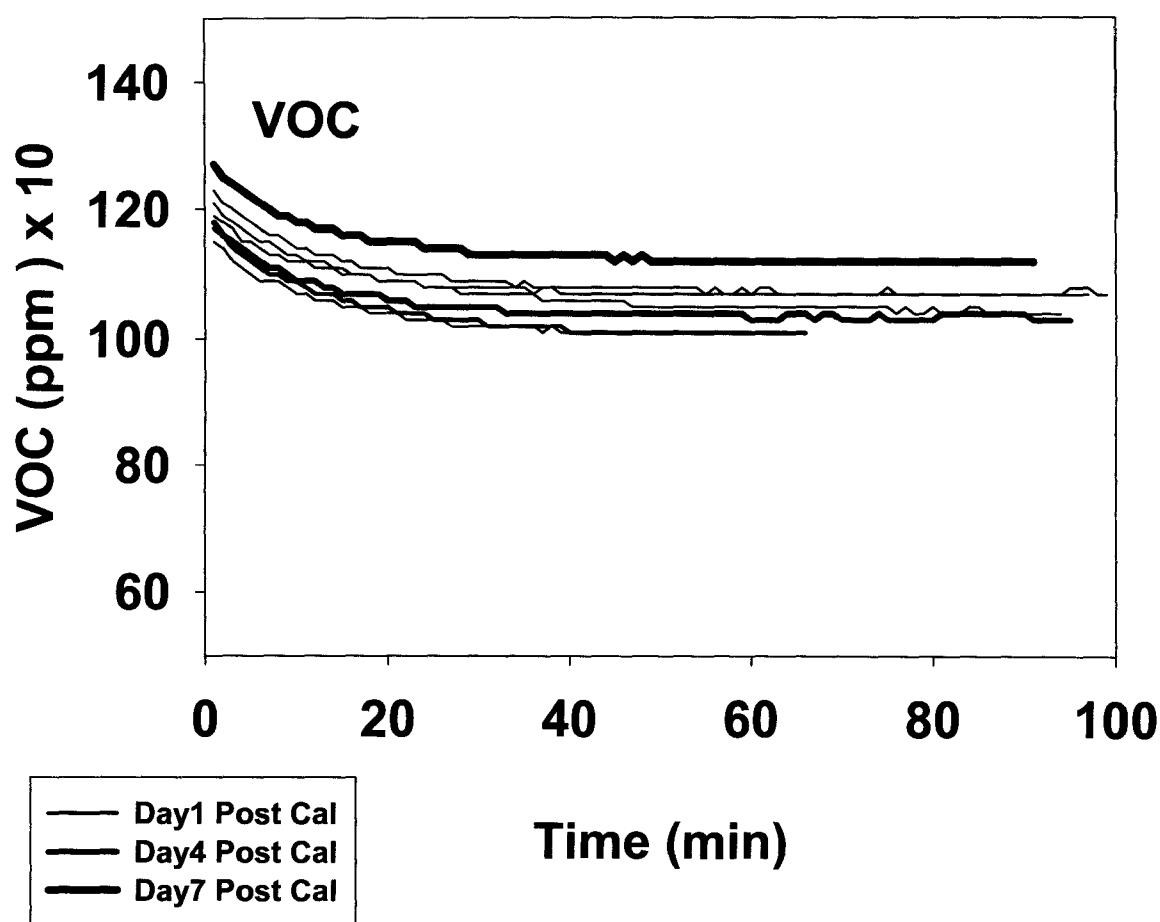


FIGURE 14D.
Start-up and Week-long Accuracy: VOC
Final Reboxed Moniator #263
7 Tests over 7 days - No Recal



FIGURES 15A-D. Start-up and week-long stability – final reboxed monitor #298.

FIGURE 15A.
Start-up and Week-long Accuracy: O₂
Final Reboxed Monitor #298
7 Tests over 7 days - No Recal

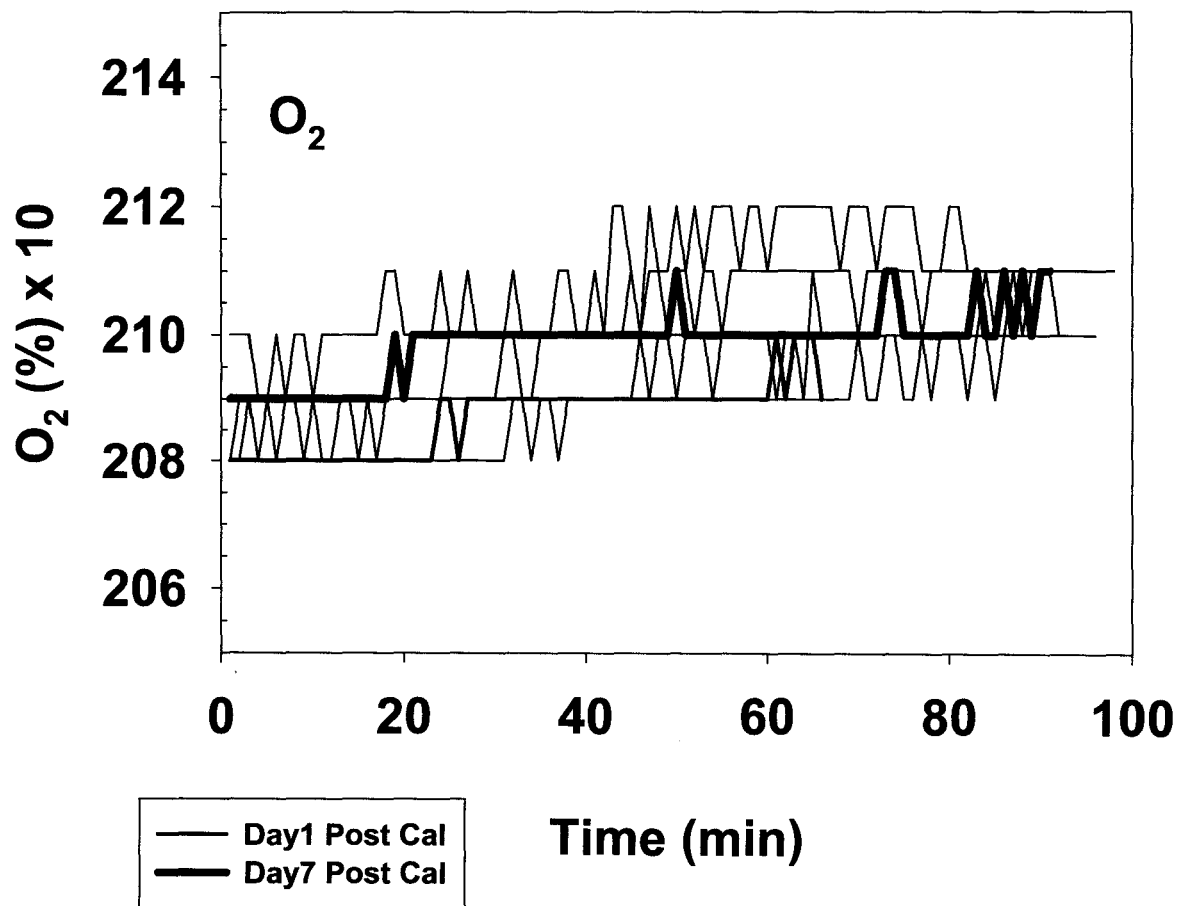


FIGURE 15B.
Start-up and Week-long Accuracy: CO₂
Final Reboxed Monitor #298
7 Tests over 7 days - No Recal

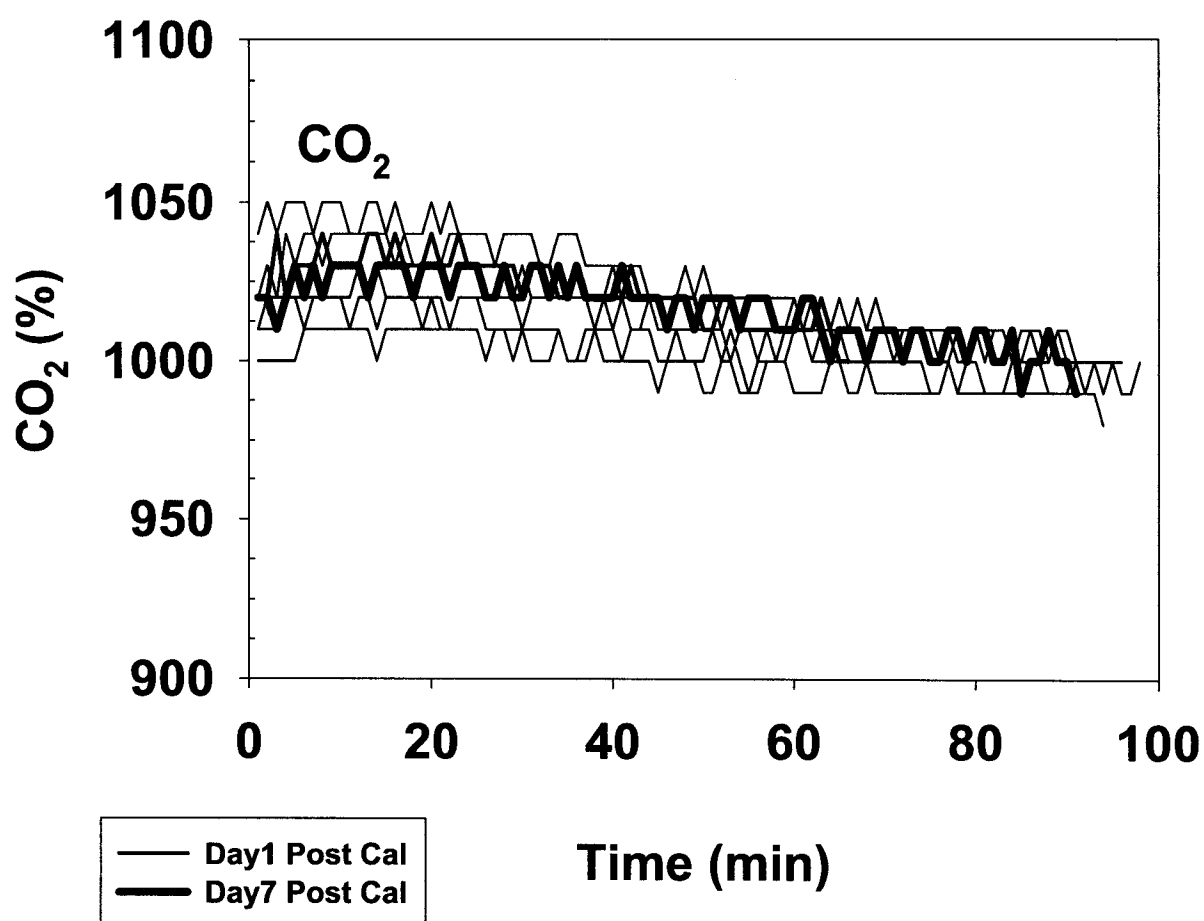


FIGURE 15C.
Start-up and Week-long Accuracy: CO
Final Reboxed Monitor #298
7 Tests over 7 days - No Recal

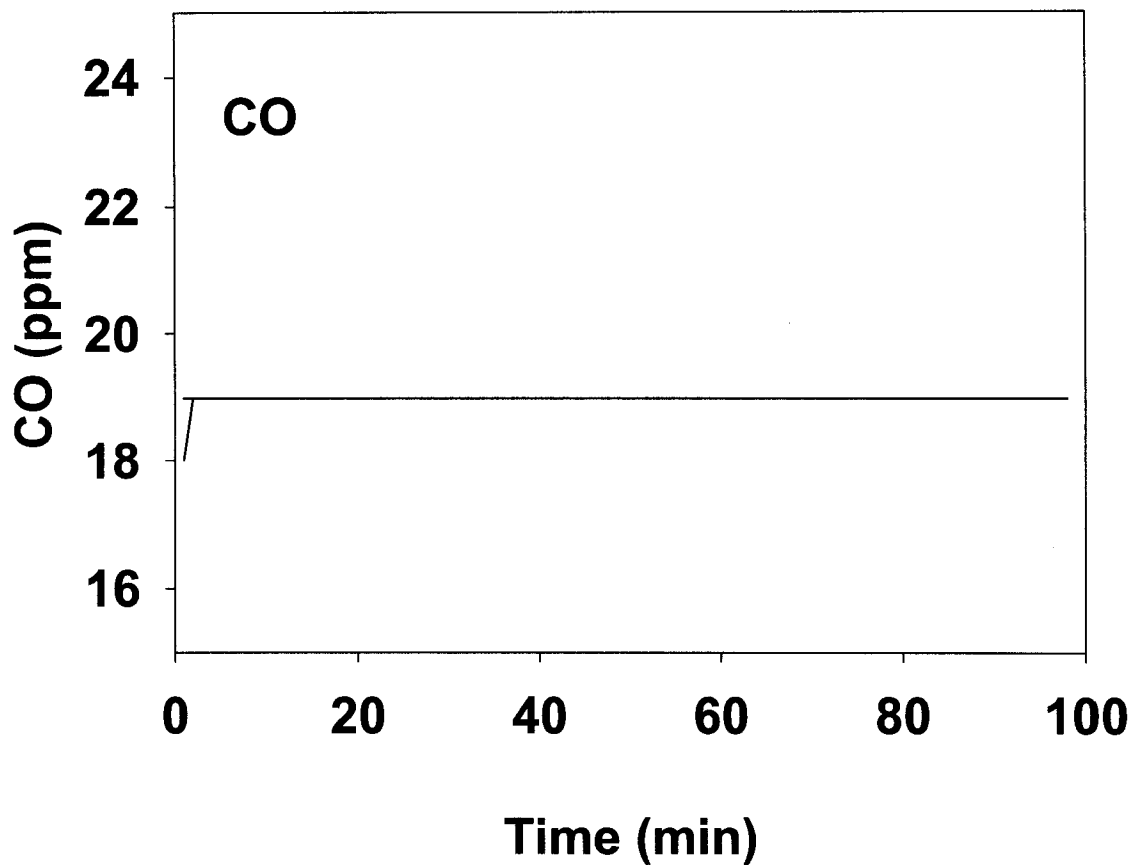
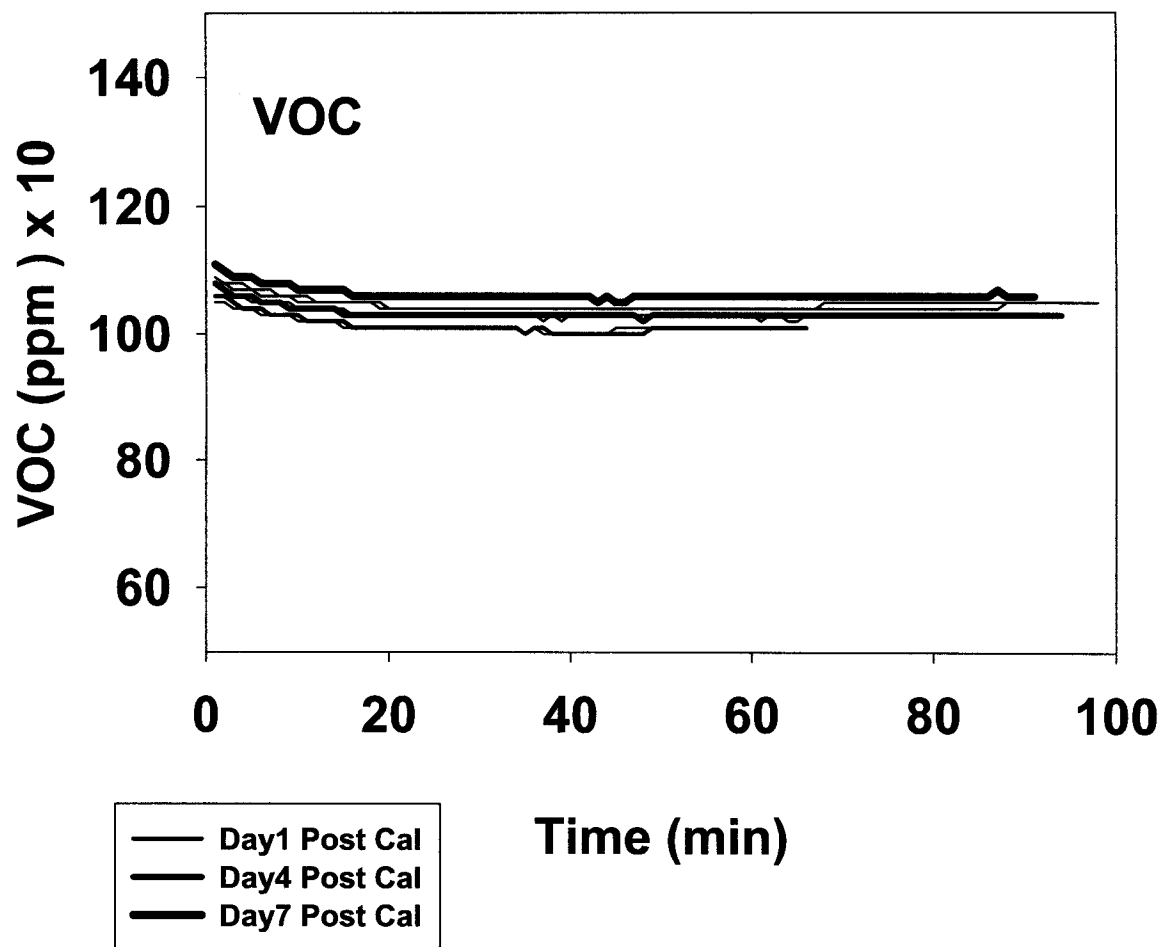


FIGURE 15D.
Start-up and Week-long Accuracy: VOC
Final Reboxed Monitor #298
7 Tests over 7 days - No Recal



APPENDIX A

DESCRIPTION OF THE FINAL DIVEAIR2 MONITOR

The final reboxed Diveair2 monitor (Anagas Diveair2, model DV 2.0, Geotechnical Instruments, Inc.; Leamington Spa, UK) is a new product line by the manufacturer (see the photographs on the next page).

The Diveair2 is a nonhyperbaric monitor that simultaneously displays levels of O₂, CO₂, CO, and VOCs on a backlit liquid crystal display (LCD), with all four readings updated every second. The displayed readings represent the actual readings at that time for O₂, CO, and VOCs, whereas the CO₂ reading is a 20-second moving average. Display resolution is 0.1% O₂, 10 ppm CO₂, 1 ppm CO, and 0.1 ppm VOC. The gas readings, except for O₂, are automatically adjusted by a temperature compensation for ambient temperature, a compensation that improves accuracy but does not eliminate all temperature effects on readings. A small internal pump, when activated, draws a gas sample at ~500 mL/min into the monitor, where O₂ and CO are measured with separate electrochemical detectors. CO₂ is measured with a nondispersive infrared detector, and VOCs are measured with a photoionization detector (PID) emitting at an energy level of 10.6 eV.

The monitor contains a large internal filter installed to remove VOCs in the gas pathway leading to the CO sensor, VOCs which can cause a positive response by the CO sensor. Although CO sensors commonly contain filter materials to reduce cross sensitivity to VOCs, experience suggests that such filters may deteriorate over time; thus, a large backup filter was incorporated into the monitor to reduce the chances for VOCs to reach the CO sensor during monitor operation.

The Diveair2 is calibrated first by simultaneously zeroing all four sensors while sampling zero N₂ (CO₂- and VOC-free), followed by spanning all four sensors together with a gas standard containing certified concentrations of the four gases. For screening the quality of diving air, the span gas is initially expected to be a nominal mixture of 21% O₂, 1000 ppm CO₂, 20 ppm CO, and 10 ppm isobutylene for VOCs, balance N₂. Spanning sensors with one gas standard containing all four gases at concentrations approximating the screening limits minimizes measurement errors about these concentrations.

It is expected that the Diveair2 will normally be operated off its nickel metal hydride battery, which is recharged between uses. However, an optional power cord designed for use in wet environments allows the reboxed monitor to be operated with or without batteries. While connected to the battery charger, the monitor should not be used, since the charging process can affect the gas readings.

ONE OF THREE FINAL REBOXED DIVEAIR2 MONITORS THAT WERE TESTED AT NEDU:



The Diveair2 has visual alarms that are triggered when the concentrations of one or more of the four gases decrease or increase enough to reach their alarm limits, which are set by the user. For O₂, the alarm limit is the low concentration value that warrants attention; for the other three gases, the alarm limit is the high concentration value of concern. The alarms consist of both an external alarm light that flashes and can be seen at a distance from all directions and a displayed blinking of the name(s) of the gas(es) (e.g., "CO₂") under alarm. In addition, two user-selectable alarm modes are provided. In the "nonlatching" mode, the triggered visual alarms stop once the gas concentrations decrease below (or, for O₂, increase above) the preset limit. In the "latching" mode, the alarms continue even if the gas concentrations return to acceptable levels, a mode thus requiring the user to reset the alarm to stop it. The latching mode would be useful during testing to ensure that a transient alarm would not be missed by the tester, who at times may be away from the immediate test area.

The datalogging function of the Diveair2 allows logging of up to 600 sets of readings at intervals of every 1 to 60 min. The logged data can then be displayed on the LCD, or, after the air monitor has been connected to the RS232 serial port of a personal computer with the supplied lead, it can be downloaded with the Diveair2 software. In addition, the Diveair2 is equipped with a program (noted in this report as the "peak program") that displays the "peak values" — the highest values for three of the gases (CO₂, CO, and VOCs) and the lowest value for O₂ — during any specified time period. The peak program is started and stopped with single keystrokes on the monitor's keypad.

The monitor provides passcode protection for many functions including calibration, alarm setting, and data logging. After entering the passcode, the user can step through the monitor menu to change parameters affecting these functions as well as to perform calibration and start and stop logging. However, even without passcode entry, the user can (1) turn the monitor on and off, to allow gas concentrations to be displayed on the LCD; (2) turn the sampling pump on and off; (3) check the battery status; and (4) start and stop the peak program.

APPENDIX B

OPERATING PROCEDURES FOR THE DIVEAIR2 MONITOR

Using open-split gas delivery with sampling pump ON

Information is provided here to calibrate the Diveair2 and use the monitor with an open-split gas delivery system to measure the quality of diving air. The open-split system allows the monitor, with its pump turned on, to freely draw sample gas through its inlet and to allow the excess gas delivered to be discharged into the atmosphere via an overflow tube. Since differences in gas delivery procedures and sampling hardware may significantly affect monitor performance, alternative operating procedures used in the laboratory or in the field will first need to be verified as producing acceptable results. The Diveair2 has not been evaluated by NEDU for screening gases other than air.

BATTERIES/CHARGING

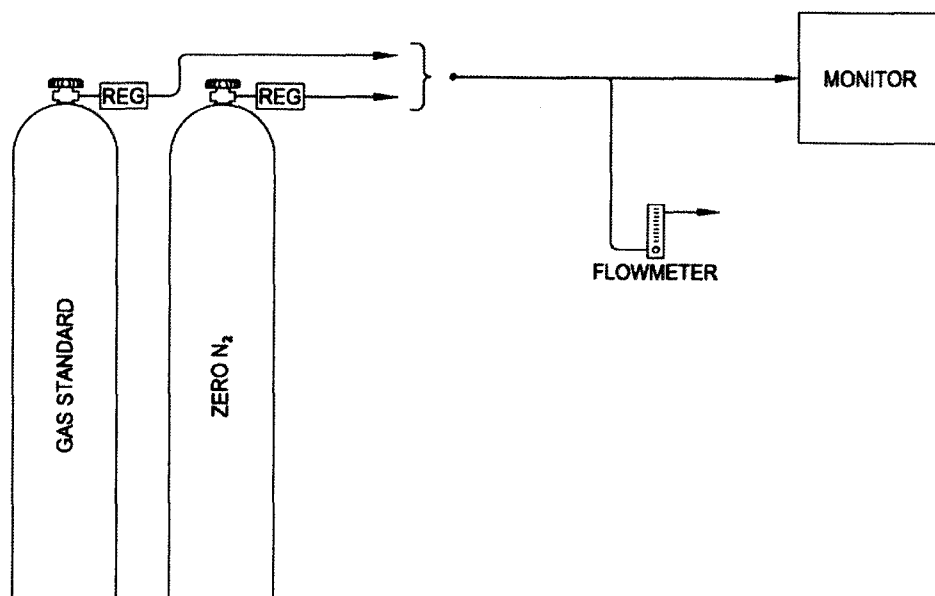
It is expected that the Diveair2 will normally be operated off its self-contained nickel metal hydride battery. When the battery requires charging, the monitor is attached to the charger, which plugs into 110-volt line current. However, the monitor should not be used while connected to the battery charger, since the charging process can affect gas readings. An optional power cord designed for use in wet environments allows the reboxed monitor to be operated with or without batteries.

When the monitor is not in use, it can be left attached to the charger — although if the monitor is used infrequently, its battery capacity may decrease. To help restore battery capacity, the battery should be completely discharged by operating the monitor until it shuts off and then by completely recharging the battery. Limited laboratory testing shows that fully charged batteries provide approximately 14 to 16 hours of monitor usage with the sampling pump on and that full recharging takes at least three to four hours. Future experience will suggest how long recharging takes and how long monitors can be operated between recharging times in the field.

CALIBRATION GAS AND EQUIPMENT

One high-pressure cylinder of zero N₂ (CO₂- and hydrocarbon-free) will be needed for zeroing the monitor's four sensors. A second gas mixture will be needed for spanning the sensors. The span cylinder will be a gravimetric standard with nominal concentrations of 21% O₂, 1000 ppm CO₂, 20 ppm CO, and 10 ppm isobutylene for VOCs, balance N₂ (the 10 ppm isobutylene gas is nontoxic and has a long history of safe use). It will be necessary to install two high-purity regulators (with stainless steel diaphragms, appropriate CGA fittings, and 0–50 delivery pressures to adequately control gas flows) onto the cylinders.

Sufficient Teflon tubing and tubing connectors are required to construct an open-split gas delivery circuit containing a side branch with an attached flowmeter (see the figure below on this page). Using Teflon ensures that the delivery system minimally affects the gas flowing through it. This tubing arrangement allows both calibration and sample gas to be delivered to the monitor, and it allows a slight gas overflow to ensure that the demand of the monitor's sampling pump is met. For these procedures, an overflow of ~400 mL/min will be used, although much greater overflows have little effect on instrument readings. For this application, a rotameter flowmeter with a maximum reading of ~1000 mL/min is suggested, so that the desired 400 mL/min flow can easily be observed. Short (~2 cm) pieces of Tygon tubing can be used as butt connectors to help construct the gas delivery circuit and to attach the Teflon tubing to the inlet of the analyzer. Take care to minimize the contact of gas with the Tygon, which can affect gas concentrations.



GENERAL PROCEDURES

1. When testing is not being done, and whenever possible, all equipment including the monitor should be stored inside at temperatures ranging between 19 and 25 °C (66–77 °F), "normal room temperature."
2. The monitor and sampling equipment noted above will be used to screen air at the sampling location given in the *U.S. Navy Diving Manual*.¹ However, the operating procedures described below assume that field personnel will supply additional approved hardware to allow delivery of gas from the high-pressure sampling site to the monitor at flows from 0 to ~1 L/min and at pressures <5 pounds per square inch, gauge (psig).
3. Until we have more experience with the Diveair2, the monitor will be recalibrated before each day's use and will be allowed to warm up for at least 20 min before being calibrated. We do not recommend use of the factory calibration function.

START-UP AND CALIBRATION

1. Use the data sheet at the end of this Appendix to record information during the test. **Complete** the top portion of the first page of the data sheet, including the monitor serial number (S/N).
2. Before each day's use of the monitor, the batteries need to be checked as follows:
 - a. Disconnect the monitor from the charger (if it has not already been disconnected).
 - b. Turn on the monitor by pressing the red key. Press "0" to exit that screen. Press "5" to turn on the pump; the "pump" text appearing in bold and the pump noise confirm that the pump is on. **Record** the start-up time.
 - c. Wait 5 min for the monitor to warm up, and then press "9" to read and **record** the available battery capacity, which should be 100%. If battery readings are less than 80% after the batteries have been recharging at least overnight, they may need to be replaced. Press "0" to return to the gas display menu.
3. If necessary, move all equipment (including calibration gas cylinders) to where the calibration will be done. If possible, this location should be indoors, protected from inclement weather, and at temperatures similar to those where the equipment has been stored (again, between 19 and 25 °C (66–77 °F)).
4. **Record** gas cylinder information on the data sheet.
5. The passcode-protected menus need to be accessed to perform all the functions (below) that relate to calibration, alarms, and datalogging. To enter the passcode, first

press “1-menu,” then “0,” “1,” “0,” and “2” (the passcode set by Geotechnical Instruments for all monitors) followed by “0.”

6. Span gas settings.

- a. Check the span gas concentrations stored in the monitor by pressing “1-Calibration” and then “4-Check/Set gases.”
- b. If necessary, change the span gas concentrations to the actual concentrations of gas being used (e.g., 21.0% O₂, 0980 or 1010 ppm CO₂, 020 ppm CO, 10.1 ppm VOC) by first pressing the number of the gas (e.g., “1” to change the O₂ value) and then entering the concentration of the span gas followed by “0.” VOC in this case is the concentration of the isobutylene.
- c. When all gas concentrations are correctly set, press “0” twice to return to the function screen.

7. Alarm settings. Visual alarms occur when the gas is out of the specified range with respect to the alarm levels.

- a. Check the alarm settings stored in the monitor by pressing “2-Alarm Settings.”
- b. Check that the alarm latching is OFF. If necessary, change this setting by pressing “1,” so that if any of the alarms are triggered, they will stop once the gas concentrations are acceptable.
- c. Check the alarm levels by pressing “2,” and ensure that the following settings are made for calibration to avoid triggering the alarms: O₂ below 00.0%, CO₂ above 5000 ppm, CO above 100 ppm, and VOCs above 050 ppm. If changes are needed, first press the number of the gas (e.g., “1” to change the O₂ value), and then enter the alarm level, followed by “0.”
- d. When all gas values are correctly set, press “0” twice to return to the function screen.

8. Datalogging settings (if datalogging will be used; otherwise, skip this section).

- a. The datalogging settings can be checked by pressing “4-datalogging” and then “1-logging options.”
- b. If desired, press “1-Check time/date” and adjust these settings, if necessary, so that the monitor’s time is synchronized with the local test time. Recheck the time/date following any adjustment; then press “0.”
- c. If desired, press “2-Set interval,” and then enter the recommended “01” minute setting for the logging interval, and press “0.”

- d. Check that logging is stopped: menu item 3 should read "Start logging," if logging is already stopped. If it is not stopped, press "3–Stop logging."
 - e. End by pressing "0" three times to return to the monitoring screen. Confirm that the pump is still on.
9. Install the regulators on the N₂ and span gas cylinders, and line up the pressures.
- a. Confirm that the pressure controlling valve on each cylinder regulator is backed off and the delivery valve is closed. Then install the regulators on the zero N₂ and span gas cylinders. Open and quickly close both cylinder valves, and confirm the absence of leakage by a stable pressure reading on each regulator over one minute. If the pressure decreases, tighten or reinstall the regulator.
 - b. Pressure cycle each regulator three times to remove all ambient air, and then dial in a delivery pressure of several psig. Leave the gas cylinder valves open, but close the regulator delivery valves so that gas is not flowing.
10. Connect the span gas to the Teflon delivery circuit, but do not connect the other end of the tubing to the monitor.
11. Ensure that the monitor has warmed up for at least 20 min before calibrating it. **Record** the calibration information (along with any comments) as indicated on the data sheet, by following the calibration procedures below.
12. Confirm that the monitor is in the monitoring mode and that the pump is on.
13. Using your thumb, block the end of the Teflon tubing that attaches to the monitor and direct all the flow out the flowmeter. Using the pressure delivery knob of the cylinder regulator, adjust the gas outflow to ~800 mL/min. Then attach the tubing to the monitor and readjust the outflow to 400 mL/min.
14. Observe monitor gas values until they are stable (at least 5 min), and then **record** span gas readings and, if possible, the calibration area temperature, as taken with a reliable temperature measuring instrument. This information will help judge calibration stability since the last time the monitor was used.
15. Disconnect the Teflon tubing from the monitor and shut off the span gas flow, but leave the cylinder valve open and the regulator pressurized. Connect the N₂ gas to the Teflon delivery circuit. Again adjust the gas outflow to ~800 mL/min, reconnect the monitor, and readjust the outflow to 400 mL/min.
16. Observe values until they are stable (at least 5 min), and then **record** N₂ readings.

17. Zero all channels by pressing "1–Menu"; "0,1,0,2" followed by "0"; "1–Calibration"; "1–Zero channels"; and "1–yes." Note the outcome (okay or failed).

18. Press "0" twice to return to the monitoring display, and **record** post-zero N₂ readings. Readings should be no greater than 0.2% O₂, 40 ppm CO₂, 1 ppm CO, and 0.2 ppm VOC. If any reading is greater than these respective values, re-zero and again **record** readings on the data sheet alongside the first set of readings (first reading/second reading). Proceed to the next step, even if any reading is still greater than the limits specified here.

19. Disconnect the Teflon tubing from the monitor. Then shut off the N₂ flow but leave the cylinder valve open and the regulator pressurized in case N₂ is needed later. Disconnect the N₂ from the Teflon delivery circuit, and connect the span gas. Again adjust the gas outflow to ~800 mL/min. Reconnect the monitor and readjust the outflow to 400 mL/min.

20. Observe values until they are stable (at least 5 min), and then **record** span gas readings before spanning.

21. Span all channels by pressing "1–Menu"; "0,1,0,2" followed by "0"; "1–Calibration"; "1–Span channels"; and "1–yes." Note the outcome (okay or failed).

22. Press "0" twice to return to the monitoring display, and **record** postspan values. Readings should be within 0.2% O₂, 40 ppm CO₂, 3 ppm CO, and 0.3 ppm VOC of the calibration values. If any gas reading is outside these respective ranges, respan and **record** the readings again alongside the earlier data. Proceed to the next step, even if any reading is still outside the respective ranges specified here.

23. Check alarms.

- a. Change the alarm levels by pressing "1–Menu"; "0,1,0,2" followed by "0"; and then "2–Alarm Settings." Press "2–Alarm levels" and change the settings to O₂ below 20.0%, CO₂ above 1,000, CO above 20 ppm, and VOCs above 10 ppm. These settings should trigger the alarms if any of the gases is out of specification, per the *Navy Diving Manual*.
- b. With the alarm latching OFF (as checked earlier), any triggered alarms will stop once the gas concentrations are acceptable.
- c. Exit back to the monitoring mode by pressing "0" three times. Note that the variations in the monitor's readings should cause one or more of the gases to initiate the alarm mode. When this occurs, disconnect the tubing from the monitor, and observe that the alarm should stop when ambient air is sampled. This three-step procedure checks the correct operation of the alarm function.

24. Shut off the span gas flow, close the cylinder valve, and bleed down the regulator. Back off the pressure controlling valve, close the delivery valve, and remove the regulator from the span gas cylinder. Repeat step 24 with the N₂ cylinder.

COMPRESSOR TESTING

1. Move the monitor and Teflon delivery circuit to the sampling location. **Record** the time.
2. Before sampling, each compressor should be operated for at least 10 minutes to warm up, and the start-up time should be **recorded**. During the warm-up period, blow out the compressor line through the sample site at a highly audible rate — to remove any water and equilibrate the line with the gas.
3. After the compressor line has been purged, ensure that no water or any liquid is being blown out: hold a cloth or tissue in the gas stream, and check for wetness with your hand. If a wet spot is noted, continue to vent the gas until the stream is dry to touch. Then close the valve at the sample site to shut off the gas flow.
4. Attach approved sampling hardware to the sample point on the compressor line, and open the valve(s) starting the gas flow. Again, this sampling hardware should allow delivery of sample gas to the monitor at rates from 0 to ~1 L/min and at pressures <5 psig.
5. Allow sample gas to purge the sampling hardware with at least 10 times the estimated dead volume before turning the gas flow off. Then connect the Teflon delivery circuit to the sampling site WITHOUT the monitor attached.
6. Open the sample site valve, and adjust the gas outflow to ~800 mL/min. Then attach the monitor and readjust the outflow to 400 mL/min, while ensuring that the monitor pump is ON. Avoid producing an excessive flow to the monitor: such a flow could blow out the tubing.
7. **Record** the time that the monitor was attached and, if possible, **record** the ambient temperature.
8. If alarm latching is desired (so that any triggered alarms will continue even when gas concentrations become acceptable), latching will need to be reset to ON. Note that any alarm that is triggered in the latching mode will have to be reset by pressing the “f” key, followed by the code (0102).
9. If datalogging is desired, first clear the data memory by pressing “1–Menu” and then “0,1,0,2” followed by “0.” Then press “4–Data logging,” “3–Clear memory,” and “1–Clear Readings,” and finally enter the code (0102). Note that the display should read “0600 Free Readings.”

10. Press “0” to return to the previous menu. To start the datalogging, press “1–Logging options” and “3–Start logging.” Exit to the monitoring display by hitting “0” three times. Again, confirm that the pump is ON, and note that “Logging” is displayed on the monitor screen.

11. To start the program to collect the highest gas concentrations observed, hit “6–Start.” **Record** the start time. Hitting “6–Stop” (do not do this now) will show the peak readings since the start of this program.

12. Allow the compressor to run as needed, and **record** on the data sheet any procedures performed with the compressor during the test time. Also **record** any information relevant to the test — information such as alarms going off, or instrument malfunctions, or the presence of any objectionable odor in the sample gas.

13. When finished with the compressor (or when desired), hit “6–Stop” to display the peak gas concentrations, and **record** the peak values and time on the data sheet. Press “0” to return to the monitoring mode.

14. Stop datalogging by pressing “1–Menu”; then “0,1,0,2” followed by “0”; “4–Datalogging”; “1–Logging options”; and “3–Stop logging.” Exit to the monitoring display by pressing “0” three times. Confirm that the pump is still ON. **Record** the time and, if possible, the ambient temperature.

15. Disconnect the monitor from the Teflon delivery circuit, and remove the delivery circuit from the sampling hardware. Shut off the gas flow, and remove the sampling hardware from the compressor line.

16. If finished for the day, **record** the battery reading and then turn off the monitor by pressing the red key. **Record** the time.

17. Move all equipment back to the storage location. If data will not be downloaded, turn off the monitor and connect it to the battery charger until the next test day.

Downloading data

1. Before the first downloading of data from the monitor, put the download program (an executable file which therefore can merely be copied onto a PC) onto any PC that has a 9-pin serial port for connecting to the monitor. For every different PC used, the same initial setup procedure described below will need to be done to download data.

- a. Insert the OPMANCDGAS CD into the PC and, using Windows Explorer, copy the file “Unicom” (path is “OPMANCDGAS\ Environmental Instruments\Software\Unicom”). A good option would be to copy the file to

"C:\Program Files". If desired, create a shortcut to this program on the PC to facilitate its use.

- b. Then use Windows Explorer to create a folder to which the data files will be saved. For this program, the folder name must have no more than eight characters. For example, a folder named "Diveair" might be created on the C:\ drive.

2. Download the data from the monitor to a PC by the following procedures:

- a. Start the UNICOM software program first. Then, while the monitor is OFF, use the downloading cable to connect it to the serial port of the PC.
- b. Turn the monitor ON: press "0"; 1–Menu"; and "0,1,0,2" followed by "0." Then press "4–Data logging" and "4–Download data."
- c. After downloading, when the PC has been used for the first time, set the data directory to the correct path by pressing "F9." For example, to save the data in a folder named "Diveair" on the C:\ drive, "C:\DiveAir" would be the path.
- d. Then press "F2" to save the file as an 8-digit name, per the limits of the UNICOM program. One suggestion is that the file name should be in the following format: last 2 digits of serial number, yr, mo, dy. Example: "55090327" for instrument #255 and test day 27 March 2009. The saved file has the extension .CSV; "csv" designates a "comma separated values" file. For subsequent file savings, the file name that automatically comes up on the screen can be typed over.
- e. When prompted to split the time and date, hit "Y" to answer yes.
- f. When finished, press "F10" to exit the program.
- g. Use EXCEL to open the saved file to confirm that the data have been correctly saved. Save the file as an EXCEL workbook. Keep both files and make backup copies as needed. **Record** the names of saved data files.

3. Turn off the monitor and connect it to the battery charger until the next test day.

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AIR SAMPLING DATA SHEET
(rev March 2009)

Date: _____ Facility: _____ Person(s) Testing: _____

Compressor make & S/N: _____ Sample site (valve or fitting #): _____

Compressor history (recent trouble or service, if any): _____

Weather conditions (if compressor is outside): _____

Comments (use back for additional): _____

Monitor S/N: _____

STARTUP INFORMATION						
Time Monitor Started:		Battery Reading post 5 min (Reading/Time):				
GAS CYLINDER INFORMATION		SPAN GAS CONCENTRATIONS				
N ₂ S/N	Span Gas S/N	O ₂ (%) (XX.X)	CO ₂ (ppm) (XXXX)	CO (ppm) (XXX)	Isobutylene (ppm) (XX.X)	
CALIBRATION (after 20 min warm-up)						
	Time	O ₂ (%)	CO ₂ (ppm)	CO (ppm)	VOC (ppm)	Cal Area Temp
Span Gas readings						
N ₂ readings						
ZERO CHANNELS (indicate times of re-zeroing and readings, if necessary)						
Post-Zero N ₂						
Prespan Span Gas						
SPAN CHANNELS (indicate times of re-spanning and readings, if necessary)						
Postspan Span Gas						
COMMENTS (recal, etc.)	Use back of sheet if necessary.					

Date: _____ Facility: _____ Compressor make & s/n: _____

COMPRESSOR TESTING						
					Time	Testing Area Temp
Start up Compressor						
Attach Monitor to Compressor (Post 10 min Compressor Running)						
Clear Data Memory and Start Datalogging; Start Peak Program						
COMMENTS (events, procedures, odor, etc.)		Use bottom of sheet if necessary.				
At end of testing, Stop Peak Program and Record Peak Values	Peak O ₂ %	Peak CO ₂ ppm	Peak CO ppm	Peak VOC ppm	Time:	
Stop Datalogging	Time:			Testing Area Temp:		
End of Testing	Battery reading (Time/Reading):			Time Monitor Turned Off:		
Downloaded Data File Name:						

APPENDIX C

RECOMMENDED INTERIM LIMIT FOR VOCS AS MEASURED BY THE DIVEAIR2

BACKGROUND AND RATIONALE

Any “total contaminant” measurement (such as one of VOCs) that is made with an air monitor will depend on (1) the specific sensor being used to detect the volatile contaminants and (2) the chemical species chosen to calibrate that sensor. In the case of the Diveair2, the PID’s relative response factors for the chemical species in the air will not only affect the magnitude of the PID signal but also determine which contaminants are detected and thus included in the total VOC measurement. Isobutylene was chosen for VOC calibration of the Diveair2 because it is nontoxic, is currently used for calibrating other PIDs on submarines and in the industrial workplace, and produces an intermediate response compared to many common VOCs. However, using isobutylene for calibration converts subsequent VOC readings of air into equivalent ppm concentrations of isobutylene. Calibrating with a different species, especially one that causes a substantially smaller or larger PID response than isobutylene, will produce a different ppm VOC reading for the same air sample.

Any recommended VOC limit should be based at least partly on assumptions about which VOCs are likely to be in diving air and likely to merit concern. However, as we could not locate any detailed reports on VOC profiles of diving air, we collaborated with TRI/Environmental, Inc. (Austin, Texas), during 2002 to 2004 to examine this question. TRI, which is the current contract laboratory analyzing samples under the U.S. Navy Diver’s Air Sampling Program, identified 36 samples collected by field personnel, samples which each had total hydrocarbon values greater than 10 ppm as determined from TRI’s testing for the Navy. Using gas chromatography/mass spectroscopy (GC/MS) to characterize the specific VOCs present, both TRI and NEDU subsequently further analyzed these air samples. As analysis of the samples proceeded, NEDU contacted the field personnel involved with some of them to try to determine possible reasons for the contamination. Although we will report details of the GC/MS testing and results elsewhere, we briefly discuss directly below our findings as they influence any proposed VOC limit.

Contamination of the compressor intake air appears to be a likely reason for the elevated VOC levels in many of the 36 samples. Ten of these samples were taken from compressors or air banks on submarines, the air of which originates from the submarine atmosphere and thus is prone to contamination from shipboard sources. For many samples not from submarines, it seems likely from our followup discussions with field personnel that VOCs were introduced by (1) the actions by the person(s) sampling the air (e.g., wiping the sampling fitting with a cleaning solution that introduced VOCs into the air sample), (2) the nearby environment (e.g., locating the compressor near exhaust sources from other engines), or (3) contaminated hardware upstream from the sample

site (e.g., sampling from a compressor with an intake manifold recently repaired with glue).

As expected, the VOCs detected in the 36 samples included a broad range of aromatic and aliphatic species, at levels up to ~6 ppm for any one species. A few of the VOCs commonly observed in the samples are listed in the table at the end of the following three paragraphs, along with their 2008 threshold limit values—time-weighted average (TLV-TWA, noted as “TWA” in the table) given by the American Conference of Governmental Industrial Hygienists (ACGIH). These VOCs are presented as examples of contaminants, although they represent only a small number of expected species. The TWAs are time-weighted concentrations, based on a normal 8-hour workday and 40-hour workweek, to which it is believed that nearly all workers can be repeatedly exposed, day after day, without adverse effect. For this discussion, we assume that the ACGIH TWAs have some relevance to divers’ exposures to VOCs. Also in the table are the PID relative response factors (relative to isobutylene) for some of the contaminants — factors taken either from NEDU’s Diveair2 test results or from those factors reported for the Toxic Vapor Analyzer (another gas monitor discussed in the report), which contains a PID with the same energy as that in the Diveair2.

The response factors in the table below allow the concentration of a specific substance in air to be estimated by dividing the Diveair2’s VOC reading by its response factor and assuming that only that species is present. However, probably more useful for our discussion is to multiply any TWA value by the respective response factor to estimate the VOC reading that equals the TWA value — and thus estimates the VOC reading of concern for that species. These estimates are given in the last column of the table.

If desired, these adjusted TWA values can be further corrected for other variables. To reflect the actual partial pressure exposure of divers to the contaminant, for example, one important additional correction would be for diving depth. Depth correction is made by dividing the adjusted TWA by the maximum depth in atmospheres absolute (ATA) for an operation. Current Navy experience indicates that use of air for diving might commonly be at depths down to 5 to 6 ATA. In the field, we will undoubtedly be concerned with mixtures of VOCs. But this exercise provides a method to potentially screen out, at least theoretically, individual compounds present at hazardous levels — if we keep in mind the potential for considerable error due partly to variability in monitor performance.

Only one of the 36 air samples contained a mixture of aldehydes and ketones — including the very toxic methyl vinyl ketone — consistent with the VOC profiles we previously reported for two actual compressor failures (Naval Medical Research Institute letter 1400, Serial 54/34131, of 5 June 1995; Naval Medical Research Institute letter 1400, Serial 54/34470, of 19 September 1995). Thus, for the air samples examined, VOC contamination seemed to be overwhelmingly an intake air problem rather than a compressor operating problem.

Species	TWA (ppm, ACGIH 2008)	PID Relative Response Factor	TWA x Relative Response Factor
Ethyl methyl benzene (Cumene)	50	NA	
Freon 114	1000	ND	
Methyl decane	NA	NA	
Methyl ethyl ketone (MEK)	200	NA	
Methyl isobutyl ketone (MIBK)	50	0.8	40
Methylene chloride (dichloromethane)	50	0.6	30
n-Butanol	20	0.1	2
n-Hexane	50	0.2	10
n-Nonane	200	0.4	80
n-Octane	300	0.3	90
n-Pentane	600	0.8	480
Toluene	20	1.9	38
Trimethyl benzenes	25	NA	
Xylenes	100	2.0	200

ND = not detected by the PID.

NA = not available.

In addition to the GC/MS analysis, we also completed a brief review (to be published elsewhere) of the composition of fuels and petroleum products that might be present at a salvage site — for example, after a plane or ship accident. The petroleum products, which would have the potential to contaminate diving air charged on site during such operations, include the following (all of which are complex aliphatic/aromatic mixtures): (1) gasoline, C₄-C₁₂ (chemicals containing 4 to 12 carbon atoms); (2) jet fuel JP-5 and JP-8, C₈-C₁₈; (3) diesel, C₉-C₂₀; (4) bunker oil, C₁₂-C₃₆; and (5) lube oil, C₁₆ and beyond. By one definition, VOCs are those with vapor pressure of 10⁻¹ torr (10⁻⁴ atm) at 760 torr and 25 °C (method TO-15, Environmental Protection Agency). By this definition, the cutoff for volatile species from these petroleum products is ~C₁₂ for aliphatics and aromatics. However, the actual composition and concentration of VOCs in the air at a dive site would be influenced by other factors such as (1) the partition coefficients for the VOCs in water and (2) the ambient temperature, humidity, and wind that would influence the transport and dispersion of the fuels.

The range of aliphatic and aromatic hydrocarbons represented by the VOC profiles of the 36 air samples, as well as by the petroleum products listed above, suggests that the VOCs that might be found in diving air probably number in the thousands. Thus, broadly screening for VOCs is a clear need, while at the same time acknowledging that many of the possible contaminants have relatively low toxicities, as judged by their exposure limits set for the industrial workplace. Although the PID is well suited for screening diving air to determine a “total VOC” value, the Diveair2 will not detect all VOCs — as discussed in the **MONITOR DEVELOPMENT** section of this report. It responds poorly, or not at all, to small, usually nontoxic gases such as methane and many freons;

however, it can detect many contaminants of concern, such as aromatic hydrocarbons, at levels down to 1 ppm.

One of the potentially most hazardous exposures to diving air would involve a true compressor failure, which experience has shown can produce highly toxic species, including at least one contaminant (methyl vinyl ketone) that at sub-ppm levels exceeds industrial workplace guidelines for even short-term exposures. Unfortunately, reliable detection of such low field concentrations of these types of reactive contaminants would be difficult if not impossible, due to the limitations of portable monitors such as the Diveair2 and the nearly unavoidable introduction of low VOC concentrations into the air by the sampling hardware. More importantly, since the Diveair2 provides a single measurement of VOCs without identifying specific contaminants (something that would be extremely hard to do in the field, even with instrumentation much more complex than the Diveair2's), to distinguish normal low-level PID readings from similar readings that might occur when trace levels of highly toxic VOCs were present would be impossible. However, our experience suggests that high levels of a range of VOCs would likely be produced during any compressor failure, a condition that should be easily detectable with the Diveair2.

In this report, the mathematical exercise we have presented to estimate unsafe VOC readings of individual contaminants by correcting for PID response factors and variables such as depth shows that, depending on what species are assumed to be present, a large range of potentially "unsafe" Diveair2 VOC readings (as given in the last column of the table on the preceding page) exists. In fact, even if we could reliably measure some of the very toxic contaminants expected following a compressor failure, such measurements would be in the normal "noise" level of the screening because of the hardware and other factors. Therefore, the approach used to recommend a VOC limit, as measured with the PID of the Diveair2, will be to set an interim limit low enough to avoid exposure to unsafe levels of many VOCs that might be expected, while minimizing the chances of falsely concluding that the air is unsafe (i.e., minimizing false positive errors). We have adopted this approach while we acknowledge that it is impossible to use any field screening procedures to rule out all hazardous exposures to contaminants, especially the very toxic ones.

Defining the VOC limit as interim acknowledges that field experience will suggest whether any adjustments to the initial VOC limit will be needed, particularly to ensure that false positive errors are reduced. In terms of readiness and the ability to perform missions in a timely manner, false positive outcomes indicating that "chemically safe" air should not be used are more an operational than a health concern. False negative responses (i.e., falsely concluding that the air is safe) are a diver health issue that depends on the rationale for accepted VOC exposure limits — including any corrections for factors such as depth and the implications of exceeding those VOC limits.

RECOMMENDED INTERIM VOC LIMIT

1. Our experience over the last 25 years suggests that the “noise level” of PID readings due to residual VOCs from hardware at gas sampling sites is commonly ~1 ppm, but these levels can be higher, depending on how well on-site hardware is maintained and kept clean. Therefore, for the Diveair2 application, we will define VOC readings of 1 ppm and below as unreliable.

2. On the basis of the discussion in this appendix, the interim limit for VOCs is set at 10 ppm, as measured with the Diveair2 calibrated with isobutylene, but this limit is subject to change depending on experience with actual air testing in the field. From current ACGIH guidance, and after correction for differences in PID responses to VOCs (and, if desired, in diving depth), a VOC limit of 10 ppm should (1) avoid exposing personnel to unsafe levels of many VOCs that might be expected, and yet (2) be high enough to reduce false positive responses. Although a PID limit of 5 ppm has proved for more than five years to be practical for air bank screening with the Toxic Vapor Analyzer before this air is used for Dry Deck Shelter operations, we choose the higher 10 ppm limit as the initial one for the Diveair2, until we gain additional experience with the range of air sampling conditions anticipated in the field.

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