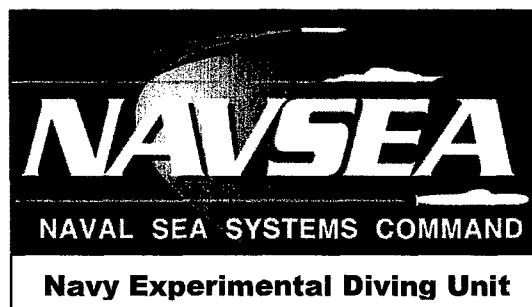


Navy Experimental Diving Unit  
321 Bullfinch Rd.  
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NEDU TR 05-16  
September 2005

## LABORATORY EVALUATION OF THE ANALOX SUB MK II P-S PROTOTYPE HYPERBARIC O<sub>2</sub>/CO<sub>2</sub> ANALYZER



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| 19. ABSTRACT<br>Three prototype AnaloX hyperbaric analyzers (model SUB MK II P-S), modified by the manufacturer from a commercially available model designed for submarine escape situations, were evaluated as devices suitable for monitoring O <sub>2</sub> and CO <sub>2</sub> under pressure during Dry Deck Shelter (DDS) operations. Analyzers were tested in two locations in the laboratory: (1) on the laboratory bench at ambient pressure, and (2) inside a temperature-controlled hyperbaric chamber at pressures ≤6 atmospheres absolute. The instruments were easy to use in the laboratory and provided no major operating problems during the test period. At 25 °C, they met desired accuracy limits for both O <sub>2</sub> and CO <sub>2</sub> . However, both cold and hot exposures caused O <sub>2</sub> and CO <sub>2</sub> readings to exceed these limits. The instruments also operated with a single set of new batteries for a sufficient time (6 hours daily over a multiday period) and over a range of ambient temperatures to support DDS operations. Following deliberate immersion, clearing water from the instruments' inlets and returning them to operation in the laboratory was often difficult; doing so in the field would be even more challenging. Before any decision can be made about advancing these analyzers to field-testing, the manufacturer needs to make the following changes to the instruments, and the laboratory needs to verify their acceptability with additional testing: (1) improving the compensation of gas measurements for changes in ambient temperature, and (2) redesigning the gas inlet to facilitate the clearing of water following accidental immersions. |                                                    |                                                                                                                              |                                                                                                                                                                |                                                  |
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## INTRODUCTION

The Dry Deck Shelter (DDS) is a hyperbaric system used on submarines to transport SEAL delivery vehicles (SDV) into an operating area. The system uses air from submarine banks to ventilate the DDS for carbon dioxide removal and to provide breathing air to the divers. To improve the efficiency of ventilation, the Naval Medical Research Institute (NMRI, now the Naval Medical Research Center [NMRC]) previously developed a portable hyperbaric analyzer (Model HB 1.1, Geotechnical Instruments, Inc.; Leamington Spa, UK) for monitoring carbon dioxide (CO<sub>2</sub>) within DDSs.<sup>1</sup>

In 1998, the Naval Sea Systems Command (NAVSEA [PMS-395, now PMS-399]) approved this analyzer as the primary ventilation control during DDS operations.<sup>2</sup> For this purpose, the analyzers are carried into each of the three compartments of the DDS and mounted. Ventilation can then be adjusted in response to changes in measured CO<sub>2</sub> levels within the DDS. This procedure minimizes use of air bank gas during operations and ensures that ventilation is sufficient to avoid exceeding the current DDS limit of 1.5% surface equivalent value (SEV) for CO<sub>2</sub>.

When divers operating from the DDS develop decompression sickness, they can be treated in the chamber compartment of the DDS with recompression and oxygen (O<sub>2</sub>) for breathing. During treatment, O<sub>2</sub> is delivered to them via masks connected to the built-in-breathing system (BIBS) supplied by an O<sub>2</sub> bank that is part of the DDS system. Concern existed about O<sub>2</sub> leaking from the masks, increasing the O<sub>2</sub> levels within the chamber, and thus increasing the fire hazard. However, O<sub>2</sub> analyzers used previously inside the DDS chamber during treatments were considered unreliable. Consequently, PMS-395 tasked NMRI (and subsequently the Navy Experimental Diving Unit [NEDU]) in August 1998 to add an O<sub>2</sub> monitoring capability to the Geotechnical hyperbaric CO<sub>2</sub> analyzers that were being used inside the DDS. This work resulted in a hyperbaric CO<sub>2</sub>/O<sub>2</sub> monitor that displayed O<sub>2</sub> in partial pressure and was approved for the DDS atmosphere.<sup>3</sup>

This monitor was later modified to display O<sub>2</sub> in percentages, and is designated as model HB 1.2,<sup>4</sup> which is similar to HB 1.1 except for the O<sub>2</sub> capability. The Geotechnical product number for the U.S. Navy version of its HB 1.2 is 1.2A, for which the following features desired for Fleet use are specified: blue analyzer case, blue carry case, battery case sealed with silicone rubber and an aluminized adhesive label, battery charger, five spare Teflon filters, and an operating manual. The HB 1.2A is also used in the approved procedures for screening compressed air in submarine banks that will be used as the supply air during DDS and advanced SEAL delivery system (ASDS) operations. However, for these applications, the Geotechnical analyzer ensures that the air does not exceed the CO<sub>2</sub> limit of 1000 parts per million (ppm), which is much lower than the 1.5% SEV CO<sub>2</sub> limit within the DDS.

## ALTERNATIVES TO CURRENT DDS ANALYZER

Although Fleet experience with the Geotechnical hyperbaric analyzers has been very favorable over the more than five years that these instruments have been used, the SDV teams now believe that having the ability to purchase an alternative DDS analyzer from a different manufacturer may better restrain rising costs of both the analyzers and their service plans. Consequently, upon the request of PMS-395, NEDU looked into the possibility of an alternative to the current Geotechnical analyzer for DDS operations. We found that, to the best of our knowledge, no instruments that directly replace the Geotechnical analyzer are commercially available. The only similar instrument is the Sub MK II P hyperbaric atmosphere monitor manufactured by Analox Ltd. (North Yorkshire, UK) and designed for submarine escape situations.

However, the current Analox unit (1) is optimized for higher CO<sub>2</sub> (up to 10% SEV) compared to the 1.5% SEV CO<sub>2</sub> of most concern for DDS operations, and (2) displays O<sub>2</sub> in partial pressure atmospheres absolute (ppATA) vs. the currently desired percentage of O<sub>2</sub> for the DDS. Furthermore, the Analox units (1) are believed to be only water resistant (not waterproof, as are the Geotechnical analyzers), which raises concerns about their use in the DDS, part of which can be flooded, and (2) lack a gas pump but rely on diffusion to move the gases into the gas sensors. A pump would speed the analyzer's response to changing gas concentrations, an advantage which is not extremely important for DDS use. However, the pump in the existing Geotechnical analyzer is required to draw gas from the back portion of the hangar compartment, which is flooded during part of the operation, a situation requiring the analyzer be mounted in the forward part of the hangar where it stays dry.

To make the Analox Sub MK II P comparable to the Geotechnical DDS unit, the Analox would have to be changed to (1) optimize it for lower CO<sub>2</sub> levels at ~2% SEV under pressure for within-chamber use and at 1000 ppm for screening air banks at the surface; (2) convert its O<sub>2</sub> in ppATA to percentages, a conversion which would necessitate correcting the ppATA by depth; (3) make it immersion-proof; and (4) add a gas pump that is brushless to eliminate potential explosion when it is operated under pressurized air exposures. Analox agreed to make these modifications to the SUB MK II P and to provide us with three prototype instruments to evaluate in the laboratory. This report provides results from laboratory testing of these three prototype atmosphere monitors (designated by Analox as model SUB MK II P-S) to determine how well they meet the requirements for use within the DDS.

## ANALYZER REQUIREMENTS

Requirements used to develop the currently approved hyperbaric analyzer for monitoring CO<sub>2</sub> and O<sub>2</sub> in the DDS are given in previous reports.<sup>1,3</sup> We summarize the essential, as well as desired but not essential, requirements, along with any changes or additions necessary to ensure consistency with current operational uses and needs.

## ESSENTIAL REQUIREMENTS

1. Pressure range: 1 to 6 ATA.

This meets the pressure range for DDS compartments during operations.

2. CO<sub>2</sub> measurement range and units: <1,000 ppm to 25,000 ppm SEV.

This range brackets the current 15,000 ppm (1.5%) SEV limit within the DDS. The low end of the range allows the analyzer to be used to screen air bank gas for CO<sub>2</sub> before DDS use; the current air bank limit is 1,000 ppm CO<sub>2</sub>.

3. Oxygen measurement range and units: 0 to 25% O<sub>2</sub>.

This upper end of the measurement range extends beyond that expected to occur within the DDS chamber atmosphere if O<sub>2</sub> were to leak during treatments for decompression sickness.

4. Gas sampling pump: required to draw gas from the back portion of the DDS hangar compartment.

5. Hyperbaric chamber safety.

Analyzer must be able to be operated safely (i.e., not inducing fires or explosions) inside a hyperbaric chamber exposed to high-pressure O<sub>2</sub> mixtures. Offgassing of volatile contaminants must be maintained at limits less than those acceptable for U.S. Navy diving systems.

6. Ambient temperature range: 10 to 40 °C.

This requirement falls within the specifications of the manufacturer, although during operations analyzers might be exposed to ambient temperatures higher than these: for example, in the Mideast.

7. Water resistant.

Analyzers will be exposed to high humidity and will probably have some water contact (including that from potentially being dropped into the water) during DDS floodups. Protection against failure under these conditions should exist.

8. Relative humidity (RH): dry to ~90 to 100%.

As given in item 7, the high humidity requirement acknowledges conditions inside the DDS.

9. Electrical power: powered by rechargeable or replaceable batteries, capable of continuous operation without requiring recharging or replacing for periods greater than eight hours.

Analyzer batteries are expected to be checked and recharged or replaced, if necessary, immediately before DDS operations. Analyzers will then be installed inside DDS compartments, where they will be operated on battery power. Required eight-hour analyzer operation should ensure sufficient battery life during all DDS operations.

#### **DESIRED, BUT NOT ESSENTIAL REQUIREMENTS**

1. Short-term O<sub>2</sub> measurement repeatability (within 10 minutes):  $\pm 0.2\%$  absolute, as judged by sampling the calibration span gas at the surface in the laboratory.

A well-designed analyzer should easily meet this level of precision.

2. Short-term O<sub>2</sub> accuracy (within 24 h of calibration):  $\pm 1.0\%$  absolute over the measurement and pressure range, as determined in the laboratory.

There is no official requirement for O<sub>2</sub> measurement accuracy in the DDS. However, this level of accuracy for O<sub>2</sub> in the laboratory should meet the need for reliable monitoring of O<sub>2</sub> levels, even if a doubling of the error occurs in the field. Analyzers are expected to be used for much less than 24 h before being recalibrated.

3. Short-term CO<sub>2</sub> measurement repeatability (within 10 minutes):  $\pm 1\%$  relative, as judged by sampling the calibration span gas at the surface in the laboratory.

Again, a well-designed analyzer should easily meet this level of precision.

4. Short-term CO<sub>2</sub> accuracy (within 24 h of calibration):  $\pm 10\%$  relative over the measurement and pressure range, as determined in the laboratory.

Less accuracy (up to  $\pm 20\%$  relative) over the range of operating conditions would be acceptable if  $\pm 10\%$  accuracy cannot be met and has been deemed satisfactory for DDS use (meeting of Closed Living Space Environmental Concerns Working Group, 14 December 1993). This degree of deviation from either the 15,000 ppm (1.5%) SEV DDS limit or the 1,000 ppm limit of air bank gas should not affect diver safety or performance. As with O<sub>2</sub>, analyzers are expected to be used for much less than 24 h before being recalibrated.

5. Calibration: At 1 ATA, both sensors are zeroed with N<sub>2</sub> and then spanned with a gas standard having the nominal concentrations of 15,000 (1.5%) CO<sub>2</sub>, 20.9% O<sub>2</sub>, balance N<sub>2</sub>.

The span gas CO<sub>2</sub> concentration is chosen to maximize accuracy at the concentration of concern, the CO<sub>2</sub> limit within the DDS during operations. Calibrating the O<sub>2</sub> sensor at

1 ATA with 20.9% O<sub>2</sub> as the standard is probably the most practical approach in the field and should maximize accuracy at this pressure/concentration point. As air is used for recompression treatment in the DDS, the span gas concentration of 21% O<sub>2</sub> should be very close to O<sub>2</sub> levels normally existing within the DDS. If needed, alternative sources of calibration air (or equivalent) are also likely to be available in the field.

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

This rate should be more than adequate, as gas concentrations within the DDS should not change quickly.

## **METHODS**

### **MONITORS**

Three modified Analox analyzers (model SUB MK II P-S) — serial numbers 2001, 2002, and 2003, which will be noted in this report as units #1, 2 and 3 — were delivered to NEDU in December 2003. These analyzers measure and display simultaneously levels of O<sub>2</sub>, CO<sub>2</sub>, and depth, as well as temperature, and pump and battery status. Manufacturer specifications state that sensor readings are updated approximately every two seconds. Laboratory testing of instrument performance began in January 2004 and most testing was completed by April 2004. However, some additional temperature testing was performed in April 2005. Offgas testing was performed several times from May 2004 to March 2005, to judge chemical safety. No field testing was done.

### **TEST SUMMARY**

The three Analox analyzers were tested together for:

1. precision (short-term variability or repeatability);
2. accuracy from 1 to 6 ATA,
  - a. following normal calibration vs. factory calibration and
  - b. over a range of ambient temperatures;
3. instrument stabilization and signal noise;
4. battery duration;
5. effect of RH from ~0 to ~95% RH;
6. offgassing of volatile organic compounds (VOCs);

7. water immersion; and

8. overall performance, including ease of use.

## TEST PROCEDURES

Instruments were stored, calibrated, and tested (other than inside a hyperbaric chamber) at laboratory temperatures between 22 and 26 °C. During periods when instruments were not being used, the analyzers were turned off and stored on the laboratory bench. At the beginning of each test day, analyzers were turned on and allowed to warm up for at least 30 minutes before being calibrated together on the bench. All testing was done with analyzers powered internally by their 4 D-size alkaline batteries. The external power supply option was not tested.

At the beginning of each test day, at ~1 hour intervals throughout the day, and at the end of the day, laboratory temperatures within 1 foot of the analyzers when they were on the laboratory bench were recorded with a digital Thermopen thermometer (Model 211076, Electronic Temperature Instruments; West Sussex, UK); barometric pressures were recorded with a digital barometer (Model AG-200B/9772-01, Sensotec; Columbus, OH) that had been calibrated within the year by the manufacturer. In addition, at the beginning of each test day the battery status was recorded 1 min and 5 min after instrument start-up; two measurements were taken as battery status was often observed to change slightly during the first few minutes after analyzers are turned on.

The following gases were used during testing:

1. Zero N<sub>2</sub>: CO<sub>2</sub>-free, hydrocarbon-free. This was used for zeroing O<sub>2</sub> and CO<sub>2</sub> sensors during calibration and as a diluent for testing with the precision gas divider as described below.
2. Gravimetric standards of nominal concentrations of 1,500 to 25,000 ppm CO<sub>2</sub>, 21% or 25% O<sub>2</sub>, balance N<sub>2</sub>.

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.

Analyzers were tested in two locations in the laboratory: (1) on the laboratory bench at ambient pressure, and (2) inside a temperature-controlled hyperbaric chamber at pressures up to 6 ATA. During calibration and most bench testing, a precision gas divider (STEC Model SGD-701, Horiba Instruments, Inc.; Ann Arbor, MI; Fig. 1) was used to deliver test gas to all three analyzers simultaneously via a branching circuit of Teflon tubing. Joined by stainless steel and chrome-plated brass connections, this branching circuit included a side branch with an attached flowmeter to allow a slight gas overflow, one exceeding what the analyzers consumed via their sample pumps. This insured adequate but not excessive gas supply to analyzers and thus minimized back

pressure (<1 psi). A short (~15 mm) piece of Tygon tubing was used as a butt connector to join the branching circuit to a 6 mm OD plastic inlet port adaptor (supplied by the manufacturer) that was inserted into the analyzer.

For bench testing, the delivery flow from the STEC to the three analyzers was adjusted to produce an overflow of ~400 ml/min, although much higher overflows were demonstrated to have no 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 gas standards with a diluent gas (here, zero N<sub>2</sub>) in 10 equal steps of 10% each, from 0 to 100% of the standard concentrations. We have previously shown that this gas divider, using low ppm levels of VOCs and up to 25% of fixed gases (e.g., O<sub>2</sub>, CO<sub>2</sub>), is linear within the manufacturer's specification of ±0.5% of full scale.<sup>1</sup> 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 consisted of going from 0 to 100 and back to 0% in five equal steps of 20% to reduce the total test time.

After reaching 100% and recording the first set of readings, we left the STEC unchanged and took a second set of measurements 10 min later. The STEC was then stepped back down in 20% intervals to 0%, where again two sets of measurements were collected 10 min apart. These repeated tests at 100 and 0% were used to check the stability of readings over this time. The complete test as just described will be referred to as a "STEC test" throughout this report. During all STEC testing, readings from the instrument display were recorded on a data sheet after they had stabilized, typically 3 min after a gas switch using the STEC.

For hyperbaric testing, a specially designed test system used previously and described fully in Reference (1) allowed controlled delivery of test gases to multiple analyzers under pressure (Fig. 2). This system included a hyperbaric chamber configured with a gas manifold system that could handle up to six different test gas standards. The gas delivery tubing used for STEC testing was removed from the STEC and attached to a connection inside the chamber. This change allowed the gas from a selected gas standard outside the chamber to be delivered via an external port through the tubing to the analyzers inside the chamber in a fashion similar to that on the bench. A slight overflow of ~400 ml/min, as measured with a flowmeter inside the chamber, was again maintained during testing with no effect on instrument readings observed when gas flow to the instruments was widely varied inside the chamber at pressures to 6 ATA.

Rated well beyond the maximum test pressure of 6 ATA, the chamber was equipped with separate air supply and decompression circuits so that it could be compressed with air or decompressed at precise rates. The travel rate for testing in this study was 1 foot of seawater per second (fsw/s) during both compression and decompression. For analyzer testing, chamber pressure was monitored from a Mensor digital pressure

gauge (Model 2101, Mensor Corp.; San Marcos, TX) that had been calibrated within the year by the manufacturer. The temperature of the chamber was maintained to within 1 °C of the set points used for testing (5, 25, or 42 °C) by a temperature controller (Model 89000-10, Cole-Parmer Instrument Co.; Vernon Hills, IL). Analyzers were allowed 30 min to equilibrate inside the chamber, after the chamber had stabilized at the setpoint temperature, before testing began.

Individual gas standards were delivered to the analyzers at pressure inside the hyperbaric chamber. Testing started at 1 ATA; pressure was then increased in 1 ATA steps up to 6 ATA and then back to 1 ATA waiting at each new pressure for 4 minutes for readings to stabilize. Each test depth was controlled to within 0.03 ATA of desired value. During testing inside the chamber the analyzer's data logging was required, because poor visibility through the chamber ports prevented reliable viewing of instrument displays. A 20-second datalog period was used so that a new set of values were stored in the instrument's memory every 20 seconds.

### Calibration

Analyzers were calibrated on the bench with the STEC delivering both zero N<sub>2</sub> and the span gas (nominally 21% O<sub>2</sub>, 1.5% CO<sub>2</sub>, balance N<sub>2</sub>) to all the instruments simultaneously. Precalibration calibration values for O<sub>2</sub> and CO<sub>2</sub> stored in the analyzer memory were checked and corrected if necessary: low O<sub>2</sub> = 0.0, high O<sub>2</sub> and CO<sub>2</sub> = actual span gas concentrations; low CO<sub>2</sub> was fixed at 0.0 by the manufacturer.

Before most calibrations, the calibration status of the instrument was checked by first supplying the span gas for 3 min, recording the stabilized readings, and then supplying the zero gas and again recording readings. This test provided data on stability since the last calibration. These span and zero checks were often repeated one or more additional times to gauge precision (see Precision and accuracy below). We waited 3 min for readings to stabilize, and then using the pushbuttons on the front of the analyzer according to the manufacturer's procedures recalibrated the instruments by first zeroing and then spanning both the O<sub>2</sub> and CO<sub>2</sub> sensors. Following calibration, the span and zero were again checked one or more times to verify the effectiveness of the calibration.

The pressure sensor was not calibrated during testing, although pressure data from the analyzer were collected and are reported in this report; these data therefore are based on the factory calibration. The temperature sensor was also not calibrated, but no data from this sensor were collected.

### Precision and accuracy

Just as described for calibration, precision was evaluated by supplying the zero and span gases to the analyzers and repeating this process two to five times. After each gas switch, 3 min was allowed before the stabilized readings were recorded.

We assessed accuracy at 1 ATA over a range of gas concentrations by performing STEC tests at room temperature with the two gas standards: (1) 25,000 ppm CO<sub>2</sub>/21% O<sub>2</sub>/balance N<sub>2</sub> and (2) 2,500 ppm CO<sub>2</sub>/21% O<sub>2</sub>/balance N<sub>2</sub>. Accuracy at 1 ATA was evaluated within 1 hour following normal calibration or "factory calibration," whereby the instrument was reset (via a keystroke) to factory settings stored in memory.

Accuracy under pressure was tested by delivering each of six different gas standards to the analyzers inside the hyperbaric chamber at pressures up to 6 ATA as shown in Table 1. For the two standards with 5,000 ppm CO<sub>2</sub>, the maximum test pressure was limited to 5 ATA to avoid exposing the instrument to concentrations above 25,000 ppm (2.5%) CO<sub>2</sub> SEV, the upper range of the instrument. Testing began with the lowest CO<sub>2</sub> standard and then was repeated with the other two standards in order of increasing CO<sub>2</sub> concentration, with a given test series consisting of the three standards with the same O<sub>2</sub> concentration (i.e., 21% or 25%). Hyperbaric accuracy was evaluated within 3 hours following normal or factory calibration and at one of three chamber temperatures: 5, 25, or 42 °C. To examine instrument stability, some hyperbaric testing was also done on two consecutive days without recalibration between test days. Although the upper test temperature falls just outside the manufacturer's specification for operating temperatures (0 to 40 °C), the potential use of these analyzers at higher ambient temperatures during operations led us to test at 42 °C, the highest temperature at which our chamber could be reliably maintained.

#### Chamber heating experiment

Due to unexpected results from hyperbaric testing at 42 °C (see **RESULTS AND DISCUSSION**), we performed an additional test at the surface one day inside the unpressurized hyperbaric chamber. We first calibrated all three analyzers, put them into the chamber, and allowed them to equilibrate at 25 °C for 30 min while sampling 25,000 ppm CO<sub>2</sub>/21% O<sub>2</sub>/balance N<sub>2</sub>. We then raised the chamber's temperature setpoint first to 38 °C and allowed 30 min to pass before we raised the setpoint again to 40 °C. We then ended the test 45 min later. Following each change in setpoint temperature, it took ~10 min for the chamber to fully reach stability, where the chamber varied within 1 °C of the setpoint. During this test, datalogging at 20-second periods was used to collect data.

#### Instrument stabilization and signal noise

We evaluated how long it took for instruments to stabilize following initial start-up on the laboratory bench while they were sampling 1.5% CO<sub>2</sub>/21% O<sub>2</sub>/balance N<sub>2</sub>. For this testing we used datalogging with a 10-second period, the minimum allowed by the software. This testing also provided information about signal noise, although such noise would have been better evaluated with a shorter datalogging period, one closer to the two-second period at which sensor readings are updated.

### Battery duration

We tested operating duration on battery power at room temperature (22 to 26 °C), 5 °C, and 42 °C. New batteries were installed immediately before testing, with the datalogging period set to 5 min. For room temperature testing, instruments were turned on and allowed to operate continuously until they shut off because of low batteries. The datalog record was then examined to determine when datalogging had stopped, and that time was used to determine the total operating time. During the day the battery status was also recorded periodically from the analyzer display. According to the manufacturer, the battery status value is supposed to represent the number of hours of operation: a maximum of 50 hours for new batteries.

For testing at 5 and 42 °C, the instruments were turned on at the beginning of each day, battery status was recorded, and instruments were placed into the unpressurized hyperbaric chamber that had already stabilized at one of these two temperature settings. At the end of each day after ~8 hours of cold or hot exposure, the instruments were removed from the chamber, battery status again was recorded, and instruments were turned off and stored overnight on the laboratory bench. The next day, the analyzers were again placed inside the chamber for another 8-hour exposure. We tested instruments in the cold and hot in this manner only during workday hours: we did not want to leave the chamber's temperature-controlling system turned on without having someone in the laboratory in case of a mishap. However, as a typical DDS operation may last up to 6 hours with the gas monitoring instruments to be removed from the DDS at the end of each day's operation, our chamber test profile probably better represented actual usage than does a continuous hot or cold test exposure.

### 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 partially submerged in a water bath at 35-45 °C. The humidified span gas was then blended with a flow of dry span gas to adjust the final mixture to the desired RH.

For these tests, adjustment to a precise RH was not necessary, and repeatedly adjusting and readjusting the flows of the dry and wet gas with fairly coarse valves would have required time to achieve precise levels. Rather, dry (~0%), wet (~95%), and midrange RH span gases were produced and delivered to the analyzers via the same branching circuit of tubing used with the STEC device. A hand-held humidity and temperature meter (Model HM70, Vaisala Oyj; Helsinki, Finland) with calibration traceable to the National Institute of Standards and Technology (NIST) was used to measure the temperature and RH of the gas delivered to the analyzers from the gas overflow site just upstream from the analyzers. Simultaneously with these measurements, analyzer gas readings were recorded. Because of the potential for the 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 Reference (5) to determine the actual concentrations of O<sub>2</sub> and CO<sub>2</sub> delivered to the analyzer.

#### Offgas testing

All three analyzers were individually tested for offgassing with 10-liter Tedlar bags (SKC Inc.; Eighty Four, PA) that have low permeability and are designed for accurate sampling of trace levels of contaminants in air. Each Tedlar bag was first filled and emptied three times with hydrocarbon-free gas before it was filled a fourth time and the bag valve was closed. The bags were then stored on the laboratory bench at room temperature (19-24 °C) for at least 24 hours or in the unpressurized hyperbaric chamber held at 42 ± 1 °C for at least 4 hours to equilibrate before baseline (empty bag) sampling. Each bag was sampled by attaching an evacuated 500 ml stainless steel canister to the bag valve and allowing the canister to draw gas via the bag valve and equilibrate at 1 ATA. Each canister was subsequently backfilled to 2 ATA with hydrocarbon-free gas to facilitate sample loading into a gas chromatograph to screen for contaminants. After baseline testing was completed, each bag was cut open, one analyzer was placed into the bag, the bag was secured by twisting the Tedlar to close the opening, and a rubber band was attached on the outside. Bags were resampled and analysis was performed after 70 hours (for room temperature tests) or at least 6 hours (for 42 °C tests).

Gas samples were screened for a broad range of VOCs with Shimadzu GC-9A gas chromatographs (Shimadzu Corp.; Columbia, MD) with flame ionization (FID).<sup>1</sup> Organic species were identified, when possible, by comparing GC retention times of sample peaks to those times of five species from a commercially acquired primary gas standard, each ~10 ppm, in air: Freon 113, methyl chloroform, benzene, toluene, and xylenes. Limited analysis was also done with GC/mass spectroscopy (GC/MS; Shimadzu GCMS-QP5000), with preconcentration followed by thermal desorption via a Perkin Elmer TurboMatrix TD thermal desorber (Perkin Elmer Instruments; Norwalk, CT) using an intermediate polarity column designed for VOCs (designated "VOCOL" column by the manufacturer; 60 m length x 0.32 mm inner diameter, 3.0 micron thick film; Supelco, Inc.; Bellefonte, PA). For GC/MS, a similar standard to that for GC was used, except that each component was ~2 ppm. Identification by GC/MS was made after careful review of library search results obtained from the NIST/EPA/NIH Mass Spectral Database (NIST107) with Shimadzu CLASS-5000 software.

Quantification of organic contaminants was based on the 5-species gas standard and the GC/FID or GC/MS peak areas. Individual contaminants other than these chemicals were quantified relative to the species in the standard closest to their retention times. All contaminant concentrations were corrected for sample dilution when the canisters were backfilled following sampling from the Tedlar bags.

These tests determined whether significant levels of volatile contaminants that might be hazardous during Fleet use were being released. By using low permeability test bags and a small gas volume surrounding the analyzer, test procedures enhanced our ability to detect contaminants. For these reasons, contaminant levels measured during this

test are expected to be much higher than those that might occur during actual analyzer use, where a large gas space surrounds the analyzer and the DDS is being ventilated.

Using methods approved for ASDS/DDS testing, one additional offgas test was performed by the chemistry laboratory at the Naval Surface Warfare Center (NSWC), Panama City, FL.<sup>6</sup> This test involved placing one analyzer in an offgassing chamber of ~113 liters, pressurizing the chamber to 50 psig with air, and holding it for four hours at 60 °C before sampling and analysis with various detectors including infrared, GC/FID, and GC/MS.

### Water immersion

When all the laboratory testing had been completed, one analyzer was tested for its ability to tolerate water immersion. After turning the analyzer on and allowing it to warm up to confirm normal operation, the instrument was then turned off, its case opened, and several sheets of tissue paper placed inside to facilitate detection of whether any water might enter.

The instrument case was then closed, and the analyzer was placed on its back at the bottom of the sink in our laboratory, with the display facing up. After first weighting the analyzer down with an ~7 lb flat circular plate (barbell weight) carefully positioned on the display to keep the instrument from floating, we slowly filled the sink with warm water (~35 °C). Under these conditions, approximately 4.5 inches of water was on top of the analyzer during the test. Fifteen min was then allowed to pass, during which we watched for any air bubbles to exit from the analyzer, a sign that might suggest that water was leaking into the case. We then removed the instrument from the sink, dried it off with paper toweling, and allowed it to air dry for more than three hours before we opened the lid of the case and investigated the outcome.

On several other occasions, we turned analyzers on, floated them in the water-filled sink, and tipped them purposely to allow water to be drawn into their inlet ports and cause their gas pumps to stop. The instruments were then removed from the sink and dried, and water was carefully shaken out of the inlets before we unscrewed the inlet fittings and removed the inlet filters. We then gently shook and blew out the filters with a gentle air flow. The inlet chambers, inlet fittings, and inlet filters were dried with cotton swabs and allowed to air dry on the laboratory bench for up to 24 hours before these analyzers were reassembled and retested.

### **DATA ANALYSIS**

O<sub>2</sub> and depth data were used to calculate absolute error:

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

where the expected reading for O<sub>2</sub> during STEC testing at the surface was equal to the product of the gas standard concentration and the STEC setting. At depth, the expected O<sub>2</sub> reading was simply the O<sub>2</sub> concentration of the test gas, as the instrument was

designed to compensate for the effect of depth. As depth during testing was controlled to within 0.03 ATA of the desired value, the test depths (and therefore the expected depth values) were simply defined as 1.0, 2.0, 3.0, 4.0, 5.0, or 6.0 ATA. However, to allow comparison to the Analox pressure data given in fsw, the expected depths were converted to fsw by multiplying by 33 fsw/ATA.

CO<sub>2</sub> data were used to calculate relative percentage error:

$$\text{error} = \{(\text{observed reading} - \text{expected reading}) / \text{expected reading}\} \times 100,$$

where the expected reading for CO<sub>2</sub> during STEC testing at the surface was equal to the product of the gas standard concentration and the STEC setting. At depth, the expected CO<sub>2</sub> reading was equal to the product of the gas standard concentration and the test depth.

During workup of the logged chamber data, the analyzer-generated data files were edited by deleting much of the data to produce one set of stabilized readings for each test pressure before error calculation and further analysis.

Means and standard deviations (SDs) were calculated from the error data. No data were corrected for barometric pressure.

## **RESULTS AND DISCUSSION**

### **GENERAL PERFORMANCE**

During the evaluation period, the three hyperbaric analyzers were tested for many hours in the laboratory. During this time, no significant operating problems were observed. Other than occasionally replacing the alkaline batteries, we performed no other maintenance or servicing during the testing period. Instruments are turned on by rotating the power switch on the front of the case to the battery; in a couple of seconds this automatically puts the instrument into the monitoring mode and turns the pump on. Calibration procedures are easy to perform with the four push buttons also located on the front of the case.

### **PRECISION**

Repeatability based on readings of the zero and span (21% O<sub>2</sub>, 1.5% CO<sub>2</sub>) gases taken directly from the display over less than 10 min was  $\pm 0.1\%$  for O<sub>2</sub> and  $\pm 50$  ppm absolute ( $\pm 0.3\%$  relative) for CO<sub>2</sub>. These findings agree with the level of signal noise seen during datalogging and described below (see **INSTRUMENT STABILIZATION AND SIGNAL NOISE**).

**Conclusions.** Precision is important to determine first, as all other accuracy testing is affected by short-term changes in measurements. All three analyzers met the desired

$\pm 0.2\%$  absolute short-term repeatability requirement for  $O_2$  and the  $\pm 1\%$  relative requirement for  $CO_2$ .

## **SURFACE ACCURACY**

After calibration with 21%  $O_2$ , the  $O_2$  measurement error at surface pressure (1 ATA) at room temperature was on average less than 0.4% absolute over the range of 0 to 21%, with good consistency among the three analyzers (a consistency shown by the overlap of their three plots) and over test days (a consistency shown by the small standard deviations; Fig. 3, top graph). The  $O_2$  error was overwhelmingly negative, an indication that instrument readings were generally lower than expected. However, the concentration extremes of 0 and 21%  $O_2$  showed little or no error; this was expected, as the zeroing and spanning steps for the calibration procedures were made at these two concentrations. Two repeated  $O_2$  measurements made 10 min apart of both the span gas (shown on both graphs in Fig. 3) and zero  $N_2$  (not shown on Fig. 3) agreed well. After the analyzers were reset to the factory calibration, the  $O_2$  error on average increased to nearly 1% absolute: the error was again negative but with more variability showing among instruments (Fig. 3, bottom graph). In contrast to laboratory calibration, resetting the instruments to the factory calibration produced significant error at the 21%  $O_2$  point.

After instruments were calibrated with 1.5%  $CO_2$ , the  $CO_2$  measurement error at ambient pressure at room temperature was on average less than 5% relative for  $CO_2$  concentrations from 2.5% down to ~2,000 ppm, with good agreement in accuracy among instruments and over test days (Figs. 4-5, top graphs). Below ~2,000 ppm  $CO_2$ ,  $CO_2$  errors increased up to ~10% for relative concentrations down to ~1,000 ppm, an increase reflecting in part the translation of small absolute errors into large relative errors at these levels. Differences among instruments and over test days were also greater than they were at these lower  $CO_2$  levels. As was the case for  $O_2$ , two repeated  $CO_2$  measurements made 10 min apart of both the span gas and zero  $N_2$  agreed well. Following resetting instruments to factory calibration, the  $CO_2$  error increased to ~7% for concentrations down to 2,000 ppm, with errors greater than this at  $CO_2$  levels below 2,000 ppm (Figs. 4-5, bottom graphs).

As judged by the symmetry between the error plots with increasing vs. decreasing gas concentrations, no significant hysteresis was observed for either  $O_2$  or  $CO_2$  during the STEC tests.

**Conclusions.** Within eight hours following laboratory calibration, at room temperature all three analyzers met (1) the desired  $\pm 1\%$  absolute accuracy for  $O_2$  at the surface over the range from 0 to 21%  $O_2$  and (2) the desired  $\pm 10\%$  relative requirement for  $CO_2$  at the surface over the range from ~1,000 to 25,000 ppm. Following resetting instruments to factory calibration, the  $O_2$  and  $CO_2$  errors increased but remained within desired levels.

## HYPERBARIC ACCURACY

Absolute errors were on average within 0.2% when 21% O<sub>2</sub> was measured and within 0.6% for 25% O<sub>2</sub> at pressures from 1 to 6 ATA at 25 °C (Fig. 6, top and middle graphs). After resetting instruments to factory calibration, the error for 21% O<sub>2</sub> increased only slightly at pressure but substantially at the surface up to 0.6% absolute (Fig. 6, bottom graph). As expected, the latter finding agrees with results from the surface testing described in the preceding section. The average difference between results obtained on two consecutive days without recalibration was small and within 0.1% O<sub>2</sub> (Fig. 7A). Cold exposure (5 °C) caused instruments to read 21% O<sub>2</sub> up to nearly 1.5% low, whereas heat (42 °C) increased error only slightly from its level at 25 °C (Fig. 8).

Relative errors were on average within 10% for CO<sub>2</sub> concentrations from 1,500 to 25,000 ppm (2.5%) SEV at pressures from 1 to 6 ATA at 25 °C (Figs. 9-14), with good agreement among instruments and over test days. Factory calibration increased the CO<sub>2</sub> error primarily at the surface, from less than 5% that was observed following laboratory calibration to more than 10% (Fig. 15). The average difference in CO<sub>2</sub> measurements obtained on two consecutive days without recalibration was again small and generally within 3% (Fig. 16).

The main effect of the cold was to reduce instrument CO<sub>2</sub> readings at and near the surface, so that the relative errors for one instrument using the lowest CO<sub>2</sub> standard of 1500 ppm approached 20% (Figs. 9-11). Heat had the opposite effect by increasing instrument readings, again most noticeably at the surface, so the relative errors for two of the analyzers approached or exceeded 10% (Figs. 12-14). The effect of heat on the third instrument (unit #2) was so great that the relative errors of CO<sub>2</sub> measurements at the surface were nearly 100% higher than the expected readings.

Depth readings at 25 °C generally were within 2 fsw of actual values and in all cases higher than the true depth (Fig. 17, top graph). All readings corresponded to factory calibration, as we did not recalibrate depth in the laboratory. Depth error between two consecutive days was within 0.5 fsw (Fig. 7B); some of this day-to-day error undoubtedly resulted from deviations in barometric pressure in the laboratory, as we did not correct instrument readings for this. Both heat and cold did not appear to appreciably affect instrument depth values (Fig. 17, middle and bottom graphs).

As was true for the STEC testing, no significant hysteresis was generally observed for O<sub>2</sub>, CO<sub>2</sub>, or depth during hyperbaric testing when we compared plots with pressure increasing to those with pressure decreasing. The one exception to the absence of hysteresis was CO<sub>2</sub> measurement at 42 °C where the increased CO<sub>2</sub> readings due to heat (especially with unit #2) were often greater during the decompression phase of the test compared to the preceding compression phase (Figs. 12-14, middle graphs); this difference presumably reflects the greater time that the instrument had been exposed to the heat.

**Conclusions.** Within eight hours following laboratory calibration, at a test temperature of 25 °C all three analyzers met (1) the desired  $\pm 1\%$  absolute accuracy for O<sub>2</sub> from 1 to 6 ATA over the range from 0 to 25% and (2) the desired  $\pm 10\%$  relative requirement for CO<sub>2</sub> from 1 to 6 ATA over the range from ~1,000 to 25,000 ppm. Measurements taken without recalibration the following day showed little change in both O<sub>2</sub> and CO<sub>2</sub>. After resetting instruments to factory calibration, the O<sub>2</sub> errors increased but were still within desired levels; however, the CO<sub>2</sub> errors in some cases increased more than 10% at the surface. Cold and hot exposures affected both O<sub>2</sub> and CO<sub>2</sub> measurements and caused many errors to exceed the desired limits. Although no level for accuracy in depth reading is required, the small error consistently shown by the instruments should be acceptable for monitoring needs in the field.

### CHAMBER HEATING EXPERIMENT

Results from the chamber heating experiment at the surface confirmed the large effect of heat on CO<sub>2</sub> readings in unit #2 compared to those effects in the other two instruments (Fig. 18). All three graphs show increasing instrument temperatures as the chamber temperature rises. Analyzers #1 and #3 compensate well for the temperature rise and show only minor increases in CO<sub>2</sub> readings. However, unit #2 shows an apparent problem in compensating at high temperatures, with the instrument reading more than 4% CO<sub>2</sub> (and still rising) while sampling 2.5% CO<sub>2</sub> at the end of the test.

**Conclusions.** Unit #2 does not compensate well for heat.

### INSTRUMENT STABILIZATION AND SIGNAL NOISE

During the two tests performed on different days, the O<sub>2</sub> reading stabilized immediately upon start-up (Fig. 19), with stabilization defined by an absence of significant upward or downward signal drift. During both tests, each lasting more than 2 hours, the short-term O<sub>2</sub> variability (noise) was generally over a 0.3% range when 20.9% O<sub>2</sub> was sampled. The CO<sub>2</sub> signal stabilized within 20 min in all cases but one — that being during the second test, when the CO<sub>2</sub> readings for analyzer #1 continued to drift upward more than 2 hours following start-up (Fig. 20, right top graph). Short-term variability for CO<sub>2</sub> was less than 100 ppm when ~15,000 ppm CO<sub>2</sub> was sampled. Depth, similar to O<sub>2</sub>, appeared to stabilize immediately upon start-up, with short-term variability generally within a 0.4 fsw range (Fig. 21).

**Conclusions.** These data suggest that for best accuracy, instruments after being turned on should be allowed to warm up for at least 30 min before being calibrated and used. This time period is much longer than the 40 sec warmup specified in the *Analox User Instruction Manual*.

### BATTERY DURATION

During the one test performed, the three instruments operated continuously at room temperature for 141 to 183 hours (5.9 to 7.6 days) before data logging stopped and

shutoff occurred. When operated for ~8 hours each day at 5 or 42 °C inside the chamber at surface pressure, the three analyzers ran for five days (Monday through Friday) without shutting off; the tests were then terminated, as the need to continue them for what could be another one to two weeks was thought to be unnecessary.

The battery status measured immediately at the end of the last day of cold exposure ranged from 16 to 24 (maximum reading again is 50) for the three analyzers; that following the last day of heat exposure ranged from 28 to 45. However, by the Monday following the test, readings for the batteries had partially recovered to ranges from 43 to 47 (cold) or from 45 to 50 (hot), after the instruments had remained, turned off, on the laboratory bench over the weekend. Such battery recovery following instrument shutoff had also been observed routinely during all our testing. In addition, we found that battery status often declined nonuniformly with instrument usage. For example, the reading for battery status sometimes remained at 50 for up to 8 hours and then dropped precipitously.

**Conclusions.** These tests demonstrate that the instruments operate with a single set of new batteries for sufficient time (6 hours each day over a multiday period) and over a range of ambient temperatures to support DDS operations. However, battery status should be used only for roughly estimating the remaining operating time.

## RELATIVE HUMIDITY

Compared to the dry gas (<1% RH), humidifying the span gas (>95% RH) reduced the O<sub>2</sub> reading by up to 0.5% absolute (2.4% relative) but had no observable effect on the CO<sub>2</sub> reading. When the span gas was partially humidified at ~50% RH, the O<sub>2</sub> reading was proportionately reduced (i.e., O<sub>2</sub> = 20.7%). The effect of water vapor on O<sub>2</sub> is consistent with the expected reduction because of the addition of water vapor to the dry gas and the resulting reduction in the O<sub>2</sub> partial pressure. Our GC results showing that up to 3% of the O<sub>2</sub> and CO<sub>2</sub> were removed from the gas during the humidifying process confirm the expected reduction and suggest that little, if any, additional gas is removed through the scrubbing action of the water. The latter observation undoubtedly results from the saturation of the water in the bubblers with the span gas, a saturation preventing further gas from going into solution. The reason that humidity has no effect on the CO<sub>2</sub> reading is unknown, but perhaps a drying filter is upstream from the CO<sub>2</sub> sensor.

**Conclusions.** Water vapor had only minimal effects on gas measurements.

## OFFGAS TESTING

The initial offgas test performed on two of the analyzers in May 2004 revealed relatively high levels of VOCs (Table 2). Consequently, an additional three tests were conducted over the next six months with the expectation that total contaminant levels would decline with time as residual solvents from the manufacturing process came off the instruments. As the tests in May, July, and November were all performed at 42 °C for a similar time

(6-8 hours), we should be able to directly compare the offgassing results from them. Results showed that contaminant levels declined substantially from May to July for analyzer #1 but rose again in the November test. For analyzer #2, contaminant levels increased from July to November; for analyzer #3, levels declined from May to November. Thus, these results were equivocal about whether a reduction in offgassing occurred with time. Results from the one test done in August at room temperature for 70 hours were also ambiguous: they showed the lowest VOC levels of all the four tests for analyzer #1 and the highest levels for #2.

GC/MS results suggested that the volatile contaminants include many alkanes and alkenes with 6-11 carbon atoms/molecule, Freon 12, methyl ethyl ketone, and toluene. However, other than the 5-species calibration standard, no pure chemicals were injected into the GC/MS to confirm the search results or to allow more accurate quantitation.

Results from the offgas test in March 2005 by the NSWCL laboratory showed much lower concentrations of volatile contaminants than did our results, but this laboratory reported some of the same species that we observed. All of the laboratory's reported measurements were below the allowable limits defined by its procedures for Advanced SEAL Delivery System (ASDS) and DDS use, and thus it concluded that the tested prototype analyzer produced acceptable offgassing for ASDS and DDS use. Through GC/FID — a method of quantitation expected to significantly overestimate the level of contaminants in comparison to the actual concentration or to findings using our approach — the laboratory found 5.2 ppm total hydrocarbons in methane equivalents. Although conversion to methane equivalents is a standard procedure in the gas analysis industry, it is known to raise the estimated total hydrocarbon value because of the increased sensitivity of the FID to contaminants as the number of carbon atoms increase. In addition, the laboratory's testing was conducted at a temperature higher than ours (60 °C vs. room temperature or 42 °C), a temperature which should increase offgassing.

Despite these two factors that by themselves should have elevated the NSWCL laboratory's total hydrocarbon measurement, the fact that all its measurements were much lower than ours was expected. Perhaps the most important test conditions affecting the results were (1) the much larger gas volume of their test chamber, compared to the 10-liter gas bag we used for testing and (2) its conducting of the test at a pressure of more than 4 ATA, in contrast to our testing at the surface. If we assume no effect of pressure on the offgassing rate, the NSWCL laboratory test conditions would have significantly diluted the contaminant concentrations in its testing. Its tests were also shorter than ours, a factor that would also reduce VOC concentrations.

**Conclusions.** The one instrument tested with methods approved for ASDS and DDS produced acceptable offgassing.

## WATER IMMERSION

During the 15 min immersion test with one instrument, many small air bubbles were observed to appear around the edge of the lid, where the gasket seals the instrument, and to float to the surface. However, following the test, no water was detected inside the instrument, and the tissue paper that had been placed inside was dry, a condition suggesting that no water had leaked into the analyzer. Thus, the bubbles that were seen may have been air trapped along the lid-analyzer interface rather than air coming from inside the case as water entered. Following the postimmersion inspection, we restarted the instrument — which then operated with no apparent problems.

Additional testing exposing the gas inlet of two of the instruments to water while the sampling pump was operating confirmed that the pump immediately shuts off, as designed, as water enters the inlet and is trapped by the filter. However, it was difficult then to clear the water adequately from the inlet and the inlet filter so that the pump would restart. One problem was that water collected in the large internal gas space of the inlet housing between the external gas tubing and the filter simply due to the presence of this space upstream of the filter. Water also collected in the outside split ring assembly, where the sampling tubing is inserted. Before unscrewing the inlet fitting to dry out the interior of the inlet and clear the filter, we gently shook the analyzer with the inlet facing down to try to remove as much water as possible from the inlet. However, upon removing the inlet fitting, we found considerable water still inside the inlet housing; this water was soaked up with cotton swabs before the filter and its front and rear gaskets were removed. Unfortunately we found that, apparently because of a blocked filter, the pump did not restart after it had been reassembled.

Through trial and error we discovered that we could sometimes get the analyzer running after immersion if we reversed the inlet filter from the original orientation (with the female fitting facing outward) so that the smaller filter opening (the male side) faced outward. Several hours later, after the gas flow apparently had removed the trapped water, the filter could be reversed again and instrument would continue to run. If we started with the smaller male end of the filter facing outward, water could sometimes be blown out by mouth and the instrument restarted following water exposure. When filters became blocked with water, we tried replacing them with a few of the spare filters originally supplied by the manufacturer. However, we found that these filters would not fit the inlet of these prototype instruments. The manufacturer subsequently told us that the filters that originally came installed in the analyzers had been machined slightly so that they would fit into the inlet opening; the spare filters apparently had not been modified this way. The manufacturer has assured us that any production units will be able to accept the standard filters without any alteration.

**Conclusions.** Clearing water from the inlet and returning the instrument to operation in the laboratory was often difficult. Doing so in the field would be even more challenging.

## SUMMARY

1. Instruments were easy to use in the laboratory and provided no major operating problems during the test period.
2. At 25 °C, instruments met desired accuracy limits for both O<sub>2</sub> and CO<sub>2</sub>. However, both cold and hot exposures caused O<sub>2</sub> and CO<sub>2</sub> readings to exceed these limits.
3. Stabilization of the CO<sub>2</sub> readout required a much longer warmup period than the manufacturer has recommended.
4. Instruments operated with a single set of new batteries for sufficient time (6 hours daily over a multiday period) and over a range of ambient temperatures to support DDS operations. However, battery status should be used only for roughly estimating the remaining operating time.
5. Water vapor affected measurements only minimally.
6. The one instrument tested with methods approved for ASDS and DDS produced acceptable offgassing.
7. Clearing water from the inlet and returning the instrument to operation in the laboratory was often difficult. Doing so in the field would be even more challenging.

## **RECOMMENDATION**

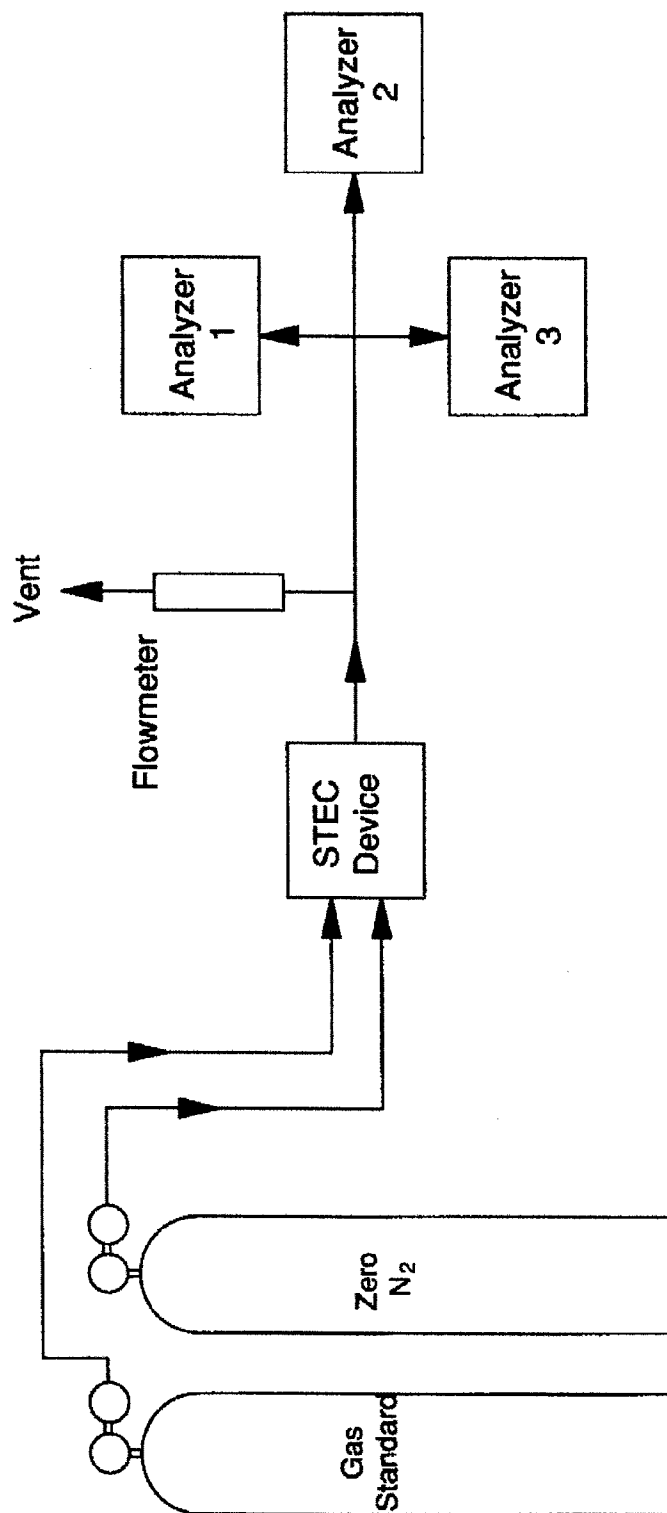
Before any decision about advancing these analyzers to field-testing can be made, the manufacturer needs to make the following changes to the instruments and additional testing in the laboratory needs to verify their acceptability:

- a. improving the compensation of gas measurements for changes in ambient temperature, and
- b. redesigning the gas inlet to facilitate the clearing of water following accidental immersion.

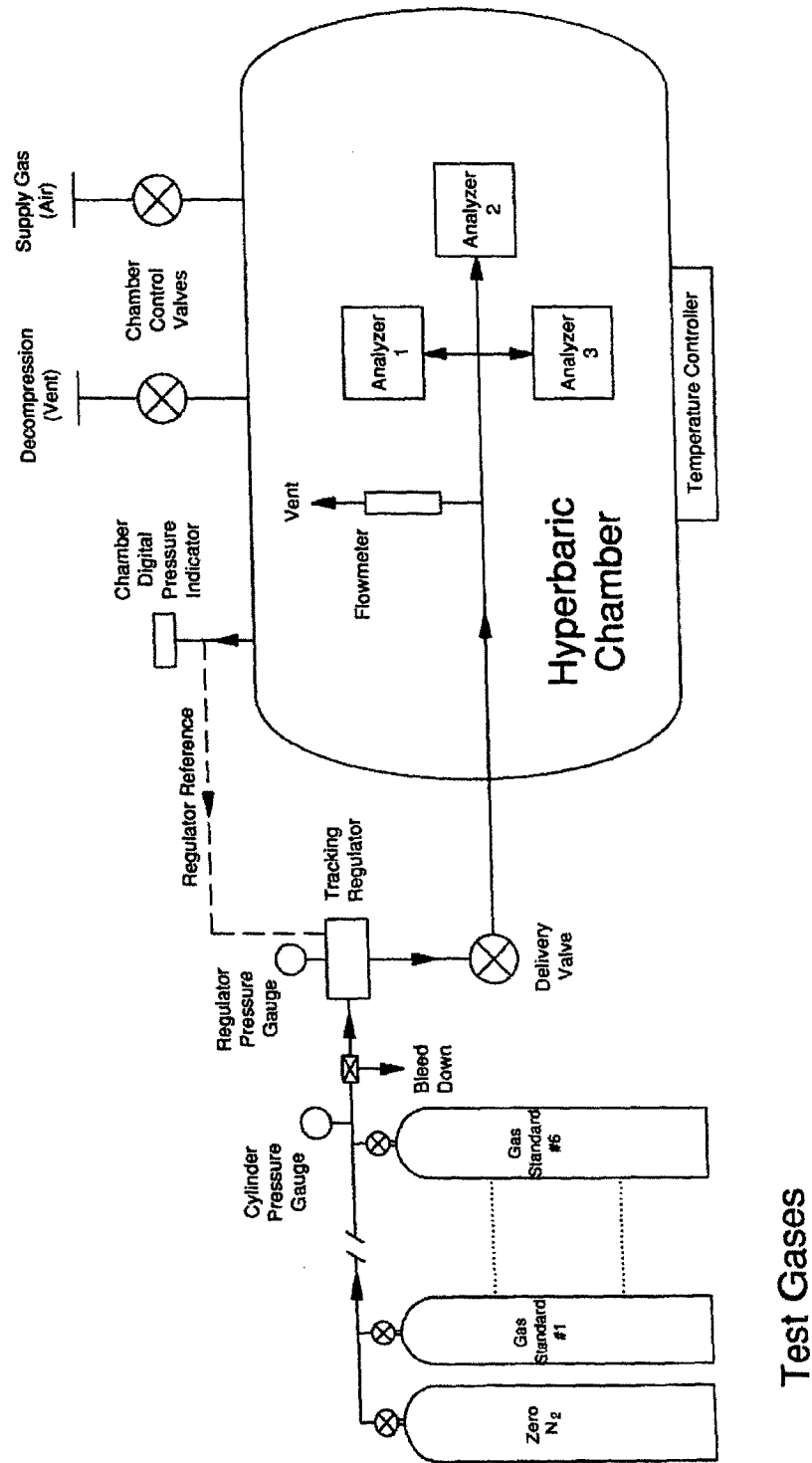
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1. R. S. Lillo, W. R. Porter, A. Ruby, W. H. Mints, J. M. Caldwell, and J. F. Himm, *Development and Evaluation of Hyperbaric Carbon Dioxide Analyzer for Dry Deck Shelter Operations*, NMRI Report 98-01, Naval Medical Research Institute, 1998.
2. Naval Sea Systems Command letter, *Installation of Oxygen Monitoring Capability in the Geotech Analyzer*, 9086, Ser 395A2T/174 of 5 September 2000.
3. R. S. Lillo, W. R. Porter, and J. M. Caldwell, *Development of Oxygen Monitoring Capability for the Existing Hyperbaric Carbon Dioxide Analyzer Used in Dry Deck Shelter Operations*, NEDU TR 01-01, Navy Experimental Diving Unit, January 2001.
4. Navy Experimental Diving Unit letter, *Percent Oxygen Monitoring by Hyperbaric Analyzer for Dry Deck Shelter Operations*, 3903/01-19, Ser 02/052 of 13 March 2002.
5. R. S. Lillo, J. M. Caldwell, and W. R. Porter, *On-site Evaluation of Field-based Procedures for Screening Diver's Air*, NEDU TR 04-12, Navy Experimental Diving Unit, April 2004.
6. Portsmouth Naval Shipyard, *ASDS/DDS System and Mission Equipment Testing Procedures*, NAVSEA Drawing #7328847, 16 March 2004.

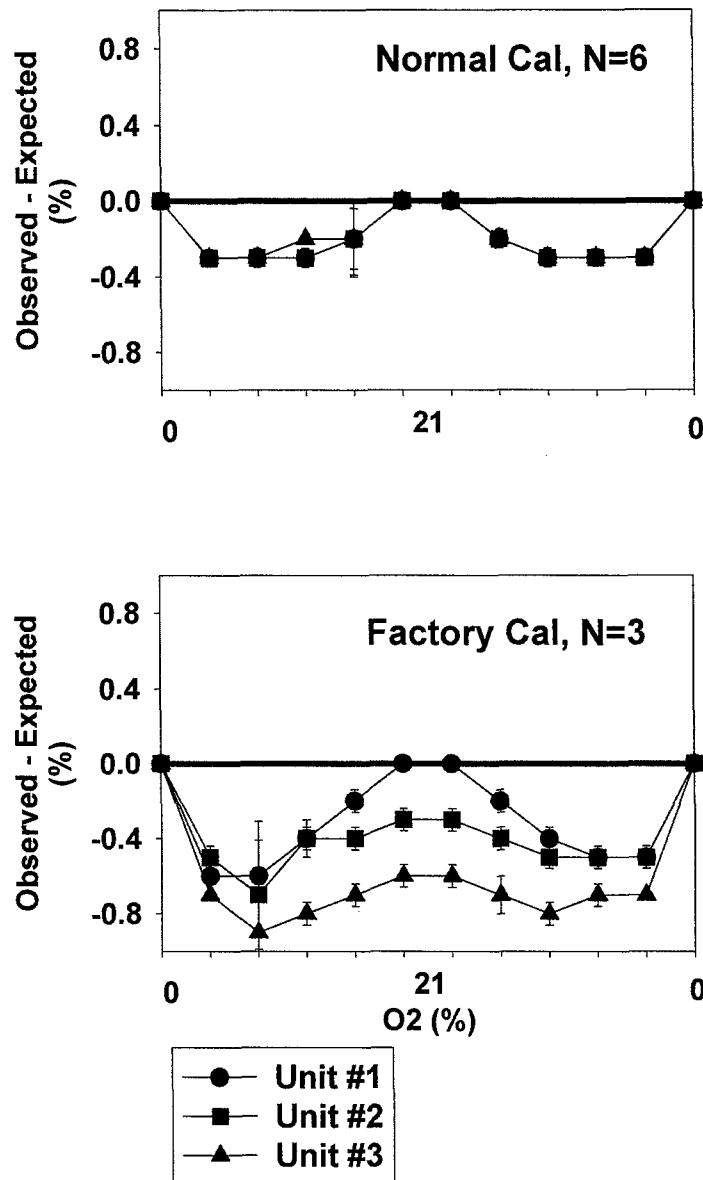
**Figure 1. Ambient pressure test system.**



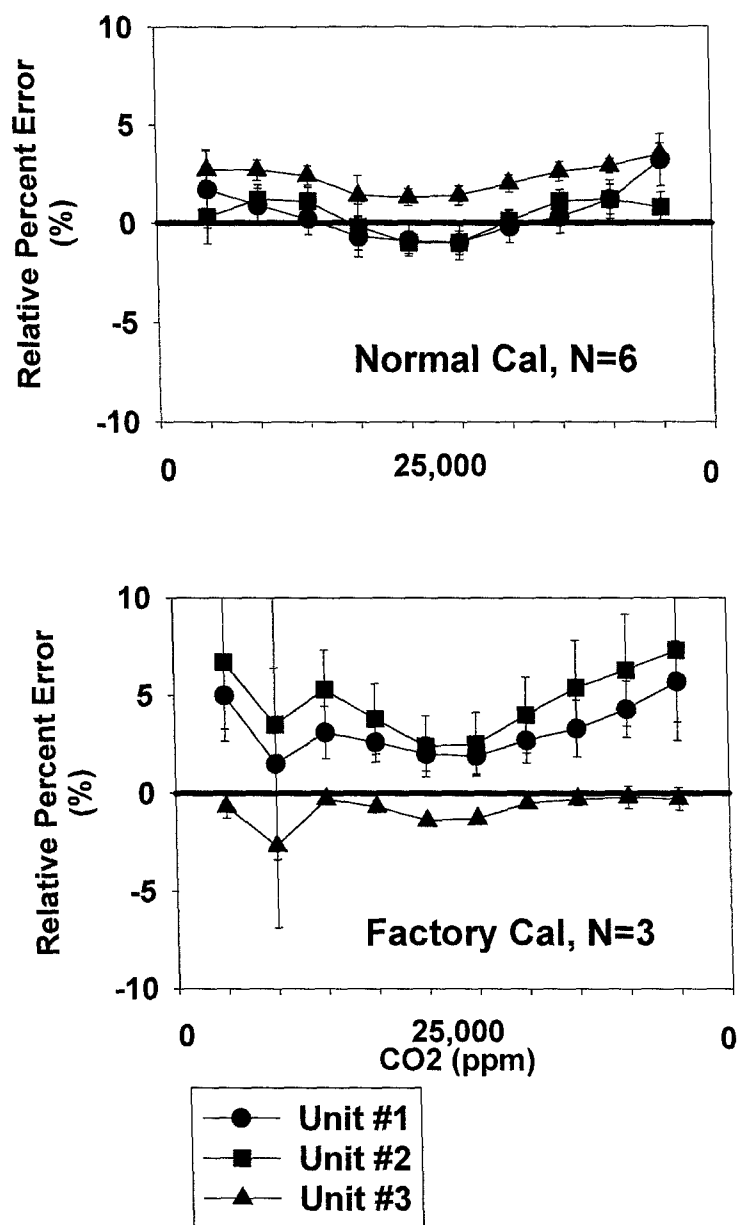
**Figure 2. Hyperbaric test system.**



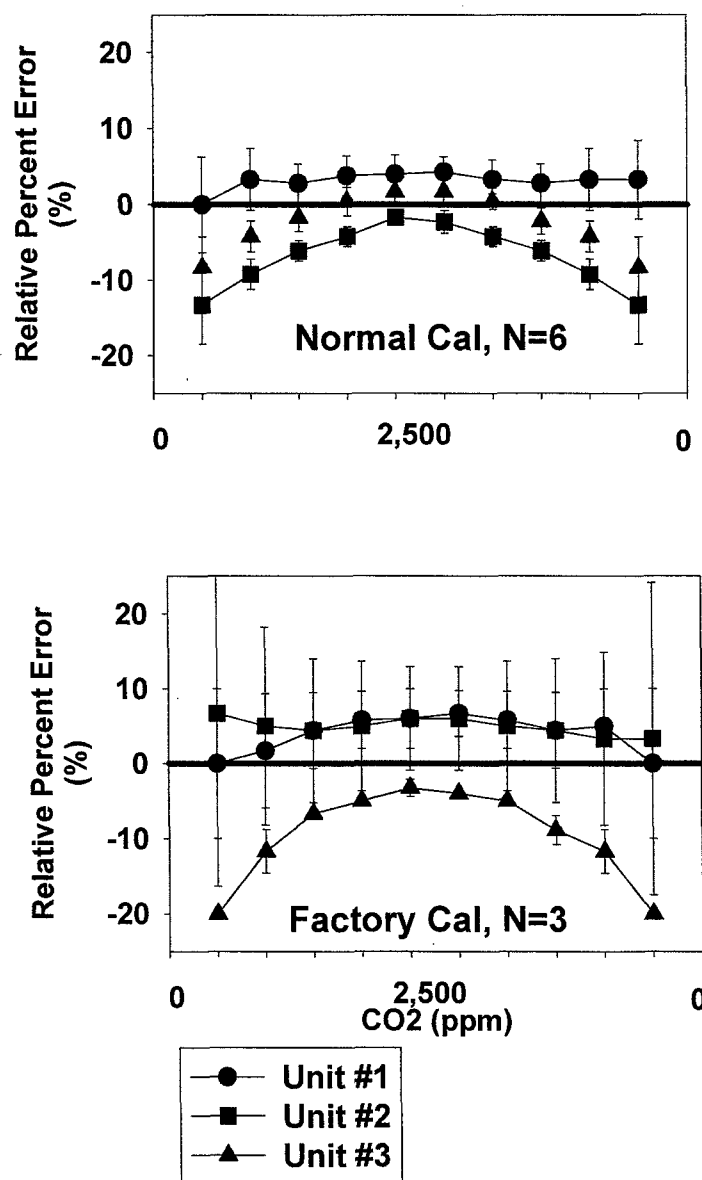
**FIGURE 3.**  
**SURFACE TEST**  
**O<sub>2</sub>**  
**Means and SDs Plotted**



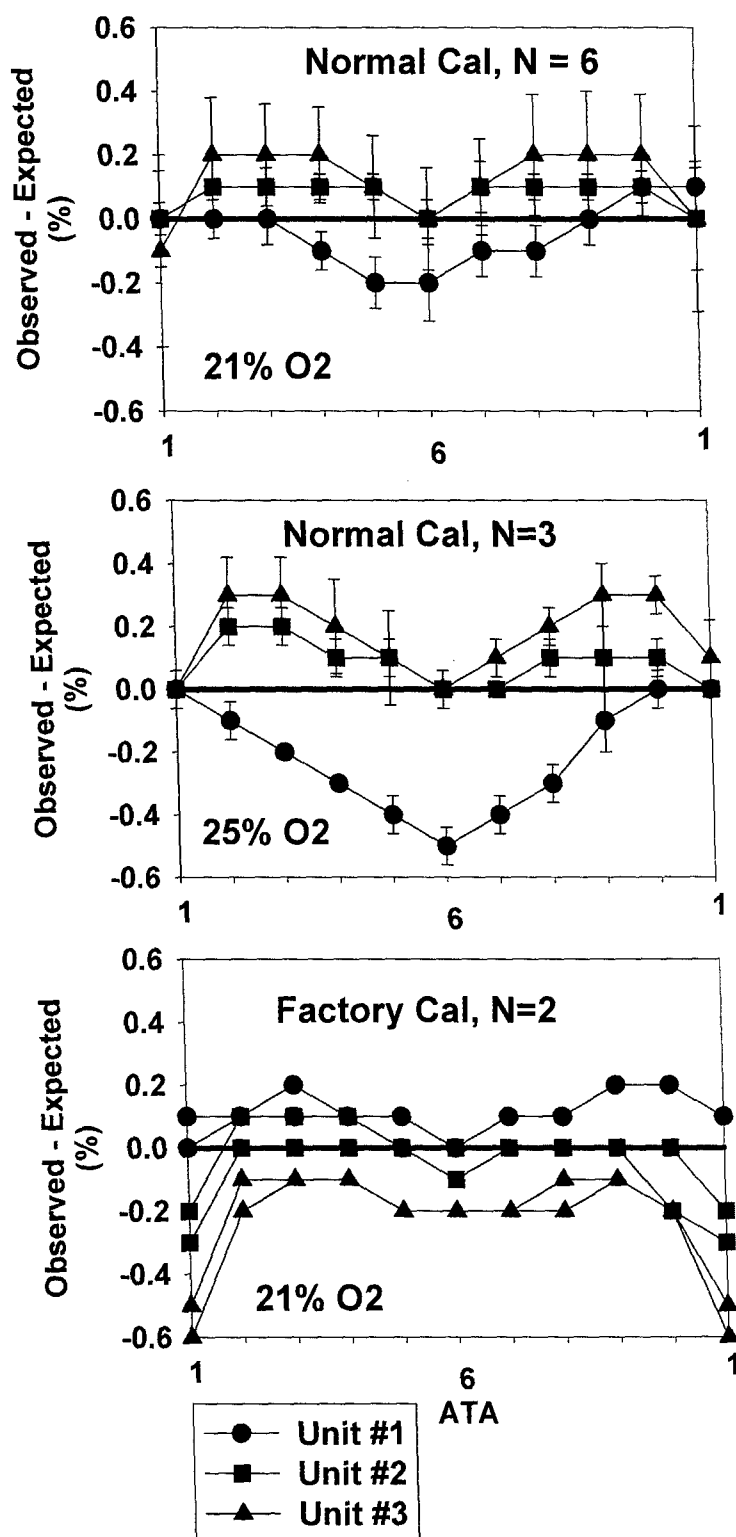
**FIGURE 4.**  
**SURFACE TEST**  
**HIGH CO2**  
**Means and SDs Plotted**



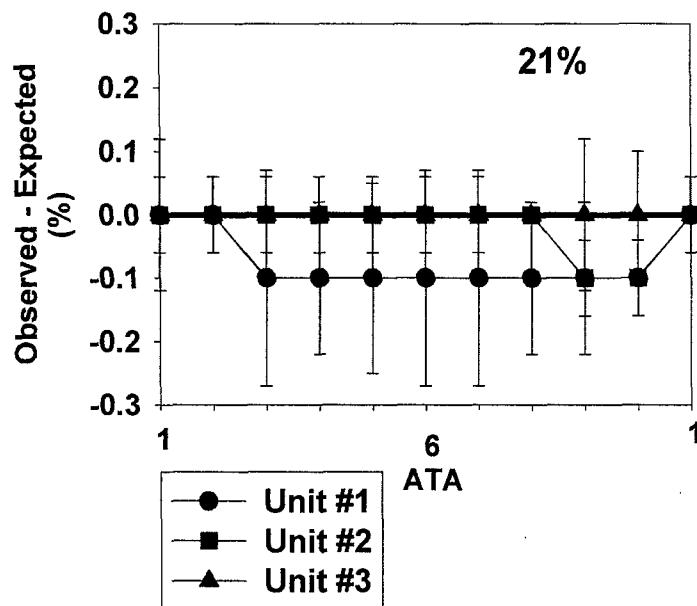
**FIGURE 5.**  
**SURFACE TEST**  
**LOW CO<sub>2</sub>**  
**Means and SDs Plotted**



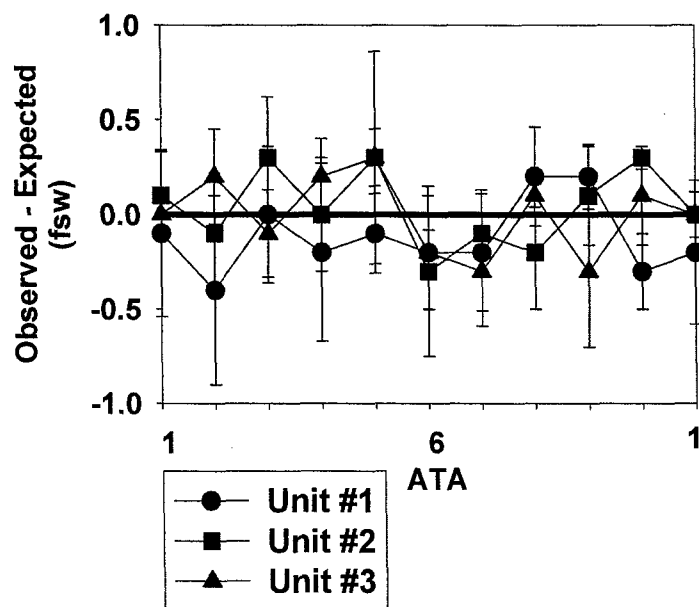
**FIGURE 6.**  
**HYPERBARIC TEST**  
**O<sub>2</sub>**  
**Means and SDs or Raw Data Plotted**



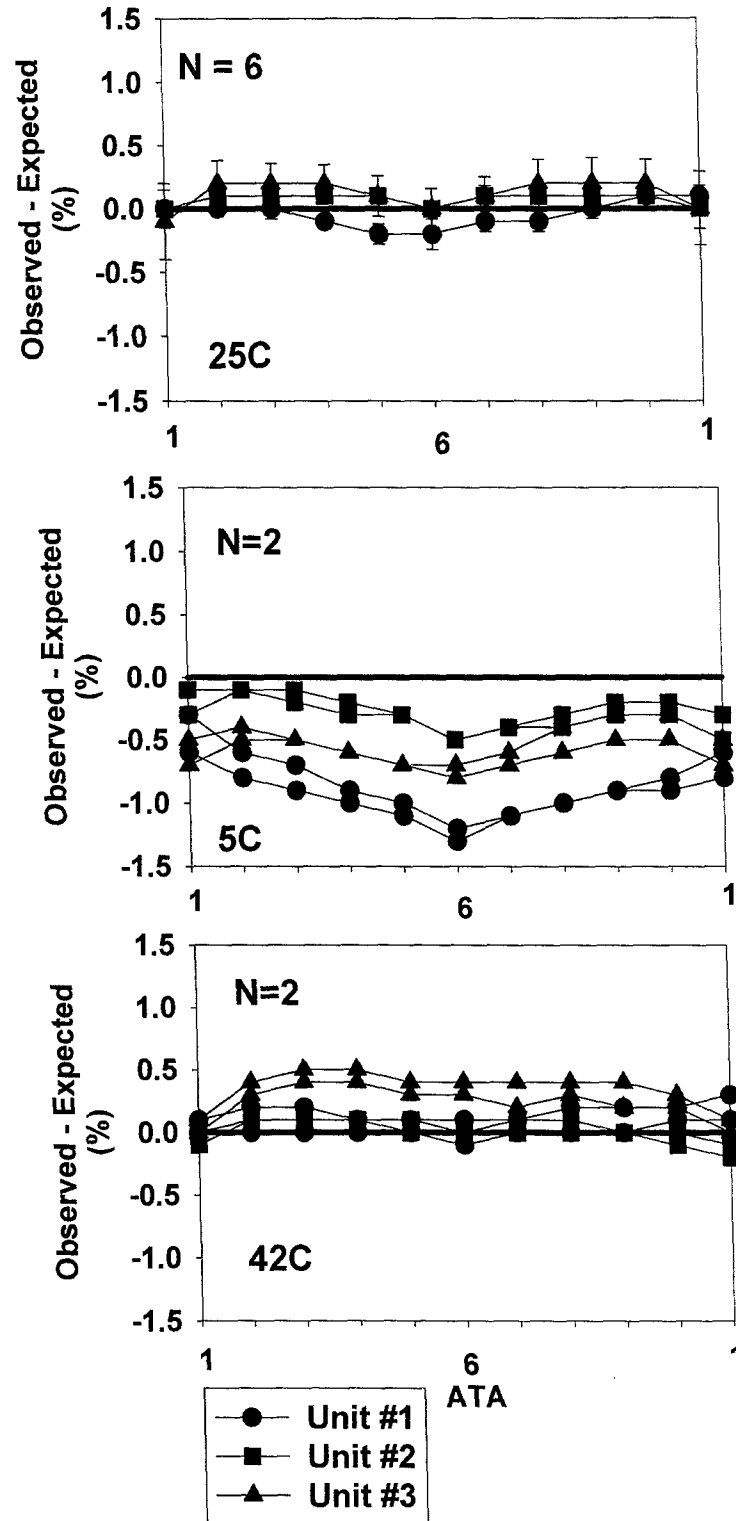
**FIGURE 7A.**  
**HYPERBARIC TEST**  
**21% O<sub>2</sub>, DAY1-DAY2, N=3**  
**Means and SDs Plotted**



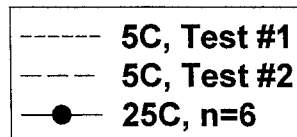
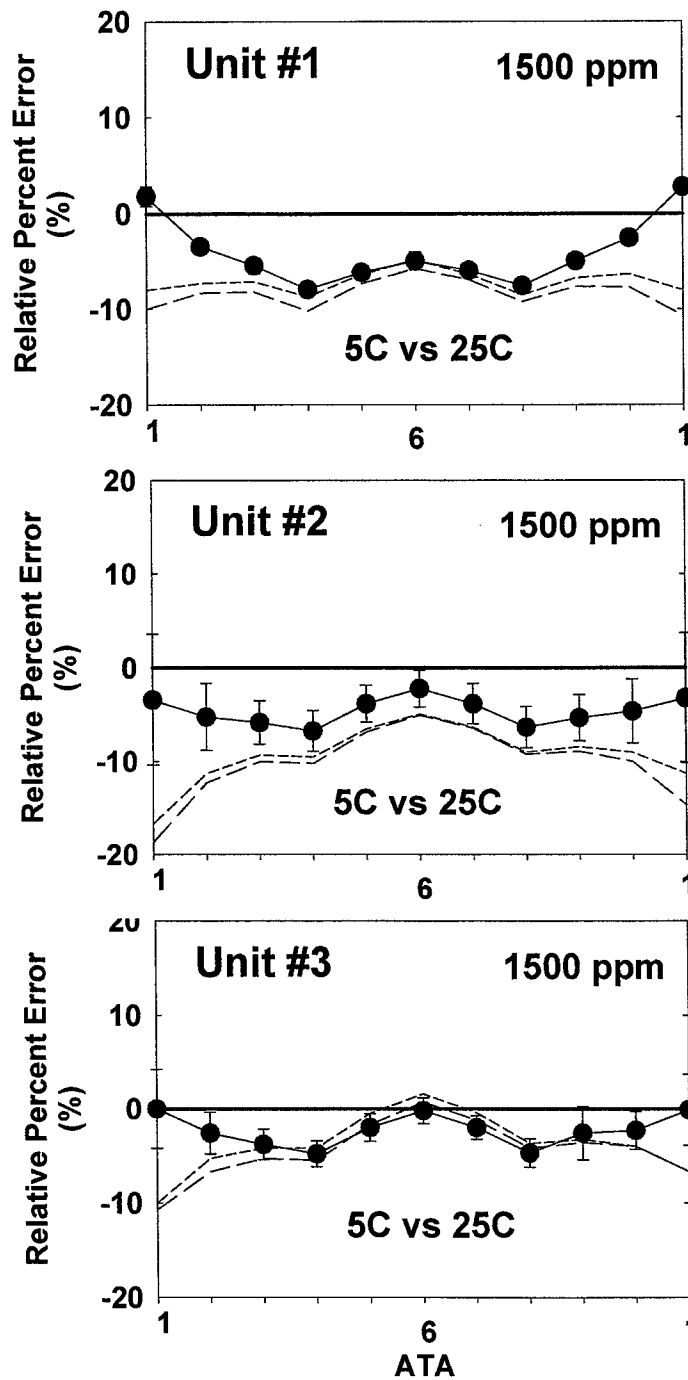
**FIGURE 7B.**  
**HYPERBARIC TEST**  
**DEPTH (FSW), DAY1-DAY2, N=3**  
**Means and SDs Plotted**



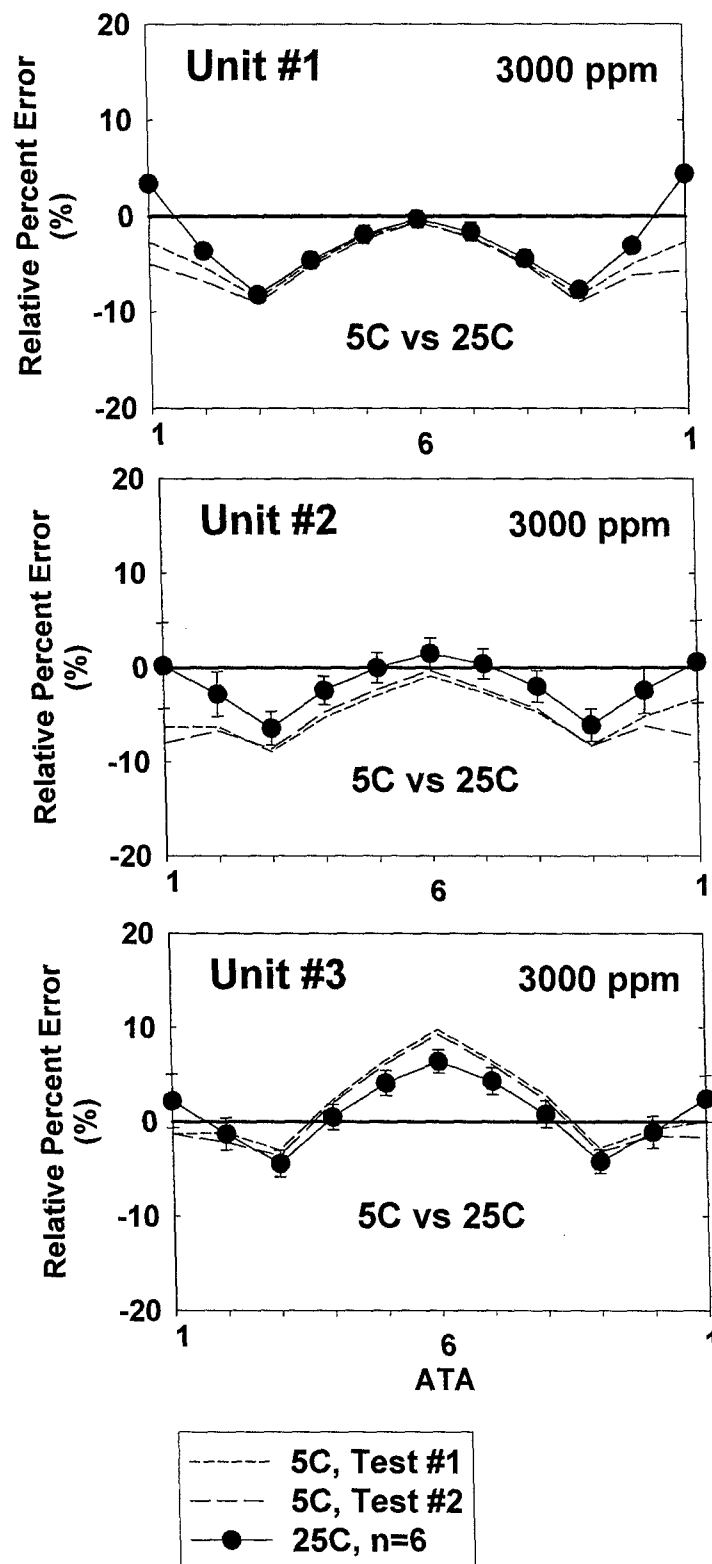
**FIGURE 8.**  
**HYPERBARIC TEST**  
**21% O<sub>2</sub>, 3 TEMPERATURES**  
**Means and SDs or Raw Data Plotted**



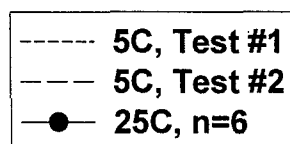
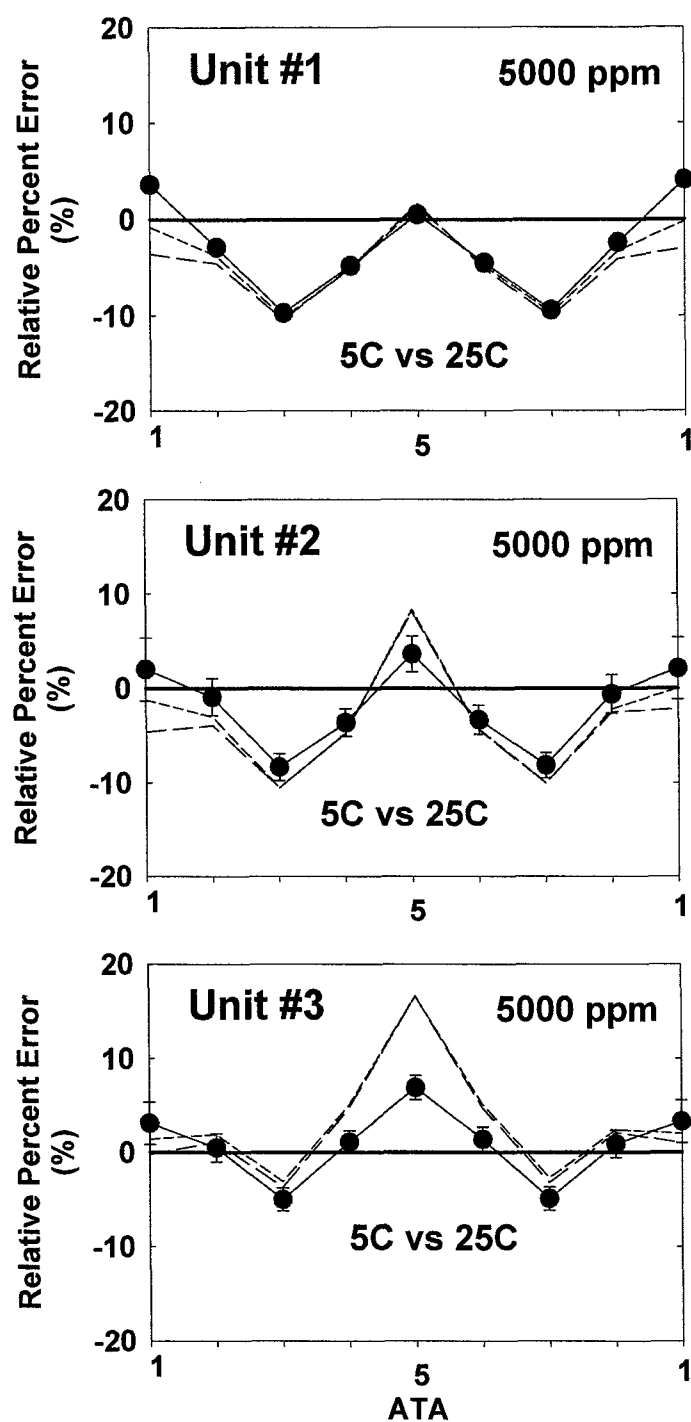
**FIGURE 9.**  
**HYPERBARIC TEST**  
**1500 PPM CO<sub>2</sub>, 5C vs 25C**  
**Means and SDs or Raw Data Plotted**



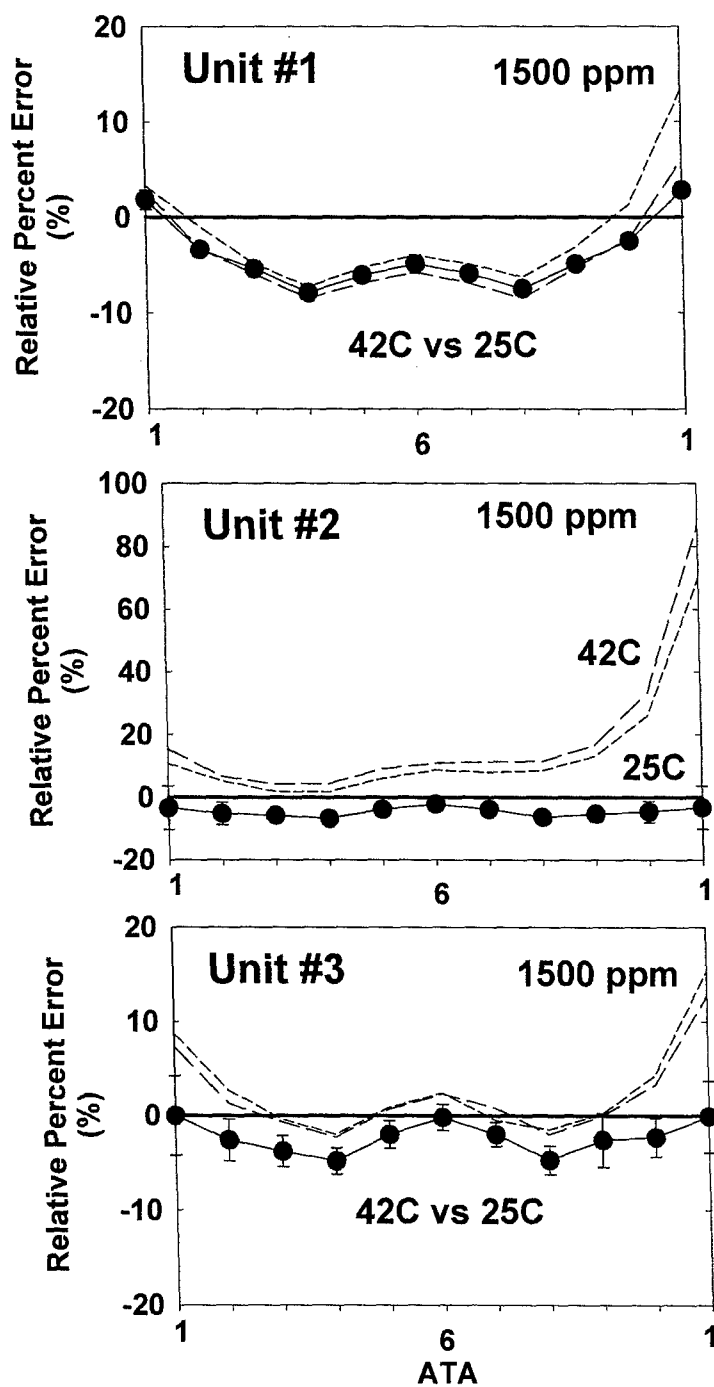
**FIGURE 10.**  
**HYPERBARIC TEST**  
**3000 PPM CO<sub>2</sub>, 5C vs 25C**  
**Means and SDs or Raw Data Plotted**



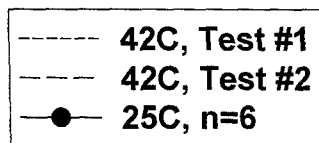
**FIGURE 11.**  
**HYPERBARIC TEST**  
**5000 PPM CO<sub>2</sub>, 5C vs 25C**  
**Means and SDs or Raw Data Plotted**



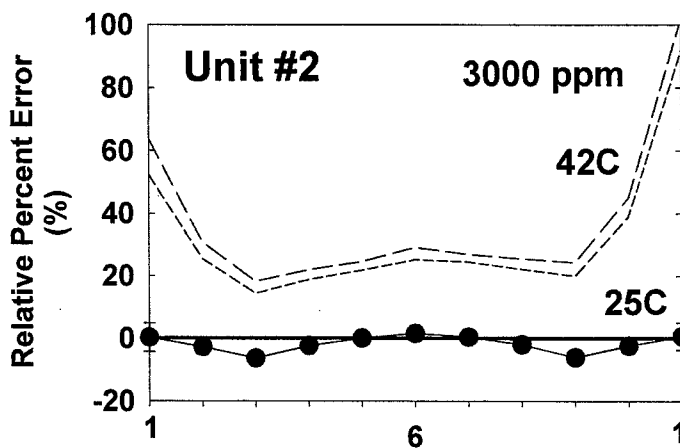
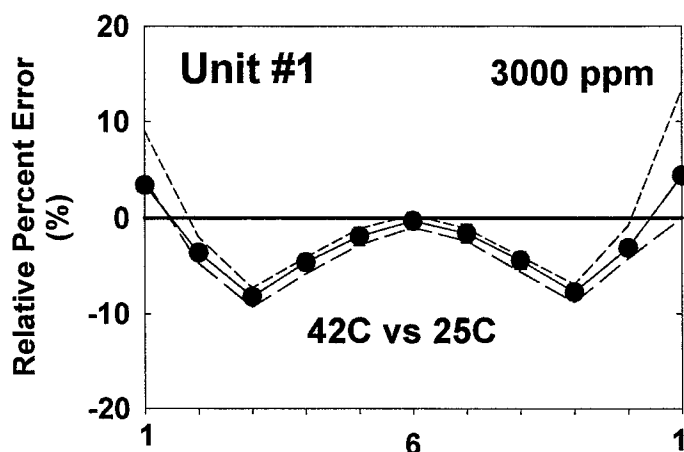
**FIGURE 12.**  
**HYPERBARIC TEST**  
**1500 PPM CO<sub>2</sub>, 42C vs 25C**  
**Means and SDs or Raw Data Plotted**



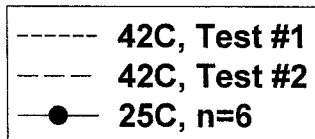
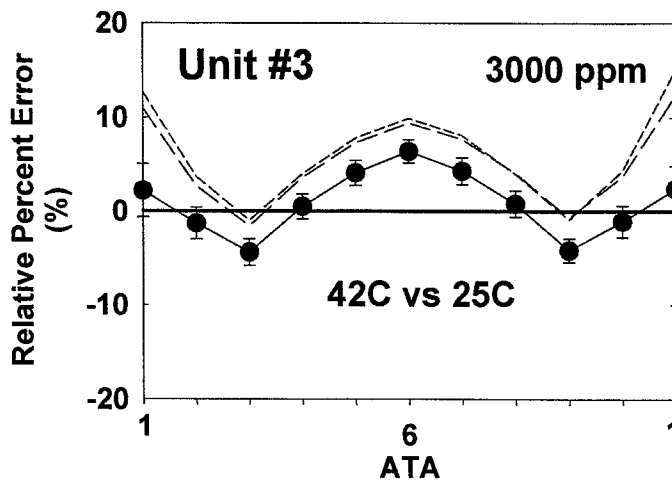
EXPANDED  
Y-AXIS  
RANGE



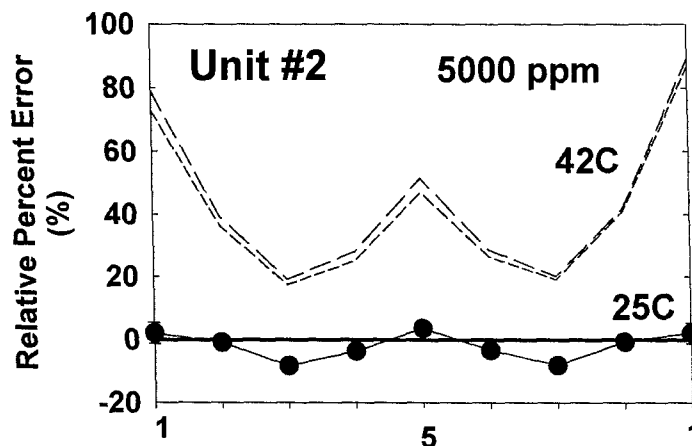
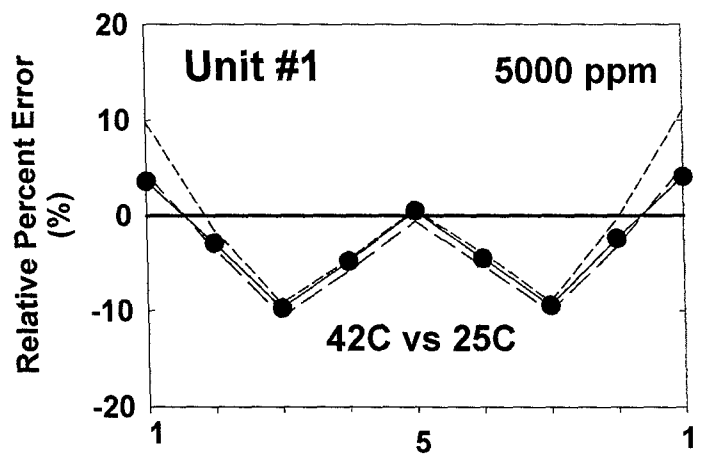
**FIGURE 13.**  
**HYPERBARIC TEST**  
**3000 PPM CO<sub>2</sub>, 42C vs 25C**  
**Means and SDs or Raw Data Plotted**



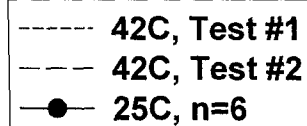
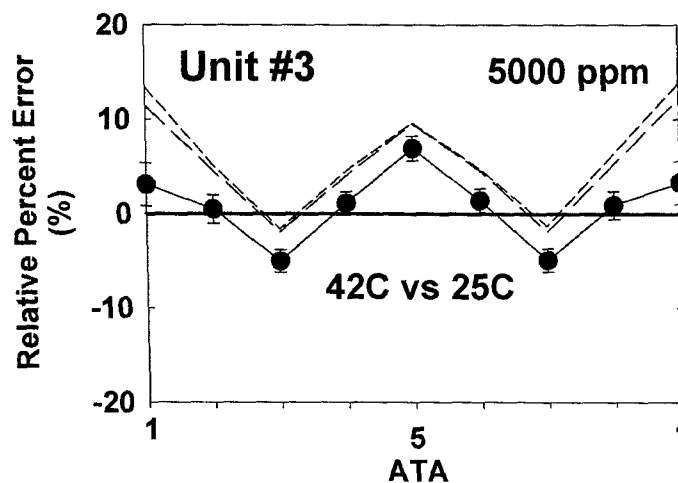
EXPANDED  
Y-AXIS  
RANGE



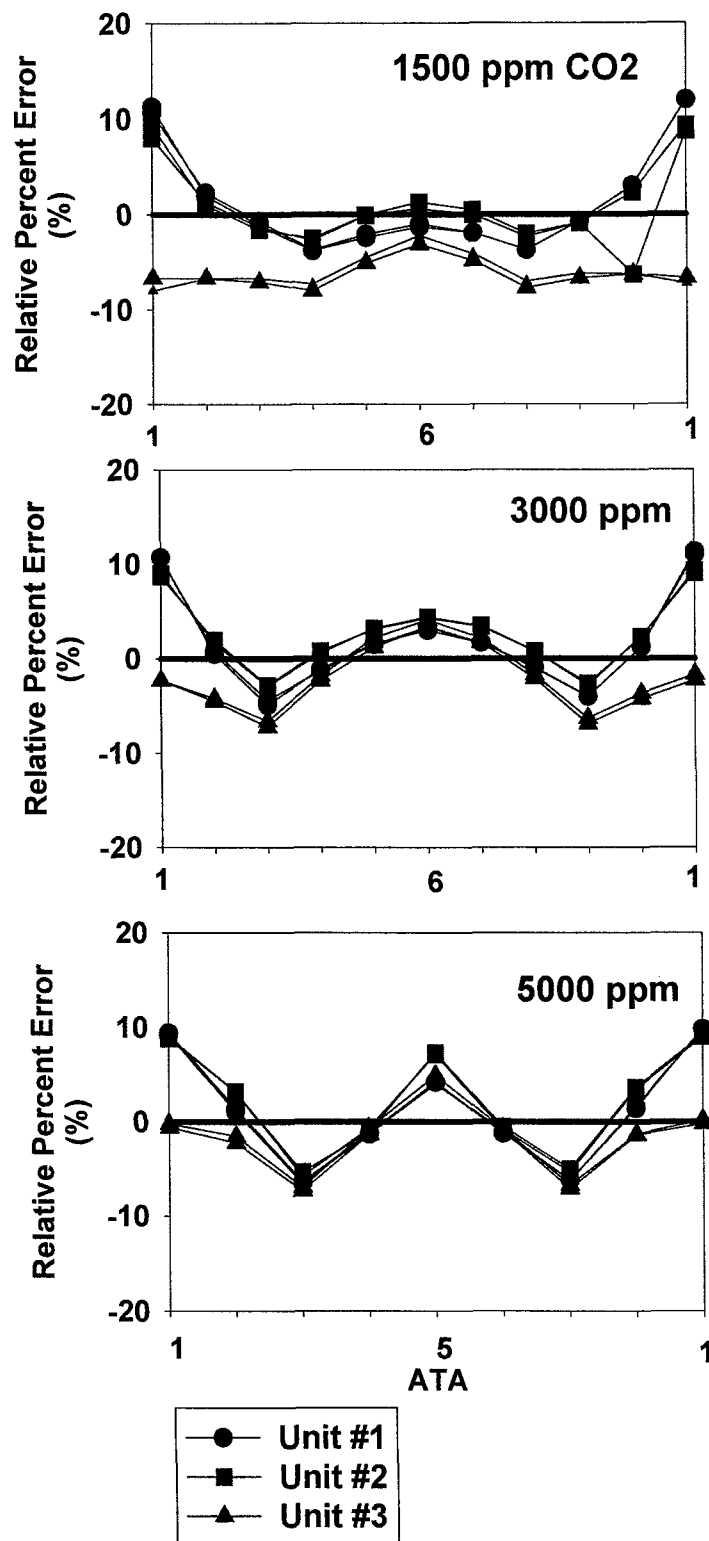
**FIGURE 14.**  
**HYPERBARIC TEST**  
**5000 PPM CO<sub>2</sub>, 42C vs 25C**  
**Means and SDs or Raw Data Plotted**



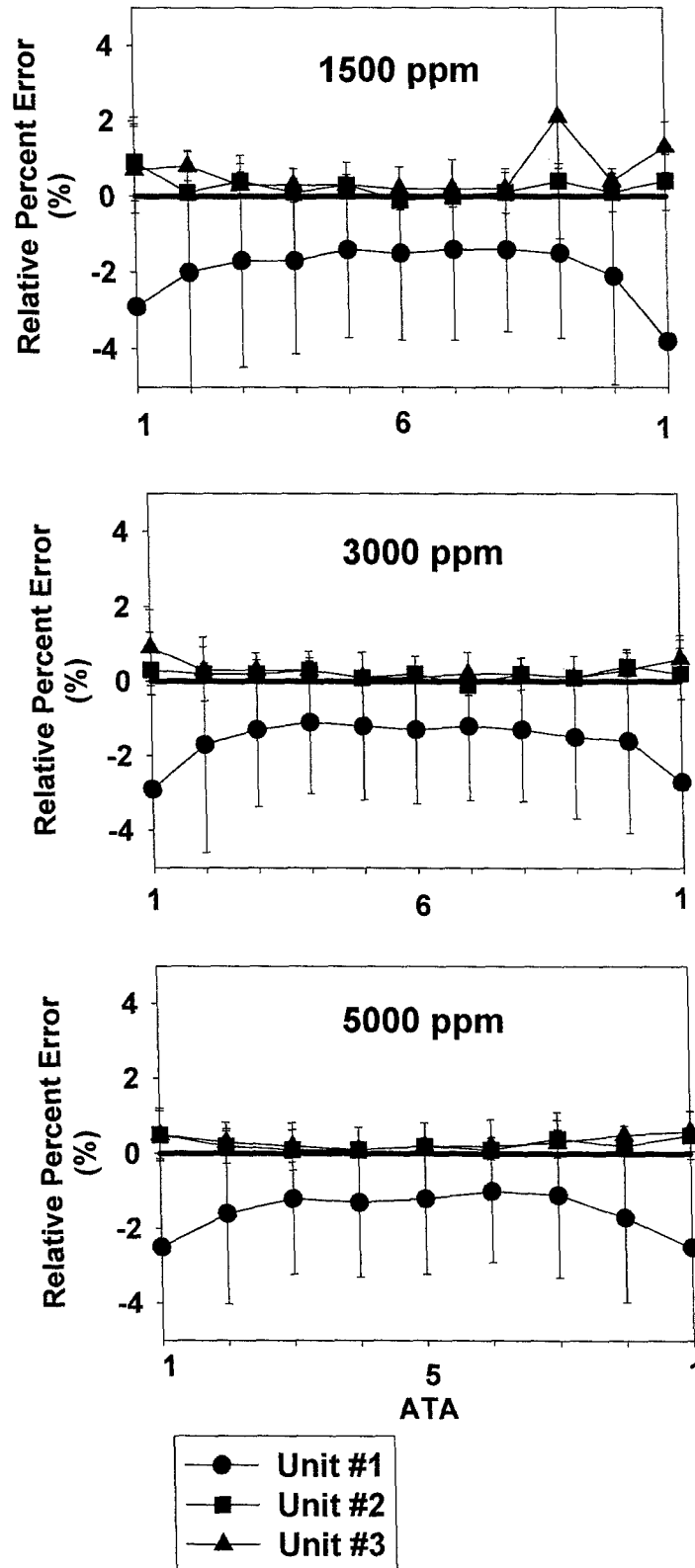
EXPANDED  
Y-AXIS  
RANGE



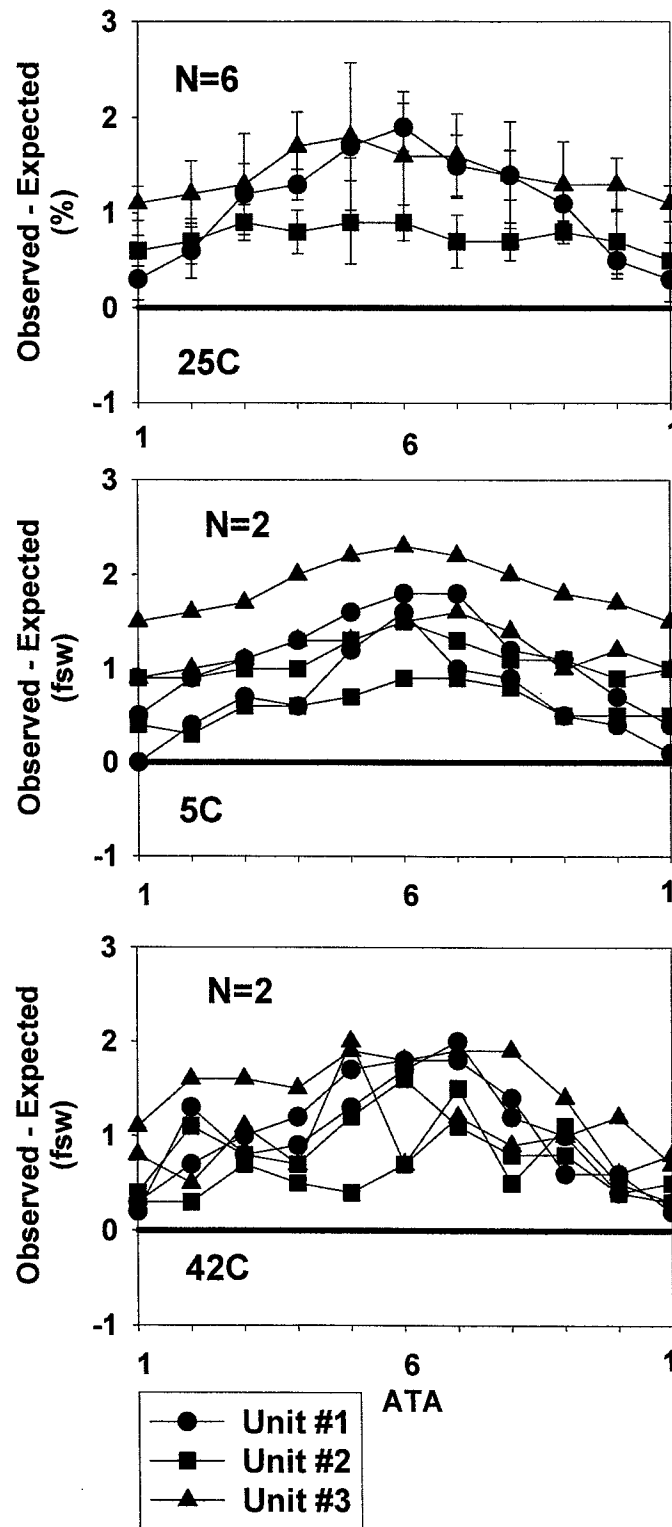
**FIGURE 15.**  
**HYPERBARIC TEST**  
**FACTORY CAL, CO<sub>2</sub>, N=2**



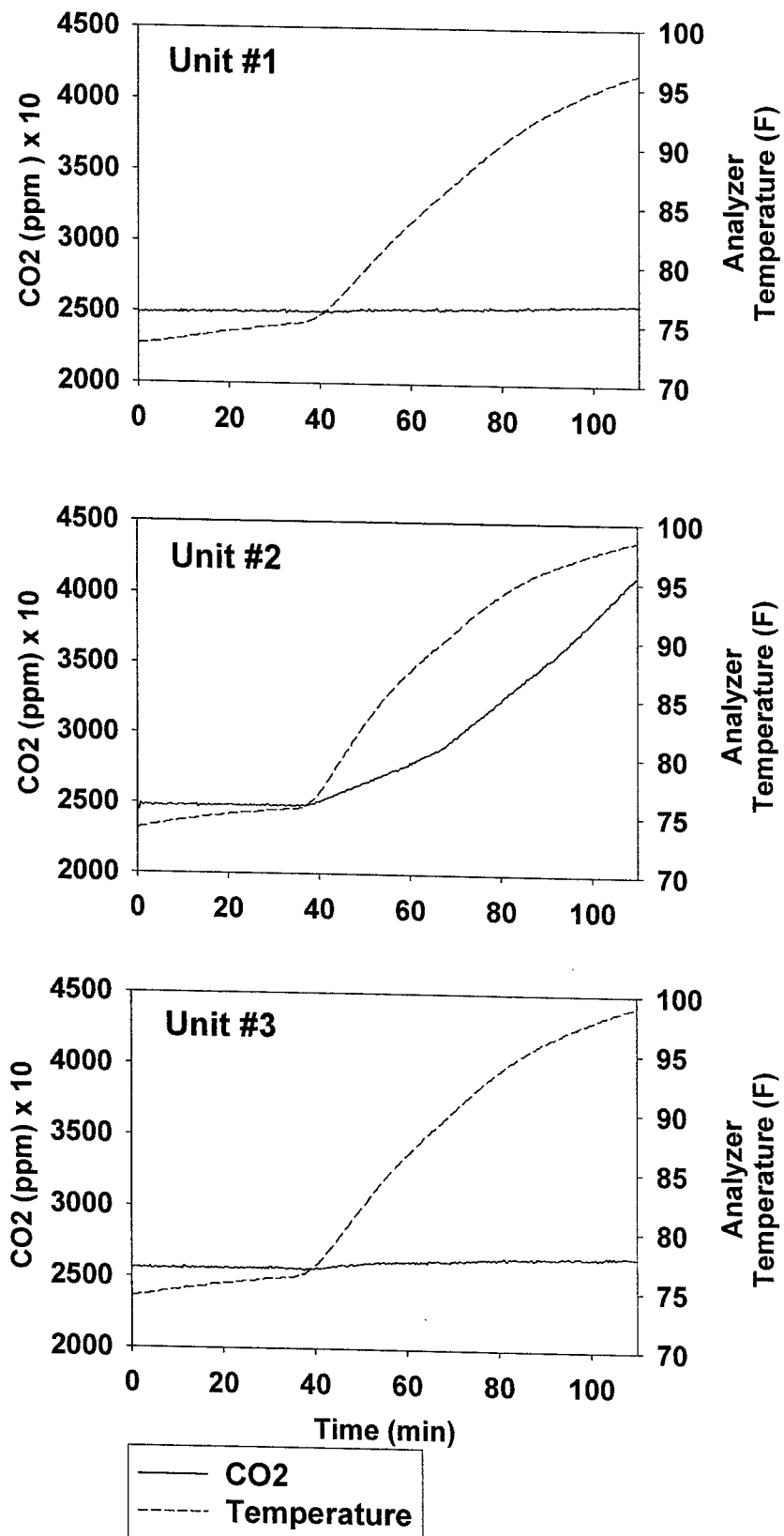
**FIGURE 16.**  
**HYPERBARIC TEST**  
**CO<sub>2</sub>, DAY1-DAY2, N=3**  
**Means and SDs Plotted**



**FIGURE 17.**  
**HYPERBARIC TEST**  
**DEPTH (FSW), 3 TEMPERATURES**  
**Means and SDs or Raw Data Plotted**

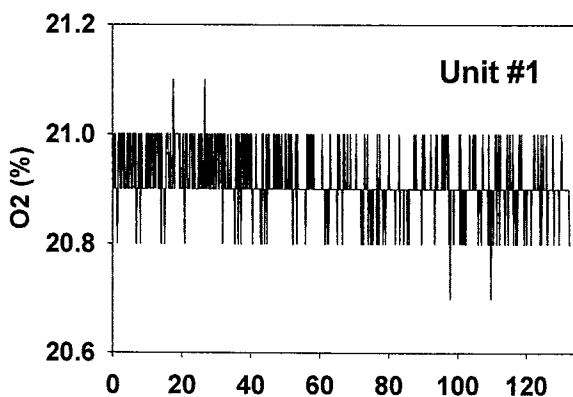


# FIGURE 18. CHAMBER HEATING 25,000 PPM CO2

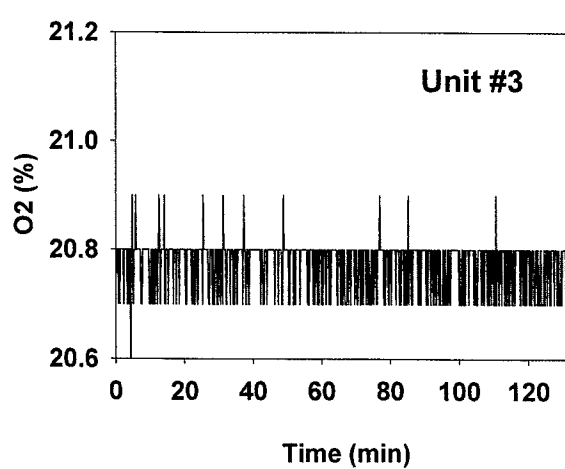
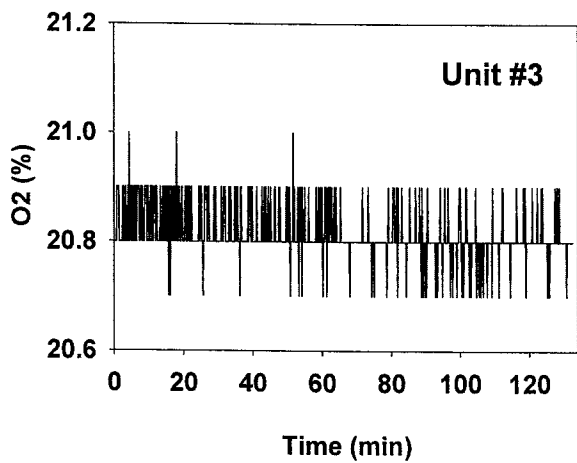
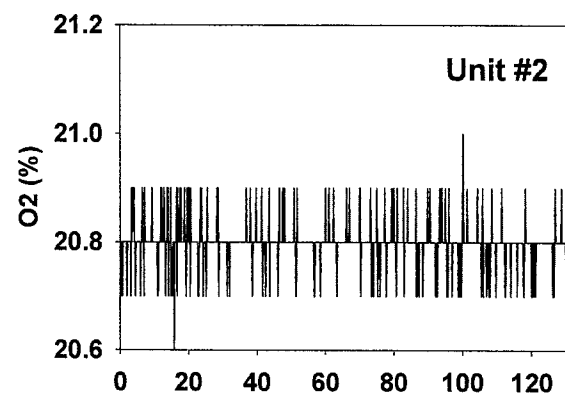
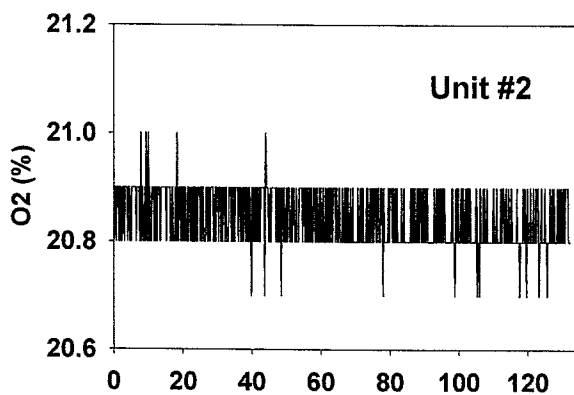
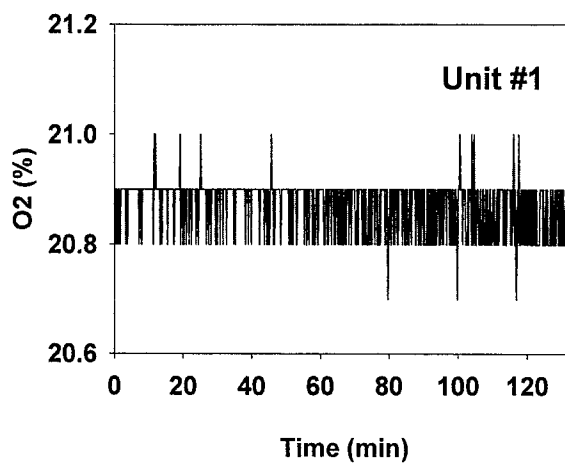


# FIGURE 19. STARTUP TESTS 21% O<sub>2</sub>

TEST #1

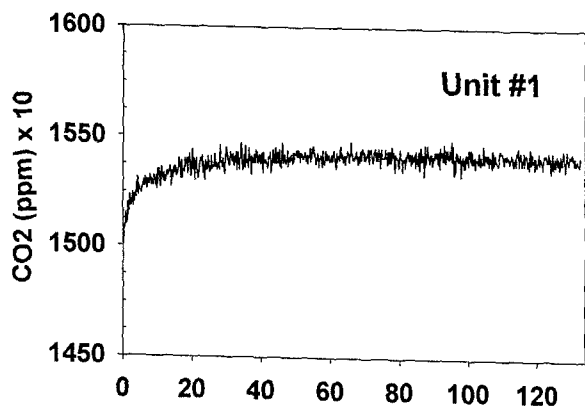


TEST #2

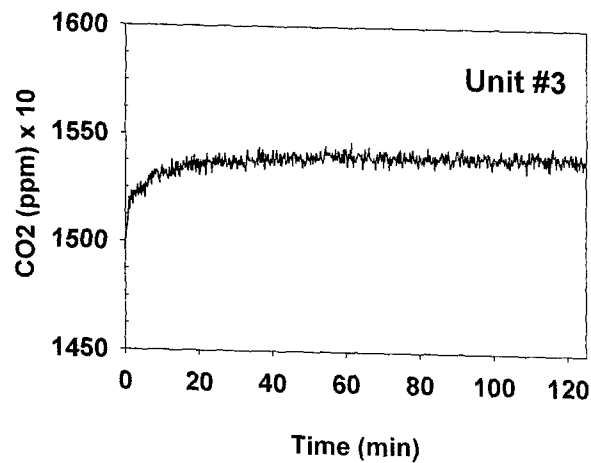
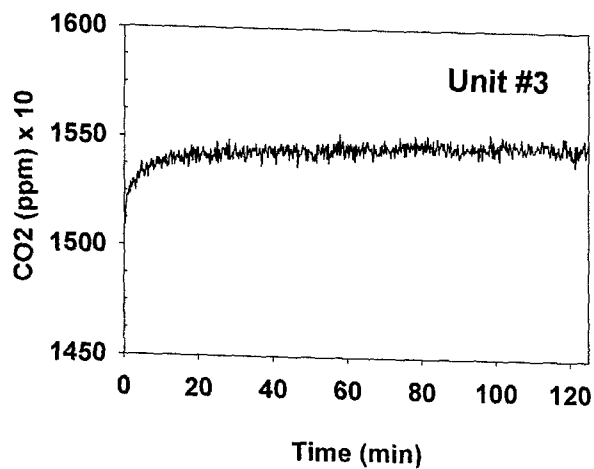
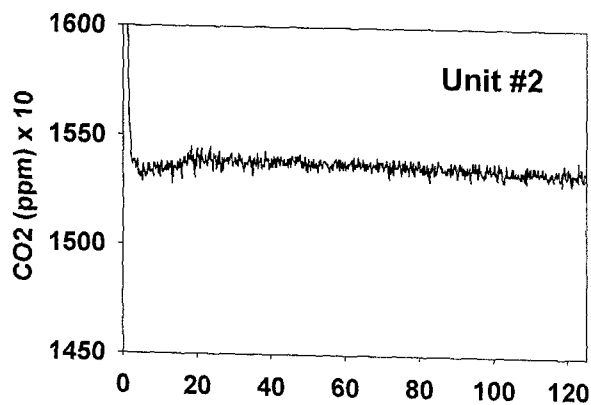
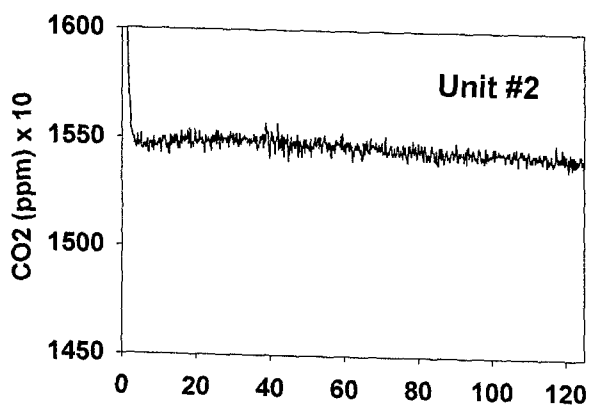
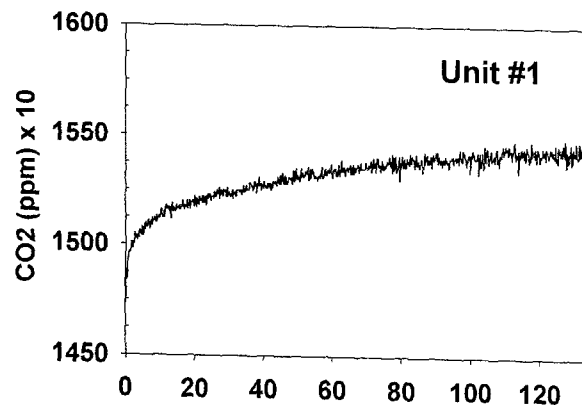


# FIGURE 20. STARTUP TESTS 15,000 PPM CO2

TEST #1

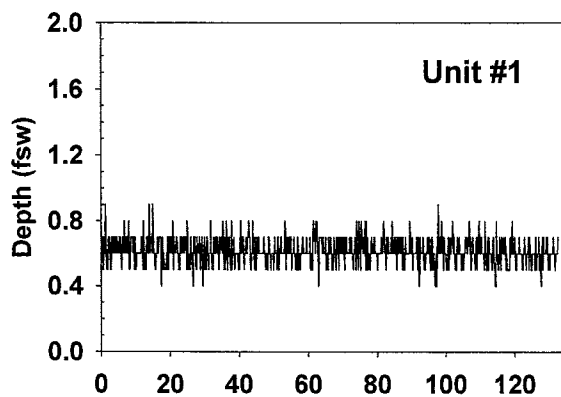


TEST #2

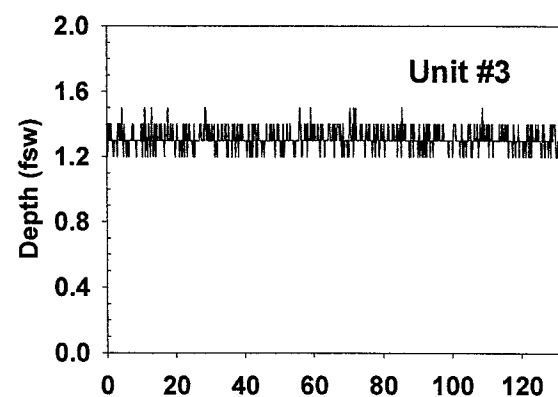
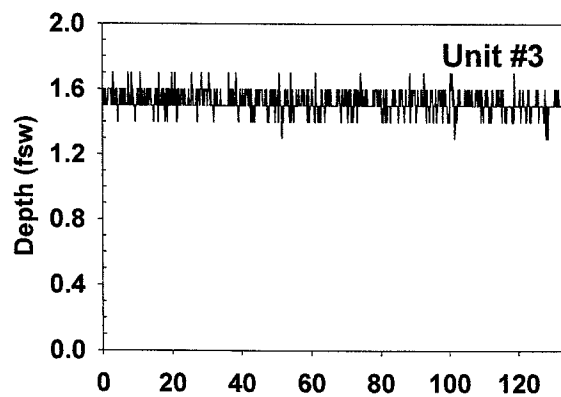
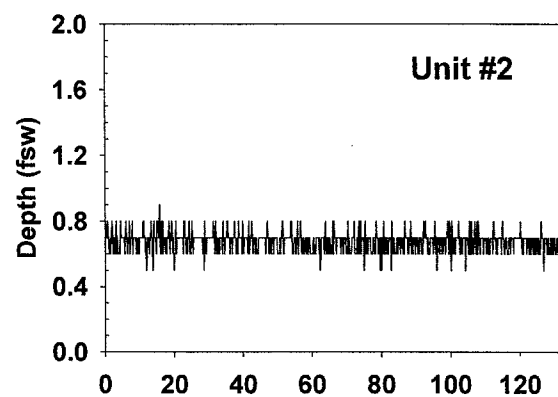
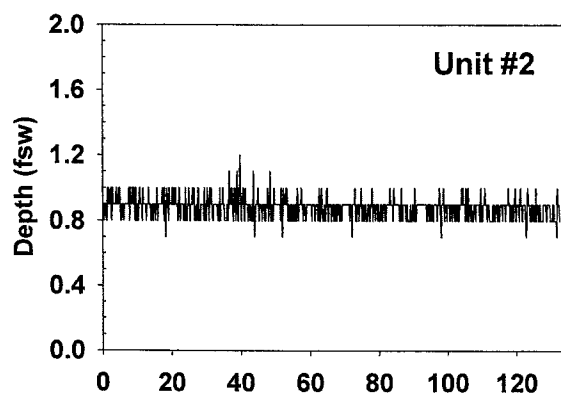
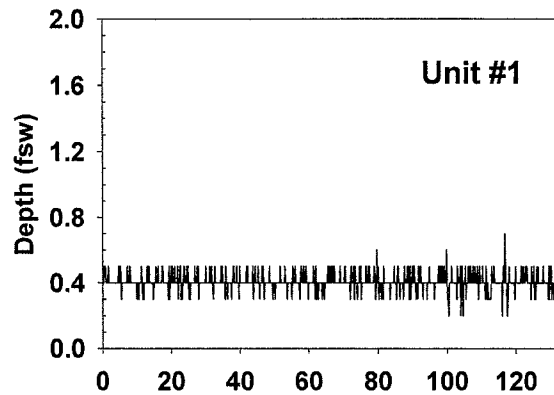


# FIGURE 21. STARTUP TESTS DEPTH = SURFACE

TEST #1



TEST #2



Time (min)

Time (min)

**Table 1. Gas standards and test pressures used during hyperbaric testing.**

CO<sub>2</sub> values in table are SEV concentrations delivered to analyzer.  
O<sub>2</sub> values are absolute percent delivered to analyzer.

| Test Pressure (ATA) | Gas Standards*<br>ppm CO <sub>2</sub> / % O <sub>2</sub> |           |           |          |           |           |
|---------------------|----------------------------------------------------------|-----------|-----------|----------|-----------|-----------|
|                     | 1,500/21                                                 | 3,000/21  | 5,000/21  | 1,500/25 | 3,000/25  | 5,000/25  |
| 1                   | 1,500/21                                                 | 3,000/21  | 5,000/21  | 1,500/25 | 3,000/25  | 5,000/25  |
| 2                   | 3,000/21                                                 | 6,000/21  | 10,000/21 | 3,000/25 | 6,000/25  | 10,000/25 |
| 3                   | 4,500/21                                                 | 9,000/21  | 15,000/21 | 4,500/25 | 9,000/25  | 15,000/25 |
| 4                   | 6,000/21                                                 | 12,000/21 | 20,000/21 | 6,000/25 | 12,000/25 | 20,000/25 |
| 5                   | 7,500/21                                                 | 15,000/21 | 25,000/21 | 7,500/25 | 15,000/25 | 25,000/25 |
| 6                   | 9,000/21                                                 | 18,000/21 | -         | 9,000/25 | 18,000/25 | -         |

\* = gas standards are in nominal concentrations; - = not tested

## Table 2. Offgassing Results.

Concentrations in table are ppm levels of volatile organic compounds (VOCs) quantified as described in text.

| Test Date     | Test Time (hours) | Temperature (°C) | VOCs (ppm) |    |    |
|---------------|-------------------|------------------|------------|----|----|
|               |                   |                  | Analyzer # |    |    |
|               |                   |                  | 1          | 2  | 3  |
| May 2004      | 6                 | 42               | 80         | -  | 57 |
| July 2004     | 6                 | 42               | 27         | 3  | -  |
| August 2004   | 70                | 22-25*           | 6          | 32 | -  |
| November 2004 | 8                 | 42               | 38         | 15 | 38 |

\* = room temperature

- = not tested