The Availability of Oxygen and Carbon Dioxide Sensors for Diving Applications

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LONG-TERM GOAL

The long-term goal of this research is to identify technical solutions for measuring oxygen and carbon dioxide pressures in the breathing gas in divers' closed and semiclosed breathing gear. Knowledge of breathing gas composition is very important, both for the divers' safety and performance. No CO_2 sensors are currently used in divers' gear and O_2 sensors presently in use (for instance in USN's MK16) have an inconveniently short and hard-to-predict life span.

OBJECTIVES

This research will provide information about candidate gas sensors, available in the market, for installation in divers' breathing gear. The sensors' characteristics with regard to accuracy of analysis, reliability, ruggedness and practicality were tested under extremes of temperature, humidity and pressure which are all factors that may vary widely in actual use.

APPROACH

Candidate sensors have been identified in an extensive search of commercial sources, the scientific literature, and the patent literature (over 1,000 patents have been evaluated and this search is being updated as the project proceeds). Based on the written information, the sensors were ranked with regard to potential suitability as judged by physical characteristics and availability.

Four CO_2 sensors and two O_2 sensors were selected for testing. The CO_2 sensors are: "Texas Instruments 9GS-4" (USA), "Valtronics 2015" (USA), "RMT DX6000" (Russia), and "No. 4 Telaire 6004" (USA). The O_2 sensors are: "Ocean Optics FOXY" (USA) and "Teledyne R10-DS" (USA).

The test equipment that has been designed and built is shown as a schematic in Figure 1.

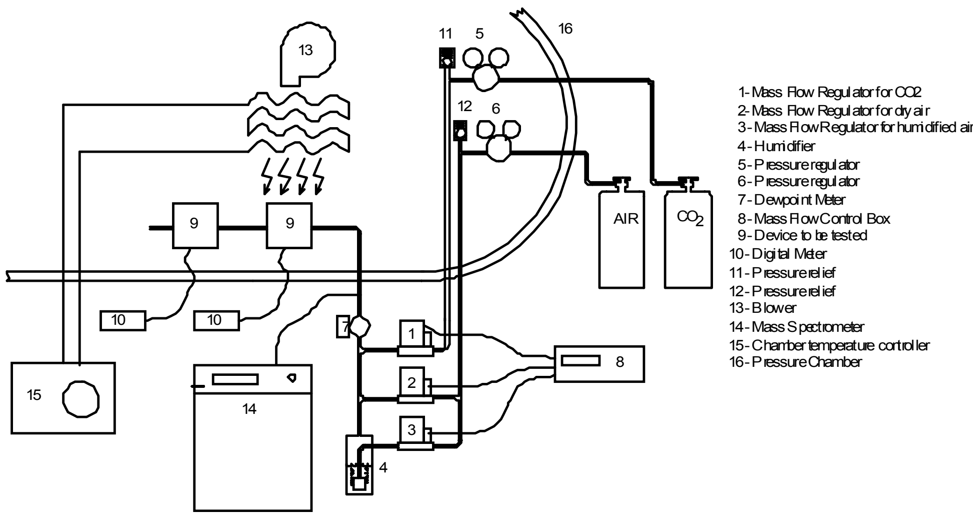

Figure 1.

Essentially, a test sequence consisted of: (1) installation of sensor(s) to be tested in pressure chamber; (2) calibration of mass spectrometer; (3) setting of test temperature (up to 60 min required for thermal equilibrium); (4) setting of test pressure in chamber; (5) setting of test gas composition and humidity condition (about 20 min for equilibrium); (6) record sensor output; (7) change to next test condition(s) and repeat steps 3-6 as necessary.

The following test requirements and conditions were used: (1) The sensors' ability to measure CO_2 pressures corresponding to 0-5% (surface equivalents) as provided by mass-spectrometer analyzed CO_2 in air mixtures; and (2) The sensors' ability to measure O_2 pressures ranging from 0-2 atm as provided by mass spectrometer analyzed O_2 in N_2 mixtures.

The following test conditions were applied: temperature: ~0, 10, 22, 33 and 40°C, relative humidity: 0, 50, and 95%, and total gas pressure: equivalent to 0, 33, 99, 190, and 300 fsw (1, 2, 4, 7, 10 atm).

WORK COMPLETED

During the reporting period, two major and unforeseeable technical problems were encountered which caused a delay of the project of about one month. One problem was that, at the highest test pressures, the gas mixing system did not yield stable and reliable test-gas compositions. This was caused by the mass-flow controllers (items 1-3 in Fig 1) not being accurate enough at the low flows required at high gas pressures. This problem was solved by installing more sensitive mass flow controllers and changing to a gas mixture lower in CO_2 but flowing at a higher rate. The other technical problem was a breakdown of the Perkin Elmer (Model 1100) mass spectrometer constituting an obliterated sample-flow control port and malfunction of the ion pump. The estimated cost for out of town repair was in the $10,000-20,000 range (for which the project was not budgeted) and the time delay would have been considerable. However, the repairs were successfully completed by our in-house engineering specialists Mssrs. A. Barth and C. Eisenhardt, at considerable savings to the project. The testing has, apart from the delay just described, progressed (and is continuing) as planned. Thus, 900 experimental data points have been obtained. The bench testing of sensors is expected to be completed by the end of October 2001.

RESULTS

Based upon the testing completed so far, which is summarized in Table I, the TI 9GS4 sensor appears to be most suitable as judged on the criteria of power consumption and insensitivity to variations in temperature and humidity. An example of this CO_2 sensor's stability under different temperature conditions is shown in Figure 2. Moreover, it has a nearly linear change in output as a function of pressure (depth).

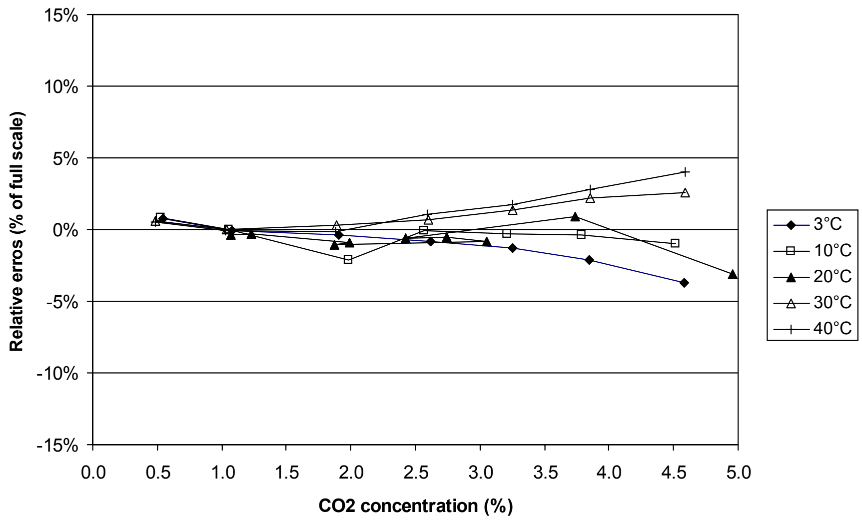

Figure 2. Texas Instruments CO_2 sensor (TI9GS-4); temperature effects in dry gas. Relative errors (expressed as per cent of full scale) vs. CO_2 concentrations. Each solid line represents one temperature.

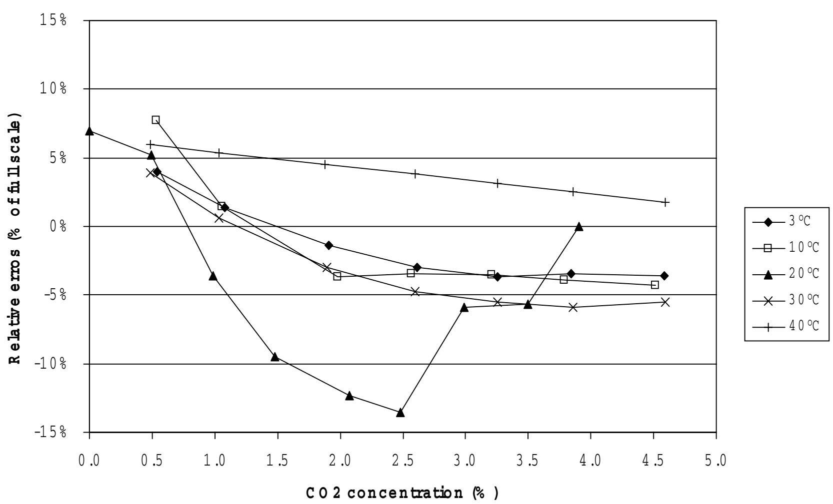

Figure 3. Valtronics CO2 sensor (Mod. 2015); temperature effects in dry gas. Relative errors (expressed as per cent of full scale) vs. CO_2 concentrations. Each solid line represents one temperature.

Table I. CO_2 Sensor Overview

Attributes	TI 9GS-4	Valtronics 2015	RMT DX 6000
Sensor type	NDIR ***note 3***	NDIR	NDIR
Construction	Good	Good	Good
Ease of use	Excellent	Good	Adequate ***note 1***
Cost	~$500	~$1,000	$1,000
Size (inches)	3.5 x 3.5 x 1.4	3 x 5 x 1.25	2 x 2 x 4
Power consumption	50-150mA @ 12v	130-250mA @ 12v	~50mA @ 6-8v
Signal noise ***note 2***	Low	Medium	Low
Documentation	Adequate	Good	Adequate/poorly written
Origin	USA	USA	Russia
Temperature effects	Small	Significant	Work in progress
Humidity effects	Small	Small	Work in progress
Depth effects	Correctable	Significant	Work in progress

Note 1: While the RMT hardware seems to be well designed and built, the supporting computer software is poorly implemented and ill suited to a finished product application. However, these shortcomings could be easily improved upon.

Note 2: The signal noise is related to the internal signal processing firmware and may be improved upon.

Note 3: NDIR – Non Dispersive Infra Red, referring to the basic principle of measuring CO_2 concentration by sensing the absorption of infrared energy in the gas sample.

The Valtronics 2015 sensor shows a considerably greater variation in output for changes in temperature (Figure 3) and a non-linear variation as a function of pressure. The testing of the RMT DX6000 sensor is currently being completed. In its present configuration, as a general-purpose laboratory CO_2 sensor, it requires the use of a Windows 95 computer to run the setup and operating software. If it proves to be an improvement over other sensors, the internal CO_2 sensing mechanism could be designed into a more directly applicable design.

A preliminary evaluation of the results as listed in Table I indicates that the TI9GS-4 sensor is the leading candidate. Table II list the O_2 sensors currently being tested.

IMPACT/APPLICATIONS

Two major concerns related to diver safety and performance pertain to the use of closed and semiclosed breathing apparatus (aka rebreathers). One is that exposure to high CO_2 concentrations in the breathing gas may incapacitate the diver (CO_2 narcosis). This can happen by either one of two mechanisms. One is when the diver exhibits a, not uncommon, inadequate breathing pattern (in so-called CO_2 retainers). Furthermore, the CO_2 absorption in the equipment may become inadequate for a number of reasons (poorly packed absorption canister, gas channeling through absorber chemical that has been inactivated by water intrusion, etc.). In any of these scenarios, a CO_2 sensor in the equipment, warning the diver of the situation could be life saving. Currently there are, to the best of our knowledge, no breathing apparatus with CO_2 sensors available. The present and emerging results of this project indicate that it will provide a technical solution to this problem. Another difficulty in the use of rebreathers is that the O_2 concentration may vary considerably because of technical

Table II. O_2 Sensor Overview

Attributes	**Ocean Optics FOXY**	**Teledyne R10-DS**
Sensor type	Fluorescence quenching	Electrochemical
Construction		
Ease of use		
Cost	~$3,500 ***note 1***	~$50
Size (inches)		
Power consumption		
Signal noise		
Documentation		
Origin	USA	USA
Temperature effects		
Humidity effects		
Depth effects		
Note 1: The FOXY system is a general purpose laboratory instrument, a sensor based upon FOXY technology will be considerably cheaper.		

problems or changes in the diver's oxygen usage. In the one extreme, too low an oxygen content may cause loss of consciousness or, since a low oxygen fraction is coupled to a high inert gas fraction, increased risk of decompression sickness on ascent. At the other extreme, too high an oxygen concentration may result in life-threatening oxygen intoxication. Current rebreathers (example: the US Navy MK16) have oxygen sensors to monitor and control the oxygen fraction in the breathing gas. However, the sensor in question (Teledyne R10DV) has a short and hard-to-predict shelf life. The present project may identify better O_2 sensors for installation in rebreathers.

TRANSITIONS

The final stage of this project is to install, in a US Navy MK16 rebreather, the sensors which, in the current bench testing, have been deemed satisfactory as is, or after in-house modification. The equipment will then be subjected to manned and unmanned testing under realistic diving conditions. The sensor technology passing such testing will be made available to Navy equipment designers and evaluators and equipment manufacturers as directed by the sponsor of this project. To the extent that the information is deemed non-proprietary, it will also be published in the open literature.