



Gas Analysing Equipment in Commercial Saturation Diving Systems



Technical Report

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1. INTRODUCTION

The purpose of the report is to provide a clear guide to the requirements for gas analysis in commercial diving systems and to describe the capabilities and limitations of equipment currently in use across the industry.

This report presents some findings that may at first examination appear to be alarming, particularly with regard to the accuracies and capabilities of certain types of widely deployed analyser systems. These findings should be interpreted carefully, particularly where system changes are recommended, and due consideration should be given to how the equipment is used rather than simply considering published specifications.

2. REQUIREMENT FOR GAS ANALYSIS

When conducting hyperbaric diving operations in both air and mixed-gas environments, it is a fundamental requirement to monitor the breathing gas of divers to ensure that they breathe a safe and appropriate gas composition for the depth and type of diving operations that they are involved in. This requirement can either take the form of a prescriptive regulation from a particular certifying body / authority, or alternatively as an implicit requirement when following well established diving procedures and 'tables' whilst employing 'best practices'.

The limits and requirements of breathing atmospheres for divers has been well established over time, and are clearly set out in the various diving 'tables' used by commercial diving contractors (and also military divers) during diving operations. These tables and the limits that they stipulate are generally based on the human body physiological model, where significant research has been carried out to establish the effects of different gas compositions at elevated pressures on the human body.

This report concentrates on mixed gas commercial saturation diving operations, where divers are maintained in hyperbaric conditions for prolonged periods, breathing a mixture of helium and oxygen. In such operations, the following gases must be controlled:

- a) **Oxygen (O₂)** – this is the most important gas that must be controlled during operations, with the limits for oxygen concentration being normally expressed as a partial pressure of oxygen in Bars for the purposes of physiological limits. Oxygen concentration is however often measured at surface (referenced to 1 atm.) pressure conditions and expressed as a percentage of the gas concentration. Continuous monitoring of oxygen concentration a required during saturation diving operations. Insufficient oxygen concentration in the breathing gas will lead to shortness of breath, and in extreme cases asphyxia. Increased O₂ concentrations also have physiological implications as oxygen becomes toxic with increased concentration. There are two areas where the body is affected by the toxicity of breathing an increased oxygen concentration – as follows:

- **Pulmonary oxygen toxicity** Bronchopulmonary dysplasia or "BPD" is caused by exposure over 16 hours to partial pressures of 0.5 bar or more causing breathing difficulty and pain resulting in lung damage which may be irreversible.
- **Central nervous system (CNS) oxygen toxicity** may begin its onset at partial pressures over 1.2 bar, manifesting as dizziness, nausea and twitching, especially on the face. As pressure or duration increases, it leads to more severe symptoms, such as convulsions, which although not lethal themselves, can cause drowning of divers

At the opposite end of the oxygen concentration scale, there is the risk from insufficient partial pressure of oxygen to sustain life (due to hypoxia).

The following list shows the key thresholds of typical partial pressures that may be found during diving operations:

- Less than 0.16 bar ppO₂ - Below this partial pressure the diver may be at risk of unconsciousness and death due to hypoxia, depending on factors including individual physiology and level of exertion.

- 0.21 bar ppO₂ – normal concentration of oxygen in air at 1-atmosphere. This ppO₂ is the endpoint of a decompression cycle.
 - 0.4 bar ppO₂ – typical concentration maintained inside hyperbaric chambers during long-term storage of divers.
 - 0.45 to 0.5 bar ppO₂ – typical concentration maintained inside hyperbaric chambers during decompression activities.
 - 0.6 to 0.75 bar ppO₂ – typical concentration of breathing gas supplied to divers when in the water (for controlled durations).
 - Above 0.8 bars – onset of both pulmonary and CNS toxicity, the severity of symptoms dependant on exposure times and actual concentrations.
- b) **Carbon Dioxide (CO₂)** – this is a waste product of breathing by divers, and accumulates inside closed diving chambers over time as the divers convert oxygen to carbon dioxide by metabolic combustion during normal breathing. Carbon dioxide levels are specified for physiological purposes as partial pressures in Bars, but in many cases the sampled gas is measured at surface (1 atm.) pressure conditions, and expressed as a gas concentration in parts per million (ppm). Continuous monitoring of CO₂ is not normally a stipulated requirement, but the facility to regularly check the CO₂ concentration of the breathing gas / chamber atmospheres must be provided (e.g. by patching or valves). Many diving systems are however fitted with multiple CO₂ analysers to allow continuous monitoring of some if not all chamber locks / breathing gas supplies. The following list shows typical CO₂ concentration effects on the human body:
- 0.03 % (300 ppm) No effect. Normal atmospheric concentration.
 - 0.5% (5,000 ppm) Slightly deeper breathing.
 - 2% (20,000 ppm) Lung ventilation increased by 50%.
 - 3% (30,000 ppm) Lung ventilation doubled.
 - 5% - 10% (50,000-100,000 ppm) Three-fold increase in respiratory rate leading to rapid exhaustion and headache.
 - Above 10% (100,000 ppm) Intolerable panting, severe headache, collapse, followed by death.
- c) **Carbon Monoxide (CO)** – carbon monoxide is not normally present in diving gases and is therefore not normally monitored.
- d) **Hydrocarbon Gases** – this group of gases presents specific hazards to divers working in the oil and gas sector, where diving bells (SDCs) are positioned for long periods close to the seabed in areas where hydrocarbon contamination / escapes may be present. Recently developed infra-red analysis equipment is now fitted inside diving bells for the purposes of condition monitoring of the bell atmosphere for the presence of hydrocarbons.

e) **Hydrogen Sulphide (H₂S)** – This is a highly toxic gas that can occur naturally in small concentrations, but may also be present in natural gas (and therefore in contamination from oil and gas activities) at much higher concentrations. Monitoring of H₂S concentration is carried out inside diving bells using the same equipment as used for monitoring of hydrocarbon contamination. The physiological effects of H₂S are given below:

- 0.0047 ppm is the recognition threshold, the concentration at which 50% of humans can detect the characteristic rotten egg odour of hydrogen sulphide
- 10-20 ppm is the borderline concentration for eye irritation.
- 50-100 ppm leads to eye damage.
- At 150-250 ppm the olfactory nerve is paralysed after a few inhalations, and the sense of smell disappears, often together with awareness of danger.
- 320-530 ppm leads to pulmonary edema with the possibility of death.
- 530-1000 ppm causes strong stimulation of the central nervous system and rapid breathing, leading to loss of breathing;
- 800 ppm is the lethal concentration for 50% of humans for 5 minutes exposition;
- Concentrations over 1000 ppm cause immediate collapse with loss of breathing, even after inhalation of a single breath.

Significant research work has been carried out recently in implementing hydrocarbon and H₂S monitoring methods and requirements. This work is well referenced, and is therefore not covered in this report.

This report therefore only considers the analysis techniques for Oxygen and Carbon Dioxide.

3. OXYGEN MONITORING

The requirement to continuously monitor the oxygen concentrations of diver's breathing gas leads to a large number of oxygen analysers being deployed worldwide on commercial diving systems. The locations where these analysers are used on a typical single-bell saturation diving system might be as follows:

1. Sampling the gas from inside every lock of each surface decompression chamber in the system (this might be typically three living compartments and three entry locks for normal Saturation diving systems). A total of 6 analysers would be used, located at the control stand (SAT Control room) for the chambers.
2. Sampling the gas supplied down the umbilical for the divers to breathe (monitored at the last point, after all valves, before the gas enters the umbilical). 1 analyser is installed in this location and is located at the Dive Control station.
3. Sampling the atmosphere of the SDC or diving bell. This is a gas sample taken from the bell to the surface via a hose in the bell umbilical. 1 analyser is installed in this location and is located at the Dive Control station.
4. Measuring the oxygen concentration inside the SDC (bell) by means of a sensor fitted inside the bell whose output is connected to a display in the Dive Control station. This sensor/analyser is used as either a back-up or in some cases instead of the sampled SDC atmosphere (in 3. above). This sensor is exposed to the hyperbaric pressures, and often displays its concentration as a partial pressure of O₂ (ppO₂).
5. Sampling the oxygen concentration of the gas reclaim system output. This gas is monitored as it is re-supplied to divers after processing. 1 analyser is installed in this location and is located at the Dive Control station.
6. Sampling the concentration inside the hyperbaric lifeboat (SPHL). This atmosphere is normally sampled by an analyser located in the Sat Control station, as the SAT control technicians are responsible for ensuring that the correct concentration is present in the SPHL chamber at all times.
7. An analyser is fitted inside the cockpit / control station of the SPHL that is used to monitor and maintain a correct atmosphere for divers inside the SPHL should it be necessary to deploy the SPHL under emergency conditions.
8. The gas reclaim equipment (e.g. Gasmizer™ Panel) is normally fitted with an O₂ analyser as a part of its control equipment.
9. The gas blending system used to produce correct helium/oxygen concentrations for breathing and chamber gases at the diver's working depths uses an O₂ analyser to check concentrations during and after blending.
10. Inside each chamber lock, and inside the SDC (bell) there is always a portable O₂ analyser, used as a backup or secondary reference by divers. These portable units are exposed to the hyperbaric conditions, and provide a direct read-out of partial pressure of oxygen.
11. Onboard Diving Support vessels there is a requirement to monitor equipment rooms and closed (unventilated) spaces where there exists the possibility of a build-up of gas caused by leakage from components of the diving system. In these areas, either a centralised oxygen sampling system or discrete oxygen

analysers are used to warn of abnormal oxygen concentrations. There can be as many as 10 or more monitored areas on a typical DSV.

With the exception of the portable analysers fitted inside the chambers and the hyperbaric sensor inside the diving bell, most O₂ analysers measure the oxygen concentration of a flowing gas sample taken from the area of interest. This gas sample is normally regulated from a higher pressure (e.g. the pressure inside the chamber) down to a low pressure of typically less than 1 barg. Analysers are often fitted with variable-aperture (VA) flowmeter and a needle-valve to allow the operator to adjust the flowrate of gas being supplied to the sensor.

There are various techniques available for measuring the concentration of oxygen, ranging in accuracy, complexity and cost. Sensors that are used in diving applications are normally one of two types:

1. *Electro-galvanic fuel-cell:*

This type of sensor is the simplest and lowest-cost, but has the worst accuracy. It operates on the principle that a chemical reaction occurs in the fuel cell when the potassium hydroxide in the cell comes into contact with oxygen. This creates an electric current between the lead anode and the gold-plated cathode through a load resistance. The voltage produced is proportional to the concentration of oxygen present.

Electro-galvanic fuel cells have a limited lifetime which is reduced by exposure to high concentrations of oxygen. The reaction between oxygen and lead at the anode consumes lead, which eventually results in the cell's failure to sense high concentrations of oxygen. Typically, a cell used for diving applications will function correctly for up to 3 years if stored in a sealed bag of air but only for four months if stored in pure oxygen.

Fuel cells are available from a number of manufacturers and are produced in different specifications for output signal, life expectancy and response time. Normally with longer lifetime cells, a longer response time is seen as the internal source impedance is higher.



Fig. 1 – Electro-galvanic fuel cells used for diving applications

Fuel cells used in commercial diving applications are normally rated for sensing partial pressures of oxygen from 0 to 1 bar ppO₂. Fuel cells are also available in an operating range of 0 to 2 bar pp O₂. The typical accuracy of fuel cells is +/- 1% of full-scale output, so for sensors with an operating range 0-1 bar ppO₂ this corresponds to an accuracy of +/- 10mBar ppO₂ (or +/- 1% O₂ by concentration when sampled at 1-atmosphere). This accuracy reduces to +/- 20mBar ppO₂ (or +/- 2% O₂ by concentration when sampled at 1-atmosphere) for cells that have a 0-2 bar ppO₂ range.

For normal sampling applications in the diving industry (i.e. where an electro-galvanic fuel cell is used to measure a gas sample at 1-atmosphere), the cell is mounted in its own housing that is attached to a device known as a flow-cap. The flow cap is a small chamber that has an inlet and outlet gas connection, the inlet of which is connected to the sample line downstream of the VA flowmeter and needle valve. The outlet connection from the flow-cap is normally vented to atmosphere, sometimes through an exhaust system, where pipework directs the exhausted sample gas to a safe area where its concentration will not cause any hazard.

The following diagram shows the typical architecture of a 1-atmosphere sampling system using an electro-galvanic fuel cell:

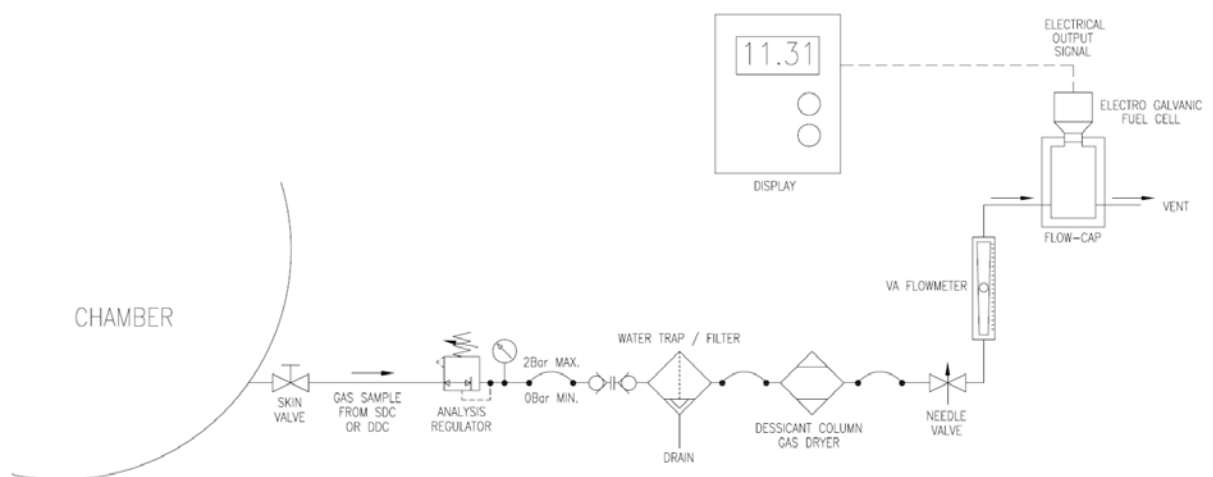


Fig. 2 – Typical Fuel-Cell gas sampling system

We will consider the accuracies and shortcomings of electro-galvanic fuel cells in the 'Oxygen Monitoring Accuracy' section below.

2. Paramagnetic gas sensor:

This type of oxygen sensor is significantly more sophisticated than the fuel-cell type and provides much greater accuracy. Paramagnetic sensors are more expensive to purchase, are less robust (mechanically) than fuel-cell types and are therefore less widely used in diving systems.

The paramagnetic sensor comprises a sealed sample chamber through which the gas to be measured flows. Inside this chamber there is a sensor assembly that relies on the paramagnetic effect of oxygen to measure its concentration. Oxygen is attracted into a strong magnetic field, and most other gases are not.

This paramagnetism is used to obtain fast, accurate oxygen measurements by the following mechanism:

- A focused magnetic field is created. Any oxygen that is present will be attracted into the strongest part of the magnetic field.
- Two nitrogen filled glass spheres are mounted on a rotating suspension within a magnetic field. A mirror is mounted centrally on the suspension and light is shone onto the mirror. The reflected light is directed onto a pair of photocells.
- Oxygen attracted into the magnetic field will displace the nitrogen filled spheres, causing the suspension to rotate. The photocells will detect the movement and generate a signal.
- The signal generated by the photocells is passed to a feedback system. The feedback system will pass a current around a wire mounted on the suspension causing a motor effect, which will keep the suspension in its original position.
- The current measured flowing around the wire will be directly proportional to the concentration of oxygen within the gas mixture.

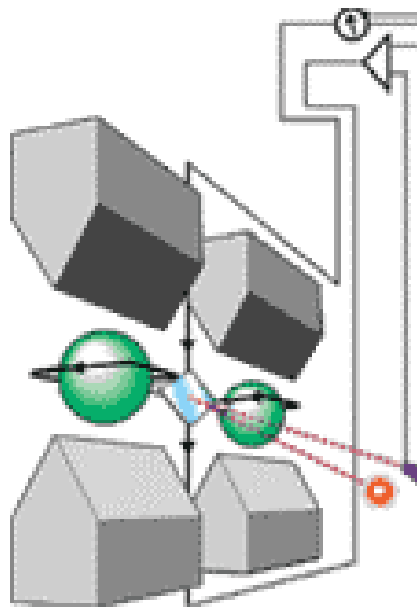


Fig. 3 – Internal mechanism of a Paramagnetic Oxygen Sensor

There are a number of manufacturers who produce paramagnetic oxygen sensors, with the types suitable for diving gas measurements having a typical accuracy of $\pm 0.1\%$ of full-scale value. Some manufacturers' sensors have a sensing range of 0-100% O_2 and therefore an accuracy of $\pm 0.1\%$ O_2 by concentration. Other sensors are available is a narrower range (e.g. 0-50% O_2) and can have an increased accuracy of the actual percentage O_2 measured value, based on the narrower sensing range.

In addition to having accuracies 10 or more times better than fuel-cell sensors, the paramagnetic sensor does not have a limited operational life like the fuel-cell. This means that over time, the a paramagnetic sensor will outlast many fuel-cells. The frequent re-calibration required for fuel-cell based systems (as a result of the

changing end-point voltage as the fuel-cell becomes exhausted) is not necessary for paramagnetic types.

Care must be exercised when deploying the paramagnetic sensor in diving applications however, as the sensor does measure an offset in its signal as a result of the slight paramagnetic effect that helium exhibits. This value is a constant, and assuming that all the non-oxygen content of the sample is helium, can be easily corrected dynamically by analyser systems.

There is also a greater susceptibility of the paramagnetic sensor to humidity and particular contaminants in the sample gas. For this reason, additional care must be taken to prepare the sample by filtration and drying.

Some sensor manufacturers use a 'heated cell' approach for their sensors, where the entire paramagnetic sensor unit is electrically heated and maintained at a constant temperature (typically 50°C). This has the advantage of improving the temperature stability of the sensor and reducing the likelihood of condensation from moisture in the sample gas.

The sample gas piping / delivery system is similar to that used with fuel-cell sensors (as shown in Fig. 2 above), with the paramagnetic sensor being fitted in place of the fuel-cell and flow-cap.

4. CARBON DIOXIDE MONITORING

Carbon dioxide measurements must be taken at regular intervals (if not measured continuously) from the same areas of the diving system that are described in the Oxygen Monitoring section above.

Techniques for acquiring the gas sample are similar to those described for oxygen, with the high pressure sample being regulated in both pressure and flow before passing through the sensor at ambient pressure.

There are various techniques for measuring carbon dioxide concentrations in gases, but the method best suited to diving analysers is the use of a Non-dispersive Infra Red (NDIR) sensor. Carbon dioxide absorbs infra-red light at a particular wavelength, and NDIR sensors measure the absorption by the sample gas at this wavelength compared to a wavelength that carbon dioxide does not absorb. The difference between these absorption rates gives an indication of the concentration of CO₂ in the sample.

As with O₂ sensors, there is a wide range of quality and therefore accuracy of NDIR CO₂ sensors available, with those being widely used in diving gas analysers having specified accuracies of typically +/- 2% of reading. Sensors of this type are available with accuracies of better than +/- 1%, with the highest theoretical accuracy of an NDIR sensor being somewhere between +/- 0.3 and 0.5% of full-scale reading.

For diving applications, the sensor must have a range from typically 5000ppm down to 0ppm as this covers exposure values within the commonly used limits of the diving tables. In order to achieve a suitable accuracy of surface sampled CO₂ readings for deep diving operations, it is sometimes necessary to implement a CO₂ sensor with a lower range (e.g. 0-2500ppm). For ultra-deep diving activities, the use of alternative measuring techniques with greater accuracies (e.g. gas chromatography or mass spectroscopy) have been used, but this incurs significantly greater cost and complexity.

5. ANALYSER ACCURACY

As mentioned above, it is very important to measure the oxygen and carbon dioxide concentrations being breathed by the diver, whether as the atmosphere in the chamber or as the 'lock-out' gas supplied to the diver's helmet when in the water. Measuring this concentration accurately ensures that unsafe levels of oxygen are not reached, and the physiological toxicity levels (or hypoxic levels) are avoided. It also assures that toxic CO₂ levels are avoided.

This requirement to manage the O₂ and CO₂ concentrations assumes a particular accuracy of the analyser systems in use.

The overall accuracy of the readings given by the analyser are a function of the combined inaccuracies of all aspects of the analysing equipment, from sample preparation through to the electronic display – not simply the manufacturer's published accuracy of a particular sensor.

When considering the accuracy of a sensor, it is important to understand the difference between accuracy and resolution. Accuracy describes the ability of a sensor to measure a gas concentration correctly – at different signal levels, over a period of time and at differing environmental conditions. Resolution on the other hand can be described as the ability to provide consistent outputs with a small distribution range for constant sample, and the ability to detect small changes in sample concentrations.

Inaccuracies are caused by a number of factors, the key ones being described below:

a) Inherent Sensor Inaccuracy:

The sensor chosen for measuring oxygen will have a published accuracy figure, as calculated and guaranteed by the sensor manufacturer. The inaccuracies in the sensor output are made up such factors as its absolute accuracy, linearity, hysteresis and offset. Published accuracies are often specified at steady-state conditions (e.g. of temperature and pressure).

b) Temperature Stability:

As the ambient temperature of the sensor (or the sample gas) changes, most sensors will produce some change in their output that has a relationship to this temperature change. Some sensor types are 'temperature compensated' which is the manufacturer's attempt to eliminate the effects of changing temperature on sensor output by some method. The effectiveness of the temperature compensation varies from sensor to sensor, and should be considered carefully.

c) Pressure Dependency:

This phenomenon has probably the most significant effect on system accuracy of vented sensor analysers. It is also the most commonly ignored (i.e. not compensated or corrected for) error generating effect.

When the sample gas enters the sensor – whether it be a fuel-cell and flow-cap or a paramagnetic cell, the outlet (exhaust) from the sensor is normally vented to atmosphere. The sensor is therefore measuring the partial pressure concentration of oxygen at the current barometric pressure (exhaust pressure) of the analyser. Due to climatic effects, barometric pressure can vary from the Mean Sea-level Pressure (MSLP) of 1013.25mbar to as high as 1080mbar and as low as 880mbar. These excursions are exceptional, but give an indication of the maximum range that may be experienced. Such excursions will lead to an error in analyser reading of – 15% to +7% of the MSLP value. It is therefore easy to see how an uncorrected

barometric pressure on the sensor system can contribute significantly to the overall system error.

Correction of the signal for ambient pressure can be easily accomplished by using a pressure transducer to measure the barometric pressure, and using this pressure value to implement a dynamic ratiometric correction to the measured O₂ sensor signal.

Another factor that can affect the accuracy of systems due to pressure change is an 'artificial' pressure increase or decrease in the analyser location. Such pressure changes can be caused by forced ventilation or air-conditioning systems in the control room, pressure variations caused by moonpool surge, fans and ventilation inside equipment enclosures etc. All these can contribute to errors if the analyser system is not compensated for ambient pressure.

d) Sample Gas Flowrate:

The flowrate of the sample gas across or through the sensor is vitally important to repeatable and accurate measurements. If the flowrate is too low, there may be insufficient sample gas to effectively oxidise the fuel-cell or to maintain an evenly distributed sample in the sample cell. The response time of the system may also be too long, due to the time taken for a sample to pass through sample pipework.

When the gas flowrate is too high, there exists the likelihood that there will be a pressure increase inside either the flow-cap or the paramagnetic sensor cell. This pressure increase is caused by the back-pressure from the exhaust duct on the sensor / flow-cap, causing an increased partial pressure of the sample and a corresponding increase in the sensor output. Under extreme conditions this can contribute to several percent error in the readings. This type of error will not be compensated for by conventional barometric pressure compensation unless the barometric pressure sensor measures the pressure *inside* the sensor or flow-cap.

In order to avoid these effects, the exhaust outlet from the sensor should be reasonably large and unrestricted. The gas flowrate should be adjusted carefully and maintained at a constant level by the operator of the analyser.

Some analyser systems include electronic flow measurement and automatic mass-flow regulation of the sample gas.

e) Sensor Depletion:

In the case of Electro-galvanic fuel cells, the sensors have a finite life. As they approach their end-point (when they are 'used up'), the output voltage for a given oxygen concentration drops off. This decrease in output can exhibit significantly non-linear behaviour, where high oxygen concentrations produce relatively lower signal values, but low concentrations still produce an output closer to the expected value. This can lead to situations where there is a greater risk of a high oxygen concentration error.

f) Measuring System Inaccuracy:

The output signal from the sensor is normally an analogue voltage. In the case of Electro-galvanic O₂ fuel cells, this sensor signal is a very low DC voltage – typically 20 to 30mV. For paramagnetic and NDIR sensors, their output is an amplified signal with a 0-1V DC range typically.

The analyser takes the analogue signal from the sensor and converts this to a digital value that is in turn displayed on a digital display or read-out. The conversion process from analogue to digital may involve amplification followed by

an analogue-to-digital converter stage. The quality and accuracy of this electronic circuitry will affect the overall system accuracy.

g) Calibration Gas Errors:

The use of calibration gases to assure correct analyser performance is discussed in the section below, but inaccuracies can be introduced during the calibration process from factors such as:

- Inconsistent flowrate between sample and calibration gases;
- Incorrect (or absent) barometric compensation at calibration time
- Atmospheric pressure reference during calibration gas blending
- Calibration gases with concentrations significantly different from sample concentrations (exacerbating any non-linearities in the sensor performance)

When implementing analyser systems for diving applications, the overall system performance should be considered when establishing the suitability of a particular analyser design for the intended duty. It is also evident that with increasing depths at which the diving operations are carried out, the required accuracy and quality of the analyser equipment increases, as the thresholds between safe and dangerous conditions become smaller.

6. CALIBRATION PROCESS AND FUNCTIONAL ASSURANCE

From the dialogue in the previous section, it is clear that the absolute accuracy of many analyser systems in common usage is questionable, particularly when the sum of all potential errors is combined into an overall inaccuracy figure.

Fortunately however, there are processes and procedures that are used in the industry that help mitigate many of these factors and reduce the overall system errors to an acceptable level. The key procedure that avoids dangerous situations is the regular calibration of analyser systems using controlled calibration gases with precisely known compositions.

On most diving systems there will be at least three calibration gases used for analyser re-calibration activities. These gases are:

- 'Zero gas' which is typically pure helium with negligible impurities;
- Low-span gas – normally a low concentration of oxygen (often around 4% by volume) and a trace of CO₂ (often around 1000ppm). The balance gas is helium.
- High-span gas – a higher concentration of oxygen (possibly 10% or higher) and a greater CO₂ concentration (possibly around 4000ppm). Balance gas is helium.

Operational procedures require that supervisory personnel at the analyser control stations check the function of their analysers against the zero gas and one or more span gases on a regular basis. This may be typically once per shift (once every 12 hours) or more often. The zero-point and span of the analysers is checked (and adjusted) by the operator, using the span-gas closest in concentration to the actual concentration readings that are being measured in the sample. Using a similar concentration avoids the effects of sensor non-linearities.

Calibration gases are produced by specialist gas suppliers, who firstly blend the gases by weight (using very accurate gas weighing technology) and once mixed, analysing the actual gas composition using very accurate techniques (typically gas chromatography). The measured concentration of the gas is recorded on a tag affixed to the gas bottle, and is often marked permanently on the outside of the bottle.

Even with calibration techniques as described above, there still remain areas where errors can manifest themselves. Some examples of such areas are listed below:

- a) Calibration gas concentration is significantly different from sample concentration. This introduces the possibility of linearity errors in the transducer contributing to accuracy errors when the analyser is returned to the sample gas. The chart in Fig. 4 below shows an actual calibration sequence carried out on a DSV operating in the Norwegian sector at 140MSW. In this case, the % O₂ calibration gas was 8.8%, whereas the actual sample of the chamber gas was 2.78%.

Oxygen Analyser Calibration Sequence (Chamber at 140 MSW)

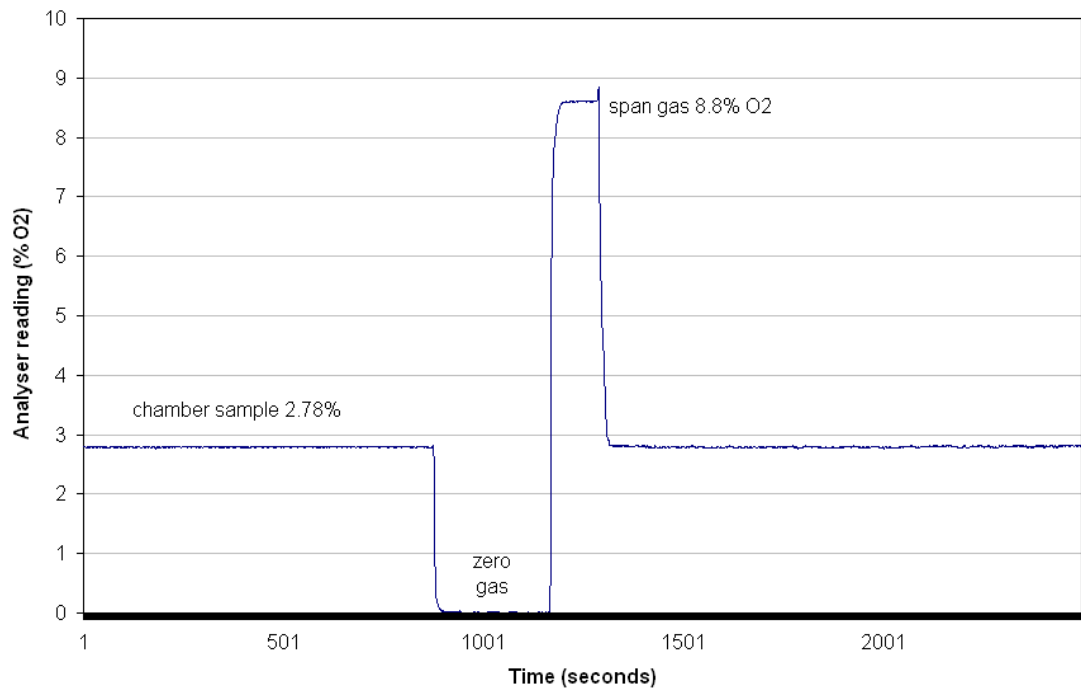


Fig. 4 – Oxygen Analyser output during calibration sequence

- b) Calibration gas flowrate is different to sample flowrate. In this case, any back-pressure in the sensor chamber / flow-cap and exhaust pipework will contribute to a difference in reading between the sensor signal during calibration gas flow and during live sampling.
- c) Temperature difference between sample gas and calibration gas. This can lead to errors in calibration where the sensor is not effectively temperature compensated.
- d) Barometric pressure differences between calibration time and the ambient pressure when the calibration gas was analysed by the manufacturer. This is often avoided by the calibration gas being analysed at (or normalised to) standard atmospheric conditions (1013.25 mbar).
- e) Shelf-life of calibration gases. This is normally around 2 years, and in most diving systems a cylinder of calibration gas will be used much quicker than this. It should also be noted that there is no evidence of stratification of calibration gases during long-term storage in cylinders, and after manufacture calibration gases remain homogeneous due to Brownian motion of the gas molecules. No stirring (by mechanical means, or heating) is therefore required.
- f) Barometric pressure offset at calibration time. This can contribute to absolute accuracy errors that may contribute to sample-time errors in uncompensated systems.
- g) Actual accuracy of the calibration gas. This becomes more significant when very low concentrations are produced, as would be required for close-reference calibration during ultra-deep diving activities (e.g. >300 MSW depth).

7. OPERATIONAL CONSIDERATIONS

When analyser systems are put into service, there are a number of areas where care should be taken to avoid system induced errors. Examples of a number of these are given below:

- a) Gas sample lines taken from SDCs – the volume of gas in the bell umbilical sample hose can lead to a slow response time of the sampled value – dependent on the flowrate in the sample hose and (as the analysing regulator is at the surface) on the pressure of the gas inside the bell. Increasing the sample flowrate can improve this significantly.
- b) Hyperbaric fuel-cell based O₂ analysers cannot be calibrated regularly (in the same way as surface sampled types), but procedures for cross-checking these against the calculated partial pressure sample concentrations from surface analysers should be implemented.
- c) Operation of fuel-cells at elevated hyperbaric pressures is widely used, but actual sensor performance under these conditions may not be fully understood.
- d) Portable NDIR CO₂ analysers in hyperbaric chambers are not normally used. Instead, chemical sampling techniques are used as a back-up to surface sampled systems (e.g. Drager tubes). This presents a less rigorous quality check than with O₂ sensors, as the Drager tubes are normally only used in emergency situations.
- e) Sample preparation systems should be carefully designed. Use of water-traps, gas drying columns and filtration to protect sensors is recommended, but the choice of desiccant material should be made carefully to ensure that there is no chemical reaction with the target sample gases, affecting the measured values.
- f) For sampled systems, there must be sufficient pressure in the sample-line to ensure a satisfactory flowrate through the sensor. When chambers are at very shallow depths, this may present a problem, and in such cases the use of a pump to provide an adequate sample flow should be considered.

8. PRESCRIPTIVE ANALYSER ACCURACY REQUIREMENTS

There is no industry-wide standard specification for Oxygen and Carbon Dioxide analyser accuracy, but physiological limits of the human body model will allow specification requirements to be derived.

There are however published accuracy requirements in the DNV 'Offshore Standard for Diving Systems DNV-OS-E402'. These requirements are established as a function of partial pressures so as to be implicitly linked to the operating depth, and have been developed with a good understanding of the physiological effects of hyperbaric gases and diving medicine. The following is extracted from the DNV standard:

E 400 Oxygen analysing systems

401 Oxygen analysing systems shall have an accuracy of at least ± 0.015 bar partial pressure oxygen.

402 The bell and the living compartments shall have separate oxygen analysers inside.

E 500 Carbon dioxide analysing systems

501 Carbon dioxide analysing systems shall have an accuracy of ± 0.001 bar partial pressure.

502 Carbon dioxide gas for calibration shall be available.

503 The bell shall have self-contained carbon dioxide analysing systems.

E 600 Other gases

601 The instrumentation for systems intended for other gases than air or helium and oxygen mixes shall be considered in each case.

Guidance note:

Operations in connection with exploration of oil, may require instrumentation for the analysis of hydrocarbon gases and H₂S.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

602 Calibration gases shall be available for each relevant gas mix.

For diving systems that are certified by DNV and which therefore are compliant to the above standard, these figures of accuracy must be used. For other diving systems not certified by DNV (e.g. Lloyd's certified systems), there may not be a stipulated accuracy requirement, but best-practices would recommend that accuracies similar to the DNV standard should be implemented.

When examining these accuracy requirements, it becomes clear that with deeper diving operations, the analyser system accuracy becomes more important. The following tables give an indication of the required accuracy of analysers with increasing depth, and indicate the limits of accuracy that can be expected from different sensor types:

Analyser system accuracies																			
SE - surface equivalent																			
<table border="1"> <thead> <tr> <th>Type</th> <th>Description</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>CO2 sensor with 5000ppm range and accuracy = <+/- 1%FSD = <+/-50ppm</td> </tr> <tr> <td>2</td> <td>CO2 sensor with 5000ppm range and accuracy = <+/- 2%FSD = <+/-100ppm</td> </tr> <tr> <td>3</td> <td>Paramagnetic O2 sensor with 0-100% range and accuracy = <+/- 0.1%FSD</td> </tr> <tr> <td>4</td> <td>Fuel Cell O2 sensor with 0-100% range and accuracy = <+/- 1%FSD</td> </tr> </tbody> </table>		Type	Description	1	CO2 sensor with 5000ppm range and accuracy = <+/- 1%FSD = <+/-50ppm	2	CO2 sensor with 5000ppm range and accuracy = <+/- 2%FSD = <+/-100ppm	3	Paramagnetic O2 sensor with 0-100% range and accuracy = <+/- 0.1%FSD	4	Fuel Cell O2 sensor with 0-100% range and accuracy = <+/- 1%FSD								
Type	Description																		
1	CO2 sensor with 5000ppm range and accuracy = <+/- 1%FSD = <+/-50ppm																		
2	CO2 sensor with 5000ppm range and accuracy = <+/- 2%FSD = <+/-100ppm																		
3	Paramagnetic O2 sensor with 0-100% range and accuracy = <+/- 0.1%FSD																		
4	Fuel Cell O2 sensor with 0-100% range and accuracy = <+/- 1%FSD																		
Operating depth (MSW)	DNV required ppO2 accuracy	DNV required pO2 SE accuracy +/- %	Type 3	Type 4	DNV required ppCO2 (bar) accuracy	DNV required pCO2 SE accuracy +/- ppm	Type 1	Type 2											
0	0.015	1.5000	pass	pass	0.001	1000.0000	pass	pass											
5	0.015	1.0000	pass	pass	0.001	666.6667	pass	pass											
10	0.015	0.7500	pass	fail	0.001	500.0000	pass	pass											
20	0.015	0.5000	pass	fail	0.001	333.3333	pass	pass											
50	0.015	0.2500	pass	fail	0.001	166.6667	pass	pass											
90	0.015	0.1500	pass	fail	0.001	100.0000	pass	pass											
100	0.015	0.1364	pass	fail	0.001	90.9091	pass	fail											
140	0.015	0.1000	pass	fail	0.001	66.6667	pass	fail											
150	0.015	0.0938	fail	fail	0.001	62.5000	pass	fail											
190	0.015	0.0750	fail	fail	0.001	50.0000	pass	fail											
200	0.015	0.0714	fail	fail	0.001	47.6190	fail	fail											
250	0.015	0.0577	fail	fail	0.001	38.4615	fail	fail											
300	0.015	0.0484	fail	fail	0.001	32.2581	fail	fail											
350	0.015	0.0417	fail	fail	0.001	27.7778	fail	fail											
400	0.015	0.0366	fail	fail	0.001	24.3902	fail	fail											

Fig. 5 – Analyser accuracy requirements from DNV-OS-E402

It is clear from the figures above that when considering simple accuracy values quoted for sensors, currently installed equipment is well below these accuracy requirement thresholds for deep diving. As explained in the section on Calibration above, system these accuracies can be significantly improved by effective and regular calibration activities.

When examining accuracy specifications, it is also worthwhile considering the thresholds where a dangerous situation might occur due to lack of system accuracy. This is based on calculating where physiological danger thresholds are exceeded, unknown to the operator as a result of analyser inaccuracies. The tables below give two typical examples for O₂ measurement, the first for long-term exposure in the chamber and the second for limited exposure when a diver is in the water:

O2 Analyser system accuracy (+/- 1%) Nominal ppO2 0.4 bars					O2 Analyser system accuracy (+/- 1%) Nominal ppO2 0.6 bars				
Depth (MSW)	SE O2 % value (ideal)	ppO2 Low limit	ppO2 Hi Limit		Depth (MSW)	SE O2 % value (ideal)	ppO2 Low limit	ppO2 Hi Limit	
0	21.000	0.2000	0.2200		0	21.000	0.2000	0.2200	
5	21.000	0.3000	0.3300		5	21.000	0.3000	0.3300	
10	20.000	0.3800	0.4200		10	21.000	0.4000	0.4400	
20	13.333	0.3700	0.4300		20	20.000	0.5700	0.6300	
50	6.667	0.3400	0.4600		50	10.000	0.5400	0.6600	
90	4.000	0.3000	0.5000		90	6.000	0.5000	0.7000	
100	3.636	0.2900	0.5100		100	5.455	0.4900	0.7100	
140	2.667	0.2500	0.5500		140	4.000	0.4500	0.7500	
150	2.500	0.2400	0.5600		150	3.750	0.4400	0.7600	
190	2.000	0.2000	0.6000		190	3.000	0.4000	0.8000	
200	1.905	0.1900	0.6100		200	2.857	0.3900	0.8100	
250	1.538	0.1400	0.6600		250	2.308	0.3400	0.8600	
300	1.290	0.0900	0.7100		300	1.935	0.2900	0.9100	
350	1.111	0.0400	0.7600		350	1.667	0.2400	0.9600	
400	0.976	-0.0100	0.8100		400	1.463	0.1900	1.0100	

Fig. 6 – Illustration of unsafe condition thresholds for 1% accurate O2 analyser system

9. CONCLUSIONS

In the diving industry at present there are a wide range of analyser systems in use that are based on sensors and technologies with published accuracies well below the desired thresholds – if used in isolation.

Effective periodic calibration procedures are used to improve the confidence in the readings provided by these analyser systems, but these procedures in themselves are not without the potential for inaccuracies and errors. These techniques have ensured the safety of diving operations over many years, but there is a general lack of understanding of the **actual** accuracies and uncertainties of systems in use.

It can be demonstrated that unsafe conditions are unlikely under current operating procedures, but their likelihood increases with operating depth.

There are a number of techniques that are currently not implemented in many analyser systems that can in themselves make a significant improvement in the intrinsic system accuracy (e.g. barometric pressure compensation, sample flowrate management, temperature compensation, selection of appropriate calibration gases etc.).

When specifying new or replacement systems, a good understanding of the overall system specification requirements will allow selection of appropriate equipment and good system design.