A New Approach to Closed-Circuit Rebreather Gas Monitoring: Why Two Oxygen Sensors can be Better than Three

Presented by developers of the Cis-Lunar series of rebreathers
and Poseidon Diving Systems

Introduction

Closed-Cycle underwater breathing apparatus (CCUBA), alternatively known as "closed-circuit rebreathers" (or "CCRs"), offer distinct advantages over the more common open-circuit (SCUBA) systems, such as reduced bubble noise, extremely high gas usage efficiency, and optimized breathing gas composition. These advantages derive from the fact that the exhaled breathing gas is recycled, filtered of carbon dioxide, replenished with oxygen, and returned to the diver for breathing again. The lack of bubble noise and the increased gas efficiency of a CCR both result from the fundamental function of recycling the breathing gas. The optimized breathing gas composition results from the fact that the oxygen control system of a CCR maintains a constant partial-pressure of oxygen (rather than a constant fraction of oxygen, as in conventional open-circuit SCUBA).

The partial pressure of a gas is a function of the fraction of the gas multiplied by the ambient pressure. As a diver descends and the depth increases, the ambient pressure also increases. Thus, for a given fraction of oxygen, the partial pressure increases as the depth increases. If the oxygen partial pressure exceeds a certain threshold (approximately 1.4 atm/bar), the risk of hyperoxia-induced seizure and other "oxygen toxicity" symptoms is considered unsafe for the diver. For example, the maximum safe depth at which a diver can breathe a mixture containing 50% oxygen is about 60 feet (~18m). On the other hand, the lower the oxygen concentration, the greater the concentration of non-oxygen gas constituents, such as nitrogen or helium. These non-oxygen components of the breathing mixture are what lead to problems of decompression sickness (DCS), also known as "the bends", which can include symptoms ranging from pain in the joints, to paralysis, to death. To maximize the amount of time that can be safely spent at any given depth, the non-oxygen portions of the breathing gas should be kept to a minimum; which means that the oxygen should be kept to its maximum safe limit at all points during the dive.

Thus, the advantage of CCR over conventional open-circuit SCUBA in terms of optimized breathing gas composition results from the fact that a CCR can maintain the maximum safe partial pressure of oxygen (PO_2) throughout all depths of a dive, thereby minimizing the concentration of non-oxygen gas constituents – leading to increased allowed time at any given depth and/or reduced risk of DCS.

But this advantage comes at a cost. Whereas the breathing mixture for a conventional open-circuit SCUBA diver is fixed based on the composition of the gas in the supply cylinder, the breathing mixture in a CCR is dynamic. Although it is this dynamic mixture capability that affords CCR one of its primary advantages, a failure of the oxygen control system can be extremely dangerous. A malfunction that allows the PO_2 to get too high places the diver at risk of a hyperoxia-induced seizure, almost certainly causing the diver to drown. A malfunction that allows the PO_2 to get too low will lead to hypoxic-induced blackout, causing the diver to black-out and drown, leading to severe brain damage or death. Therefore, perhaps the most critical aspect of any CCR design involves the reliability of the oxygen control system.

Oxygen Sensors: The Critical Link

The oxygen control system of most closed-circuit rebreathers depends mostly on electronic oxygen sensors that directly measure the PO_2 of the breathing gas. Most such sensors involve a galvanic reaction that produces a voltage output that is proportional to the concentration of the oxygen exposed to the sensor. Electronic systems interpret the signals from the oxygen sensors to control a valve connected to an oxygen supply. When the oxygen sensors detect a PO_2 below a certain “setpoint” threshold, the valve is opened and a small amount of oxygen is injected into the breathing gas. The reliability of the oxygen sensors, therefore, is of paramount importance for ensuring a safe breathing gas mixture when using a CCR.

There are a number of ways that oxygen sensors – considered by most experienced CCR divers as the weakest link in the oxygen control system – can fail (i.e., provide false readings). The sensors themselves may fail due to reactive material consumption and other age-related degradation of active sensing elements. The sensors may also fall out of proper calibration, leading the electronic control system to misinterpret the readings. One of the most common modes of oxygen sensor failure involves condensation. The breathing gas of a CCR is typically supersaturated with moisture, due to the warm humid gas expired from the diver’s lungs being cooled by the surrounding ambient water temperature. As a consequence, the inside walls of CCR breathing pathways are typically dripping wet with condensation after a short period of time. If such condensation comes in contact with the sensing surface of the oxygen sensor, it will prevent the sensor from monitoring the breathing gas. In some circumstances, a thin film of condensate can form across the active sensing face of the PO_2 sensor (frequently a metal mesh or hydrophobic membrane), trapping a tiny pocket of gas against the sensor that is isolated from the breathing gas mixture. This is among the most dangerous forms of oxygen sensor failure, because it provides a false but plausible reading to the electronics, concealing the nature of the failure. If the trapped pocket of gas has an oxygen concentration that is *below* the “setpoint”, then the control system will continue to add oxygen to the breathing loop until the actual breathed PO_2 reaches dangerously high levels. If the PO_2 of the trapped pocket of gas is *above* the “setpoint” value, the control system will fail to add any oxygen at all, and the PO_2 of the breathing gas will gradually diminish due to the diver’s metabolic oxygen consumption until hypoxic levels are reached and the diver blacks out.

Triple Redundancy: The Traditional Approach

Almost all electronically-controlled CCR systems thus far developed attempt to safeguard against the consequences of failed oxygen sensors through the incorporation of triplex redundancy (that is, by incorporating three oxygen sensors in the CCR). This practice began with the very first electronically-controlled CCR (the “Electrolung” developed by Walter Starck), and has been followed by almost every CCR design since.

The use of three sensors makes intuitive sense. If only one oxygen sensor is used, and it fails in a way that gives otherwise plausible readings, then there is no logical way to recognize that the sensor has failed. If two sensors are used and one of them is giving a false reading, the control system can logically recognize that a problem exists (unless both sensors fail in exact the same way), but cannot determine which sensor is correct and which has failed. With three oxygen sensors (so the thinking goes), the system has "voting" logic. Assuming only one sensor fails at a time, then the control system can be designed to interpret the two readings that agree within some pre-accepted tolerance as correct, and thereby isolate the bad sensor reading.

Though ubiquitous among modern rebreather designs, the three-sensor approach to monitoring oxygen concentration in the breathing mixture is far from perfect. First, some arbitrary threshold values must be established in order to carry out the voting logic. Because sensor readings can be slightly unstable in the chaotic breathing gas mixture of a CCR, a sensor must be allowed to deviate from the other two sensors by a certain minimum threshold amount before it is considered suspect. Then there is the question of what this threshold is measured against. For example, should the basis for the threshold comparison of one potentially errant sensor reading be the average value of the remaining two sensors, or the value of the sensor with the closest reading (i.e., the sensor giving the "middle" reading of the three)?

Another problem with reliance upon the triple-redundant oxygen sensor system is the fact that sometimes two sensors fail in the same way – often due to particular patterns of condensate formation or because a user may have replaced one sensor with a fresh one and the other two are at the end of their useful life but may have exhibited in-range readings prior to the start of a dive (there are many such possibilities). In such situations, the apparently errant sensor reading is actually the correct reading. This mode of failure is particularly dangerous in that the control system might actively ignore the correct reading. Although this failure mode may seem unlikely, it has been documented through logged sensor readings on multiple occasions during actual dives. Indeed, there have even been documented cases where all three sensors fail simultaneously such that all three give the same, but false reading. Other documented cases involve situations where no two sensors agree.

Once the threshold values and basis of comparison (i.e., voting logic algorithm) are determined, there is still the question of how best to adjust the oxygen control system in the event of an apparently failed sensor. Given two concordant values, and one errant value, should the control system simply ignore the errant value altogether and base its control logic on the average of the remaining two sensors? Should it trust the dynamic sensor values and ignore the static values on the premise that dynamic values are more likely to be "live" readings? Or, should it base its control on the "middle" value of the three sensor readings – just in case the apparently errant sensor may be correct? Or, should additional logic be used such that the "setpoint" is adjusted dynamically, so that the highest sensor value and the lowest sensor value are both kept within life-sustaining limits at all times? And what should the control system do in the event that no two oxygen sensors agree? Should it bias its logic to safeguard more rigorously against hypoxia, or hyperoxia? Indeed, there are as many different answers to these questions as there are people who have designed CCR oxygen control systems.

Active Sensor Validation (ASV): A More Reliable Approach

Herein we describe a new approach to CCR oxygen control systems, involving automated active testing and monitoring of the oxygen sensors, that is more reliable than the passive triple-redundant control system that is currently in common use. This new approach capitalizes on the recent availability of very small (miniature),highly reliable solenoid gas valves, microprocessor-controlled gas monitoring and controlling technology, and the availability of both pure oxygen and a primarily non-oxygen gas supply (e.g., air), which are both typically available on almost all CCR systems.

This new approach to oxygen control systems has its origins in the Cis-Lunar series of closed-circuit rebreathers, and as such represents the culmination of more than 20 years of experience designing, developing, and diving some of the most sophisticated rebreathers ever built. Beginning with the Cis-Lunar MK-III (third-generation) system, two important features were incorporated in the design to address some of the problems of oxygen sensor reliability. The first of these two features was to allow the manual injection of diluent gas directly on the oxygen sensors at any point during a dive. This feature served two functions: it purged any condensation that might have accumulated on the sensors (thereby restoring function to sensors blocked by a film of water on the sensing membrane) and, more importantly, it exposed the oxygen sensors to a known fraction of oxygen. Given a known ambient pressure (i.e., depth), this allowed the sensor function to be verified by observing whether the sensor readings corresponded to the known PO_2 exposed to the sensors.

The second important feature introduced on the Cis-Lunar MK-III to address oxygen sensor reliability is that the primary LCD display presented sensor PO_2 values to within 0.01 atm precision. The sensors themselves were not accurate to within this level of precision; however, displaying the extra precision allowed the diver to determine whether the displayed PO_2 values were static or dynamic. Minor fluctuations in the gas mixture passing over the oxygen sensors cause corresponding fluctuations in the displayed readings – but only if the sensors are exposed to the breathing gas. On the other hand, if one (or more) of the sensors have a film of condensate trapping a small pocket of gas against the sensor, they will not respond to the minor fluctuations in the breathing mixture. Instead, the sensor values will be static (changing only in response to depth changes). Thus, a static PO_2 sensor reading at the 0.01 atm precision is indicative of an unreliable sensor value.

These features (among others) were expanded upon and improved in the Cis-Lunar MK-IV and MK-V rebreather systems, enhancing the diver’s ability to asses not just what the O_2 sensor values are, but the extent to which they can be trusted as reliable. With the development of the new Cis-Lunar MK-VI (“Discovery”) rebreather system through a collaboration of the original Cis-Lunar design team (including Dr. William “Bill” Stone, Nigel Jones, and Dr. Richard Pyle) and Poseidon Diving Systems, these features have been improved and enhanced to the point where they represent an entirely new approach to CCR oxygen control systems: Active Sensor Validation (ASV).

In its simplest form, the ASV control system incorporates two oxygen sensors (one designated as the “Primary Oxygen Sensor”, and the other designated as the “Secondary Oxygen Sensor”) and a minimum of three electronically-controlled gas valves. One of these values is used to perform the same basic function as the solenoid valve found in virtually all CCRs: to replenish the oxygen metabolized by the diver. In the case of the Poseidon Cis-Lunar MK-VI rebreather, there are actually two electronically-controlled valves to serve this purpose – allowing both greater control and precision of injected oxygen volume, and allowing redundancy of the oxygen addition system.

Unlike any other existing or previous CCR oxygen control system, the ASV approach also incorporates two additional electronically-controlled valves: one to inject oxygen directly onto the “Primary Oxygen Sensor”, and the other to inject “diluent” gas (i.e., a mixture containing primarily non-oxygen but nonetheless constituting a gas mixture that is directly breathable in open circuit mode within some regime of a planned dive – typically it is designed to be breathable at the maximum planned dive depth). For the purposes of this description, the “diluent” gas supply is assumed to be air (~21% oxygen, ~79% nitrogen and other trace gases), but any breathable mixture containing at least some (known) oxygen fraction will serve the same purpose. The basic principle of the oxygen control system described herein is to periodically validate the readings of the Primary Oxygen Sensor using controlled direct injections of either oxygen or diluent (depending on the depth and the circumstances) and monitoring the response of the sensor to validate accurate readings. These gas injections also serve the purpose of removing any condensation that may form on the face of the sensors, thus eliminating one of the common failure modes described above.

The purpose of the “Secondary Oxygen Sensor” is to monitor the oxygen content of the breathing gas while the Primary Oxygen Sensor is being validated, and also to safeguard against possible failure modes of the Primary Oxygen Sensor validation system, as described in more detail below.

The components of the simplest form of the Active Sensor Validation system (see Figure 1) include:

1) Primary Oxygen Sensor. An oxygen sensor, exposed to the breathing gas through a small gas chamber that can be flushed with oxygen or diluent gas via electronically-controlled valves.
2) Secondary Oxygen Sensor. An oxygen sensor, exposed to the breathing gas through a small gas chamber that is not connected to either the oxygen or diluent gas supplies, but is in relatively close proximity to the Primary Oxygen Sensor.
3) Oxygen Supply. A supply of oxygen gas (normal for any closed-circuit rebreather), equipped with pressure-reducing regulator establishing a supply of intermediate-pressure oxygen gas.
4) Diluent Supply. A supply of diluent gas (also normal for any closed-circuit rebreather), equipped with pressure-reducing regulator establishing a supply of intermediate-pressure diluent gas (e.g., air).
5) Oxygen Test Valve. An electronically-controlled valve that allows a small measured volume of oxygen gas to be injected directly onto the sensing surface of the Primary Oxygen Sensor.

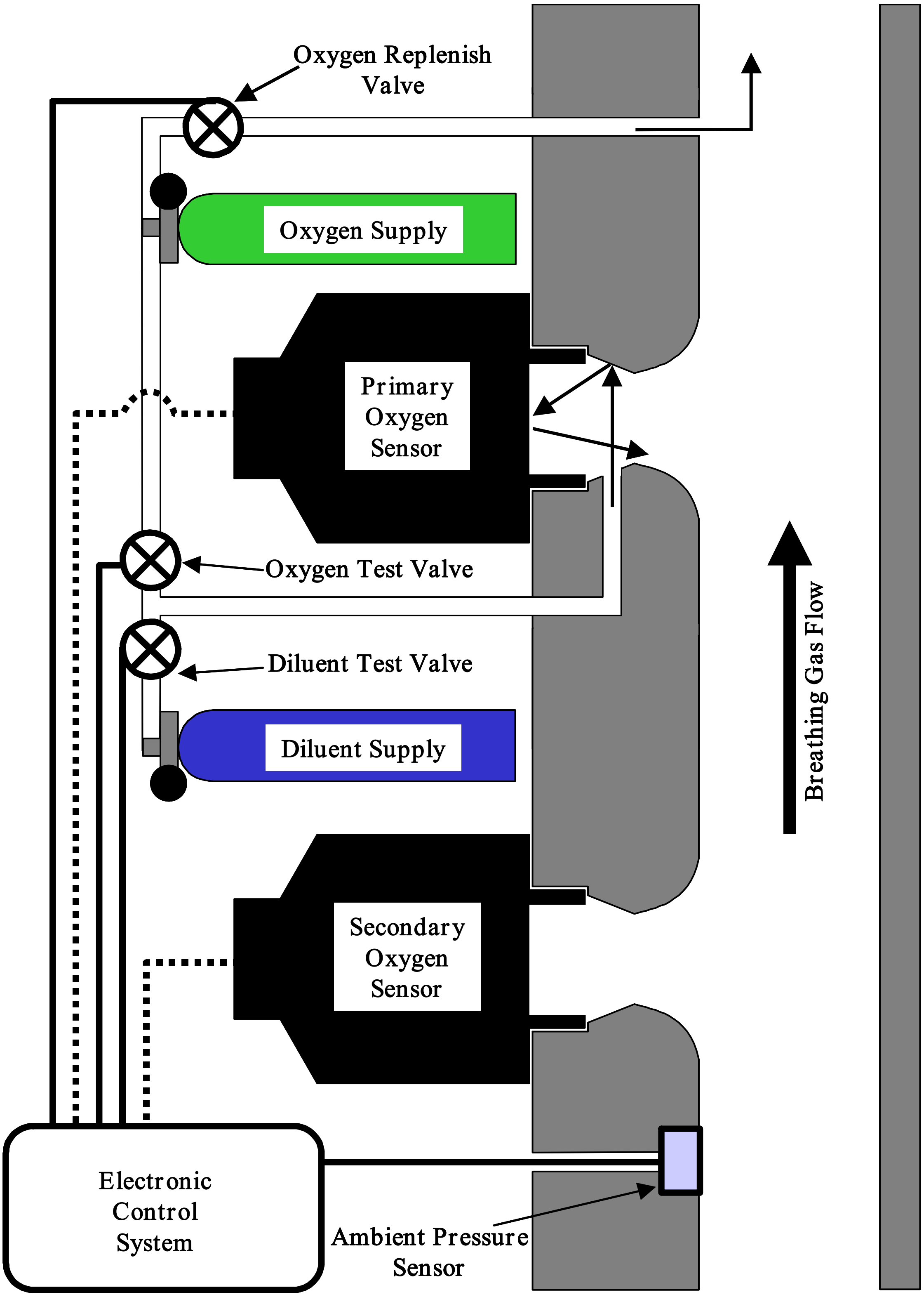

Figure 1. Diagrammatic illustration of Simple Active Sensor Validation (ASV) system.

6) **Diluent Test Valve**. An electronically-controlled valve that allows a small measured volume of diluent gas to be injected directly onto the sensing surface of the Primary Oxygen Sensor.

7) **Oxygen Replenish Valve**. One or more electronically-controlled valve(s) that allow a measured volume of oxygen to be injected into the breathing loop, in a place where the injected gas is not exposed directly to either oxygen sensor until it has been adequately mixed with the breathing mixture.

8) **Ambient Pressure Sensor**. An electronic sensor that detects the ambient pressure of the breathing gas.

9) **Electronic Control System**. An electronic computer system that can read the output from both the Primary and Secondary Oxygen Sensors, monitor the Ambient Pressure Sensor, monitor the passage of time, and control the three electronically-controlled valves (Oxygen Test, Diluent Test, and Oxygen Replenish).

To explain the importance of the Active Sensor Validation system, it is helpful to review the various failure modes of CCR oxygen control systems.

Review of CCR Failure Modes

Most CCR systems rely on oxygen sensors to provide information on the oxygen content of the breathing mixture. When multiple sensors are used, some method to derive a single estimated value for the oxygen concentration is usually incorporated. When the oxygen concentration (PO_2) drops some defined threshold below the control setpoint, an electronically-controlled valve is opened or adjusted to replenish the oxygen supply in the breathing mixture. In the discussions that follow we will use for our example a commonly available galvanic oxygen sensor (essentially a fuel cell that produces voltage output in response to the PO_2 level) that is widely in use in CCR apparatus. However, the following discussions equally apply to all manner of sensors that produce an output signal proportional to PO_2. As described above, traditional methods for using multiple oxygen sensors have several limitations, including:

Calibration

All galvanic oxygen sensors must be calibrated to ensure accurate readings. The calibration process typically involves exposing the sensors to one or more known gas mixtures at a known ambient pressure, and deriving calibration constants to the electronic logic that interprets the sensor readings. Calibration is typically conducted manually or semi-automatically prior to the dive, but is sometimes only done once periodically over many dives. Calibration constants can be recorded incorrectly if the calibration gas mixture deviates from expected (e.g., if the calibration process assumes a mixture of 100% oxygen when a contaminated calibration gas is actually only 80% oxygen), if the ambient pressure is not properly taken into account, if the sensor fails in certain ways as described below, and/or if the user performs the calibration process incorrectly. Attempts to mitigate these problems have included automated calibration routines as part of the standard pre-dive process, incorporation of ambient pressure sensors into the calibration process, and testing against threshold values intended to detect calibration errors.

Sensor Failure

Galvanic oxygen sensors eventually fail either through exhaustion of their chemical reaction or from a host of other environmental and user-caused effects (e.g. abuse). In many cases, a sensor will simply fail to generate sufficient output voltage at the time of calibration, and will be identified. In other cases, however, a sensor can perform normally up to a certain point, but deviate significantly from linearity in output voltage once the oxygen concentration exceeds a certain value. For example, a sensor could perform normally up to an oxygen concentration of 1.1 atm partial pressure, but then fail to produce a correspondingly higher output voltage at higher oxygen concentrations. Because the calibration process of most CCR systems uses 100% oxygen at ambient pressure (i.e., 1 atm partial pressure), the calibration process may appear to complete correctly, but the system may not be able to properly interpret readings when the sensor is exposed to oxygen partial pressures above 1 atm. In other words, while the sensor calibration may be linear in the range of 0.2 through 1.0 atm PO_2, it will fail to produce accurate readings at higher PO_2 values. This form of sensor failure is particularly insidious if it happens below the selected setpoint, because the control system will continue to add oxygen to the breathing gas until the actual PO_2 is dangerously high.

Condensation

The breathing gas in a CCR is humidified to the point of super-saturation when the gas exhaled from the diver’s lungs is passed through the breathing loop of the rebreather. In most cases, ambient water temperature is cooler than body core temperature, and as the breathing gas is cooled in the CCR breathing loop, liquid condensation inevitably forms. The total volume of condensate can exceed several tens of milliliters per hour of dive time. This condensation can affect the oxygen sensor readings, and can even lead to erroneous readings if a film of condensate traps a pocket of gas against the sensing membrane. It can also lead to premature failure of the sensor. Attempts to mitigate this problem include “water traps” and absorbent pads in the breathing loop designed to divert collected condensate away from the oxygen sensors; strategic placement of sensors in areas least likely to form condensation; placement of sensors on different planes to reduce the probability of multiple sensors collecting condensate simultaneously; and active condensate removal via a blast of injected gas directed at the sensing membrane.

Although using multiple oxygen sensors and using sensors designed specifically for humid environments can mitigate some of these problems, all known CCR oxygen control systems are subject to failures due to one or more of the above problems.

Solving the Problems of Oxygen Sensor Reliability: Active Sensor Validation

The Active Sensor Validation (ASV) oxygen control system described herein addresses these (and other) problems in the following ways:

Initial Sensor Calibration

Because the Primary Oxygen Sensor has direct access to both oxygen and known diluent mixtures (e.g., air) via electronically-controlled microvalves (see Figure 1), the ASV system is capable of **exactly** calibrating itself without any input from the user, and it is capable of performing such calibration with an **exceedingly small volume** of consumable gas, which is an important performance measure in a CCR[1]. This system does not require any reliance of proper user-initiated calibration routines or, indeed, any interaction of the user at all. At initial power-up, the ASV system will automatically inject a burst of pure diluent gas (e.g., air) directly on the Primary Oxygen Sensor, reliably exposing it to a known low-oxygen mixture. A sufficient volume of injected gas will also expose the nearby Secondary Oxygen Sensor. The same procedure applies to the oxygen supply mixture as well. These two known points provide a precise two-point calibration for the primary oxygen sensor. Others have purported to have developed "automated" calibration systems for rebreathers but the ASV system represents the first true achievement of exact, and efficient, auto-calibration for a CCR.[2] Because of the availability of oxygen *and* diluent (e.g., air) directly applied to the Primary Oxygen Sensor via the electronically-controlled Oxygen Test Valve and Diluent Test Valve, and the proximity of the Secondary Oxygen Sensor to the Primary Oxygen Sensor, the ASV system is much more effective and efficient for establishing accurate calibration of the oxygen sensors prior a dive. The ASV system can be made even more reliable by:

1) incorporating threshold limits to detect when a sensor falls out of acceptable output voltage values at calibration time;
2) use of algorithmic analysis of a stored log of calibration values to detect calibration trends, alerting the user to a need to replace a sensor;
3) detection of mouthpiece valve position to ensure that the calibration does not proceed unless the mouthpiece valve is in a position that prevents breathing through the loop during the calibration process[3]; and
4) clear and unambiguous "Do not Dive" indicators that prevent the user from operating the rebreather in the event that the pre-dive calibration process does not complete successfully[4].

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[1] *It is the gas utilization efficiency that is one of the hallmarks of CCR systems and that allows these systems to be substantially more compact than open circuit systems providing equivalent diving range at a given depth. However, conversely, the loss of gas in a CCR has a commensurately greater impact on the dive range than it would in an open circuit apparatus because CCR systems typically use much smaller gas supplies. Therefore, one important goal of any auto-calibration system should be absolute minimization of consumable gases used in the process of the calibration.*

[2] *Although at least one commercial CCR system attempts to automatically calibrate oxygen sensors as part of the normal start-up routine, it only applies to the pure oxygen portion of the calibration, and it requires a large, wasteful volume of oxygen to adequately ensure that the sensors themselves are exposed to a reliably high fraction of oxygen. The reason this approach is wasteful and inaccurate with regard to auto-calibration is because the same system used to add metabolic oxygen is the one used in the calibration. It is traditional industry practice to inject metabolic make-up oxygen in a fashion that mixes the gas in the breathing loop long before reaching the oxygen sensors. Because of this, a large amount of oxygen is needed to approximate a good calibration. Even so, such loop-flushing procedures are not likely to be 100% complete and are subject to user intervention (e.g. setting a valve position wrong prior or during the calibration). The only way to mitigate the need for such extensive oxygen flushing is to position the oxygen injection point close to the sensors, which introduces a series of other problems associated with the oxygen control system. Similarly, the breathing loop must also be flushed with air manually in order to achieve the two-point calibration. Both actions require the interaction of the diver with the system and are therefore not truly automatic. Further, this approach is only possible on the surface prior to a dive; it cannot be used to detect a true sensor failure during a dive. Further, such an approach is subject to all of the above-described sensor failure and spoofing scenarios which increase the probability of an incorrect calibration.*

[3] *A novel patent-pending mouthpiece position detection system that is used in conjunction with the auto-calibration system has been designed by Poseidon Diving Systems, AB.*

An additional benefit of the automatic pre-dive check system is that it can also serve as a pre-dive verification that the correct gas mixture (oxygen or diluent) is connected to the correct supply regulator (within calibration threshold tolerances of the sensors).

In-Dive Sensor Verification and Monitoring With Diluent Gas

Another new feature of the ASV system described herein is the ability to monitor and test the function of oxygen sensors during the course of the dive – either at periodic time intervals, or in response to specific circumstances detected by the Electronic Control System. When desired, the system can automatically inject a small amount of diluent gas onto the Primary Oxygen Sensor, and then observe the resultant reading from the sensor as it is interpreted by the electronic control system. With an ambient pressure sensor and a known oxygen fraction in the diluent supply, the Primary Oxygen Sensor can be exposed to a known partial pressure of oxygen at any moment during the dive, and monitored to ensure that the sensor responds with the correct reading. Failure of this test can initiate an alert to the diver that the dive should be aborted immediately.

In-Dive Sensor Testing and Monitoring With Oxygen

Because the system also has access to 100% oxygen and can inject it directly onto the Primary Oxygen Sensor, the ASV system is also capable of testing the linearity of the sensor voltage output at partial pressures in excess of 1 atm (i.e., the maximum calibration value during pre-dive). For example, when the Electronic Control System detects via an ambient pressure sensor that the diver has reached a depth of 20 feet (6m), where the ambient pressure is approximately 1.6 atm, a small burst of oxygen directly on the Primary Oxygen Sensor can ensure that the calibration constants apply reliably for readings at partial pressures well above 1.0 atm. Thus, if the system is set to maintain an oxygen partial pressure of 1.3 atm, there can be confidence in the reliability of the readings at that value, even though it is higher than the maximum pre-dive calibration value of 1.0 atm. As with the diluent injections, the volume of oxygen needed to be injected to perform this test is so small that it would not have a significant impact on the overall gas composition in the CCR breathing loop[5]. The ASV system described here is thus the first to offer full range sensor calibration verification. Furthermore, this

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[4] *A novel patent-pending system that provides this capability has been designed by Poseidon Diving Systems, AB.*

[5] *Furthermore, as a safety precaution in the calculation of decompression debt and in the performance of routine metabolic oxygen makeup solenoid firing calculations (both of which depend on the real-time use of the measured system* PO_2 *level), this system incorporates a software algorithm that temporarily disables the real-time feed of* PO_2 *data to these two decision making algorithms while calibration injections are taking place. During an actual dive, the safety algorithm tracks the prior history of the* PO_2 *variations for some pre-specified period of time and computes a smooth predictive transition (filtering) curve until the resumption of real-time data several seconds following the calibration event. Although empirical data can be used to determine the minimum wait period until resumption of real-time oxygen control and decompression status calculation, computational fluid dynamics calculations performed by the authors in the design of MK-VI CCR indicate that an eight-second gap is more than sufficient to complete thorough mixing of the breathing loop gas at the location of the sensor surfaces. Since eight seconds is approximately the maximum firing rate for metabolic solenoids in most CCR systems thus far developed, an eight-second gap (representing absence of live sensor data) does not constitute any problem provided a good data smoothing predictive algorithm is used. Further, with substantial empirical data the predictive algorithm can be improved into a fuzzy logic controller that utilizes more than just the* PO_2 *sensors and is extended to use all* PO_2 *sensors, depth sensors, and individual tank pressures. The advantage of this is that the auto-calibration periods become "transparent" to the* PO_2 *control and decompression calculation algorithms.*

calibration is performed in a fully automated fashion that is “transparent” to, and requires no interaction from, the user.

The Importance of the Secondary Oxygen Sensor

The incorporation of a Secondary Oxygen Sensor into the ASV system adds to the reliability of the overall sensor monitoring architecture in several ways. During periods when the Primary Oxygen Sensor is not being actively tested, the Secondary Oxygen Sensor can be compared to the Primary Oxygen Sensor to ensure concurrency of readings. If the readings are not concurrent, the system can be triggered to perform a test on the Primary Oxygen Sensor. If the discrepancy of readings was caused by condensation on the Primary Oxygen Sensor, the test itself may correct the problem. If the Primary Oxygen Sensor fails the test, the system can issue an abort alert, and initiate a test of the Secondary Oxygen Sensor by increasing the volume of gas injected at the Primary Oxygen Sensor. If the Primary Oxygen Sensor passes the test, but the Secondary Oxygen Sensor is still providing inconsistent readings (e.g., if condensation has formed on the Secondary Oxygen Sensor, or if the Secondary Oxygen Sensor has failed for some other reason), then an abort alert can be issued to the diver. Another reason for incorporating a Secondary Oxygen Sensor that is not connected directly to the output from the Diluent Test Valve and Oxygen Test Valve, is to serve as a “sentry” to safeguard against small leaks from either of the test valves. In the event of a large leak of either of these valves, it is likely that the control logic of the Electronic Control System would recognize it immediately, and initiate an abort alert to the diver. However, if there was a very small leak in either of the test valves, a trickle of gas onto the Primary Oxygen Sensor might be such that it would bias the reading, but not so much that it could be detected by the Electronic Control System. The sensor would be functioning normally, and would pass all tests, but because the gas in immediate proximity to the sensor membrane is exposed to a contaminated gas mixture (not the actual breathing gas mixture) it would provide erroneous readings and lead to a malfunction of the oxygen control system[6]. Having a Secondary Oxygen Sensor that is not directly exposed to the gas coming from the test valves would result in detection of this failure mode due to discrepancy of readings between the two sensors (as described above). If the leak is so large that it causes contamination of the Secondary Oxygen Sensor, it would be large enough to detect by itself, and even still would not affect the Secondary Oxygen Sensor as much as the Primary Oxygen Sensor, hence causing a (detectible) discrepancy in readings. Yet another reason for having a Secondary Oxygen Sensor is that it can be used to monitor the actual breathing gas while the Primary Oxygen Sensor is being tested. Whereas the Primary Oxygen Sensor is not exposed to the actual breathing mixture during tests, the Secondary Oxygen Sensor continues to monitor the breathing loop gas (see footnote 5 for further information on how this system deals with this situation). A proprietary, patent-pending real-time calibration method has been developed by Poseidon Systems that insures that the Secondary Oxygen Sensor remains properly calibrated during a dive.

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[6] *“Malfunction” in this sense meaning that the metabolic oxygen addition solenoid would fail to add oxygen in the event that the true* PO_2 *dropped below the pre-set threshold for adding oxygen or, alternatively, that the metabolic oxygen addition solenoid would add oxygen when the true* PO_2 *was within acceptable limits or higher than acceptable limits.*

Why Not Three Oxygen Sensors?

Given the industry-standard design incorporating three oxygen sensors into oxygen control systems for rebreathers, some discussion is necessary to explain why three sensors are not used in the Cis-Lunar/Poseidon MK-VI CCR. Although the incorporation of three sensors is standard, how the information from those three sensors is interpreted is not standard. The main reason for having three sensors is to ostensibly allow for “voting logic”. With only one sensor, there is no way to know if it is reading incorrectly. With two sensors, it’s possible to know they are out of synch (and that at least one is reading incorrectly), but it is not possible to determine which sensor is correct, and which is incorrect. Thus, the reasoning goes, three sensors are needed to allow a “majority vote” regarding which readings to believe. In March of 2006, one of the authors posed a question to a room full of highly experienced rebreather divers:

> *Suppose you have three sensors that give you readings of 0.5 atm, 0.5 atm, and 1.1 atm. What should the control system assume to be the correct PO_2, and how should it use this information to maintain a safe breathing mixture?*

Each experienced rebreather diver gave an answer. No two answers were the same. One said the PO_2 should be interpreted as 0.5 atm (voting out the high reading as erroneous). Another said the PO_2 should be interpreted as 0.7 atm (the average of all three sensors). Another said that the PO_2 should be interpreted as 0.8 atm (mid-point between the two values). Another said that the sensor with a dynamic reading should over-ride the static readings, if any. Another said that the control system should use the low value for preventing hypoxia and for calculating decompression, and the high value for preventing hyperoxia.

Each of these answers is either correct or incorrect, depending on which of the many possible failure modes has caused the readings to be out of agreement. In some failure modes, the correct value is 0.5 atm. In other failure modes, 1.1 atm is the correct value. Indeed, some failure modes involve all three sensors being wrong. Because there is no way to easily determine which failure mode has caused the discrepancy, there is no one “correct” response of the control system.

The Active Sensor Validation (ASV) system described here allows a real-time validation of the Primary Oxygen Sensor with as much reliability as laws of physics (i.e., Boyle’s Law), and certainty of diluent composition (verified to some extent during initial sensor calibration). With sensor validation and condensate purging combined into a single fully automated system, most failure modes are resolved. In fact, a strong argument can be made that a single sensor with active validation capabilities is more reliable and more informative than three passive sensors that cannot be validated.

However, there is at least one failure mode in this new system that mandates the need for the Secondary Oxygen Sensor, which is the possibility (described above) that a small trickle leak through one of the calibration solenoid valves could skew the value of the Primary Oxygen Sensor. By having an independent Secondary Oxygen Sensor that is not connected to the calibration solenoid valves, it is possible to detect this new failure mode and respond accordingly with appropriate alerts to the diver.

In the context of the Active Sensor Validation system as used on no-decompression dives, the introduction of a third sensor provides no additional information of value for interpreting the actual PO_2 of the breathing gas. Other ASV systems involving additional sensors and/or solenoid valves have been designed by Poseidon Systems AB (all are in patent-pending stage) and are being developed for use in exploratory rebreather systems for use in overhead environments (including decompression diving). Discussion of these more advanced systems is outside the scope of this document.

Diluent Injection Capability

Having an electronically-controlled diluent valve also provides an opportunity for a feature not available in any other known CCR control system: that is, the ability to automatically *reduce* the oxygen concentration in the breathing loop. Whereas most CCR oxygen control systems operate by injecting oxygen via an electronically-controlled valve whenever the oxygen concentration in the breathing gas drops below a certain “setpoint” value, they are incapable of responding in any way to a situation when the oxygen level increases above the setpoint value. They are, in fact, “open loop” control systems. The system described here is capable true closed-loop control – that is, by injecting a substantial volume of diluent gas into the breathing mixture if the detected oxygen concentration is too high. Although this would temporarily obfuscate the readings of both oxygen sensors, the sensors would restore functionality as soon as the breathing gas moved through the loop as the diver breathed [again, see footnote 5 on this subject], and the important factor is that a safer (reduced oxygen concentration) gas mixture would be delivered to the diver.

Oxygen Replenish Valve

Because oxygen replenishment is a normal function of the oxygen control system, it would be unwise to use the Oxygen Test Valve for this purpose, due to persistent spoofing of the Primary Oxygen Sensor, and exposure of this sensor to potentially very high PO_2 values. Thus, a separate Oxygen Replenish Valve (or, in the case of the MK-VI, two Oxygen Replenish Valves) is incorporated into this system that injects oxygen intended to replenish that which is consumed by the diver into a location on the breathing loop where it will not impact the oxygen sensor readings directly. The oxygen injected to replenish the metabolized oxygen would be adequately mixed with the breathing loop gas before it reaches either oxygen sensor.

However, in an emergency situation in which the normal oxygen replenish valve(s) fail to add oxygen to the system, or in a situation wherein an auxiliary safety valve (either manually operated or automatically operated) has closed the oxygen supply feeding the oxygen replenishment valves, then it would be possible to use the oxygen test valve to automatically add oxygen to the system. In such an event, which would be rare, the firmware residing on the system microcontroller would halt the normal oxygen sensing and firing algorithm and would wait for a period of time necessary for the oxygen that was injected through the oxygen test valve to have cleared the respective oxygen sensor cavities and been flushed with the mixed breathing gas resulting from the emergency oxygen addition pulse. At this point the firmware emergency algorithm would re-assess the situation, measure the system PO_2, and determine if further emergency oxygen addition is required through the oxygen test valve.

Automated Turbulent Condensate Purge

The injections of (dry) diluent gas directly onto the sensor also have the simultaneous effect of blowing off any accumulated condensation near the sensor membrane. Through proper mechanical design, this injection process can be turbulent in such a fashion (through computational fluid dynamics modeling and empirical testing) as to lift off condensation from the oxygen sensor sensing surface and cause it to be ejected into the breathing loop (through radial drain holes in the sensor chamber) where it can be captured and stored (e.g. in a sponge trap). This can be achieved with the least amount of expended consumable gas. The injected gas can be pre-warmed by exposure to a heat exchange mechanism with the ambient breathing loop gas to offset the chilling effect on the gas when it is decompressed from an intermediate pressure stage (i.e., upstream of the test valves). The volume of gas injected is small enough that it will have negligible impact on the overall breathing gas composition but it will have the beneficial effect of purging condensate automatically from the Primary Oxygen Sensor without diver intervention.