ANALOX

looking after the air you breathe®

Oxygen sensors in rebreather applications

- Guidelines for use

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Contents

1. Introduction

Analox have supplied oxygen sensors for use in diving applications for many years. To some of our users this may simply be the sensor fitted in their analyser such as the O2EII® which they use for cylinder verification. However we have also been heavily involved in many other specialised applications. These include:

- saturation diving – diving bell, chamber complex and hyperbaric lifeboats
- submarine escape monitors
- submarine rescue vehicles
- submarine dry deck shelters
- diver decompression chambers
- military rebreather systems – single user and multi-occupancy

Recently we have been asked by several customers whether our sensors can be used in their rebreathers.

Our understanding is that the interest in our sensors has come about following the withdrawal of the Teledyne R22D from the market place.

So are our sensors useable in a rebreather. Clearly, from the list above, the answer is very likely to be 'yes'. However, due to the inherent dangers of the application, we feel it is necessary to set out guidelines that a potential user should consider. Hopefully this will better inform rebreather divers and let them arrive at a logical decision before opting to use our sensors. We certainly do not want divers to think that our sensors will solve all the known problems of this technology. Present day sensors will continue to fail for a number of reasons. The design of the rebreather itself will go some way to allowing for some of these failures. At the end of the day, if you don't want to carry risk, please don't dive. If you want to dive, then please read this document and then consider for yourself whether you would like to use our sensors.

We would welcome any further queries from any customers if this document fails to answer any specific questions you may have. Our contact details are on the front page of this document.

2. Sensor types available from Analox

Analox sell an enormous number of different oxygen sensors, and the purpose of this document is not to exhaustively list what all of these are. However we can say that the sensor types include

a) diffusion mode electro-chemical oxygen sensors
b) capillary mode electro-chemical oxygen sensors
c) paramagnetic oxygen sensors

It is the first of these, the diffusion mode electro-chemical sensor, with which this document is concerned. The capillary sensors are intended for use within a narrow band of pressure around standard atmospheric pressure, and are hence unsuitable for diving.

The paramagnetic sensors are excellent sensors, but they are not intended for use where the sensor is moving while measurements are being taken. Even the motion of a ship can cause instability, let alone the movement of a diver.

Within the diffusion mode type of sensor, we have numerous alternatives designed to optimise one or more of the following characteristics:

a) size
b) measuring range
c) mechanical mounting detail
d) waterproofing
e) electrical signal output
f) connections
g) response time
h) temperature range and optimised temperature compensation
i) operating life

So what is a diffusion mode oxygen sensor? Please read on.

3. Oxygen sensor fuel cell

The oxygen sensor is essentially a fuel cell referred to as an electrochemical sensor. The most common electrochemical device is a battery which transforms chemical energy into electrical energy. Although less well known, a fuel cell performs the same transformation. The primary difference between a battery and a fuel cell is the place where the chemical energy is stored. In the instance of batteries, the chemical energy is stored inside the device itself. With fuel cells the chemical energy is stored externally; the rate at which the chemicals are fed into the fuel cell determines the amount of energy or power that is obtained.

Most Analox oxygen sensors use a lead anode and potassium hydroxide electrolyte. The cathode is a perforated metal disc which is plated with an inert or noble metal.

Whenever handling oxygen sensors, always take care to avoid contact with potassium hydroxide which may leak out of the sensor. A leaking sensor will not work properly – discard it (**safely**). There will be instructions in the documentation for your product (if supplied by Analox) which tell you what to do in an emergency. A simple internet search for a material safety data sheet for potassium hydroxide will provide all you need to know for most other sensors.

The fuel cell itself is the heart of the oxygen sensor and is the most important item in determining the performance of the sensor. Does Analox make the fuel cell? ‘No’ is the honest answer. We buy fuel cells from one of several manufacturers, all of which we have assessed and selected for their ability to supply us high quality cells. We then build these cells into our sensors to meet our own specifications.

So what makes the fuel cell into an Analox sensor? Essentially we configure the cell for a specific application by designing the sensor to meet the overall requirements taken from the list of characteristics listed in section 2.

And which characteristics are important to a sensor for use in a rebreather? Simple answer would be ‘all of them’. The manufacturer of the rebreather will have designed it to use a particular sensor with defined mechanical properties, electrical properties and performance characteristics. If you are considering fitting a replacement sensor, clearly it has to meet all of the characteristics of the original sensor, and perhaps provide better performance. In other applications, a user may add cost to the list of characteristics since we all like to grab a bargain. However this is probably less of an issue in a hazardous application such as diving rebreathers. You are probably more concerned at obtaining higher reliability (since your life may depend on it) as opposed to buying the lowest cost sensor.

4. How can Analox help?

The R22D is very similar to other sensors which Analox have been purchasing for several years now. To demonstrate the similarity of sensor characteristics, let's compare a Teledyne R22D with other sensors that Analox sell.

	R22D	9HSUB	O2EII®
Analox Part No	N/A	9100-9212-9HSUB	9100-9220-9B
size	R22 standard	Slightly larger than R22	Same as R22
measuring range	0-2000mbar ppO2	0-2000mbar ppO2	0-100%
mechanical mounting detail	Standard R22D thread	Analox proprietary thread	Standard R22D thread
waterproofing	Pcb conformally coated, hydrophobic membrane	Pcb conformally coated, hydrophobic membrane	Pcb conformally coated, hydrophobic membrane
electrical signal output	7-13mV in air at STP	7-13mV in air at STP	Only for use directly with O2EII®
connections	Molex header	Molex plug	JST
T90 response time	<6 s	<10 s	<10 s
temperature range	0 to 40 °C	-10 to +50 °C	-5 to +50 °C
temperature compensation	Teledyne	Analox	External
typical operating life	3 years in air	5 years in air	5 years in air

There are two things that Teledyne did to their R22D, which differentiated it from the R22S with which they have replaced the product. These are:

a) they applied a conformal coating to their printed circuit board to protect the electronics from effects in the presence of high levels of humidity
b) they fitted a hydro-phobic membrane over the front of the sensor to prevent water causing problems.

Most Analox sensors share both of these properties – we too were using the sensors in environments where water would cause problems. So we too had to use these additional protections.

One important proviso though.

The R22D hydro-phobic membrane was made of the same material as in the Analox sensor, but it was thinner. This meant that oxygen could pass into the R22D slightly more readily. There are three effects of this:

a) faster uptake of oxygen provides a faster response time
b) faster uptake of oxygen causes the sensor to age more rapidly
c) more uptake of oxygen generates a higher current output from the fuel cell

The higher current output is handled by the specific temperature compensation component values, which result in the millivolt signal output being identical. In the Analox sensor, the power generated by the sensor is slightly lower, which means the life will be longer in the absence of any other ageing criteria.

Is this increase in life important in a rebreather? In Analox's opinion, categorically 'No'. We often use the sensor in a different, less arduous application, where a customer is more concerned about how long the sensor will last. It is also calibrated/adjusted immediately prior to use, and therefore at the time of measurement, it is very likely that a faulty sensor will already have been identified. In the rebreather, this claim cannot be made. Yes, the sensor may have been calibrated/adjusted at the surface prior to diving, but it is then essential that the sensor continues to work faultlessly for the duration of the dive, whatever that may be.

For that reason, we assume it is very unlikely that an existing R22D user would even contemplate waiting 3 years to change their sensors. They need to be more certain that the sensor will work faultlessly, and in practice this is usually achieved by more frequent renewal of sensors. Certainly, our military customers of similar sensors opt to change at either 12, 18 or 24 month intervals depending on their own usage mode and frequency. If a customer were to expose a sensor continuously to say 1000mbar ppO2, the sensor life would be considerably shorter than normal – in fact it would be consumed at least five times faster. Hence why some customers try to prolong the life of their sensors by storage in inert atmospheres. We would generally say that because the sensor will last more than 3 years in air, the more frequent replacement in a rebreather (say 12 or 18 months) essentially lessens the need to bother about storage in inert atmospheres. But it is vitally important to flush through any system using higher than air oxygen levels after use, so as not to over-expose the sensors to oxygen.

So because we are not claiming any advantage of the longer life in this application, essentially our sensor actually has the overall disadvantage of a slightly poorer response time.

Does this matter?

Well the honest answer has to be ‘we don’t really know’. So perhaps we need to think about what effects this could cause.

If the oxygen sensor responds too slowly, as the rebreather injects oxygen into the breathing loop, the additional delay in the sensor responding may result in the injection over-dosing oxygen into the loop. How much will depend on the design of the injection system. Can Analox do anything about this? Well we certainly don’t recommend that you start messing about with the injection characteristics of your rebreathers. But what we could do is to fit a thinner membrane to our sensor which would then give it the same response time characteristics as the Teledyne R22D sensor.

Let us know if you would be interested in buying such a sensor.

5. Further guidelines and considerations when using sensors in rebreathers

In this section we want to discuss items specific to the oxygen sensors in rebreathers. It is not meant as a replacement for any advice already given to you by your rebreather manufacturer. So, you must do everything that you have already been advised to do, and then pick out some of the items below which you don't feel are covered adequately.

We came across an excellent article on the Rebreather World forum written by Stuart Ford and titled "Minimising Rebreather Fatalities".

It can be accessed at:

http://www.rebreatherworld.com/general-and-new-to-rebreather-articles/9134-minimising-rebreather-fatalities.html

So why are there problems using oxygen sensors in rebreathers, or in other applications for that matter?

5.1. Ageing of cell

Well as we've said above we are essentially using a device, not unlike a battery, to measure oxygen which is vital for our life support.

Now would we trust our lives to a battery? The honest answer would be that we would prefer not to have to do so. Batteries cause all sorts of problems as we all know simply from using them in a host of items ranging from cars, motorbikes, laptops, mobile phones, portable music players and even the mundane torch.

So why should we trust our lives to the oxygen sensor? Well in short it's probably the best way at present of measuring oxygen in the diving rebreathers, so if we want to go diving, we don't have much choice. So, instead we then need to focus on how to gain the most benefit from the sensor.

For this we need to understand why a sensor may fail? If we know that, then we can work out tests that we can perform prior to a dive to ensure that the sensors are working as expected before a dive. This minimises the risk of entering the water with sensors that are already faulty.

We all know a battery ages. The internal chemicals are consumed in use. In the case of the oxygen sensor, the lead becomes used up, and as there is less lead, the physical output of the fuel cell falls. Also the internal resistance of the fuel cell increases, and it becomes more difficult for the sensor to respond to higher levels of oxygen.

So how do we ensure that the sensor is still capable of measuring oxygen?

Well the short answer is we need to exercise the sensor to make sure it can still respond to high levels of oxygen.

You wouldn't check a battery on a small load. It should be checked on the sort of load it needs to supply. Hence why a car battery might power the radio, but then fail to turn the starter motor. So don't just check your oxygen sensor in air – check it on a higher level of oxygen.

What is a high level of oxygen? Well the R22D (and similar sensors) are capable of measuring up to 2000mbar partial pressure of oxygen (2000 mbar ppO2), and a little further beyond. Your rebreather may limit the range of the measurement, so check its specification. Perhaps you need to decide what maximum level of ppO2 you will need to measure. Whatever that may be, you should add a bit of margin and test to a higher level still. Can you do this at the surface? Well this will depend on the design of the rebreather and whether you can subject the sensors to pure oxygen at say 2 bar absolute without causing other damage. Certainly we are aware of a military breather in which our sensors are used and in which we understand the sensors are tested at 2300 mbar ppO2 prior to every dive. Now with many commercial rebreathers you are unable to perform this check, which is why some divers have either constructed their own pressure testing vessels or purchased commercially available cell-checkers in order to test their sensors. In the absence of such a device, it is common practice to perform an initial test dive say to a depth of 6 metres. Using pure oxygen, the sensors would be expected to read around 1600mbar ppO2. If all of the sensors respond correctly, then use of the sensors to around 1300mbar ppO2 should be OK. But of course you need to be able to interpret the output of each sensor. Don't be misled by any voting software, which may only present to you one reading from the combined set of sensors. If you can't access a reading for each sensor, then this method doesn't provide much benefit.

Now you may have noticed we are talking about 'sensors' rather than 'sensor'. If you are using a rebreather that uses just one oxygen sensor, we suggest that you take a little while to consider your safety.

With one oxygen sensor, you could purely be at the mercy of that sensor if anything does go wrong. This is why most rebreather manufacturers fit more than one sensor.

If you fit two sensors, you may argue that the chances of both sensors failing at the same time are much less. And hopefully you may notice that the two sensors disagree with each other. But how do you know which one is right?

This is where the concept of fitting three or more sensors comes from. The hope is that with three sensors, if one sensor fails, its output will be noticeably different to the other two, such that with a fairly high degree of certainty, the supposed faulty sensor can be ignored, and the dive continue on the basis of the remaining sensors. This ought to be flagged as a fault by the rebreather electronics, such that you should complete your dive so that the suspected fault can be repaired in safety at the surface. Of course we then have to consider how to get to the surface which raises decompression issues, and the time it will take to get there. And in a military dive we may have the added complication that the surface itself may not be safe, due to the presence of hostile enemies or whatever. These are reasons why some rebreathers may have even more complex designs, such that a dive can be continued for longer in the event of one or more sensor failures.

If you did perform a dive with an old, tired sensor that appeared to measure 20.9% (air) correctly at the surface but then tried to maintain say a constant level of say 600mbar ppO_2 at depth, what would happen? Well let's say that your O_2 controller is trying to inject oxygen into the breathing loop, but the sensors only manage to indicate 500mbar ppO_2. The natural action of the controller would be to inject more oxygen into the loop, but the sensor will still limit itself to around the 500mbar ppO_2 reading. The end result would be that the oxygen content in the loop would continue to increase, unless the rebreather electronics was designed to recognise the unexpected conditions and alert you to the danger. Even if you are alerted, you are still in a position of serious risk underwater.

What other faults can occur with the sensor?

5.2. Electrical faults/corrosion

There are the basic electrical type problems associated with any electrical circuit. The fact you are in an underwater environment increases the risk with likely contamination (from salt water in particular). Hopefully, the electronic modules on your rebreather and the sensor modules are well protected to keep the water out. But of course on the inside of the breathing loop, there will be moisture present due to the water vapour present in your exhaled breath. This vapour will condense out and you will experience presence of water inside the loop. Hopefully the desiccant in your rebreather maintains this at comparatively low levels.

So, routine inspection of the sensor modules and the various seals that maintain them dry are recommended. There are two electrode wires which exit from the fuel cell and terminate on the temperature compensation board within the sensor itself. If these connections fail, the oxygen sensor will give an incorrect or eventually zero output. Check your sensors for any signs of corrosion regularly. Check in particular your own electrical connection to the sensor. This is one of the major failure points in some systems. Some people try to avoid having a connector altogether by using a soldered connection, but even this isn't without its own problems. You should still inspect the solder connection for signs of corrosion and contamination.

5.3. Gas bubble in electrolyte

If you were to look inside the sensor itself (we recommend you don't do this because of the chemical hazards, and certainly not with a good working sensor), you would see a soft seal between the electrolyte and the temperature compensation circuit board. In the electrolyte you may sometimes notice a bubble forming. The problem then arises that depending on the orientation of the sensor, the bubble may move to the front face of the sensor which is where the cathode is located. The bubble interferes with the operation of the cathode, and causes a drop in sensor output. So now we have a mechanism by which the fuel cell output will vary with orientation. When a fuel cell is new, it should essentially be immune to this effect, and the sensor output will not vary to any degree that will normally matter. However, as the sensor ages it is worth just checking the orientation effect – you don't want to have a sensor that gives an erratic output depending on your movement. The worst position is when the sensor gas inlet port is pointing vertically upwards, which coincidentally is also an orientation you are best to avoid if there is any excess moisture around the sensors. A layer of water covering the hydrophobic membrane will not damage the sensor, but it will prevent diffusion of gas into the sensor. In this condition the sensor output will simply ramp down at the same rate as the sensor uses up the oxygen already inside the sensor.

5.4. Storage Issues

Storage of the sensor is an interesting subject. How should you store the sensors? Indeed how should we store the sensors before they reach you, because the sensors life starts as soon as it is made.

Any chemical reaction occurs at a faster rate if the temperature increases. Hence the sensor should preferably be stored in cooler rather than warmer locations. Higher temperatures also tend to dry out the electrolyte, which further reduces the life. So keep the sensors either at or around normal room temperature (20 to 22°C), or even cooler. However, do not place the sensor in a domestic freezer which is likely to be around -15 to -20°C. The potassium hydroxide solution will freeze just below -10°C, and it is likely that you may damage or deteriorate the seals within the sensor. If this happens, the sensor will be useless, and remember the safety precautions to be taken if the electrolyte does leak out. Remember to keep your rebreather out of the sun to prevent it, and the oxygen sensors in particular, getting too hot. We don't recommend storing the sensors in a refrigerator either. Doing so ought not to damage the sensor, but the improvement in life is barely perceptible, hence we say not worth the hassle.

5.5. Vacuum packing truths

Some people talk of vacuum packing their oxygen sensors. We would strongly recommend against this for the following reason. If you were to manage to obtain a near perfect vacuum, the electrolyte within the sensor would start to boil. You would rapidly destroy the sensor. The sensors will work to their specified accuracies down to around 800 mbar absolute. Indeed they are used like this in submarines and the like. As you go lower in pressure, the performance drops off, as the effect of the vacuum becomes more pronounced. No noticeable damage occurs even going to 500mbar absolute, but the performance does degrade.

You may have noticed when receiving new sensors from some manufacturers that the sensor appears to have been partially vacuum packed. This actually isn't the case. What is happening is that the sensor has been packaged in a barrier bag, which offers an almost inpenetratable barrier to oxygen. The sensor is actually packaged in the bag in a normal air atmosphere. The bag is then sealed, and the sensor consumes the 20.9% oxygen trapped inside the bag. This creates a partial vacuum inside the bag, which effectively now is almost entirely nitrogen. This partial vacuum deflates the bag and gives it the characteristic part 'vacuum' appearance. This does not damage the sensor, and indeed would be classed as a method of prolonging the sensor's shelf life. Effectively the sensor goes to 'sleep' and only awakens when you cut the bag open. You should allow the sensor time to wake up when opening the bag after prolonged storage periods. You may get away with allowing a couple of hours, but to be sure allow at least a day.

5.6. Shelf life

How long can the sensor be kept in this barrier bag? Shelf lives of up to 24 months are quoted by some suppliers. We would recommend that you did not carry spare sensors for anything approaching this sort of time interval. Remember the real sensor life starts from when the fuel cell was first constructed – not from when you receive it. Buy replacement sensors as you need them, and if you must carry a spare, it is preferable to start using it before it reaches say a 6 month age. If you have an old 'spare' sensor of more than a year old, we would strongly recommend you discard it rather than trusting your life to it. If you really insist on using it, test it thoroughly at elevated oxygen levels to ensure it is still operating satisfactorily.

We have heard of some divers who have rebreathers with multiple sensors, who rather than changing out all sensors at say a one year service interval, opt to change one sensor out at say a 3 or 4 month interval. The claimed advantage is that they don't risk fitting a new set of sensors all from one manufacturing batch, and hence ought not to encounter any batch related problems that could have caused their entire set of sensors to fail. We don't disagree with this philosophy, and would suggest you consider it. It is probably only relevant to you if you use your rebreather regularly around the year. Sadly many of us don't get the opportunity to go diving so frequently unless we work in the diving industry.

5.7. Effect of CO2

It should be noted that carbon dioxide degrades the oxygen sensor. Lead carbonates are formed within the sensor, limiting the amount of lead available for reaction. In a rebreather, the level of CO2 between the exhale and the scrubber will typically be around 30-50 mbar ppCO2. After the scrubber, the CO2 content will almost 0 mbar, increasing up to 5 mbar ppCO2 at the point when your scrubber material is effectively exhausted.

Now since the oxygen sensor is affected by carbon dioxide, clearly the sensors should be located after the scrubber. Also, you can see that frequently changing your scrubber material not only aids your own safety, but it also prolongs the useful life of your oxygen sensors.

5.8. Effects caused by leaking sensors

We've talked above about the health and safety effects of leaking potassium hydroxide. We assume some readers of this document will have experienced a leaking sensor at some time. Presumably they cleaned up the residue of the chemical and fitted a new sensor. One extra caution to mention here. We have heard of a diver who experienced a leaking sensor, cleaned up and replaced it, and then later suffered loss of sensor signal from the replacement sensor. The potassium hydroxide had already leached up the inside of some of the fixed wiring in the rebreather. It had two effects. One was to discolour and corrode the copper wires. The second was that it acted a bit like a thermocouple and actually generated a small millivolt signal which was assumed to be an indication of oxygen. It wasn't oxygen at all. The corroded wires had become brittle and snapped, so the actual oxygen sensor was not even connected. So the advice here is that if you have suffered a leak in the past, or ever suffer a leak in the future, always scrutinise the condition of wiring. If the wiring is discoloured at the ends, it must be stripped back further until there are no signs of corrosion. If this means fitting new wiring looms, then do so!

6. Conclusions

We've talked a lot about problems you may experience with oxygen sensors. We'd much prefer to tell you there were no problems – but we can't, and neither can anyone else at this moment in time.

We do not want you to use our sensors with a false impression of your personal safety. We have tried to present the facts to allow you to be better informed of the pitfalls. We've intentionally kept technical detail to a minimum to make the text more readable.

We hope you have found this interesting. If you would like to discuss any of the technical issues further, we would be pleased to hear from you.

And if you are interested in the supply of specific variants of our sensor, then please do contact us.