How Rebreathers Kill People (and what can be done about it)

Objective: To make using a rebreather no more dangerous than getting on a Boeing 737 shuttle from Edinburgh to London

July 2005

Oct 2005 Updated with Incident 13

July 2006 Updated with Incidents 14 to 20

Sept 2007 Updated with Incident 21 and comparison with O.C. safety

Dec 2007 Updated with incidents 22 to 24

Feb 2010 Updated with accident numbers from the fatality list

Sources of Safety Data

- Failure Mode Effect and Criticality Analysis (FMECA)
- Incident Reports:
  - Incidents Survived
  - Coroner´s Reports
  - Fully Documented Fatalities
  - DAN Reports
  - BSAC Reports
  - Accident investigations

Hundreds times more dangerous than Open Circuit

- DAN report 80 to 100 fatal accidents per 500,000 to 1 million active SCUBA divers in the USA, per year. Non-obese divers (typical rebreather diver), have half the risk: 1 fatal accident per 22,000 diver years.
- BSAC and DAN O.C. accident rates are very similar, despite a larger proportion of BSAC dives being deep decompression dives, and DAN dives are mostly PADI no-deco.
- 164 fatal rebreather accidents have been documented from 1994 to Feb 2010. Even with the conservative assumption of linear growth of rebreather use and an average of around 2500 active participants over that time, this is one a fatal accident rate of one in 243 per year.
- This means that rebreathers have over 100 times the accident rate of Open Circuit; they are getting safer, but still the safety level is astonishingly low.
- There is an order of magnitude difference between the accident rates per user on different rebreathers.
- Each of these statistics indicate that equipment choice has a dramatic effect on dive safety. Why?

FMECA Reports

- Requirement of EN14143 that manufacturers perform an FMECA
- No requirement to publish results
- Most manufacturers keeping their FMECA report confidential
- EN14143:2003 requires compliance with EN 61508, which in turn requires Critical Failures in Time of > 1 in 100 million hours, but is not implemented by manufacturers (CE Marks are being put on equipment falsely)

Users and Government Safety Organisations are turning a blind eye.

- Result is no existing rebreather can tolerate one worst case failure
- Result is users have not the faintest idea of the safety of what they are diving
- Result is no-one can challenge wrong conclusions in a FMECA
- Result is there is no FMECA data on which to built better systems

Recommendation: All manufacturers selling any piece of life critical equipment to the public should publish the full FMECA Report on their web site along with the EN 61508 calculation and safety case.

Some Example Incident Reports

Incidents 1 to 10 are from one dive club. Incidents 11 to 22 are from fatality or serious accident reports.

1. ECCR computer decided to do a cal underwater, all on its own
2. ECCR computer Hanging
3. Displaying wrong PPO2 values when all sensors are working
4. Sudden massive flood, including CO2 hit and caustic cocktail
5. All O2 sensors failed
6. Mistakenly injecting O2 on descent instead of diluent
7. Loss of diluent on descent
8. O2 injector sticks on
9. Connector mismated: flood
10. Manifold O ring fails
11. CO2 retention due to increase in Work of Breathing caused by fitting faulty component
12. CO2 hits due to scrubber failure
13. Unit not switched on
14. PPO2 falls below that required to sustain life due to slow O2 sensors
15. O2 injection rate insufficient for ascent: this is an error in EN14143:2003
16. PPO2 set point allowed to be lower than that required for safe ascent
17. Errors in O2 sensor calibration
18. Bugs in decompression software
19. CNS toxicity
20. Use of uncalibrated "O2"
21. Software error on restart underwater
22. Majority cell error

Incident 1: Jump to Cal

Location: Scapa Flow, May

Dive Profile: Diving to 100ft, displays showed PPO2 at set point of 1.3.
Incident Report: "I heard O2 injector come on and stayed on all of its own accord. Looked at handset. It had jumped to performing a calibration and was injecting pure O2. Bailed out. No alarms. If I had not heard the injector, I would be dead from hyperoxia"

Cause: This eCCR was the market leader. Checks by qualified electronics engineer found:

- Controller was effectively a single unverified microcontroller,running unverified code, compiled using an unverified compiler, running in an incompetent design
- No recognised safety architecure was in use
- Unused memory locations were random codes when they should have been a jump to a recovery point.
- The Brown-Out Circuit was tested and design found to be completely ineffective.
- Power supply circuits were prone to brown out (Battery bounce widely reported)
- Multiple software errors that are liable to cause a fatal accident. No recognised safety architecture is used.

Action taken: Manufacturer advised, corrected some of the shortcomings on new product, but did not recall any product. Another diver died on one of these units in 2007: seven years after manufacturer was made aware of the problem.

Incident 2: Hanging Computer

Location: Scapa Flow, June

Dive Profile: Diving to 110ft, displays showed PPO2 at set point of 1.3.
Incident Report: "It occurred to me that the O2 injector was not firing (it was silent for too long). Did a flush. Displays stayed the same. Did not respond to buttons. Concluded computer had hung. No alarms sounded. Tried switching off and back on. Computer insisted on calibrating O2 sensors. On cal, computer injected pure O2 even though depth was 110ft.
Bailed out. If I had not been listening for the O2 injector, I would be dead from hypoxia."

Cause: The software / electronics engineer for the Inspiration, Nick Hester, reported to have had no engineering qualifications or formal training whatsoever – he was a salesman. Martin Parker, the effective Project Leader, had no formal education after after the age of 16. Both were completely unaware that they were completely incompetent in Functional Safety, making layer upon layer of basic engineering mistakes. Miller and Kruger described the situation well:

"It is one of the essential features of such incompetence that the person so afflicted is incapable of knowing that he is incompetent. To have such knowledge would already be to remedy a good portion of the offence. (Miller, 1993, p. 4) "

- Quoted from J. Kruger, D. Dunning' paper "Unskilled and Unaware of it: How Difficulties in Recognizing One's Own Incompetence Lead to Inflated Self-Assessment", Journal of Personality and Social Psychology, 1999, Vol 77, No.6 1121-1134, a paper highly recommended for rebreather divers.

Recommendations: Certified competencies are a prerequisite for safety engineering

Incident 3: PPO2 errors due to poor circuit board layout

Location: Leith Dock, October

Dive Profile: Quayside

Incident Report: "When injector fires, display PPO2 drops due to current drain. Almost new batteries. System then keeps injector on for too long, so PPO2 level see-saws." Engineers from two companies each specialising in dive safety were present.

Cause: Problem caused by lack of screening on O2 sensor cables and poor power supply circuit layout.

Manufacturer advised, investigated but declined to fix problem until years later. It was a power supply fault (ground loop in the controller itself). This demonstrates a poor level of design expertise in the rebreather controllers, and lack of verification. There was no product recall.

Recommendation: Publishing the information to back up the FMECA would have highlighted the problem. Manufacturer should abandon their policy removing chip markings, painting the board and use of potting compound because it stress the components and hides bad practice: it is also ineffective.

Incident 4: Sudden Flood

Location: Lower Clyde, June

Dive Profile: Deep Support Diver for an extremely deep dive

Incident Report: "Sudden massive flood and CO2 hit. Caustic cocktail inhaled, lots of it. Difficult getting back to surface and staying on surface due to loss of buoyancy because of flood. When CO2 hit, under influence of CO2 hit, caustic cocktail in mouth but hallucinated it was in nose. No warning headache. Became a critical situation. Averted by last second bail out. Due to CO2 did not think of dropping my weight belt."

Forums and bulletin boards contain a number of similar reports.

Cause: Caused by inadequate keying of hose: unit passes pressure tests with hose rotated and not in keyed position if hose nut is tightened down. However, a bump on the hose causes it to fail with water pouring into the scrubber. The hose keying is a serious design fault. Manufacturer advised, disregarded problem, but charged for service of rebreather, writing "Not dishwasher proof" on inside of scrubber lid after user completely stripped it down and tried a dishwasher to remove caked on caustic chemicals. Early warning of a flood (gurgle) not covered in course.

Recommendation: Manufacturer should perform a HAZOP on every component, and its interfaces, in accord with professional safety practice to reduce risk of poor design. Training agencies should ensure students know effect of flood and of CO2 hit: underwater the symptoms of a CO2 hit do not usually include a headache!

Incident 5: Multiple O2 Sensors Fail

Dive Profile: To 160ft, Beside Bass Rock, Dunbar, Scotland, August

Incident Report: “One O2 sensor failed during the dive (lower than others). Continued running on 2 sensors. Injector starting injecting more often than I would expect given constant depth. My respiration was normal. Flush indicated PPO2 was different to what I expected, but not massively (air dil gave a PPO2 of 1.1 instead of 1.2). Concluded (incorrectly) that O2 injector was firing more often due to blockage in O2 line. Aborted dive remaining on closed circuit because handsets showed PPO2 was fine. Twitches on lip developed towards the end of a deco stop at 40ft, assumed (again incorrectly) to be a due to a jellyfish: there were a lot of Lion´s Mane about and one had touched my mask. Bobbing up and down from SMB due to surface conditions, noticed that descending just 6ft again caused injector problem to return. Based on depth and set-point at which injector was working normally (25ft, PPO2 of 1.2), I finally recognised this as a ceiling error on the other two cells and bailed out to air.”

Cause: Unsafe O2 injection algorithm: PPO2 was up to 5.8 at onset of problem! Flush and immediate ascent saved a CNS hit. Replacement of all cells at the same time is a bad practice.

Recommendation: Training agencies should emphasise that a flush with a gas with sufficient FO2 to create a PPO2 greater than the set point is needed to check O2 cells underwater: otherwise procedure should be to flush check O2 and manually add O2 until 0.2 above set point, then allow rebreather controller to take over - diver needs to know what is a normal O2 manual injector press to increase PPO2 by 0.2. Manufacturer should adopt a policy of not fitting sensors from the same batch to all 3 cell positions. Rebreather design can check for ceiling faults such as this much better (by adding causing the PPO2 to oscillate periodically above the set point).

Incident 6: Injecting O2 Accidentally

Location: Dunbar, September

Dive Profile: To 130ft, Beside Bass Rock

Incident Report: "Was very tired that day as I had had a lot of hassle. Still thinking about it during start of dive. Thought alarm was from another diver who had something bleeping (boat load going down together). Before I saw the bottom, felt very bad and left eye was twitching then left eye closed out (like seeing a curtain come down half way and what was left was in negative colour). Saw handset with other eye which was normal. PPO2 was showing over 2.1. Bailed out and simultaneously did max rate ascent to 20ft. Ascent so fast it was off scale of dive computer, a Cochran, which locked out afterwards. Then from 20ft slow ascent to surface. Took about 10 minutes for eye to return to normal."

Cause: User kept pressing O2 button instead of dil button on descent.

Recommendation:

- Would have been avoided if Auto Shut-Off valve fitted.
- Question on why O2 manual button is needed.
- Requires clearer alarms, such as voice annunciation.
- Risk of CNS hit on suddenly reducing the PPO2 should be taught to divers. A commercial diver was accidentally sent pure O2 instead of heliox, giving a PPO2 of over 9.2 - the supervisor noticed the diver's very low voice via the helium descrambler and asked him to return to the bell. The bellman took off the diver's helmet and the diver had an immediate CNS convulsion. This effect is well known to medical chamber operators.

Incident 7: Loss of Dil

Location: Dunbar, September

Dive Profile: To 60ft

Incident Report: "Dil injector came off during descent. Descent accelerated while trying to turn on bail out gas to bail out reg. Hit the bottom so hard it formed a mushroom cloud in the water. Fortunately only 60ft. Embarrassing minute. Had been concentrating on turning on bail out gas (switched off because I did not want freeflow on a back flip into the water from a RHIB), rather than filling the BCD which I should have done: when in a real squeeze, you get tunnel focus on breathing rather than depth."

Cause: Dil connector not plugged in properly, and requires only action to disconnect. No ADV fitted by rebreather manufacturer.

Recommendation: Suggested to manufacturer and to forums that an ADV be created. Many disagreed with need for ADV with connector that is not plug-in.

Incident 8: O2 Injector Stuck On

Location: Scapa Flow, April

Dive Profile: To 110ft

Incident Report: “O2 alarms went off. Injector was firing continuously.”

Cause:

- Injector stuck on, after first stage changed without checking the interstage pressure.
- Solenoid Injectors fail too easily. Solenoid not designed for life critical systems.

Recommendation:

- Cheap solenoid injectors designed for machine automation should not be used for rebreathers as they are prone to rust and cannot tolerate the full range of intermediate pressures provided by dive first stage regulators in common use.
- The injector should be made from a rust free material, with reasonable oxygen compatibility, such as SS 6ML.
- The valve should be controlled by two solenoids, as they are in space systems, to address the problem of solenoid failure, and to ensure there is adequate power reserve available to operate the solenoid under fault conditions.
- Solenoids themselves are fail-critical: both on and off states are critical failures. A variable orifice or variable flow valve should be used instead.

Incident 9: Connector Unplugs

Location: Scottish West Coast, May

Dive Profile: To 90ft

Incident Report: "Flood on an SCR. After an earlier flood event on a CCR, I had changed the original BCD to OMS 110lb dual wing, so no problem with buoyancy this time around, so was able to do instant bail out with no buoyancy problems."

Cause: Connector at the back of the unit: connector seals before it has positive ident. This allows unit to pass all negative and pressure tests with connector not properly engaged. Connector has a single button, which if pressed when the loop has positive pressure (which it always has on an SCR), then the hose connector comes out causing a catastrophic flood.

Recommendation: Where connectors are used in the breathing loop, they must not seal until locked. Locking and unlocking should require two actions. It should be very clear to the user when a connector is locked and when it is not locked.

Incident 10: Manifold Ring Fails

Location: Swimming Pool, Edinburgh

Dive Profile: To 12ft

Incident Report: "Lots of bubbles suddenly. Rotating around I could see it was from back of the unit. Manifold cap came loose. Just swam back on the surface. Rarely use the manifold. Removed it now permanently: it is completely unnecessary."

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Cause: Superfluous manifold, created additional failure points.

Recommendation: FMECA had failed to remove all non-essential points of failure. Apparently the manufacturer had not carried out any formal HAZOPs or HAZIDs.

Incident 11: WOB Failure

Location: Bushman´s Hole, South Africa

Dive Profile: To 900ft

Incident Report: See Report on accident on http://outside.away.com/outside/features/200508/dave-shaw-1.html and analysis of fault on http://www.rebreatherworld.com/showthread.php?t=1337&page=2&pp=10.

Cause: Fitting incorrect scrubber filter material causing increase in Work of Breathing at extreme depth.

Recommendation:

- Fit a Respiratory Monitor, so when respiratory rate becomes too high, or tidal volume too low, warn the user to breathe more deeply and slowly. Same monitor could detect increase in WOB at outset.
- Deep Life have a WOB monitor using the same hardware components as scrubber monitor. This means that adding a WOB monitor does not cost a cent more in terms of hardware build.

Incident 12: CO2 Hits

Location: Numerous reports

Dive Profile: Occurs usually during decompression

Cause: Scrubber expires and no alarm.

Recommendations:

- Fit a CO_2 alarm - these are now entering service in rebreathers (2007)
- Fit an effective scrubber life monitor
- Redesign the scrubber so it does not fail suddenly, but gradually, giving time for the alarm to sound and for the diver to take corrective action.

Incident 13: Unit not turned on

Location: Several deaths where the unit has been found to be switched off

Dive Profile: Not applicable

Incident Reports: Multiple fatal accident reports

Cause: User error and serious safety design errors: lack of HAZOPs, lack of accident analysis

Recommendations:

- All eCCRs should turn on automatically when the PPO2 is below 0.18, or when the PPO2 falls by 0.2 within 10 minutes.
- The use of pressure or wet contacts to turn dive equipment on has been accepted practice for years with dive computers, and is on some rebreathers, unfortunately, not all. However, the falling PPO2 is a more reliable indicator.
- There is no additional cost to the manufacturer to have auto-switch on: there is no reason why this feature should be omitted from a rebreather controller.
- When the unit is switched on automatically, it is essential the design is one where it cannot hang under any possible circumstance. Therefore the user should never need to switch it off underwater.
- The rebreather should not have any software mode where it does not maintain the PPO2 above 0.18. Verified, non-interrupt driven software should be used, if a microcontroller is used at all, to cntrol the PPO2 levels.

Incident 14: PPO2 falls below that required to sustain life due to slow O2 sensors

Location: Found using formal verification tools checking O.R. design, reported on a dive forum, then users of existing rebreathers reported near fatal accidents due to use of slow sensors (I.e. users are fitting the wrong sensor). In a second incident, one batch of R22 sensors was found to have a 50s response time instead of 8s.

Dive Profile: Rapid ascent

Cause: User error and design limitation in one case, design error and manufacturing error in another case.

Recommendations:

- The sensors should be keyed so users cannot change the sensor type
- The control software should check the rate of change of the sensors during cal and reject slow sensors. No existing CCR did this: it was possible to pass cal on all rebreathers that were checked, using sensors with 25 second response.
- 9 of the 11 possible O2 sensor failure modes result in a low PPO2 reading or a slow sensor reading. The sensor voting algorithm can track this. The sensor processing should test for slow O2 response.
- Sensors should be fitted by a technician who has tested them, not by users.
- Use of an Auto Shut Off Valve safeguards the user in the event of this fault

Incident 15: O2 injection rate insufficient for ascent

Location: Found using formal verification tools checking O.R. design

Dive Profile: Low PPO2 set point followed by rapid ascent.

Incident Reports: On dive forums

Cause: Design limitation

Recommendations:

- EN 14143:2003 specifies a minimum rate of 6 litres per minute of O2: this should be 12 litres.
- Manufacturer must allow ascents up to 350ft/min (max possible with an inflated BCD), from the maximum depth and with the lowest PPO2 set point supported by the CCR.

Incident 16: PPO2 set point allowed to be lower than that required for safe ascent

Location: A distinct variant on Incident 15: Found again using formal verification tools checking O.R. design

Dive Profile: Low PPO2 set point followed by rapid ascent.

Incident Reports:

Cause: Design error on particular rebreathers

Recommendations:

- Exhaust valve was on exhale counterlung, so all injected oxygen was swept away from the diver and vented. Exhaust valve must be on the inhale counterlung to avoid this potentially lethal fault.
- The min PPO2 set point when shallow, must allow the diver to “pop” to the surface without the PPO2 falling below 0.21. Within 3m of the surface, the rebreather should operate as a pure oxygen unit. Users need to be taught the need to flush periodically: the PPO2 monitor will highlight this anyway.

Incident 17: Errors in O2 sensor calibration

Location: Red Sea

Dive Profile: Deco dive

Incident Reports: Reported and discussed on RebreatherWorld. Note of much higher DCI incidence with CCRs than expected statistically.

Cause: User error and design omission, allowed the user to calibrate the CCR as if it was 98% O2, when PPO2 level in the loop could have been as low as 48%. Result was Cat III DCI.

Recommendations:

- All O2 sensors should calibrate in air when the unit is open: users should not be asked to calibrate with a gas supply which may not in itself be calibrated, injecting an uncalibrated amount of gas into an uncalibrated loop volume (the procedure used by the manufacturer).
- The rebreather must check the sensors after calibration using pure O2, such as by filling the loop with O2 after the negative pressure test. The rebreather can calculate what the FO2 of the “O2” actually is. Some divers are using membrane separated O2, which is as low as 92% O2: the remainder includes a high proportion of argon. If this gas is used, then as the O2 is metabolised, the loop fills with argon. This can cause a sudden loss of consciousness at depth: argon anaesthesia is very different to nitrogen narcosis. This is related to Incident 20.

Incident 18: Bugs in decompression software

Location: Multiple incidents and locations

Dive Profile: Deco dives

Incident Reports: Analysis of statistically high incidence of DCI on rebreathers, followed by formal verification of dive software in the O.R. project which compared results with those from several sources. No direct link, but strong indicator of link.
Formal verification of the original Buhlmann papers, show even the implementation used to create the results published in those papers, is not actually from the algorithm that is described: it uses only 13 tissue compartments instead of 16 to 18.

Cause: Failure to follow mandated design procedures (in EN61508, to comply with PPE Directives)

Recommendations:

- All decompression software should be formally verified to prove that the algorithm implemented is actually that intended.
- Unproven decompression algorithms should not be used.
- The reliability of the decompression computer should be sufficient such as to mitigate the risk of a diver using one computer for a series of dives, then switching to another because the first one has locked out or failed. Lockout is a dangerous feature.

Incident 19: CNS toxicity

Location: Multiple

Dive Profile: Long dives

Incident Reports: 6 accidents involving of CNS convulsions. See http://www.rebreatherworld.com/rebreather-accidents-incidents/1632-o2-convulsion.html#post16022 and http://www.rebreatherworld.com/technical-rebreather-forum/4304-guide-about-setpoint-selection-deep-dives.html

Cause: Incorrect use of CNS calculation. Original papers describing CNS calculation is based on a 4% reduction in vital capacity with 100% CNS loading (Oxygen Toxicity Calculations. E. Baker). NUI research paper indicating 1% of users having CNS toxicity effects at 75% CNS loading. Despite this, users believe they can tolerate 100% CNS loading as a basic plan: some report regular dive planning with 175% and 250% CNS loading. There is also a problem that if hypercapnia occurs, then the CNS tolerance is reduced enormously: CNS convulsions have occurred with a PPO2 as low as 1.0 under those conditions.

Recommendations:

- Modified CNS algorithm, with margin to reduce statistical incidence of measurable CNS damage. Published on DL Web Site, and on RebreatherWorld, with formal model to enable implementation to be verified
- CCR controller should track CNS and maintain within safe limit by adjusting PPO2 set point if necessary

Incident 20: Low FO2 in O2 Cylinder

Location: Singapore and UK

Dive Profile: Not applicable

Incident Reports: RebreatherWorld http://www.rebreatherworld.com/rebreather-accidents-incidents/5513-my-first-screw-up-boris-2.html and one incident reported through dive club

Cause: User error and design omission allowed user to dive with 60% O2 in cylinder used as 100% O2. Almost a fatality in both cases.

Recommendations:

- Rebreather itself should check the O2 composition before every dive. It has calibrated O2 sensors (if the recommendation to force calibration in air), and can inject O2 and check the composition of the loop gas on the surface to give an injector cal. It is not complex to compensate the injector cal for depth, such that no gas switch can introduce a low FO2 gas
- Voice annunciation of the resulting low PPO2 level would have prevented the problem affecting the diver's safety: buzzers are too difficult to locate, and too frequent underwater.
- See incident 17 also.

Incident 21: Software Error

Location: Isle of Man, fatal accident, several others very similar

Dive Profile: To 37ft / 11msw

Incident Reports: Detailed accident report available to authors

Cause: When unit is reset due to battery bounce, it does not re-enter dive mode automatically. Due to unit thinking it has a cell error, due to the high PPO2, it cannot enter dive mode. In another incident, if the master is disabled, the slave sat in a non-dive mode until diver died from hypoxia.

Recommendations:

- On reset, if the rebreather is under pressure or the diver is breathing (measured by the PPO2 falling), then the unit should immediately measure the PPO2 and if less than 0.18 inject O2 to maintain a breathable gas in the breathing loop.
- A recognised safety architecture should be used for rebreather electronics, such as Time Triggered Architecture (applied to software, as well as communicating hardware units). This would mean that the frequency at which the controller checks the PPO2 level would be fixed and cannot be disturbed by other interrupts.
- There should be no software mode where the rebreather does not maintain PPO2 within the range 0.4 to 1.3.

Incident 22: Cell Error

Location: Australia

Dive Profile: Under 40msw

Incident Reports: Fatal Accident. Detailed accident report available to authors

Cause: Unit did not require any regular factory service. User had not replaced O2 cells in 3 years. User was partially deaf and could not hear the buzzer.

Recommendations:

- Units should lock out if not serviced annually, with a 3 month margin.
- Units should test the O2 cells properly before a dive, automatically. This can be done within ALARP.

Incident 23: Poor rebreather profile

Location: Incident in Turkey and two fatal accidents

Dive Profile: 190ft / 56msw

Incident Reports: The rebreather was being tried out in the configuration in which it left the factory. This did not have any provision for attaching weights to the top of the rebreather. As a result the attitude in the water was not horizontal, but at an angle, and as the dive progressed the diver became tired and vertical. In a current, this would cause a very large increase in effort, and breach safe Work of Breathing (WOB) limits.

It is noted that this rebreather, and almost all others, fail to meet the WOB limits in EN14143 (which are a copy of well established limits for Open Circuit regulators). A high WOB to start with plus the diver being unable to keep a prone profile, has caused fatal accidents before, but the lesson has not been learnt.

Cause: Absence of a simple weight pouch.

Recommendations:

- Manufacturer should have made provision for users to correctly weight the rebreather
- Some users are attaching weights to the cylinders using CAM bands: this is dangerous, as sooner or later, they will fall off and may cause an uncontrolled ascent.
- Manufacturer needs to carry out HAZOPs and other safety processes, that would have identified this and other errors.

Incident 24: Poor PPO2 control

Location: Incident in Turkey and other reports on dive forum

Dive Profile: Incident occurred in surf

Incident Reports: The PPO2 set point was 0.7: unit allows users to set as low as 0.4. Access to the water involved a walk across sand carrying the heavy rebreather and a 12 litre bail out cylinder. Diver still breathing heavily when putting his fins on. Found the PPO2 was varying, to as low as 0.36. Reported on Rebreatherworld, other users confirmed problem and that they had experienced it going hypoxic on a 0.7 set point.

Cause: Error in PPO2 control design, with sensors on different side of scrubber to injector.

Recommendations:

- Delay in PPO2 control loops reduce accuracy
- High RMVs need to be tested for (as they are in NORSOK U-101 and by navies).
- Manufacturer needs to carry out HAZOPs and other safety processes, that would have identified this and other errors.

Incident 25: Electronics potted with hot glue

Location: Red Sea

Dive Profile: Two divers at 100msw

Incident Reports: One diver suddenly lost consciousness, rescued by second. Regained consciousness within a few minutes. Dive aborted.

Cause: Clearly a failure to control PPO2. Diver ripped the controller apart to see what it was, and found the wires and electronics very corroded. Controller is potted in black epoxy (not potted under vacuum, so the potting contains many voids). Underneath the black potting compound the electronics was found to be covered in hot glue. Water had come down the cable into the hot glue, which had separated from the pcb due to the heat from the black epoxy, had caused the corrosion. This is one of the leading brands of rebreather.

Recommendations:

- Rebreather electronics should be in silicone oil, not hot glue or potting
- Electronics in silicone oil should include a sensor to detect water in the oil and advise the diver

Other Reports

- No coordinated central body receiving information on rebreather deaths.
- Diver Mole was doing a good job for Inspiration, but list very incomplete, and sometimes puts down to user error what is equipment failure.
- Too many reports simply cite "User Error". Needs to be a change of attitude to: "Nobody dies on a rebreather from user error, unless they take the mouthpiece out of their mouth and do not replace it with something."
- Diver Mole´s List of Inspiration Fatalities is:
- http://www.btinternet.com/%7Emadmole/DiverMole/DMDanger.htm#Mick

How to make rebreathers safe

- The first obstacle facing organisations wishing to improve rebreather safety is that there has been no database for incidents and accidents from which to learn, to prevent repeating mistakes of the past. To address that issue, Deep Life Ltd has created a central comprehensive database of rebreather accidents and is sharing that with the dive safety agencies and manufacturers.
- The second issue with rebreather safety involves equipment and training:
  - Contemporary rebreather designs are nowhere near the standard expected of other life critical systems. Deep Life is campaigning for all rebreathers to be brought up to EN61508 as is required by law in Europe, and will assist lawyers claiming damages that result from failure to meet this basic safety standard.
  - Most manufacturers have no staff with formal training in the design of life critical systems. Complying with EN61508 would require companies to remedy that gap, thereby providing better safety designs to benefit all rebreather users.
  - Open review and fitting better safety systems could have prevented all of the incidents reported here. Deep Life is forging the way with open review of safety systems.
  - Technologies are available that would have prevented every one of the incidents cited here. Deep Life is publicising those technologies and making them available to rebreather OEMs.
  - Some of the accidents could be mitigated by better diver training. Deep Life is campaigning to eliminate training that is irrelevant or hazardous, such as practicing removing a rebreather underwater, and focus on the core diver education: keeping PPO2 and CO2 within safe limits.