REBREATHER SAFETY

FMECA Volume 6: Top Down Faults

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Controlled Document ☐ Classified Document ☐ **Unclassified if clear.**

Revision History

Revision	Date	Description
A	1st Aug 2004	Cases initialised.
B8	26th May 2008	Independent Review 2nd Aug 2006. Inclusion of section for Surface Supplied Diving. B1 with item 7.13. B2 with Commercial dive tool hazards and O2 cells fatal accident due to diver not hearing alarm. B3 submarine sonar hazard and ESD hazards. B4 cold water faults. B5, Isolating ADV faults. B6 (4th April 2007) ADV fault added to fault 6.1. B7, Added ADV failure incidents and connector failures. Hypoxia monitor added. B8 OPV failures broken out as a separate section and detailed. Helmet oro-nasal valve failure added. Water drain faults added.

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1 PURPOSE AND SCOPE

This document is a top down Failure Mode Effect and Criticality Analysis of the first Open Revolution rebreather submission developed by Deep Life Ltd.

This document serves a dual purpose, namely:

1. To provide a check list to ensure that top level failures are managed safely by the rebreather. This top down method is matched by a bottom up review of the electronics, mechanics, software/firmware and a hierarchical fault tree analysis down to component level.
2. To provide a structured framework for the analysis of equipment after an accident to determine whether or not the equipment contributed to, or caused, the accident The evidence can be ompared with all possible causes to develop a "plausible cause" list, that can be further reduced using formal verification (mathematical modelling of the known dive profile to identify the point where the problem occurred).

All references to "the system" refer to the Open Revolution submission by Deep Life Ltd. References to "mandatory checks" refer to the pre-dive checks performed by that specific rebreather controller.

This document covers the rebreather itself: it does not cover high pressure cylinders and other systems that may be connected to the rebreather – these should have a separate FMECA or safety certification.

2 SOURCE DATA

The failure modes listed in this document are drawn from numerous sources. The prime sources are listed in [1] to [7] in the references. Other sources include HAZID and HAZOP studies, FMECA studies on contemporary equipment, rebreather internet forums, coroner reports , equipment failure reports issued by public health laboratories or warnings issued by rebreather manufacturers., and accident appraisal advice from accident investigators

Each fault mode attributable to equipment has been encoded in a formal fault model in the Open Revolution rebreather environment. This model is a Matlab model, which has been published by Deep Life Ltd to enable the safety of new rebreather designs to be verified.

The formal verification environment allows any of these faults to be selected, combined with any other(s), and then applied to verify the safety performance of the equipment under these fault conditions.

Efforts have been made to encourage other manufacturers to use, critique and extend these formal models. There has been some independent review of the models by others working on rebreather design. The objective is to create an industry-wide consensus on the formal fault models needed to verify the safe operation of rebreather apparatus.

3 STRUCTURE

This report classifies faults into groups, based on the section of the equipment associated with the failure.

There is an inevitable duplication of some failures. For example, breathing bags (counterlungs) becoming detached is one failure, but it is also listed under WOB increase in the section on PPCO2 Control, as breathing bag detachment is one cause of such an increase. The view was taken that it is better to include duplication than miss critical failure modes. This approach also simplifies the use of the fault list in HAZOP reviews.

4 SIL COMPLIANCE OBJECTIVE

The objective of this system is compliance with SIL 4 of EN61508. This requires a mean time between critical failure better than one billion hours, and a system availability of 100,000 hours subject to routine maintenance and preparation.

The SIL 4 objective has been concluded by applying the processes in EN61508 with the ALARP principle (As Low As Reasonably Practicable risk), in the context of a rebreather which is supplied as an Open Circuit replacement with more than 10,000 units in use.

This top level fault list considers "plausible failures" as any failure with a probability greater than one in a billion hours of diving, multiplied by the number of faults listed, so the aggregate risk is less than 1 in 10^9.

5 OXYGEN SUPPLY FAILURES

5.1 Oxygen Cylinder Empty

Cause & Prevention

Use of empty cylinder: will not pass pre-dive checks but user could dive anyway.

Diving with not enough O2 for the dive: system enforces dive abort when O2 consumption and O2 remaining do not allow user to reach surface with 50 bar in tank.

A leak. System enforces abort when insufficient O2.

Hose failure from O2. Forces bail-out and abort of dive.

First Stage Failure, including over-pressure relief, O2 ring failure. Forces bail-out, and abort of dive. Dive abort can be on Semi-Closed. This situation is the worst-case test case for Auto-ShutOff valve control.

EN61508 Implication

System manages each failure mode, and where not recoverable, forces Bail-out to open circuit or diluent flush-and-fly unit in semi-closed mode.
Important that user is not allowed to dive unless there is enough O2 to reach the surface, including deco. System should monitor DIL and O2 levels. O2 fraction should not be allowed to drop below that of air at the same depth, and projection should use a 1.76l/min of O2 in calculating this availability, plus the loss of gas during ascent (using the known maximum dead volume of the loop).

Issue where hypoxic DIL is used is a serious one: diver should be warned.

5.2 Oxygen Cylinder Switched Off

Cause

Switched off on dive boat after pre-dive checks, and forgetting to switch on again.

O2 cylinder accidentally turned off during dive, due to handle rubbing on something. Use of soft materials (elastomers) for the cyclinder valve knob makes this problem occur more often than using hard handles, as does some ribbing patterns on the handle.

Symptoms

Handled, in case of Low O2, by the Injector-led O2 controller finding an imbalance between injected gas and measured gas, then going into diagnostic mode, finding that injecting gas causes no gas, and treats failure first as a cylinder-valve-shut failure, then, if user confirms valve is open, as an injector failure. If second injector has same fault, requests user to turn on cylinder valve.

Recovery action during Dive

Urgent. Open O2 valve, ready to bail out to open circuit or diluent flush-and-fly unit in semi-closed mode. User is advised of this action, and system forces it with the Auto ShutOff valve.

Preventative action

This is a common fault, as the O2 valve knob sticks out from the cylinder and is easily rubbed. The worst position is when the O2 cylinder is hung like a stage, when the valve rubs on clothing.

Check position of valve and ensure it is covered, but still accessible.

Do not use soft materials for cylinder valve knobs.

EN61508 Implication

System should not allow the oxygen cylinder to be switched off prior to the unit being switched on, unless the unit is already underwater when it is switched on, in which case the situation is handled as during the dive, as described below.

System should monitor O2 injector and O2 pressure. Where a mismatch occurs, the error message should be specifically "O2 Tank Valve is Closed. Open it!" Requires a digital contents gauge on the O2 and DIL tanks coupled to the CCR controller.

It is noted that OMS has have stopped supplying rubber knobs due to their greater risk of "grabbing" and turning themselves off or on. OMS have switched to hard plastic knobs with a surface that is less likely to move with friction.

5.3 Oxygen First Stage Failure

Same as cylinder contents empty, but sudden onset.

This fault mode includes other causes, such as the 15 micron filter being blocked prior to the O2 injectors, blockage of all O2 injectors. All have the same effect.

5.4 Oxygen First Stage Over Pressure

Cause

Poor maintenance, wear of first stage, corrosion or contamination.

Symptoms

Surface

Only if battery low. Solenoid can fail to fire before low battery warning given. Hence failure to calibrate. Failure to hold set point during pre-breathe. Low O2 Alarm Sounding.

Dive

Only if battery low. Solenoid can fail to fire before low battery warning given. Hence failure to hold set point during pre-breathe. Low O2 Alarm Sounding.

Recovery action during Dive

Urgent. Bail out to open circuit or diluent flush-and-fly unit in semi-closed mode.

Preventative action

Check interstage pressure during servicing and use fresh batteries.

EN61508 Implication

Verify the O2 injector works for all possible O2 intermediate pressures.

5.5 Oxygen Hose Leaks

Cause

Wear, poor maintenance.

Symptoms

Surface

Failure to calibrate. Failure to hold set point during pre-breathe. Low O2 Alarm Sounding. Oxygen contents gauge showing low or audible air loss from cylinder.

Dive

Failure to hold set point. Low O2 Alarm sounding. Oxygen contents gauge may show empty. Bubbles in water.

Recovery action during Dive

Urgent. Bail out to open circuit or diluent flush-and-fly unit in semi-closed mode.

Preventative action

Pre-dive checks.

EN61508 Implication

Monitor O2 usage (requires O2 contents gauge and declaration of tank size). Give specific warning of leaking hose.

5.6 Oxygen Solenoid Stuck Open

Cause

Corrosion, poor maintenance, salt crystals or contaminates in unit. High Interstage pressure. Low Battery.

Symptoms

Surface

Failure to calibrate. Failure to hold set point during pre-breathe. High O2 Alarm Sounding. Counter lungs full.

Dive

Failure to hold set point. High O2 Alarm sounding. Excessive buoyancy. Can hear solenoid injecting at all times.

Recovery action during Dive

Urgent. Close O2 valve. Bail out, or diluent flush. Option to fly manually using O2 valve or to go semi-closed.

Preventative action

Regular service. Lube and ensure solenoid clean. Check mesh filter above solenoid. Recharge Batteries.

EN61508 Implication

The oxygen injector should not be a solenoid, but a variable orifice valve, so that when it fails, the failure state maintains the average oxygen consumption.

Fit an Auto bailout and shutoff valve.

5.7 Oxygen Solenoid Stuck Closed

Cause

Corrosion, poor maintenance, salt crystals or contaminates in unit. Low battery. High interstage pressure

Symptoms

Surface

Failure to calibrate. Failure to hold set point during pre-breathe. Low O2 Alarm Sounding.

Dive

Failure to hold set point. Low O2 Alarm sounding.

Recovery action during Dive

Urgent. Fly unit manually using manual O2 injector. Consider bail-out.

Preventative action

Regular service. Lube and ensure solenoid clean. Check mesh filter above solenoid. Fresh batteries.

EN61508 Implication

The oxygen injector should not be a solenoid, but a variable orifice valve, so that when it fails, the failure state maintains the average oxygen consumption.

Fit an Auto bailout and shutoff valve.

5.8 Oxygen Manual Injector Failure

Cause

Poor maintenance. Failure to plug hose on properly.

Symptoms

Surface

Failure of pre dive checks.

Dive

Loss of gas from loop, flooding of loop.

Recovery action during Dive

Urgent. Reconnect Hose or re-screw injector down. Bail out if loop flooded.

Preventative action

Pre-Dive checks.

EN61508 Implication

Eliminate the failure point: Design out the manual O2 injector.

5.9 Wrong Gas in Oxygen cylinder

Cause

Nitrox fill or gas other than 100% oxygen.

Symptoms

Surface

Failure to calibrate (maybe). Failure to hold set point. Lungs full.

Dive

Failure to hold set point (maybe). Excessive buoyancy and injector function.

Recovery action during Dive

Bail out (diver does not know what gas he is breathing).

Preventative action

ALWAYS analyse your gases after a fill.

EN61508 Implication

Calibrate the O2 Cells in air (by detecting when the scrubber can is open). Make provision for saturation environments.

Check the O2 injector by a positive pressure test during startup, and check O2 Cell response is as expected.

5.10 Oxygen fire

Cause

Poor O2 handling.

Contamination.

Poor maintenance.

Unsuitable materials.

Preventative action

Proper design and maintenance procedures.

Proper training of operators.

Use gases with 23% less 02.

EN61508 Implication

Ensure all materials in breathing loop and all materials in contact with high-pressure oxygen are O2 compatible, as listed by the latest available NASA O2 compatibility report.

5.11 Calibration using wrong gas

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.

Preventative action

Calibrate using air when scrubber is open, then check during descent near surface.

EN61508 Implication

Rebreather itself should check the O2 composition before every dive. It has calibrated O2 Cells (if the recommendation to force calibration in air is followed), and can inject O2 and check the composition of the loop gas on the surface to give an injector call. It is not complex to compensate the injector call for depth, so that no gas switch can introduce a low FO2 gas.

Auto Shut Off Valve would have prevented the problem affecting the diver's safety.

Voice annunciation of the resulting low PPO2 level would have prevented the problem affecting the diver's safety.

5.12 Solenoid Stuck Shut, due to rise in Intermediate Pressure

Cause

Rapid ascent in combination with O2 solenoid having narrow operating range.

Preventative action

Eliminate O2 solenoids.

EN61508 Implication

Carry out a full safety verification and assessment of the O2 injector to ensure it operates correctly with all possible intermediate pressures.

5.13 O2 orifice motor driver failure

Cause

Poor maintenance, or failure of component: motor, position sensor, etc.

Symptoms

Surface

PPO2 should not equal 0.7ATA.

Should be detected automatically, as PPO2 level changes but the output of the position sensor is constant.

Dive

Should be detected automatically, as PPO2 level changes but the output of the position sensor is constant.

Recovery action during Dive

None required if system recovery is sufficient. If second unit fails, then bail out.

Preventative action

Check motor operational range during self check sequence.

EN61508 Implication

Should be detected automatically, as PPO2 level changes but the output of the position sensor is constant.

System should connect the second driver to the control loop and user is advised of this action.

Urgent (when PPO2 level increases beyond the set point after the connection of the second driver), user should be required to Flush or ascend.

5.14 Use of O2 instead of DIL, using hypoxic DIL, to excess depth

Cause

Untrained diver using hypoxic diluent, and pure O2 above hyperoxic depth.

Preventative action

Proper training and experience in buoyancy control.

EN61508 Implication

Eliminate manual O2 injection.

Detect what the DIL gases are and run as a pure O2 rebreather automatically when above 6m.

5.15 Use of hypoxic DIL in ascent to surface

Cause

Loss of O2.

Use of wrong bail-out gas.

Use of wrong cylinder of gas.

Poor training.

Preventative action

Monitor O2 and DIL gases.

EN61508 Implication

Eliminate manual gas injection.

Ensure O2 injector can keep breathing loop at full pressure at maximum rate of ascent (120m/min). Include torpedo test and fast ascent test in O2 injector verification.

5.16 Uncontrolled ascent (max 120m/min) with low PPO2

Cause

Loss of weight belt.

Catastrophic failure of buoyancy control device or injector.

Entanglement with a towed object.

Entanglement with an SMB or lift bag.

Preventative action

Improved training to handle SMBs and Lift Bags properly.

Keep weight belts to simple belts rather than weight jackets.

OPV should be fitted to inhale counterlung to ensure gas flow from injectors does get to the inhale counterlung.

EN61508 Implication

Covered by “end to end” clause.

Ensure PPO2 can be maintained with 120m/min ascent rates by specific inclusion in O2 injector verification plan.

To avoid this fault, the rebreather should not allow PPO2 set points which are lower than the corresponding fraction of O2 in air, until it becomes necessary to limit CNS exposure. Use of PPO2 not less than air, to at least 30m, is recommended.

Note OPV should be fitted to inhale counterlung, not exhale counterlung.

5.17 PPO2 low due to injection not keeping up with demand

Cause

User error and design limitation.
User flushes loop with hypoxic diluent.
Overlap with some other errors, such as running out of O2 or injector failure.

Symptoms

Dive

Gasping.

Recovery action during Dive

Control software should check the rate of the depth sensor and PPO2 cells and reject slow sensors.

Preventative action

User is advised to decrease the ascending rate. Service regularly and test /inspect.

EN61508 Implication

Eliminate design limitation: injector should be able to provide at least 12l/min of O2.

Manual flush rate should be limited so that with no O2 in diluent gas, user cannot reduce the PPO2 to below 0.2.

5.18 Low PPO2 set point followed by rapid ascent.

Cause

User error and design limitation. Implicated in several fatalities where user has a PPO2 set point of 0.4, then ascends rapidly. This is a special hazard near the surface where the diver does not have time to respond to a failure.

Recovery action during Dive

Control software should check the rate of the depth sensor and PPO2 cells and reject slow sensors.

Preventative action

The min PPO2 set point, when shallow, should allow the diver to “pop” to the surface without the PPO2 falling below 0.21.

EN61508 Implication

The rebreather should increase PPO2 to operate as a pure O2 rebreather above 6m.

The injector should be able to inject 12l/min.

5.19 ADV freeflow with hypoxic DIL near surface

Cause

ADV leakage or freeflow on entering the water, with hypoxic diluent, resulting in diver hypoxia.

Manual flush, where DIL is hypoxic.

Preventative action

Not to start dive unless PPO2 is 0.7, not to allow hypoxic dil on surface unless injectors can achieve at least 12l/min of O2.

EN61508 Implication

Hypoxic diluents should be run via a manifold and not used near the surface.

Detect what the DIL gases are and decline the dive if hypoxic on surface.

PPO2 should be 0.7 or above to start dive.

O2 injectors should be able to achieve 12l/min.

ADV injection rate should be limited to 12l/min.

5.20 ADV freeflow with high PPO2 at depth

Cause

ADV leakage or freeflow at depth with dil having excessive FO2. See also fault 6.1.

Manual flush at depth with dil having excessive FO2

Switching the wrong gas on a manifold.

Preventative action

Dive training to use appropriate gases for dil.

EN61508 Implication

Hyperoxic diluents should be run via a manifold and switched out at depth, such as by turning the cylinder off and manifold off.

O2 injectors should be able to achieve 12l/min.

5.21 Left to Right Flow, instead of correct Right to Left loop flow

Cause

Rebreather uses left to right flow, so oxygen addition is on right counterlung if diver keeps to convention of “Rich on Right”. When a problem occurs, this means DIL is added to gas being inhaled instead of oxygen (because oxygen has to pass right around the loop as it si plumbed into the exhale counterlung). This can be hazardous if DIL is hypoxic.

Preventative action

Use Right to Left loop flow, with Rich O2 on right, DIL on left.

EN61508 Implication

Covered by end-to-end scope.

6 DILUENT SUPPLY FAILURES

6.1 Diluent Cylinder Empty

Cause

Someone forgot to fill the cylinder, or a bad leak from any part of the cylinder to ADV routing.

ADV freeflow due to poorly designed or adjusted ADV or hydrostatic pressure between ADV and OPV less than the OPV cracking pressure.

Symptoms

Surface

Failure of pre-dive checks, diluent contents gauge reads zero.

Dive

Lung squeeze on descent, unable to inject diluent. Auto Air Out not functional. Dry suit inflate not functional.

Recovery action during Dive

Plug in a reserve gas supply. Inflate lungs with manual O2 inject if above 6m.

Preventative action

Pre-dive checks.

EN61508 Implication

System should monitor DIL pressure. Where a mismatch, the error message should be specifically "DIL Tank Valve is Closed. Open it!" Requires a contents gauge on the DIL tank.

6.2 Diluent Cylinder Switched Off

Cause

Valve rubbed, or forgetfulness.

Symptoms

Surface

Failure of pre-dive checks, diluent contents gauge reads zero.

Dive

Lung squeeze on descent, unable to inject diluent. Auto Air Out not functional. Dry suit inflate not functional.

Recovery action during Dive

Open valve.

Preventative action

Pre-dive checks.

EN61508 Implication

System should monitor DIL pressure. Where a mismatch, the error message should be specifically “DIL Tank Valve is Closed. Open it!” Requires a contents gauge on the DIL tank. Force user to inject DIL in pre-dive check.

6.3 Diluent First Stage Failure

Cause

Wear, corrosion or structural failure.

Symptoms

Surface

Failure of pre-dive checks, diluent contents gauge reads zero.

Dive

Lung squeeze on descent, unable to inject diluent. Auto Air Out not functional. Dry suit inflate not functional.

Recovery action during Dive

Plug in a reserve gas supply. Inflate lungs with manual O2 inject if above 6m.

Preventative action

Service correctly and pre-dive checks.

EN61508 Implication

System should monitor DIL pressure. Where a mismatch, the error message should be specifically “DIL Tank Valve is Closed. Open it!” Requires a contents gauge on the DIL tank. Valve unlikely to fail totally and suddenly. System should detect a rapid drop of pressure.

6.4 Diluent First Stage Over Pressure

Cause

Wear, poor maintenance or corrosion, poor design, icing or structural failure. Poor adjustment.

Symptoms

Surface

Auto air free flow, BC inflation.

Dive

Auto air free flow, excessive buoyancy in BC, or dry suit, or ADV.

Recovery action during Dive

Shut down diluent valve. Manually operate when needed (shouldn't need to surface). Consider bailout if alternate supply.

Preventative action

Service correctly and pre-dive checks.

EN61508 Implication

Outside the eCCR, but the “end to end” clause in EN61508 may encompass this failure. Monitor DIL contents and check for leakage pre-dive.

6.5 Diluent Hose Leaks

Cause

Wear. Poor maintenance.

Symptoms

Surface

Failure of pre-dive checks. Audible gas escape. Diluent contents decreasing.

Dive

Audible gas escape. Diluent contents decreasing.

Recovery action during Dive

Abort dive.

Preventative action

Pre-dive checks and servicing.

EN61508 Implication

Outside the eCCR, but the “end to end” clause in EN61508 may encompass this failure. Monitor DIL contents and check for leakage pre-dive.

6.6 Diluent Manual Injector Failure

Cause

Poor maintenance.

Failure to plug hose on properly.

Symptoms

Surface

Failure of pre dive checks.

Dive

Loss of gas from loop, flooding of loop.

Recovery action during Dive

Urgent. Reconnect hose or re-screw injector down. Bail out if loop flooded.

Preventative action

Pre-Dive checks.

EN61508 Implication

Design out by using an ADV. If ADV fails, diver should bail out as there is insufficient volume of breathing gas on descent, detectable as a negative pressure in the loop compared to ambient. Instruct user to bail out.
Requires independent bail-out.

6.7 Wrong Gas In Diluent Cylinder

Cause

Cylinder filled wrongly.

Symptoms

Surface

None with normal pre-dive checks.

Dive

Problems maintaining set point during descent.

Recovery action during Dive

Abandon dive, or connect alternate diluent source (not likely to notice during dive).

Preventative action

Analyse ALL gases prior to use. Once unit is calibrated you can check the diluent O2 content by doing a diluent flush. This should be added as part of the pre-dive tests.

EN61508 Implication

Monitor gas during descent, and monitor END.

6.8 Alternate Air Source Free Flow

Cause

Dirt or high diluent interstage pressure.

Symptoms

Surface

Failure of pre-dive checks. Audible gas loss.

Dive

Audible gas loss and bubbles.

Recovery action during Dive

Disconnect Auto Air, or try shaking to reseat things. Consider aborting dive.

Preventative action

Service equipment and pre-dive checks.

EN61508 Implication

Outwith the eCCR, but covered by "end to end" clause.

Monitor DIL contents.

6.9 No ADV or ADV Off

Cause

No ADV or ADV tends to free-flow, so user switches it off.

Symptoms

Surface

None.

Dive

Incident report by Dr. Mike Gadd, submitted to RebreatherWorld: http://www.rebreatherworld.com/rebreather-accidents-incidents/19356-witness-to-a-fatality.html#post189115

What's so difficult about hitting the manual add? Nothing when your sat at your desk or when doing a gentle descent.

But as a safety feature when shit hits the fan a demand valve will automatically give you enough volume to enable you to breathe when there's an unexpected (not a planned) issue that effects your loop volume (such as rapid descent) It will also facilitate and encourage 'sanity breaths' from nose breathing out at first feeling of co2 - which I believe is a good safety feature

I once jumped in carrying a large stainless steel axe a crow bar and some slings. Very negative. Unfortunately my adv was turned off and the gear I was carrying obscured my manual add. The tank feeding my wing (and bov) wasn't as the qc wasn't fully connected. As I plummeted down to the depths like a speeding train my CLs collapsed I was totally unable to breathe, unsure as to why my wing wasn't inflating, fumbling trying to find the manual add buried under all the gear/stages i was carrying, my ears were in so much pain you cant imagine. In my stressed state (rapid uncontrolled descent, unable to breathe and ear pain) I simply couldn't locate the manual add or fix the wing inflation issue fast enough. It was most unpleasant. I bailed to OC (which was fun because same qc fed the bov! so at first no gas from bov (which I found interesting) so went for offboard 2nd stage :-)) regained my buoyancy and learnt a good lesson. I was only in 95m of water……

then there was the time after a 100m dive when I had to throw the anchor over the pinnacle wed just dived so we could free float deco under the attached buoy. The descending anchor chain snagged on my stage tank and pulled me rapidly down again. On and inspo the adv shut off I had to deal with freeing myself from the dropping anchor, manually inject gas or switch on the adv so I could breathe. I couldn't do both at the same time! If the adv had been on I would have had both hands free to focus on the snag.

then there was the time i was so wasted on CO2 that I was laying on the seabed doing an impression of a fish. waiting and not really caring too much about dying. I was unable/uninterested in moving my arms tio find and press the manual add - I suspect if my adv had been shut off the extra small effort needed to turn it on would have meant I wouldn't. As it was my adv saved my life as I did the only thing I could be bothered to - breathed out my nose. My adv fired, after a few breaths my mind began to clear to a point I could do a manual flush and get my shit together....my adv saved my life

In both the above times not having an adv would have been doable - but it adds stress and task loading to an already stressful and task loaded situation - that's why I think having an adv is better than not

An adv is a simple demand valve - hardly rocket science. It will give you gas when you need the volume automatically<u>. It shouldn't fire unless you have too low a loop volume, it shouldn't fire with normal breathing, it shouldn't fire (too much) if your at different angles.</u>..imo it doesn't need to be that light. The only thing worse than not having one, is having one but needing to keep it shut off

.

Recovery action during Dive

Disconnect Auto Air, or try shaking to reseat things. Consider aborting dive.

Preventative action

Service equipment and pre-dive checks.

EN61508 Implication

Outwith the eCCR, but covered by “end to end” clause.

Monitor DIL contents.

7 CONTROLLER FAILURES

7.1 Battery Low

Cause

Over-use, or internal failure.

Symptoms

Surface

Low Bat warning on handset. Solenoid not functioning. Cannot maintain set point.

Dive

Low Bat warning on handset. O2 Injector not functioning. Cannot maintain set point.

Recovery action during Dive

Abort dive. Variable orifice valve should maintain PPO2 if ascent rate is slow, otherwise activate Auto Bail-out and Shut Off valve.

Preventative action

Pre-Dive checks and measure battery voltage before dives. Recharge when warning is shown or before big dive.

Fault incidence reduced by design: O.R. submission includes 3 independent power sources, two of which are maintained at 1 ATM.

EN61508 Implication

Lack of power is the Achilles Heal of electronics. Provide 3 power sources, with different drain rates, and do not allow dive unless adequate capacity (10 hours minimum).

7.2 Battery Failure

Cause

Over-use or internal failure. Water in battery compartment.

Symptoms

Surface

No handset.

Dive

No handset. Solenoid not functioning. Cannot maintain set point.

Recovery action during Dive

Slave should take over. Abandon dive. If both fail then bail out if you have no alternative means of monitoring PPO2.

Preventative action

Pre-Dive checks and measure battery voltage before dives.

EN61508 Implication

Lack of power is the Achilles Heal of electronics.

Show battery state during power-up sequence.

Provide 3 power sources, with different drain rates, and do not allow dive unless adequate capacity (10 hours minimum).

7.3 Power Drop-out or Battery Bounce

Cause

Poor battery and contact design. Manifest when entering water by rolling backwards on to turtle shell. Momentarily disconnects batteries.

Battery failure.

Symptoms

Surface

None.

Dive

Hanging. "Dive Now?" message and "Waiting for Data" messages.

Recovery action during Dive

Urgent. Perform start-up cycle. DO NOT CALIBRATE.

Preventative action

Design out the problem.

Always check handsets immediately after entering water.

EN61508 Implication

Battery contacts cannot meet EN61508. Design out the problem by using multiple redundant rechargeable Lithium Ion Gel batteries, soldered in.

Test using swept power drop out, with drop outs from 1us to the time interval needed to activate the Brown Out Circuit.

7.4 Handset failure apparent to user

Cause

Flooding, wiring or mechanical breakage.

Symptoms

Surface

Blank screen.

Dive

Blank screen.

Recovery action during Dive

Main controller should take over. Abandon dive.

Preventative action

Protect handsets and check wiring during service.

EN61508 Implication

Perform full JTAG testing during power-up sequence.

Use multiple devices in handset, so failure of one clock or one integrated circuit should not cause loss of handset.

Provide a HUD in addition to handset.

Base unit should be automative.

7.5 Handset or Controller Hangs

Cause

Incompetent design: single processor, single clock source, single power source, no heartbeat monitor (watchdog circuits), no brownout circuit.

Symptoms

Surface

Screen should not change.

Dive

Screen should not change, no alarms.

Recovery action during Dive

Bail out.

Preventative action

Problem should be eliminated by design.

EN61508 Implication

This is a problem that occurs with some handsets examined during FMECA studies of contemporary equipment. The normal design procedures applied for safety critical systems should prevent this. The system should check automatically during normal start-up that these safety design provisions are operating correctly.

Ensure Watchdog circuit is operating by halting the clock for the Watchdog period.

Ensure Brown-Out circuit is operating by power cycle test.

Ensure state machines have redundant states to detect failure and return unit to safe operation.

Fill all unused memory locations with recovery code.

Routines should apply predicates in input data so that random jumps to the routine can be detected and recovered.

The start-up sequence should detect if an abnormal shutdown occurs, so immediate recovery can be carried out.

Any such failure should be logged and the unit permanently locked out on the surface.

The circuit should have multiple clocks, power supplies and other circuits so that the MTBCF of the circuit exceeds the SIL 4 requirement by sufficient margin to ensure that, when coupled with the MTBCF of the mechanical components, the overall MTBCF is still above 1 billion hours.

7.6 Handsets Switched off

Cause

Design fails to keep handsets switched on when unit is being used.

User often switches handset off if it fails in an obvious or dangerous manner underwater. For example, if keeps injecting O2 despite PPO2 being sufficient, or enters calibration mode.

Be very careful to analyse all failures where user surfaces with handsets switched off, especially with experienced users.

Symptoms

Surface

Pre-dive check failure. Blank handsets. No pre-breathe.

Dive

No handset display.

Recovery action during Dive

Bail out or die.

Preventative action

Pre-dive checks and basic monitoring of unit.

EN61508 Implication

Occurs in units where there is a failure of the electronics and user switches the handset off to try and bring the unit back up. Several cases where user has died before unit has come back up.

Solution adopted is to design out the problem: ensure unit powers on automatically whenever the PPO2 is less than 0.19.

Eliminate all possibility that the unit can “hang”.

Provide an HUD which also switches on automatically when PPO2 is less than 0.19, and cannot switch off when unit is under pressure.

EN61508 requirements would demand handset switches on automatically when unit is used.

7.7 Oil Filled Chamber Leaks Oil

Cause

Mechanical damage.

Poor servicing or maintenance.

Reservoir piston to accommodate thermal expansion is stuck.

Reservoir for thermal expansion is too small.

Symptoms

Surface

Filling oil visible inside unit.

Dive

Smell of the filling oil inside the loop.

If the pressure sensor is inside the oil-filled volume, it will show a lower (smaller) depth than is the actual depth.

Recovery action during Dive

Bail out.

Preventative action

Check unit for signs of leakage.

EN61508 Implication

HC sensor will detect leakage if the oil contains any hydrocarbons, but use of hydrocarbon filling oils is a dangerous practice and not recommended. Use of waxes (solid paraffins) causes serious problems with thermal expansion.

This failure could be detected using a differential pressure sensor, but this is an expensive solution that is prone to failure due to the thermal expansion of the oil.

Solution adopted by Open Revolution submission is to use food grade silicone oil to avoid a health hazard, and to remove all components liable to offgas from the oil-filled volume (moving them to a 1ATM compartment in the sea water). The remaining components then operate as if they are inside the breathing loop. This is then not a critical failure.

Consideration should be given to adding a perfume to the filling oil, so any leakage is apparent from the smell in the loop.

7.8 Electronic Component Explodes

Cause

Use of inappropriate components.

Failure becomes critical if component is not completely separated from the breathing loop.

Symptoms

Surface

Odour inside breathing loop.

Dive

One-off noise.

Odour inside breathing loop.

Recovery action during Dive

Bail out.

Preventative action

Eliminate risk by design.

EN61508 Implication

Perform full self-test on power up.

Eliminate all components liable to explode (tantalum or electrolytic capacitors, all components incorporating a gel or a gas, all components incorporating an electrolyte).

Components that cannot be eliminated, such as the batteries, to be moved to a 1 ATM environment outside the rebreather, that can physically withstand the pressure rise from the component being vapourised. That is, the 1 ATM environment should withstand the vapour pressure from boiling off the electrolyte.

7.9 User unaware of failure message or unable to act

Cause

User should not understand the warning.
User is injured and not able to actuate unit, e.g. CNS toxicity.
User is entrapped by netting or cable limiting mobility.
Failure of back light on handset where user relies totally on the handset and is using the handset in a dark environment.
Failure of voice annunciation system where user relies totally on the voice annunciation.
Failure of buzzer, where user relies totally on buzzer.
Failure of Head Up Display.

Recovery action during Dive

Read the warning message, using a torch if necessary.

Preventative action

Proper maintenance and training.

EN61508 Implication

Provide a reference: in the Open Revolution submission this is the text display under the main handset display. This displays the failure and the action required. If in doubt the user can look to this display and receive succinct instruction on how to correct the problem, and its significance.

Provide multiple annunciation: the four above are included in the sports rebreather configuration – in the commercial diving configuration the handset functions move to a topside console.

Provide an automatic bail-out valve so user cannot ignore critical actions.

7.10 Faulty Software

Cause

Design not compliant with EN61508.

Symptoms

Surface

Any software malfunction.

Dive

Any software malfunction.

Recovery action during Dive

Bail out.

Preventative action

Ensure design meets EN61508.

EN61508 Implication

The industry is using software where nothing is verified, and even normal practices for non-safety-related software, such as automated GUI checks, are not applied.

No software or hardware control meeting EN61508 should encounter these issues at a safety critical level. The software should be formally verified.

7.11 Handsets Misread

Cause

Poor visibility in halocline or thermocline, with small font-size on handsets.

Lack of back light.

Symptoms

Surface

Error in reading handset.

Dive

Error in reading critical information on handset.

Recovery action during Dive

Check handset more carefully.

Preventative action

Check handset carefully.

EN61508 Implication

The main handset should have the largest display which it is practical to carry.

Large displays carry an increased risk of damage due to being dropped or mishandled. Suitable materials should be chosen to minimise this risk.

Displays should be backlit.

7.12 Cracked Electronics Housing

Cause

Housing subject to excessive mechanical stress, before dive or from pressure.

Inappropriate materials or stresses in handset design.

Symptoms

Surface

Electronics malfunction.

Dive

Any electronics malfunction.

Recovery action during Dive

Bail out.

Preventative action

Service correctly and pre-dive checks.

EN61508 Implication

This problem occurs with electronics, particularly handsets that are not EN61508 compliant.

If the handset has two sets of electronics, then a failure of any one part should not cause failure of the whole. This is a natural product of any design meeting SIL 4.

The electronics should perform a JTAG test on start-up: this would identify the problem prior to dive.

7.13 Corroded wiring

Cause

Caustic cocktail.

Unit left in flooded condition.

No, or inadequate, conformal coating to wiring.

Use of inappropriate cable, such as non-plated cable.

Symptoms

Surface

Electronics malfunction. Visible corrosion.

Dive

Any electronics malfunction.

Recovery action during Dive

Bail out.

Preventative action

Service correctly and pre-dive checks.

EN61508 Implication

This problem occurs with electronics that are not EN61508 compliant.

The electronics should perform a JTAG test on start-up: this would identify the problem prior to dive.

7.14 System Looping on Interrupts, raising PPO2

Cause

FMECA on a contemporary system: no battery level indicator, using primary cells (i.e. user replaceable), where the handsets resets over and over if the battery is low and the handset will fire the solenoid every time it resets.

Preventative Action

Competent design.

EN61508 Implication

Consider effect of watchdog timers and brown out circuits firing repeatedly, blocking other actions.

ISO 12207 recommends avoidance of interrupts in Cat A safety systems. Any departure from that recommendation should be fully supported by a detailed safety case and verification.

7.15 High Voltage on Connectors

Cause

Poor EMI, with static discharge. Up to 25KV static discharge can occur in operational environments, especially if rebreather is on a trolley or conveyor before being touched or contacting an earthed metal object.

Connectors that carry power and signal, e.g. commercial rebreathers where there is 24V umbilical power and twisted pair for data. Water gets into connector (such as when they are unplugged), shorting 24V to signal.

Symptoms

Surface

Loss of data.

Dive

Loss of data, which in a poor design could propagate.

Recovery action during Dive

Return to bell, or bail out.

Preventative action

Separate power and data, protect data lines from direct connection to highest voltage power source used in connection with the equipment.

EN61508 Implication

Requires unusually high degree of data line protection.

7.16 Brown out cycling

Cause

Brown out circuit activated, rebreather restarts causing increase in power consumption, causing repeated brownout.

Symptoms

Surface

Can fail to inject O2.

Dive

Ditto

Recovery action during Dive

Bail out.

Preventative action

Design out the problem.

Use fail safe injectors, and put into safe mode on detecting brown out or power down: requires sufficient capacitance to operate valve.

EN61508 Implication

Requires design verification of this failure mode, and cycling of brown-out events.

7.17 Failure to turn on

Cause

Design error: failure to use an appropriate safety critical architecture, such as TTA.

Note this fault Is covered elsewhere.

Symptoms

Surface

Diver is breathing from equipment that is turned off. Diver passes out.

Dive

Ditto but diver drowns.

Recovery action during Dive

Inject gas immediately.

Preventative action

Design out the problem.

Rebreathers need to switch on automatically with falling PPO2.

EN61508 Implication

Requires at least wet contacts to turn unit on, requires preferably automatic switch on with falling PPO2.

7.18 Single points of failure

Cause

Design error: a single short, open or component failure, causes controller failure leaving it in a unreasonably dangerous state.

Symptoms

Surface

Hung controller.

Dive

Ditto but diver drowns.

Recovery action during Dive

Inject gas immediately, bail out.

Preventative action

Design out the problem.

Use a competent safety architecture.

EN61508 Implication

MTBCF required for entire electronics system. Pay special attention to connectors, where any signal may be shorted to any signal by water. For example, power may be applied to low level signal lines.

7.19 ESD failure

Cause

Design error: failure to protect design from sufficient Electro-Static Dischrage (ESD).

Symptoms

Surface

Hung controller, jump to unexpected state, I/O lines not functioning normally.

Dive

Ditto.

Recovery action during Dive

Inject gas immediately, bail out if controlled behaves unexpectedly.

Preventative action

Design out the problem, to withstand 50KV HBM.

Use a competent safety architecture.

EN61508 Implication

Highest plausible discharge is 50KV HBM: this is generated by a person walking across a carpet. It is not expensive or difficult to protect dive equipment from this level of discharge.

7.20 EMS failure

Cause

Design error: failure to achieve adequate protection from electro-magnetic susceptibility (EMS).

Symptoms

Surface

Hung controller, jump to unexpected state, I/O lines not functioning normally.

Dive

Ditto.

Recovery action during Dive

Inject gas immediately, bail out if controlled behaves unexpectedly.

Preventative action

Design out the problem, to withstand 3000 Amps / metre DC, and 100 Amps per metre AC due to use of underwater cutting, welding and surface radar on ships.

Use a competent safety architecture.

EN61508 Implication

EMS requirements should be considerably higher than for CE standards for general equipment.

8 OXYGEN SENSOR FAILURES

8.1 O2 Cell Decompression Failure

Cause

Differential pressure on O2 cell.

Rapid decompression.

Rupture of rear membrane inside O2 Cell causes KOH to be deposited on to temperature compensation board.

Symptoms

Surface

Not apparent.

Dive

If the diver flushes the loop, the PPO2 will be different from that expected.

Recovery action during Dive

Bail out.

Preventative action

Careful inspection of sensors. It is unreasonable to expect the user to do this on every dive.

EN61508 Implication

This is a serious failure in that it causes the O2 Cell reading to fluctuate both high and low depending on temperature.

Solution adopted is to change the sensor design to allow this problem to be detected. The temperature compensation circuit is removed and replaced with a 100Ohm load. The electronics check for the existence of the 100Ohm load to verify that the correct sensor type is fitted and the load is there. Only then will it use that sensor reading (otherwise it will report a faulty sensor). This eliminates the problem at source.

8.2 O2 Cell has CO2 Contamination

Cause

High level of CO2, such as from pre-breathing without a scrubber, causes CO2 to migrate across O2 cell membrane, into KOH, where it converts KOH into water.

Symptoms

Surface

Not apparent.

Dive

If the diver flushes the loop, the PPO2 will be different from that expected.

Recovery action during Dive

Bail out.

Preventative action

If CO2 level high on start-up, check cells for droop.

EN61508 Implication

This is a serious failure in that it causes all O2 Cell readings to read low.

This should be detected automatically by doing the O2 flush under start-up sequence control, and hence eliminated.

O2 Cells need to be characterised for degree of droop in CO2 and cells selected that do not suffer from CO2 poisoning. Teledyne R22D and Analytical Industries PSR-11-39 series sensors tolerate CO2.

8.3 Load Resistor Failure in O2 Cell

Cause

Cell has a load resistor, typically 82 to 390, to bleed off the charge generated by the cell, and convert the charge into a current through the resistor, so the voltage from the cell can be measured. If the resistor becomes open circuit, the output voltage on the cell increases until there is another discharge path. This can create very high voltages with enough power stored in the capacitance of the cell to destroy 10K HBM input protection.

Preventative Action

Competent design.

Avoid cells with multiple components in the output: more components means a greater failure risk.

EN61508 Implication

Use a connector which always mates ground before signal, and protects the connections from corrosion.

Do not wire all cells to one chip, whether one ADC, one MUX or one op-amp block (e.g. a quad op-amp). This affects the redundancy design: there needs to be either four sensors so no more than two are routed to a chip, or three completely independent ADC channels.

8.4 O2 Cell Contamination

Cause

Organic material in O2 Cell KOH solution.

Symptoms

Surface

Drift of O2 Cell readings

Dive

May manifest as a ceiling fault during the dive.

Recovery action during Dive

Eliminate the sensor from the PPO2 calculation.

Preventative action

Check sensors for drift. Replace sensors that drift.

EN61508 Implication

Requires that the system check for need for sensor replacement and for sensor drift during successive calibration cycles.

8.5 O2 Cell Thermal compensation failure

Cause

Manufacturing fault, or component failure in O2 cell.

Symptoms

Surface

Not apparent.

Dive

If the diver flushes the loop, the PPO2 will be different from that expected.

Recovery action during Dive

Bail out.

Preventative action

Careful inspection of sensors. It is unreasonable to expect the user to do this on every dive.

EN61508 Implication

This is a serious failure in that it causes the O2 Cell reading to fluctuate both high and low depending on temperature.

Solution adopted is to change the sensor design to allow this problem to be detected. The temperature compensation circuit is removed and replaced with a 100Ohm load. The electronics check for the existence of the 100Ohm load to verify that the correct sensor type is fitted and the load is there. Only then will it use that sensor reading (otherwise it will report a faulty sensor). This eliminates the problem at source.

8.6 O2 Cell Loose Connection

Cause

Corrosion or poor maintenance.

Symptoms

Surface

Intermittent "Out of Range" or "Failure" messages on a cell. Failure to calibrate.

Dive

Intermittent "Out of Range" or "Failure" messages on a cell.

Recovery action during Dive

Diluent flush to check other 2 sensors respond correctly. Consider bail out. Abandon dive.

Preventative action

Service carefully.

EN61508 Implication

Use an SMB connector to minimise risk, by having a connector with multiple contact faces.

8.7 O2 Single Cell Failure

Cause

Exhausted or out-of-date cell.

Cell internal failure.

Water on the face of the cell.

Mechanical damage to the cell.

Damaged connector.

Symptoms

Surface

Intermittent "Out of Range" or "Failure" messages on a cell. Failure to calibrate.

Dive

Intermittent "Out of Range" or "Failure" messages on a cell.

Recovery action during Dive

Diluent flush to check which sensors respond correctly. Consider bail-out. Abandon dive.

Preventative action

Replace cells at correct intervals (every 12 months).

EN61508 Implication

Withstand multiple cell failures.

Engineer the cells so all failures are in the same direction (low).

8.8 O2 Two Cell Failure

Cause

Exhausted or out-of-date cells. Insufficient ions to produce voltages representing high O2 above set point.

Sensors exposed to CO2 following scrubber breakthrough.

Symptoms

Surface

Intermittent "Out of Range" messages on a SINGLE cell (the good one). Failure to calibrate.

Dive

Intermittent "Out of Range" messages on a SINGLE cell (the good one). Failure to calibrate.

EN61508 Implication

PPO2 controller should withstand multiple cell failures.

Engineer the cells so all failures are in the same direction (low).

Test the sensor ceiling by applying a higher load, while the sensor is in pure O2 during pre-dive checks. For example, if normal load internal to the sensor is 100 Ohms, then apply 50 Ohms to check ceiling is not lower than a PPO2 of 2.0.

8.9 O2 Cell Failures Tracked Incorrectly

Cause

Multiple O2 Cell failures with voting logic.

Preventative action

Do not use voting logic.

EN61508 Implication

Eliminate problem by carrying out a fault assessment of O2 Cell failure modes, then test of O2 Cells to a Test Plan to verify those modes.

Use sensor fusion algorithm that can detect one good sensor among faulty sensors.

Provide means to check sensors automatically when a sensor failure occurs, such as injecting a known quantity of O2. This requires a calibrated O2 injector: this can be done automatically during pre-dive checks.

8.10 All O2 cells fail during dive

Cause

Fatality occurred where more than two O2 cells failed but system allowed dive.

Diver was partially deaf and did not hear alarms.

O2 sensors were marked with a date code, which was not immediately obvious: all sensors were around 3 years old. Diver was old and may not have recalled change date.

Preventative action

Proper checking of sensors.

EN61508 Implication

Use sensor fusion algorithm that can detect one good sensor among faulty sensors, and detect any faulty sensors.

Use visual feedback in HUD in addition to audible alarms, or use vibrating mouthpiece.

Pre-dive checks should force the checking of the O2 sensors.

O2 sensors should be marked very clearly in large letters with a date code, such as “SEPT 06”, not “J6” in small letters.

Use different colour sensor bodies for each year.

Provide means to check sensors automatically when a sensor failure occurs, such as injecting a known quantity of O2. This requires a calibrated O2 injector: this can be done automatically during pre-dive checks.

8.11 O2 Cell Calibration Incorrect

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.

Preventative action

All O2 Cells 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).

EN61508 Implication

Eliminate problem by calibrating on air.

8.12 O2 Cells show different reading to independent PPO2 monitor

Diluent flush to check which sensors respond correctly. Bail out. Abandon dive. Unit will maintain O2 limits on the 2 bad cells as they out-vote the good one. O2 will be high.

Preventative action

Replace cells at correct intervals (every 12 months). At start of dive, drive cells above set point to ensure they can respond fully.

EN61508 Implication

Withstand multiple cell failures.

Engineer the cells so all failures are in the same direction (low).

8.13 O2 Cells have condensation on sensor face

Cause

Moist, warm, saturated gas, condensing on objects in the gas flow.

Symptoms

Surface

Normally none.

Dive

Intermittent "Out of Range" or "Failure" messages on a cell.

Recovery action during Dive

Diluent flush to check which sensors respond correctly. Bail out. Abandon dive.

Preventative action

Latest cells have face which is hydrophobic. Insulate loop to lower condensation.

EN61508 Implication

Withstand multiple cell failures.

Important issue is to ensure calibration is not carried out in cells with water on their faces. This is an issue if the calibration is performed while fitting a new scrubber. The calibration should be performed after the scrubber is closed.

The training manual should emphasise the checking of the unit by a DIL flush.

8.14 O2 Cells have differential pressure applied

Cause

Unequal pressure on front and back of sensor cells during dive.

Symptoms

Surface

None.

Dive

Intermittent "Out of Range" or "Failure" messages on a cell.

Recovery action during Dive

Diluent flush to check which sensors respond correctly. Bail out. Abandon dive.

Preventative action

Ensure gas flow to rear of cells. Make sure pressure equalisation holes are clear, and that the sensor pcb has equalisation holes.

EN61508 Implication

Withstand multiple cell failures.

Ensure the design allows adequate gas flow to rear of cells to eliminate the source of failure.

Engineer the cells so all failures are in the same direction (low).

8.15 O2 Cell Explodes or Leaks

Cause

Lockout of an O2 Cell in a chamber.

Dropping an O2 cell causing electrolyte leakage

Symptoms

Surface

Shrapnel injury to operator. Strong alkaline spray (KOH).

Dive

Not applicable.

Recovery action during Dive

Not applicable.

Preventative action

Do not decompress O2 Cells faster than a human can withstand.

EN61508 Implication

Verify that sensors specified for product do not produce shrapnel when suddenly decompressed (Torpedo test).

Warn operators that if an O2 Cell feels wet, they should wash the sensor and hands in warm water immediately. Requires note in training manual.

Verify the O2 sensors to ensure there is no electrolyte leakage if dropped from 1.5m repeatedly and from 3.0m.

8.16 Oscillating sensor

Cause

Peculiar O2 sensor failure mode, where O2 cell value oscillates.

Symptoms

Surface

Not obvious.

Dive

PPO2 is poorly controlled.

Recovery action during Dive

Switch to manual control.

Preventative action

Well designed electronics should detect this case.

EN61508 Implication

Very thorough O2 cell screening is required.

8.17 Diver fails to monitor PPO2

Cause

Diver assumes rebreather is managing PPO2, but rebreather has failed.

Symptoms

Surface

Sudden Loss of Consciousness from hypoxia.

Dive

Diver drowns after a sudden Loss of Consciousness.

Recovery action during Dive

Not applicable.

Preventative action

Electronics should time diver to ensure diver observes PPO2 with required frequency.

EN61508 Implication

Hypoxia risk alarm required, that does not use oxygen sensors: it can compute potential PPO2 deviation from changes in ambient pressure and metabolism. Deviation can be reset to zero when user observes PO2 by forcing user to use switch to see PPO2.

This is an equipment issue, not a diver failure, because the diver is human and humans cannot be relied upon to perform every function perfectly all of the time. It is unreasonably hazardous to expect them to do so on a life support system.

9 DIVER FAILURES

9.1 Breathing off loop that cannot sustain life

Cause

User fails to bail out.

User may be deaf and not hear the alarms (implicated in a dive fatality).

Frequent cause of fatalities on CCRs.

Symptoms

Surface

Any warning ignored.

Dive

Any warning ignored.

Recovery action during Dive

Bail out.

Preventative action

Force bail-out automatically if user should not act on warnings.

EN61508 Implication

Implement a fail-safe automatic shut off valve; bail-out is essential.

10 CO2 RELATED FAILURES

10.1 Scrubber Not Fitted

Cause

User error.

Symptoms

Surface

Rapid breathing, headache. Hypercapnia.

Dive

Stuffiness, rapid breathing, confusion.
Hypercapnia.

Recovery action during Dive

Bail out.

Preventative action

Provide monitoring to check presence of scrubber.

EN61508 Implication

Monitor scrubber health.

Monitor scrubber life.

Monitor when the scrubber is changed.

Monitor PPCO2.

Measure breathing resistance across scrubber, to detect this failure automatically.

10.2 Scrubber Physically Damaged, affecting gas X-section

Cause

Poor handling, with poor user check when installing scrubber.

Symptoms

Surface

Rapid breathing, headache. Hypercapnia.

Dive

Stuffiness, rapid breathing, confusion. Hypercapnia.

Recovery action during Dive

Bail out.

Preventative action

Check scrubber visually before installation. If granular scrubber, weigh the scrubber.

EN61508 Implication

Provide monitoring to check for pressure across scrubber when user opens mouthpiece after positive pressure test. Absolute pressure records drop over time, and max pressure in loop, so differential pressure across scrubber varies only as a function of poor scrubber packing, fitting or damage.

10.3 Scrubber Exhausted

Cause

Overuse or improper storage. Out of date.

Symptoms

Surface

Rapid breathing, headache.
Hypercapnia.

Dive

Stuffiness, rapid breathing, confusion.
Hypercapnia.

Recovery action during Dive

Bail out.

Preventative action

Change the scrubber every 3 hours or sooner.

EN61508 Implication

Monitor scrubber health.

Monitor scrubber life.

Monitor when the scrubber is changed.

Monitor PPCO2.

10.4 Scrubber Bypass

Cause

Gas flows rapidly through a single path in the scrubber and CO2 is not removed.

Bad packing. Material published by APD indicates that a large proportion of their user base cannot pack a granular scrubber properly to prevent this problem.

The most popular axial scrubbers have an endemic by-pass of 0.1 to 0.2% CO2 due to poor scrubber design. This means the scrubber should be tested flat in these designs.

Symptoms

Surface

Rapid breathing, headache.
Hypercapnia.

Dive

Stuffiness, rapid breathing, confusion.
Hypercapnia.

Recovery action during Dive

Bail out

Preventative action

Design-out the problem by using an EAC.

EN61508 Implication

Monitor scrubber health.

Monitor scrubber life.

Monitor when the scrubber is changed.

Monitor PPCO2.

Granular material packed by users will not meet EN61508 at any SIL level.

Design-out the problem using an EAC.

10.5 Excess Work of Breathing

Cause

Diving to excess depth for the rebreather.

Use of filter or skrim material to prevent caustic dust.

Overpacking of scrubber.

Moisture absorbed by scrubber during use increases breathing resistance and hence WOB.

Flooding.

Mushroom valve stuck shut.

Counterlungs change position.

Preventative action

Diver should be trained to be aware of an increase in breathing rate and bail out.

EN61508 Implication

Measure WOB actively during dive.

10.6 Counterlungs change position, causing CO2 hit

Cause

Possibility to put on rebreather without counterlungs being fixed down.

A fatal accident occurred where the counterlungs floated above the diver due to not being fixed down correctly, causing CO2 retention. This can be due to poor range of sizing or failure to fix down the counterlungs either within the counterlung bag, or fix down the bag itself.

Symptoms

Surface

Not noticeable.

Dive

Increased WOB leading to severe CO2 hit.

Recovery action during Dive

Bail out on to open circuit.

Preventative action

Service correctly and pre-dive checks.

Diver should be trained to be aware of the importance of fixing down the counterlungs.

EN61508 Implication

Counterlungs should be fixed down so that user cannot disconnect one end, or fail to attach counterlungs.

Active monitoring of respiratory parameters is needed.

10.7 One Way Valve (Flapper valve) Stuck Open

Cause

Valve not fitted.

Valve stuck open due to debris in the valve, particularly following a flood or vomiting into the loop.

Some valve designs allow them to jam open.

Incorrect assembly: mushroom is inserted on to the wrong side of the spider.

The wrong mushroom is inserted to the wrong side of the mouthpiece.

Symptoms

Surface

Same as scrubber breakthrough.

An attentive diver may notice the breathing bags moving in a different sequence to normal.

Dive

Same as scrubber breakthrough.

Recovery action during Dive

Bail out.

Preventative action

Pre-dive check for valve operation.

EN61508 Implication

The function of the two one-way valves fitted either side of the mouthpiece is critical to the safe operation of the unit.

The design should be of a type that shall not stick by itself. The Open Revolution design conforms with this requirement: it is a silicone mushroom valve, with no springs or other elements.

The mushrooms should be colour-coded and of a different design on each side, so the exhale mushroom cannot be inserted to the inhale valve, and vice versa.

The spider supporting the mushroom should have pegs to prevent the mushroom being assembled on to the wrong side of the spider.

The two spiders should be of different size, or keyed, to prevent the inhale valve being inserted in the place of the exhale valve.

The valve can be designed to make a soft click sound each time it closes, which the diver can listen to.

The spider should be tested to ensure the mushroom cannot fold into the spider regardless of shock: mechanical or from pulses of gas.

10.8 One Way Valve (Flapper valve) Stuck Shut

Cause

Valve stuck shut due to sticky material on the valve, particularly following a flood or vomiting into the loop.

Some valve designs are prone to jam shut.

Incorrect assembly: mushroom is inserted onto the wrong side of the spider.

The wrong mushroom is inserted to the wrong side of the mouthpiece.

Symptoms

Surface

Diver sees a very high breathing resistance.

Dive

Same as on surface. It should be obvious what has occurred on the surface.

Recovery action during Dive

Bail out.

Preventative action

Pre-dive check for valve operation.

EN61508 Implication

This is a fail-safe failure: the unit cannot be breathed because the breathing resistance is too high. This problem shows up during pre-dive checks.

11 OTHER FAILURES

11.1 Pressure causing implosion

Cause

Gas cavities in the equipment.

Use of inappropriate materials, or materials of insufficient strength.

Operating equipment beyond the design limits.

Loss of silicone oil in oil compensated chambers.

Symptoms

Surface

Not applicable.

Dive

Sudden loss of function.

Loud explosion.

Recovery action during Dive

Bail out

Preventative action

Competent design and operation.

EN61508 Implication

Ensure equipment is designed and verified to operate to at least twice the maximum operating depth any user can use the equipment.

It is hazardous to set any depth limit except that imposed by human physiology. That is, if a manufacturer sets a 100m limit, some users will take the equipment to 200m, or if 200m is set, some users are already taking those rebreathers to beyond 300m.

The human physiology depth limit is 701msw without GABA blockers. The deepest dive to date has been to 701msw, in Comex chamber dive trials.

Based on this reasoning, to verify the equipment does not implode, the test systems should be designed to subject the equipment to twice that pressure, namely 1402msw.

11.2 Allergic Reaction to Material

Cause

Use of latex or other allergenic material.

Foreign matter in loop, especially mouthpiece, such as from jelly fish.

Off-gassing of noxious compounds has been identified as the cause for nausea in deep saturation dives.

Symptoms

Surface

Can vary from difficulty breathing, burning around mouth through to toxic shock.

Dive

Same as on surface.

Nausea.

Loss of consciousness.

Recovery action during Dive

Bail out

Preventative action

Use a full-face mask.

EN61508 Implication

Eliminate all allergenic materials from loop.

Check all materials carefully for off-gassing components both from the MSDS and from rigorous materials testing.

11.3 BC Failure

Cause

Puncture or structural failure of BC.

Symptoms

Surface

Unable to inflate.

Dive

Unable to inflate.

Recovery action during Dive

Abandon dive. Use alternative buoyancy source. Ditch weight belt if necessary.

Preventative action

Service regularly and test/inspect.

EN61508 Implication

Outside eCCR, but covered in “end to end” clause.

Do not sell BC with eCCR.

Use redundant BC, such as OMS twin bladder BC.

11.4 Harness Failure

Cause

Structural failure of component.

Symptoms

Surface

Back unit swings and becomes loose.

Dive

Unlikely as unit’s weight is water-supported.

Recovery action during Dive

Tighten other straps. Abandon dive if unable to re-secure.

Preventative action

Service regularly and test/inspect.

EN61508 Implication

Use multiple attachment points.

11.5 Loop Flood

Cause

Puncture or structural failure in the loop.

Hoses from EPDM do not split, but develop small holes.

Hoses can separate from their couplings.

Breathing bag could fail catastrophically due to seam failure.

Connectors may not be installed correctly.

Connectors have inadequate keying, particularly where these penetrate the scrubber canister.

OPV diaphragm damaged, deformed or foreign material under diaphragm.

Symptoms

Surface

Pre-dive check failure. Unable to hold set point.

Dive

Gurgling and other signs of water in loop. Breathing resistance.

Recovery action during Dive

Bail out.

Preventative action

Protect hoses with covers and service regularly. Pre-dive checks.

EN61508 Implication

Monitor moisture and WOB. Warn user of flood and give instructions to bail out.

Design-out risk of connectors not being installed correctly by using very positive identification and colouring to show how far the connector should be installed.

Double-weld the breathing bag, using RF welding.

Hoses should be made from EPDM. It may be better not to have a wrap over the hoses, so damage is more immediately apparent. Survey of hose leakage on Rebreather World confirms hoses of thick EPDM construction fail with small leaks before any major leak occurs. This is not true of thin-walled hoses.

Eliminate all failure points into scrubber by providing full hose connector as an integral part of the scrubber canister, rather than using keyed or bonded elements.

11.6 Pressure Sensor Failure.

Cause

Any pressure sensor failure (gas contents, ambient, differential).

Recovery action during Dive

Abort dive.

Preventative action

Monitor pressure monitors frequently.

EN61508 Implication

The failure modes of the pressure sensors should be determined, and failure actively detected. The appropriate warning can then be raised.

11.7 Gross dry suit leak

Cause

Poor maintenance.

Zipper failure.

Ripped suit material.

Preventative action

Check dry suit carefully before use.

Handle zippers carefully.

Use proper maintenance and inspection.

EN61508 Implication

Covered by “end to end” clause.

Provide active suit heating using self-regulating carbon monomers to maintain the thermal balance for 30 minutes (max time for diver to return to bell).

11.8 Counter-diffusion hazard

Cause

Use of breathing gases with END less than 0msw.

Use of different gases between suit and breathing loop.

Switching between gases with different constituents.

Preventative action

Training on hazards of counter diffusion.

EN61508 Implication

Measure N2 by deduction of other gases, and give alarm if less than 500mbar of N2.

State hazard clearly in training manuals.

11.9 Noxious chemical off-gassing

Cause

Unsuitable materials in breathing loop.

Contamination of breathing loop.

Preventative action

Check all plastic materials and coatings used in breathing loop for health hazards, by appropriate searches and MSDS checks.

EN61508 Implication

Checks of plastics used in rebreathers identified a broad spectrum of toxic chemicals used as softeners, plasticisers or residual products from the manufacturing process.

In reviewing MSDS data, the following conclusions are found:

- The number of different plastics used should be kept to the absolute minimum.
- PTFE, PVC and PU should not be used, nor should any other complex plastic.
- EPDM normally contains Thiram, but can be supplied without it.
- Kynar is highly preferred: it is the purest of all the synthetic resins and a very tough plastic with low water absorption.
- Silicone rubber should be injection moulded, and not formed using room temperature silicone in solvents.

11.10 Vomiting into breathing loop

Cause

Contaminated breathing gas.

Sea sickness.

Alcohol, drugs or ill health.

Divers being sick underwater occurs frequently.

Preventative action

Use certified breathing gas.

Do not dive under influence of alcohol or drugs.

Do not dive in case of bad health.

Maintain an O.C. regulator to be sick through.

EN61508 Implication

It is beneficial to have an O.C. regulator in the system. This would require a breathable gas at all times.

A combined ADV/BOV, which is always in the loop, is highly desirable. It would enable the diver to be sick with switching gas supplies. This will not be able to be cleared as an O.C. regulator can be, but gives a large path for material to be purged. It is desirable that there be a method for introducing water into the loop for this purpose: such as from a drinking tube, then from the diver to the ADV/BOV.

Requires breathing hose of sufficient diameter so as not to be blocked by vomit. Experiments using frozen carrots and sweetcorn in yoghurt (20%,20%,60%) indicate that a 36mm diameter hose and fitting is required. The spider around the mushroom valve is particularly liable to be blocked. The number of fingers in the spider should be kept to the minimum subject to the mushroom valve not folding under the finger lip.

11.11 Deco dive with incorrect PPO2 level in loop

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.

Preventative action

All O2 Cells 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).

EN61508 Implication

Eliminate problem by calibrating on air.

11.12 DCS risk higher than statistical projection of deco algorithm

Cause

Bugs in deco software in handling constant PPO2.

Inherent risk of deco algorithm used not assessed properly.

Other health problem leading to predisposition to DCS.

Preventative action

All decompression software should be formally verified to prove that the algorithm implemented is actually that intended.

Full, regular health check-up. Screen for health problems known to increase DCS risk.

EN61508 Implication

Verify the deco algorithm is implemented correctly using formal methods.

11.13 CNS Toxicity

Cause

1. Failure of PPO2 controller (not meeting EN61508).
2. Serious PPO2 spiking during descent.
3. Injecting O2 instead of DIL.
4. Diver bailing out on to O2 instead of on to DIL or off-board bailout.
5. Incorrect use of CNS calculation. Original papers describing CNS calculation are 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.

Preventative action

CNS clock in common use has CNS convulsion incidents reported at as low as 25% CNS loading.

Original paper on CNS measures loss of lung surficant as primary measure of CNS damage, with 1% at 75% CNS clock and 4% at 100%. Use less CNS clock.

EN61508 Implication

Modified CNS algorithm, with margin to reduce statistical incidence of measurable CNS damage. Published on DL Web Site, and on Rebreather World, 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.

Provide a Chicken Switch for the commercial diver using a helmet, as loss of speech is one of the first indicators of CNS (from interviews with CNS tox victims).

There should be no measurable loss of lung surficant during a dive. This requires downrating the CNS clock as above.

This is a critical failure that has caused more than one death.

Eliminate all scrims in the design.

Eliminate scrubber packing variance.

Use EAC scrubber to eliminate change in breathing resistance during use.

Measure WOB actively pre-dive and during the dive, and warn user.

Measure respiratory parameters and warn the user when these move outside normal or safe ranges.

11.14 Water drain bypasses scrubber

Cause

Water drain valve that runs across the scrubber.

Preventative action

Do not use any water drain or any other valve that can bypass the scrubber.

EN61508 Implication

Verify the loop operates correctly under all plausible fault conditions and pressures using formal methods.

11.15 Premature Counterlung Failure

Cause

Use of inappropriate materials that degrade in sunlight or in salt water.

Poor welding.

Poor abrasion resistance.

Poor puncture resistance.

Preventative action

Use correct materials.

EN61508 Implication

Verify the material performance under a wider range of conditions.

11.16 Counterlung blocks ports

Cause

On negative pressures, the counterlung material folds over any of the ports, blocking it. This increases the breathing resistance considerably, and may prevent the ADV from working.

Preventative action

Fit a spring or coil in the counterlung, and ensure that sufficient coils are captured by each of the ports to prevent a large reduction of breathing loop cross section from occurring.

EN61508 Implication

Verify the WOB does not increase suddenly with negative loop pressures.

11.17 Counterlung ports pull out from counterlung

Cause

Failure to reinforce the port cutouts in the counterlung, and key the port cutout, such that the CL can pull out from the port.

Preventative action

Ensure port reinforcing rings are fitted with strong positive keying.

If a two layer counterlung is used, ensure inner layer is larger than outer layer.

EN61508 Implication

Ensure ports and counterlungs withstand a 100kg pull: the largest plausible force that will be applied, and also withstands at least a 300mbar overpressure under these circumstances.

12 OPV FAILURES

12.1 OPV diaphragm damaged

Cause

OPV diaphragm torn or displaced.

Symptoms

Surface

Pre-dive positive pressure check failure.

Dive

Gurgling and other signs of water in loop. Breathing resistance.

Recovery action during Dive

Bail out.

Preventative action

Inspect OPV diaphragm reglarly during dive checks.

EN61508 Implication

Active control over pre-dive positive pressure checks indicated.

12.2 OPV diaphragm folded causing flood

Cause

OPV diaphragm of improper type or design, with sudden pressure change such as with diver entering the water.

Symptoms

Surface

None.

Dive

Gurgling and other signs of water in loop. Breathing resistance. CO_2 hit.

Recovery action during Dive

Bail out.

Preventative action

Ensure OPV diaphragm does not fold and remain deformed under conditions of extremely high gas flow, or gas pulses.

EN61508 Implication

OPV needs to be fully characterised.

Example Incident

http://www.rebreatherworld.com/rebreather-accidents-incidents/20066-why-c02-scares-dave-incident-report-2.html#post194733

12.3 Foreign material trapped under OPV diaphragm

Cause

Diving in silt, poor maintenance.

Symptoms

Surface

May appear in a pre-dive positive pressure check.

Dive

Gurgling and other signs of water in loop. Breathing resistance. CO2 hit.

Recovery action during Dive

Bail out.

Preventative action

Wash out loop between dives, allowing water to flow out of OPV.

EN61508 Implication

OPV needs to be fully characterised, including in presence of silt.

Most OPVs are single membrane: a dual membrane would be much safer, with a filter on both inside and outside.
Fit a filter to both inside and outside the OPV membrane/diaphragm.

Example Incident

http://www.rebreatherworld.com/ouroboros-rebreathers/19877-opv-mods-options-ideas.html#post192902

12.4 Incorrect O-ring tolerance

Cause

Poor O-ring groove tolerance or design.

Symptoms

Surface

May appear in a pre-dive positive pressure check.

Dive

Gurgling and other signs of water in loop. Breathing resistance. CO_2 hit.

Recovery action during Dive

Bail out.

Preventative action

Design and manufacture O-ring groove to be within tolerance specified by manufacturer, e.g. Parker O-Ring Handbook.

EN61508 Implication

Check all O-ring designs as part of mechanical design review checklist.

Example Incident

http://www.rebreatherworld.com/ouroboros-rebreathers/19877-opv-mods-options-ideas.html#post195284

12.5 OPV stuck shut

Cause

Poor design or poor maintenance. In some cases, mal-adjustment by diver.

With valve accessible externally, it may be moved accidentally by rubbing with hawsers or ropes.

Symptoms

Surface

Should show up in the pre-dive check, as O_2 is added to the system it will not vent normally.

Dive

Breathing resistance. CO_2 hit.

Recovery action during Dive

Reset the valve to correct position, and if that does not work, then bail out.

Preventative action

Position valve so it cannot be adjusted accidentally during dive.

Check OPV cracking pressure as part of pre-dive checks (checking loop does vent with reasonable pressure).

EN61508 Implication

Locate valve where it cannot be changed accidentally during dive.

During testing, it was found that some housings are very much more liable to be adjusted than others.

12.6 OPV stuck open

Cause

Poor design or poor maintenance. In some cases, mal-adjustment by diver.

With valve accessible externally, it may be moved accidentally by rubbing with hawsers or ropes.

Symptoms

Surface

Should show up in the pre-dive check, positive pressure test.

Dive

Venting gas continuously, or on every breath.

Water ingress, Breathing resistance. CO_2 hit.

Recovery action during Dive

Reset the valve to correct position, and if that does not work, then bail out.

Preventative action

Position valve so it cannot be adjusted accidentally during dive.

Check OPV cracking pressure as part of pre-dive positive pressure check.

EN61508 Implication

Locate valve where it cannot be changed accidentally during dive.

12.7 OPV cracking pressure relative to diver changes with attitude

Cause

Incorrect placement of OPV.

Symptoms

Surface

None.

Dive

Loop volume changes as a function of diver attitude, as does Work of Breathing, OPV may vent or freeflow in some positions.

Recovery action during Dive

Avoid positions causing free-flow.

Preventative action

Position the OPV as close to the lung centroid as possible.

EN61508 Implication

Ensure correct OPV position.

12.8 OPV housing failure

Cause

Flimsy OPV.

Symptoms

Surface

None.

Dive

OPV comes apart during dive.

Recovery action during Dive

Bail out.

Preventative action

Position the OPV so it is not exposed. Design and manufacture housing from a tough material of sufficient thickness to withstand diver abuse.

EN61508 Implication

Ensure OPV is robust.

12.9 OPV fails to shut sufficiently for positive pressure check

Cause

Poor OPV design.

Symptoms

Surface

Positive pressure check vents via OPV too readily.

Dive

None.

Recovery action during Dive

None.

Preventative action

Replace OPV with a design that can maintain a 300mbar pressure when fully shut.

EN61508 Implication

Verify OPV operation.

12.10 OPV interacts with water drain

Cause

Use of an OPV as a water drain in addition to fitting a normal loop volume OPV.

Symptoms

Surface

None.

Dive

Free-flow.

Recovery action during Dive

Avoid positions causing free-flow, abort dive.

Preventative action

Do not use an OPV as a water trap that is additional to main OPV: they cannot both work unless adjustment is within an extremely tight tolerance.

EN61508 Implication

Do not use OPVs as water traps: use good water blocking and the main OPV instead.

12.11 OPV is on exhale CL instead of inhale CL where it should be

Cause

Bad design: failure to carry out full verification and testing.

User can swap OPV with ADV in error.

Symptoms

Surface

None.

Dive

In an uncontrolled ascent, gas travels from inhale CL through scrubber to exhale CL, as well as from inhale CL to diver. This gas movement carries all the injected O2 into the exhale CL, where it is vented. As a result the PPO2 in the gas breathed by the diver plummets.

Recovery action during Dive

Slow ascent.

Empty the inhale CL by deep breath and vent, regularly during ascent.

Preventative action

Locate OPV on inhale CL only.

EN61508 Implication

Ensure user cannot switch OPV with ADV accidentally.

13 FAILURES SPECIFIC TO DIVES IN COLD WATER

The exothermic heating from the scrubber may suggest that a rebreather is a suitable tool for diving in cold water. This is not the case. Rebreathers are fundamentally unsuitable for very cold water, particularly water below freezing, unless the rebreather is designed specifically for that purpose and incorporates sufficient safe heating elements to keep the equipment warm and free of ice: this requires heating to around 20C due to the speed at which ice can form on barriers such as the breathing hoses, or around objects where the gas flow is the fastest, such as mushroom valves and gas injectors.

Diving in water below 4C, poses special hazards. The risks increase with reducing temperature, as shown below.

Temperature	Risk
Above 4C	Low risk
Below 4C	Significant risk of death
Below 0C	High risk of death
Below -4C	Almost certain death

The risks occur from the following causes:

1. The moisture in the breathing loop is almost pure water, so freezes at a higher temperature than sea water. The water can freeze in the breathing hoses, on the mushroom valve, or in the scrubber.
2. The oxygen sensors do not perform correctly at very low temperatures. This will lead to large errors in PPO2.
3. The scrubber efficiency drops as the square of the temperature. At around zero, the scrubber stops working.
4. The expansion of injected gas in the humid environment of the rebreather will cause ice to form on the injector nozzle. This can block the injector, so the injector is heard to fire by the user (if a solenoid design), but is not injecting gas.
5. "Dive reflex" causes a large increase in blood pressure when the head is in cold water.
6. Risk of shock on entering very cold water.
7. Risk of dry suit leaks are much more serious in very cold water.
8. Risk of mechanical damage due to ice forming and expanding during equipment storage.
9. Risk of over contraction of silicone oil used to equalise pressure at depths rupturing electronic housings.

10. Risk of inappropriate materials cracking with mechanical shock in a cold environment.
11. LCD displays lose contrast in very cold conditions.
12. Some integrated circuits, particularly Flash memories and DRAM, do not function well in cold conditions.
13. Batteries will go flat much faster in cold conditions than in warm, and their internal resistance rises even when fully charged. This creates more power supply noise, and will cause equipment malfunction if there is any under performance in the power regulators.

EN61508 Implications

For diving in very cold water, it is necessary to have a SIL rated heating system in the counterlungs, sufficient to keep the loop temperature above 20C, and to have active monitoring of the gas flow so that any blockage can be detected.

Equipment should be stored in a warm location, and at all times when not in the warm location, the equipment should be operating to maintain its temperature.

EN14143:2003 requires the equipment to be tested with storage to minus 30C, for material suitability. Some dives are in environments colder than this, such as in Russia in winter and polar dive expeditions. The equipment is wet when it comes out of the water, so chill factors become an issue also, reducing the effective temperature of the surface of the equipment.

14 Failures Specific To Surface-Supplied Dives

14.1 Loss of Umbilical (Commercial diver)

Means complete cutting of the umbilical, or cutting it and losing some of the services on the umbilical, such as power or gas.

Cause

Disconnection.

Heavy object falling on umbilical.

Cutting of umbilical.

Failure of topside to provide umbilical support.

Preventative action

Reduce umbilical services to the minimum: power, communications and umbilical gas feed.

EN61508 Implication

Should be survivable by use of bail-out carried by diver. Maximum depth and maximum O2 concentration in bail-out gas determines bail-out size.

Put a transponder onto the diver. Separate to the rebreather.

Consider the external protection to avoid the reduction in diameter from increasing the risk of it being severed, such as using Marlin wires in the umbilical sheath.

14.2 Cut of umbilical near surface (Commercial Diver)

Cause

Disconnection.

Heavy object falling on umbilical top-side.

Cutting of umbilical.

Failure of topside to provide umbilical support.

Preventative action

Risk is the diver being sucked into the umbilical due to the pressure in the umbilical being much less than the ambient. Fit a one-way valve to the umbilical at the point where it feeds into the diver's helmet.

EN61508 Implication

One-way valve is required.

Adequate bail-out is required. Should be survivable by use of bail-out carried by diver. Maximum depth and maximum O2 concentration in bail-out gas determines bail-out size.

14.3 Entrapment of Umbilical (Commercial diver)

Cause

Heavy object falling on umbilical.

Umbilical floats and is caught by propellers or other moving objects in the water, causing impact between the diver and the object. That is the umbilical becomes a “fishing line” for divers.

Preventative action

Reduce umbilical services to the minimum: power, communications and umbilical gas feed so it can be moved more easily.

Diver should be trained to safeguard umbilical.

EN61508 Implication

Umbilical should be either disconnectable or the diver should carry means to cut the umbilical to free himself.

Procedures to avoid diver entrapment. Accidents where this has occurred the procedures were not followed.

Control weight of umbilical is important, such as a line to flood.

CNS Toxicity (Commercial Diver). System automatically modulates PPO2 to keep below CNS ceiling.

14.4 Loss of Helmet (Commercial diver)

Cause

Inadequate attachment.

Preventative action

Use helmet that requires at least two actions using two hands to detach.

EN61508 Implication

Entire helmet comes within EN61508 by virtue of it containing electronic functions (microphone etc).

Monitor electronically whether a helmet is attached correctly.

Require at least two operations using two hands to detach helmet.

14.5 Sudden change in depth (Commercial diver)

Cause

Falling into a hole, or uncontrolled rise, causing intermediate pressure from umbilical gas to be either excessive or insufficient.

In bail out, the SCR has no means to add gas to the suit, or the loop. If there is a depth excursion downwards, then the diver will have squeeze.

Preventative action

System should bleed off excess umbilical pressure.

One-way valve needed in case of negative pressure.

EN61508 Implication

Same as for umbilical being cut near surface.

The system should have an underpressure valve on the helmet.

Train diver to descend slow enough for the SCR to fill loop.

14.6 CO in loop (Commercial diver)

Cause

Contaminated breathing gas.

Metabolism product.

Preventative action

Flush loop periodically, and test for CO.

EN61508 Implication

Requires active CO monitoring on the diver.

Statoil Commercial Dive Doctor consulted specifically on this point and advised that over a 4 hour dive, the CO from metabolism products is not a safety hazard.

14.7 HC or Volatile Organic Compounds in Loop (Commercial diver)

Cause

Contaminated breathing gas.

Metabolism product.

Off-gasing of plastics or cleaning agents in rebreather.

Detailed presentation available on this topic. Hazard depends on which HC or VOC is involved: some are only midly anesthetic, others are highly carcenoginc or hazardous to health.

Preventative action

Flush loop periodically, and test for VOCs.

EN61508 Implication

Requires active HC and VOC monitoring on the diver.

Noted that some inorganic compounds such as hydrogen sulphide or mercury compounds are highly toxic and may also be in the breathing gas. Requires strict control of breathing gas, and RoHS compliant components in the dive system.

14.8 Loss of communications (Commercial Diver)

Cause

Equipment failure.

Inattentive operator.

Collision on surface.

Failure of umbilical link.

Preventative action

Use multiple communication paths.

EN61508 Implication

SIL 0 failure. Occurs very frequently with current systems (more often than once in 1000 hours), without escallation of safety issues.

Requires at least two communication paths.

Provide communications to bell in addition to comms to surface.

Question on through-water ultrasonic comms: desirable.

14.9 Loss of Gas Heating (Commercial diver)

Cause

Electrical failure or overheating of heating element (component failure).

ESA member advised that in trials at 500m loss of breathing gas heating resulted in the diver not being able to return the bell, which was 2metres away. Another member advised that at 450m, there was hypothermia to the extent of the diver foaming at the mouth when the breathing gas temperature was reduced, but still above 20C?.

Massive reduction of thermal balance when diving at extreme depth if gas heating is lost.

Preventative action

Should be redundant systems for breathing gas heating.

EN61508 Implication

Breathing gas heating should be considered as a SIL 4 action.

14.10 Overheating (Commercial diver)

Cause

Helmet overheating or suit, from insufficient thermal losses. Thelma AS report 06-20 simulations show in 4C sea water, hard working diver in 250gm undersuit with clo value of 4.5, overheats to body temperature above 44C in 200 minutes.

Preventative action

Diver should be able to flush the helmet and suit.

EN61508 Implication

Full safety case required for diver thermal balance.

Special consideration in warm water conditions. Severe problem in Persian Gulf and other near tropical conditions.

14.11 Loss of Suit Heating (Commercial diver)

Cause

Electrical failure.

Preventative action

Use sufficient passive thermal protection to return to the bell.

EN61508 Implication

State requirement for passive undersuit thermal protection in user manuals and training.

Treat gas heating as a SIL-4 requirement for very deep diving.

14.12 Excess suit heating (Commercial diver)

Cause

Electrical failure or excessive water temperature (hot water suits).

Extensive reports of 3rd degree burns in divers using electrically heated suits in the early 1970s. Divers do not realise they are burning, when under pressure: divers involved in use of these suits interviewed.

Hot water suits have uneven heating and divers are not aware of the high water temperatures. Many divers report burns.

Top-side operator error.

Divers in bell overheat while waiting to go diving.

Preventative action

Electrical: use a SIL 4 rated heating system.

EN61508 Implication

Eliminate failure mode by use of self-regulating materials, and use of active current monitoring to detect shorts or excess current drain, in a SIL 4 design.

14.13 Tools and Equipment (Commercial diver)

Cause

Any cutting or grinding tool, slipping onto the diver or his equipment.

Burning and welding, causing hot residue.

Oxy-arc cutting blowback pushes out the lexian glass in the helmet or cracks the helmet.

Oxy-arc cutting blowback Hydraulic pulse on membranes and on hoses.

Oxy-arc cutting blowback Igniting oxygen pockets while burning.

Sand and grit blocking valves and orifices for equalisation.

Electrical currents increasing corrosion through electolysis.

Do the EMS limits in CE directives, cover high current densities seen in diving? The current is enough to strip the chrome from the brass regulators used on Kirby Morgan helmets, and enough to shutdown the microphone circuits in the helmet while these operations are carried out.

Mechanical vibration from a jack hammer, transmitted through the diver to the equipment.

Noise from high pressure water jets.

Towing heavy weights over the shoulders rubbing on the suit and counterlungs.

UV from diving welding, or the ozone this creates in a habitat that has had recent welding.

Dressing on and off in a safe manner in a habitat.

Diving in extremely oily conditions where the diver has to undress in the water, then move with the helmet into a decontamination bell. Concern over nooks and crannies making it difficult to decontaminate. Contamination in the wind of the umbilical.

Preventative action

Electrical: use a SIL 4 rated heating system.

Include extreme induced current test in system evaluation.

EN61508 Implication

Test the equipment for operation between a pair of underwater burning system electrodes in use (actual burning). Measure the field.

The EMS limits in CE directives do not cover the high current densities seen in diving, so test using the highest possible current density with the unit in water.

Shield all internal electronics for magnetically induced currents.

Consider use of liquid crystal electrolytic materials such Kynar for the electronics shell, to form a Faraday shield around the electronics in the presence of intense underwater electrical currents.

14.14 Oro-nasal one-way valve failure (Commercial diver)

Cause

Failure to check valve pre-dive, or umbrella valve stalk failure: it may be missing, inverted or damaged.

Preventative action

Check oro-nasal one-way valve before every dive.

EN61508 Implication

Retained CO2 issue.

15 General Diving Hazards

Sports diving in general seems to have a risk of accident of between one in 10,000 hours to one in 100,000 hours, depending on the type of diving being carried out [3], [4]. Some of these accidents are due to equipment failure [6], most are due to lack of training, lack of attention, poor judgement or the effect of an underlying illness or predisposition. Use of rebreathers has considerably higher risks based on the same accident figures and the population of rebreather divers. The increase appears to be associated with failures to meet EN61508 in the equipment design: the rebreathers with the shortest MTBCF have the highest rates of fatal accidents, and rebreathers with the best MTBCFs have the lowest rate of fatal accidents.

Commercial rebreather diving seems to have a significantly lower accident rate than sport rebreather diving, based on IMCA accident reports [5] and the amount of commercial diving carried out. Commercial diving has had a much larger amount of research carried out into the health and safety of divers than is the case for sports divers.

All diving carries some short and long term risks to health.

Long-term risks are described by D.H. Elliott & R.E. Moon [1]. All long-term health risks appear to originate from an event that can also give rise to a short-term risk, such as an untreated DCS or barotrauma. In some cases the long-term risk is due to a succession of minor insults, in other cases, from the effect of cellular damage from a single insult which may, at the time, have appeared insignificant.

Short-term risks are compiled from D.H. Elliott & P.B. Bennet [2], DAN and BSAC accident reports, as follows:

Health Risk	Cause and effects
Respiratory Gases	Contaminated breathing gas, with effect of narcosis, anaesthesia, illness. Unsuitable breathing gas for depth: hypoxic or hyperoxic, with effect of loss of consciousness, convulsions

	Narcotic breathing gas with effect of loss of judgement, time perception, consciousness. Insufficient gas, with effect of drowning. Gas switch between gases with large difference in anaesthetic effect, with effect of loss of consciousness. Counter-diffusion with effect of DCI.
Diving Reflex and Sudden Death Syndrome	Water contact on forehead has effect of “Whale Diving Reflex”, with constriction of blood vessels, slowing of heart beat and increase in blood pressure. Implicated in Sudden Death Syndrome in older divers.
Thermal Balance	Lack of thermal protection, with effect of hypothermia or aborted dive with decompression load. Suit leaks without means to heat the suit cause hypothermia. At extreme depths, loss of thermal energy from the lungs.
Exhaustion	Swimming against strong current, effect of loss of energy to remain afloat.
Loss of Buoyancy Control	Loss of buoyancy control with effect of uncontrolled ascent or descent. Entanglement in surface towed objects with effect of loss of buoyancy control, causing DCS, barotrauma or drowning. Entanglement with object moving towards surface, such as a lift bag or SMB reel, with effect of loss of buoyancy control, causing DCS, barotrauma or drowning. On surface, diver fails to drop weight belt when in difficulty, with effect of drowning. Failure of BC valves with effect of uncontrolled ascent or descent. Confusion by diver causing diver to press inflate button when intends to deflate, or vice versa, with effect of uncontrolled ascent or descent. Weight jackets may redistribute weight, causing diver to be “up-ended”, with effect of drowning. Simple weight belts should be encouraged, with retainer to prevent accidental loss. Loss of control of dry-suit gas may cause diver to by “up-ended”, which, without training, the diver may not recover from. Recovery method is simply to form a ball and roll out. If diver does not succeed, then effect may be drowning.
Disorientation	Illness, vertigo, reduction in visibility, unfamiliar environment with effect of panic or behaviour leading to entrapment or

	becoming separated underwater. Ultimately effect may progress to drowning from insufficient respiratory gas, or barotrauma from loss of buoyancy.
Perceptual Narrowing	Stress, leading to information essential for safety being ignored.
Panic	Predisposition, asthma, lack of training, with effect of excess use of respiratory gas, behaviour contrary to safety.
Barotrauma	Breath-holding during ascent, from as little as 1.2m, with effect of gas embolism. Loss of buoyancy leading to pulmonary barotrauma, alternobaric vertigo, compression barotrauma, or any embolism. Illness causing gas blockage, with effect of embolism on lungs. Prostheses or dental cavity, with effect of acute pain.
DCS	As per CCR hazards.
Dehydration	Serious sea-sickness, or alcohol abuse, drugs, poor hydration practice, with effect of increased DCS risk and may have effect of loss of consciousness in extreme cases.
Heart Attack or Stroke induced by unaccustomed exercise	May be induced by Dive Reflex. Risk is higher with dry suits or hot water suits, Trimix (carrying multiple tanks), on a RIB or ice diving compared to diving from a hard boat, and in cold water. Effect is invariably drowning.
Military Sonar	Sports divers have been attacked by the military sonar of nuclear submarines when carrying out a dive and a submarine has been in the facility in the English Channel. Divers felt very nauseous to the point of passing out. Evidence that nuclear submarines view any diver in the vicinity as an attack and have a policy of killing the diver. A fatal accident in 1998 of a diver on a rebreather implicated military sonar from a nuclear submarine as one of two possible causes. Video footage from 1998 North Pole Expedition supplied.
Unconsciousness	Asthma, epileptic fit, insufficient or unsuitable respiratory gas, oxygen convulsion, CO2 retention, illness, generally with effect of drowning.
Underwater explosions	Proximity to naval exercises, or commercial demolition. Effect is pulmonary and intestinal rupture and haemorrhaging.

Underwater electric current	Commercial operations, leading to involuntary spasm and likely drowning. Note that where an accident has occurred due to underwater currents the electrical equipment should be checked in an active plating bath in addition to normal swept frequency testing to verify the equipment behaved correctly in that environment, so the two causes of accident (direct shock and equipment failure due to the current density) can be separated.
Venomous marine life	Contact with any venomous sea life, particularly jelly fish, stonefish, some octopus, sea snakes, conch shells, parasites. Effect: shock, pain, nerve damage, or in case of parasites, damage to internal organs or brain.
Predators	Rare, with bites from large sharks, rays, squid, eels or seals.
Hard impacts	Impact with boats, propellers, divers falling on divers below, on to rocks in surf or heavy waves, with effect of trauma.
Excess Mechanical Shock or Strain to bone	Carrying heavy objects, with effect of bone fracture, breakage, or arthritis, osteonecrosis, muscle strain. Stress can cause DCI damage to the bone. Cold water can increase risk of stress causing permanent damage, due to reduced blood flow.

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