Rebreather Accident Analysis: Method

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Process of competent rebreather accident analysis

- Secure the physical evidence
- Collate all the other sources of evidence together systematically
- Review the data and construct provisional timeline
- Identify anomalies and inconsistencies in timeline and evidence
- Perform tests or seek out specific evidence to reduce the inconsistencies in the timeline
- FMECA Review with open mind to find all plausible root causes
- Formal modelling of each plausible cause
- 2nd equipment examination if any plausible equipment issues identified in FMECA, by a technical expert not affiliated with manufacturer or trainer
- Apply Root Cause Analysis
- Conclude a timeline and accident synopsis, using the Root Cause Analysis method

Securing the physical evidence

- DAN "Chain of Custody" document is the definitive description of this process
- Treats the scene of a dive accident in the same way as a potential murder scene
- Photograph as much as possible and restrict access to the equipment
- Information is easily lost:
  - Earlier VR3 dive computers lose the profiles after a year. They need to be downloaded as soon as possible after the accident by the factory.
  - Batteries removed from dive computers cause loss of contents and of the crucial dive log
  - "Playing" with handsets can destroy logs
  - Calibrating the oxygen sensors using the handsets destroys the previous sensor calibration data so an investigator cannot then tell if the calibration was correct or not
  - Weights attached to diver may be taken to morgue: knowing the diver's weight is very important in determining how much gas is in the counterlungs on initial descent, which in turn is important in identifying the timing of hypoxia events
  - Batteries and power failures often feature in rebreather accidents. They must not be swapped over, discarded, or cleaned other than a rinse in clean water if unit has been flooded. Photograph their contacts using a macro lens, and the corresponding contact.
  - A flooded rebreather contains a strongly caustic solution that will dissolve the evidence if left in the rebreather: it should be drained, the volume measured and retained for chemical analysis.
  - Scrubber should be drained as above, but not replaced with new material, otherwise the Work of Breathing cannot be determined, nor can tunnelling.

Collate the evidence systematically

Gather and collate the following information systematically, and with rigour:

- Witness reports, taken as soon as possible after the accident, and again after a week has passed (shock can block many memories)
- Download the dive profiles and make hard copies
- Police incident report: contact the local police department and speak with the investigating officer to get the report
- Medical report: history (from next of kin or friend), and autopsy report if there is one
- Equipment examination report: NEDU, HSE or similar government body with gas analysis. These bodies do not test the electronics of the rebreather other than superficially: this will come later. They can test the gases, the scrubber chemistry and breathing parameters.
- Map of the dive site
- Photographs of the accident site and equipment as received
- Check serial numbers and status of all equipment to ensure no later changes
- Any reports onto dive forums made by witnesses: Google the name of the diver, and the diver's first name and nickname with the word "rebreather"
- Experience level of the diver: get information on his certifications and on the experience level on rebreathers as well as on the specific unit involved in the accident. This affects mildly how a diver is likely to respond to issues.
- If there is any legal claim involved, the lawyer for either party can usually obtain a court order to get any relevant missing data using provisions for "discovery".
- Contact specialists to get information on the dominant failure modes and safety weaknesses of the equipment involved
- Identify a specialist able to assess the electronics thoroughly (not just switch it on, and see if it works: most rebreather failures are transient, but leave trails that a true expert can detect)

Constructing and verifying a timeline

- The first timeline is often wrong: keep an open mind and revisit it
- Dive profiles from dive computers are the most valuable piece of data
- Ensure you gather all the profiles from the victim's computer and each of the witnesses
- The evidence needs to fit to the timeline: identify any anomalies
- Timeline works minute by minute, even second by second
  - what happened
  - at what depth
  - using exactly what equipment
  - and when: dive computers are usually set to the wrong time, minutes out, 20 mins out, an hour out (summer daylight saving time or mean time), the wrong time zone. Cross check the dive computer time with a reliable reference.
- Buddies computers should have the profile extracted and matched against the profile of the diver: scale the X and Y to the same number of pixels and use Photoshop to overlay them.
- Put all the evidence on the timeline.
- Review the result and seek out any inconsistencies: these are the keys that often open up the truth - it can be very different from first impressions.
- The job from this point on is to resolve those inconsistencies, and to challenge and verify the timeline using FMECA and Formal Modelling tools. Only once that is done is there a solid basis of "fact" that can be used for any analysis.

Value of the FMECA

- The most thorough FMECA known to exist for a rebreather is available for download from www.deeplife.co.uk/or_fmeca.php
- Use Volume 6: the Top Level analysis.
- Keep an open mind.
- To get the feel for the subtlety of an accident, read over "How rebreathers kill people" (www.deeplife.co.uk/or_accidents.php): it is often said that the devil is in the detail, and with rebreathers, it is often the detail that kills.
- Go through every possible cause, and assign a probability (0 to 1), and state your reason. Then collate all plausible causes (with probability > 0) and review.

Failure Mode	Probability	Reason
5.1 Oxygen Cylinder Empty	0	Police report "60" on oxygen gauge. Evans examination reports same and shows this is a figure in bar. Consideration was given to possibility that the gauge may have been faulty, but this was discounted because Evans was able to analyse the oxygen. NEDU did not report a faulty gauge.
5.2 Oxygen Cylinder Switched Off	0	Police report it took 2 turns to turn off: same as for diluent. This is sufficient. The cylinder was on.
5.3 Oxygen First Stage Failure	0	First stages worked and had 8 bar I.P.
5.4 Oxygen First Stage Over Pressure	0	Ditto
5.5 Oxygen Hose Leaks	0	None from Inspection
5.6 Oxygen Solenoid Stuck Open	0	I.P. insufficient to cause this. The solenoid worked during inspection by Evans and Deas.
5.7 Oxygen Solenoid Stuck Closed	0	Ditto
5.8 Oxygen Manual Injector Failure	0	Injector was inspected manually and found to work. NEDU report also.

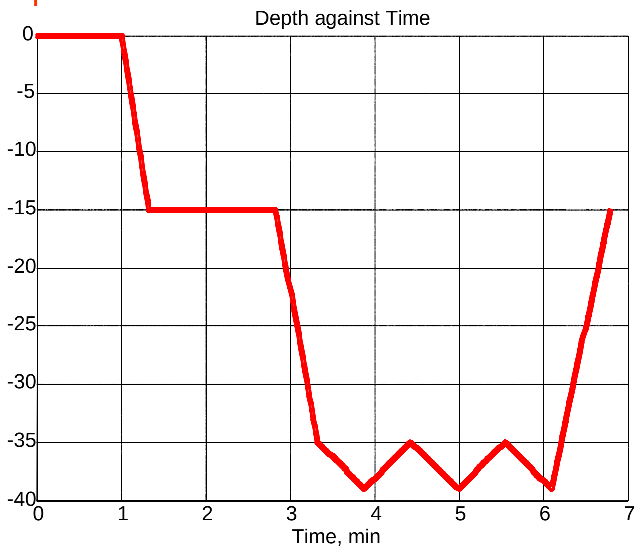
Formal Modelling

- Rebreathers have 4 dominant fault modes in addition to the faults common to diving generally:
  - Hypoxia
  - Hyerpoxia
  - Hypercapnia
  - Flooding
- The evidence will usually indicate if one of these is involved. Be aware of a look for the symptoms.
- Rebreather divers tend to do more extreme dives than Open Circuit divers. As a result, the general hazards common to diving will strike them more often. Look out for these.
- The next few slides reviews what the symptoms are of these 4 dominant failure modes, and also the general distribution of more normal diving hazards, and gives an example of how Formal Modelling can be used to verify these.

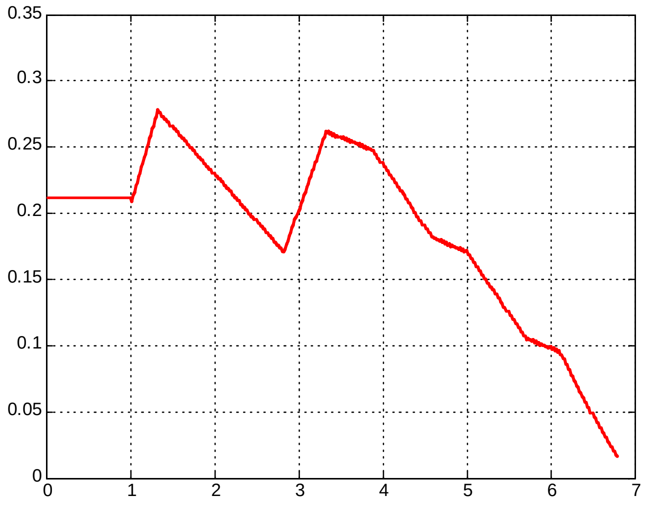
Formal Modelling

- Formal Modelling uses a very detailed model of the rebreather and of dive environments.
- The most detailed formal model for a rebreather is available free of change from www.deeplife.co.uk/or_models.php
- There is an easy to use Windows GUI, but the model itself runs in Matlab and Simulink: low cost Student and Teacher versions are available.
- It allows the dive profile to be run as a script, or interactively, and plot the PPO2, PPCO2, loop pressures etc, using different faults occuring at specific times indicated by the investigation timeline.
- It also allows the investigator to work backwards from an event, such as a LOC, to find the time the critical failure or root cause actually occurred.

Example of one possible dive profile from dive computers



Corresponding PPO2 Plot against time from modelling tool assuming controller failure at start of descent.



Some facts about Hypoxia

- Hypoxia is an insufficiency of blood oxygen, normally caused by breathing a gas with not enough oxygen in it.
- Hypoxia generally leaves no medical traces, unless there has been gradual hypoxia for 45 minutes or more (in which case, there are subtle changes to the nerve endings, and can be swelling of the heart). In diving accidents hypoxia is quick, sudden and medically untraceable: the only symptom is a very sudden loss of consciousness.
- Warning can be from the dive computer or monitor, so diver may have bailed out or tried to reset his rebreather computers (switching them off, or switching them into another state in the process).
- If someone breathes a pure gas that is not oxygen, the first breath is fine, the second full breath they will suddenly pass out and cannot be resuscitated. There is generally no warning at all.
  - We know this because 16 commercial divers have died from being given pure helium, and from experiments using gas with a few percent of oxygen.
  - With a few percent of O2, resuscitation is possible if done quickly.
- DAN data indicates that an unexplained loss of consciousness occurs less than one in a million hours in Open Circuit divers. It is very rare. It is very common in rebreather accidents.
- Hypoxia in a rebreather occurs usually fairly early on in the dive, but can occur at any time except during a fast descent unless there is no make-up-gas (dilutent gas), or the make-up-gas is hypoxic.
- During a fast descent, the PPO2 increases because the ADV injects gas, which normally contains oxygen
- An out-of-air ascent from 10msw (33ft) with a PPO2 of 0.4 is OK for an Open Circuit diver. It kills a rebreather diver because the ascent tends to be slower, so too much gas is metabolised.

If hypoxia is suspected, check it using Formal Modelling: this will confirm when the problem started, within a tight tolerance.

Some facts about Hyperoxia

- Hyperoxia is the result of breathing too high a PPO2 for too long, generally due to Central Nervous System damage.
- Symptoms are a visual narrowing (tunnelling), followed by a very violent fit that lasts for 5 minutes or so if the diver does not die first.
- Underwater, the result is usually death by drowning.
- Widely accepted CNS limits of 1.6 for 45 minutes causes 4% of divers to suffer lung damage, and a small proportion will suffer a CNS fit.
- If the PPCO2 is high, then the CNS clock limit is very much lower: CNS fits have occurred with divers with a PPO2 as low as 1.0 (Ref. Dr. Philip James, University of Dundee Medical School, and incident witnesses)
- Many medications, alcohol and some diseases also cause a reduction in the CNS tolerance for oxygen.

Evidence:

- If the diver has a buddy, the evidence for hyperoxia is usually very clear.
- If there is no buddy, use formal modelling to determine what the CNS clock was at the time the diver lost consciousness.
- If the diver has no buddy, look for loss of buoyancy control and very small oscillations in depth from the dive log.
- There is no bizarre behaviour in a diver with hyperoxia before the CNS fit, but look out for combined hypercapnia and hyperoxia with a lower CNS limit.

Some facts about Hypercapnia

- Hypercapnia is the result of breathing too high a PPCO2
- The timeline runs as follows:
  1. Feeling of dread, or "I don't want to be down here"
  2. Bizarre behaviour: poor buoyancy control, doing odd things
  3. Feeling out of control: this can lead to panic, such as the diver just swimming off on his own regardless of any decompression obligation. The more controlled diver will want to get hold of something, or sit on the sea-bed, to try and stabilise the situation.
  4. Hallucinations. The diver may imagine something, and react to it, such as an imaginary menace, a plot against him, an unrelated equipment fault.
  5. As the hypercapnia progresses, there is a rapid rise in breathing rate and heart rate. This is now completely out of control. The diver will have great difficulty in bailing out: try bailing out when at the very end of a long apnea.
  6. The diver dies as a result of any of the following:
     - Bizarre behaviour, swimming away from his buddy and losing buoyancy control then sinking to the seafloor, taking his mask and regulator off etc.
     - Panic, swimming to the surface missing decompression stops
     - Heart attack from the extremely high pulse rate and blood pressure
     - Stroke from the extremely high pulse rate and blood pressure
     - CNS fit, due to greatly reduced O2 tolerance when suffering from hypercapnia
     - Drowning, from a loss of consciousness at a PPCO2 around 0.4
- Root causes can be scrubber exhaustion, poor scrubber packing, failure to pack an O-ring or scrim in the scrubber, or simply excessive Work of Breathing

General diving hazards

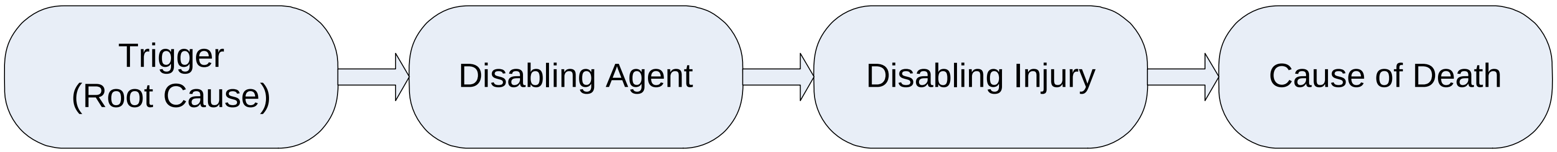
Confidential: Treat the table below as confidential until advised otherwise - it is from an unpublished paper by P. Denoble, J. Caruso, G de L. Der, C. Pieper and R. Vann, entitled “Common Causes of Open Circuit Recreational Diving Fatalities”: it is a cornerstone piece of work in this field.

Table 2. Root causes associated with 947 diving deaths.

Buoyancy Trouble	291	Rough water	210	Entrapped	71
Unspecified	142			Tangled	44
Too negative	102	Insufficient gas	195	Trapped	27
Variable	35				
Too positive	12	Equipment Trouble	103	Inappropriate gas	12
		Buoyancy compensator	30	Hyperoxic	7
Emergency ascent	284	Multiple problems	24	Carbon monoxide	3
Rapid ascent	145	Breathing apparatus	20	Hypoxic	2
Assisted to surface	42	Diving suit or dress	14		
Free ascent	30	Gas supply	7		
Buddy breathing	26	Mask	5		
Low on gas	22	Fins	3		
Unsuccessfully attempted	7				
BC activated by buddy	5				
Multiple ascents	3				

Root Cause Analysis (RCA)

- Treat the accident as a four part process:



- Example of RCA in a scrubber breakthrough accident:
  - Cause of Death: Arterial Embolism
  - Disabling Injury: DCI caused by rapid ascent missing decompression stops
  - Disabling Agent: Hypercapnia
  - Trigger: Diver failed to replace scrubber. Diver had used the same scrubber for 11 hours. The rated scrubber life at 1.6l/min of CO_2 is 3 hours.
  - Classification: Human Error/Equipment issue
  - Recommendation: Equipment should be fitted with a device that counts down from when a new scrubber is fitted to show time remaining, or use a CO_2 sensor, and alert diver and buddies when time is zero.
    Training agencies should encourage divers to label the rebreather using duct tape with the hours the scrubber has been used for.
- Run all plausible root causes and factors, then conclude the one with the most likely probability. If several are reasonably plausible, then list them.

The second equipment examination

- The second equipment examination should be carried out if possible by a technical expert familiar with rebreather controller failure modes and all of the existing evidence
- The purpose is to resolve the remaining inconsistencies in data by carrying out specific tests, and to gather evidence to prove or disprove each of the hypotheses identified from the FMECA.
- Use video or audio recording if possible, but at least take a photographic record
- Ensure an independent witness is present
- Do not damage or permanently change the state of any item
- Start with an examination of each item present and check it is the same item as recovered by the police following the accident
- Check the configuration is exactly the same as that indicated from the first examination report by the government agency
- Proceed around the rebreather loop systematically and check every item visually for state, damage or any unusual marks
- Check the dive suit for physical damage or marks that may indicate a trauma
- Check the rebreather controller for each of the failure modes identified in the FMECA and in those indicated from a study of the dive profile. This will usually require specialised test equipment:
  - O2 Cell emulator
  - Macro camera or a metallurgical camera for images of battery contacts, salts etc
  - Power supplies to emulate brown out
  - Electronic meters
  - Portable respirator able to measure breathing parameters
  - May require a pressure chamber
  - May require separate testing of identical equipment under the conditions in which the accident occurred, and then comparison with the recovered equipment

Pitfalls to avoid

- In an equipment examination, pay attention to the details but do not get misled by irrelevant failures. For example:
  - Whether or not a regulator works at all, is irrelevant if the regulator was not used.
  - If a regulator just fails the EN250 Work of Breathing test at 30msw, it is irrelevant if the dive was only to 10msw.
  - If the equipment is modified, but the modification did not trigger or exacerbate the accident, then the modification is irrelevant.
- In formal modelling it is important to get the dive profile, metabolic rate and initial counterlung volume right. If any one of these factors is not known, then run brackets: that is, a low, medium and high estimate of what the number would have been. If necessary, run a trial with a diver of similar build and experience. Check whether the model version includes human lung dead space or not.
- Loop volume reduces as the diver leaves the surface, to as low as 6 litres. The model should track this, and its effects. After the surface, the loop volume is normally minimal: this is especially true if an ADV is used.
- The ADV normally fires when a diver hits the water, or shortly afterwards: divers inject gas manually. Do tests on the equipment to determine how much gas the ADV adds.
- Older VR3 computers lose the first part of a dive after 60 minutes, so run the same profile as you are using on an identical VR3 and check the display and profile is the same as the one recovered.
- Very experienced and wise divers can made the same dumb mistakes as the rest of us: assume nothing.
- Running tests on a piece of identical equipment is very useful in filling in gaps. For example, whether the scrubber was properly packed can be determined even after a flood.
- Often the truth hurts. If an investigator hides the truth, or changes the facts, and a similar accident occurs later due to the absence of that information, then there must be a high degree of moral responsibility. The job of the investigator is to find and report the truth no matter what that is.

Reaching a conclusion

- Use the timeline to provide a chronological record of events
- Have a short synopsis of the key events
- Use the Root Cause Analysis to structure your synopsis
- Get your whole study reviewed independently
- Bind a hard copy and lodge with the parties involved with the accident, or that have commission the study. Don’t just keep a computer record, though a computer record is helpful too.
- Where data is missing, list it
- Where you have made important assumptions, list them
- Where there are remaining anomalies or inconsistencies, list them
- Have your the investigation checked by a competent independent reviewer
- Make recommendations for the training, dive procedures or equipment designer to avoid a repeat of the accident. This is after all, our purpose for carrying out the investigation
- All too often, reviewing accidents we are struck with the understanding that “there I too would have gone, if it were not for the sake of God”. That is, the accident could easily happen to you or me. Recommendations need to be in a nutshell to be acted upon to prevent that