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# The use of fault tree analysis to visualise the importance of human factors for safe diving with closed-circuit rebreathers (CCR)

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## Abstract

Closed-circuit rebreathers (CCR) have been used for many years in military diving but have only recently been adopted by technical leisure divers, media and scientific divers. Rebreather divers appreciate the value of training, pre-dive checks and equipment maintenance but it is often difficult to visualise just how important these factors are and how they inter-relate for a rebreather. In this paper, the well-known technique of fault tree analysis (FTA) is used to identify risk in a rebreather. Due to space constraints, only the branch of the tree for unconsciousness as a result of hyperoxia is considered in detail but, in common with the whole tree, end events are shown to be human-factor related. The importance of training to the emergency situation, the use of formal pre-dive checklists and the value of good design to prevent accident escalation are discussed further.

**Keywords:** CCR, closed-circuit, rebreather, SCUBA, diving, risk, human factors, fault tree analysis

## 1. Introduction

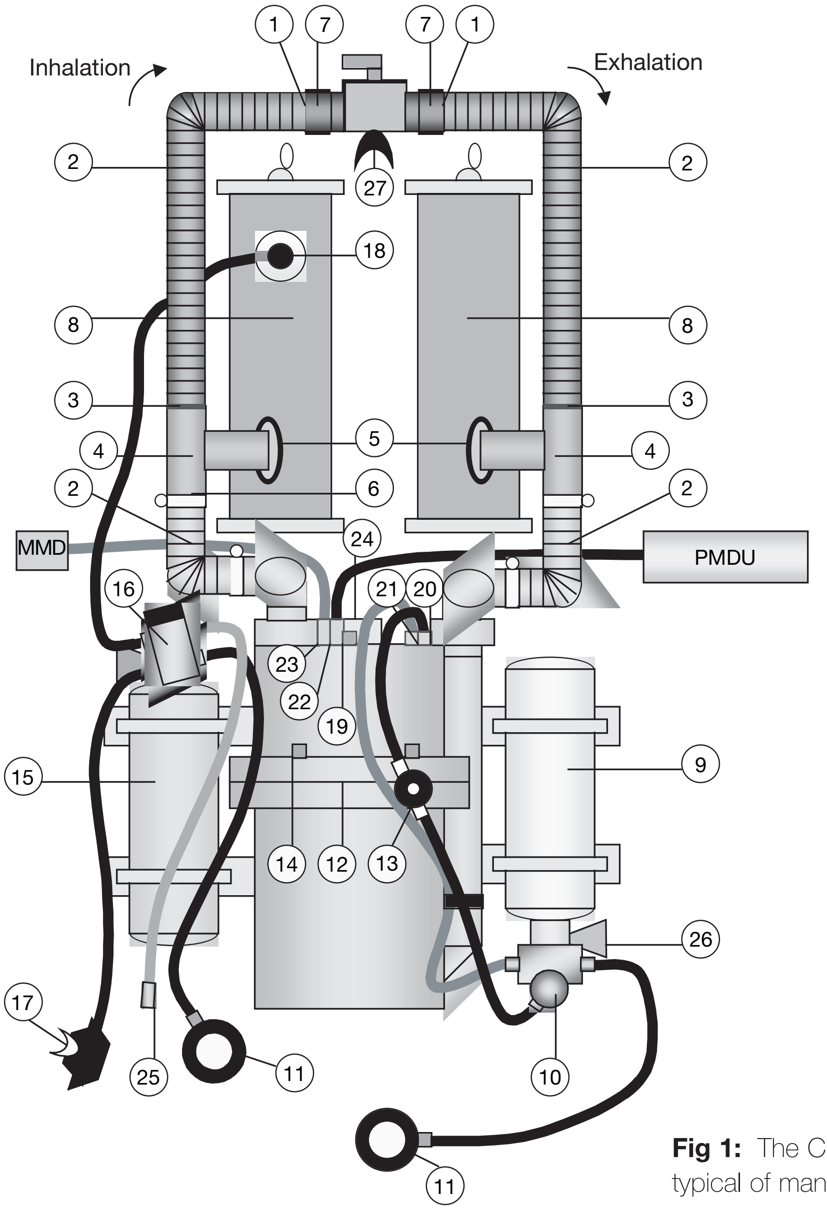
Rebreathers are being used increasingly in the recreational market, in the media and for various forms of scientific diving.[1] They pose several advantages ranging from enhanced decompression, reduced noise and stealth, to deeper diving for prolonged periods.

Two types of rebreather are currently in widespread use.[2] In the semi-closed rebreather, a pre-mixed gas is introduced into a breathing loop. The gas is scrubbed for carbon dioxide by a chemical scrubber, and because the volume of gas exhausted to the water is less than that of open-circuit SCUBA, the gas is used more efficiently. The closed-circuit rebreather (CCR) maintains the partial pressure in the breathing loop within much tighter limits by electronically analysing the gas and replacing the utilised oxygen. Whilst this represents a more efficient and elegant approach, it does have a high burden of associated risks.[3]

One of the problems for many rebreather divers is how to evaluate and quantify the associated risks for their diving activity. Many rebreather divers, especially the veterans, can rely on their experience of ‘near misses’ and lessons learned but this does not necessarily help the new diver or the designer. This paper attempts to use fault tree analysis (FTA) as a simple methodology to formalise risk assessment in a CCR. The advantage of this technique over others, such as Failure Modes and Effect Criticality Analysis (FMECA), is that it is possible to visualise the risk easily and see how common human factors, such as training, pre-dive checks and design, impact on safety. It is this combination of inter-related human issues that makes rebreather diving so interesting, especially for the risk analyst.

## 2. The Cranfield closed-circuit rebreather

The overall design of the rebreather used in this study is typical of any CCR and is shown in Fig 1. Gas from the diver is exhaled through a closable mouthpiece and is forced clockwise around a breathing loop by the use of non-return valves. A ‘jason bag’ exhalation counterlung ensures the work of breathing (WOB) is unaffected by the orientation of the diver. This is achieved by positioning the counter lung such that it lies over the shoulder of the diver ensuring that the difference in pressure with the lung centroid is minimised. The gas then enters the bottom of the scrubber unit where there is a void to act as a water trap. Gas then progresses up the scrubber through a bed of ‘sofnalime’ that scrubs out the carbon dioxide by an exothermic chemical reaction. At the top of the ‘stack’, the oxygen partial pressure is measured and oxygen added to bring the mix up to a pre-defined ‘set-point’. The oxygen is provided from a high pressure cylinder and injected under the control of a solenoid valve. The mixed gas then returns to the diver via an exhalation counter lung. Inhalation and exhalation counter lungs are adopted to reduce the gas velocity and increase the dwell time of the gas in the scrubber. As the diver descends, the reduction of loop gas volume caused by increasing pressure is compensated for by the addition of a ‘diluent’ gas that contains a breathable amount of oxygen. In this case, the diver adds this manually but many rebreathers have an automatic diluent addition valve.



| No. | Component |
|---|---|
| 1 | O-ring |
| 2 | Hose |
| 3 | Tie-wrap |
| 4 | T-pipe |
| 5 | Washer |
| 6 | Connector clip |
| 7 | One-way inhalation and exhalation valves |
| 8 | Counterlungs |
| 9 | Oxygen supply |
| 10 | Oxygen first stage |
| 11 | Pressure gauge |
| 12 | O-ring |
| 13 | Manual oxygen supply valve |
| 14 | Screws |
| 15 | Diluent supply |
| 16 | Diluent first stage |
| 17 | Diluent second stage |
| 18 | Counterlung input valve |
| 19 | Depth transducer |
| 20 | Manual oxygen input connection |
| 21 | Automatic oxygen input connection |
| 22 | Primary Master Display Unit (PMDU) cable connector and cable |
| 23 | Mask Mounted Display (MMD) connector and cable |
| 24 | PC input connector |
| 25 | Dry-suit hose connector |
| 26 | Oxygen cylinder valve |
| 27 | Mouthpiece switch |

**Fig 1:** The Cranfield closed circuit rebreather – typical of many rebreathers

To analyse the gas in the loop, three oxygen sensors are monitored by electronics and the values obtained are voted on. If the voted value is less than the desired set-point an oxygen bolus is injected. The oxygen sensor values and voted value are shown to the diver on a LCD display. In addition to this display, the diver also has a mask-mounted display (MMD) positioned in his peripheral vision. The MMD has a high and low oxygen detection level. If the oxygen level detected is between these two limits, then a green LED is displayed to the diver. If the limits are exceeded, then a red LED is flashed. Separate LEDs indicate if either high or low limits have been exceeded.

## 3. Fault tree analysis (FTA)

Fault tree analysis is just one technique for risk identification and assessment. Other methods include brainstorming, FMECA, Hazard and Operability Studies (HAZOPS), event tree analysis to name a few, all of which are well documented.[4] A good introduction to the use of FMECA, FTA and reliability block diagrams (RBD) to identify risk in a simple diving life support system can be found in Strutt and Tetlow.[5]

In a fault tree, a top event is established such as ‘rebreather diver has no breathable gas’. The analyst then asks the question: ‘How does the diver end up with no breathable gas?’ His response might be ‘gas in the loop is unbreathable’ AND ‘gas in the bailout is unbreathable’. The analyst then asks how each of these event occurs in turn and uses AND/OR gates to link the events into a tree until further resolution of the problem is not possible. Unfortunately, it is not possible to cover the whole fault tree in this paper and so only the branch of the tree for unconsciousness as a result of hyperoxia is considered to its end events.

## 4. Topology for the rebreather fault tree

As with any fault tree, the topology can vary significantly for each analyst. That is not to say that each fault tree gives a different result since differing topologies can

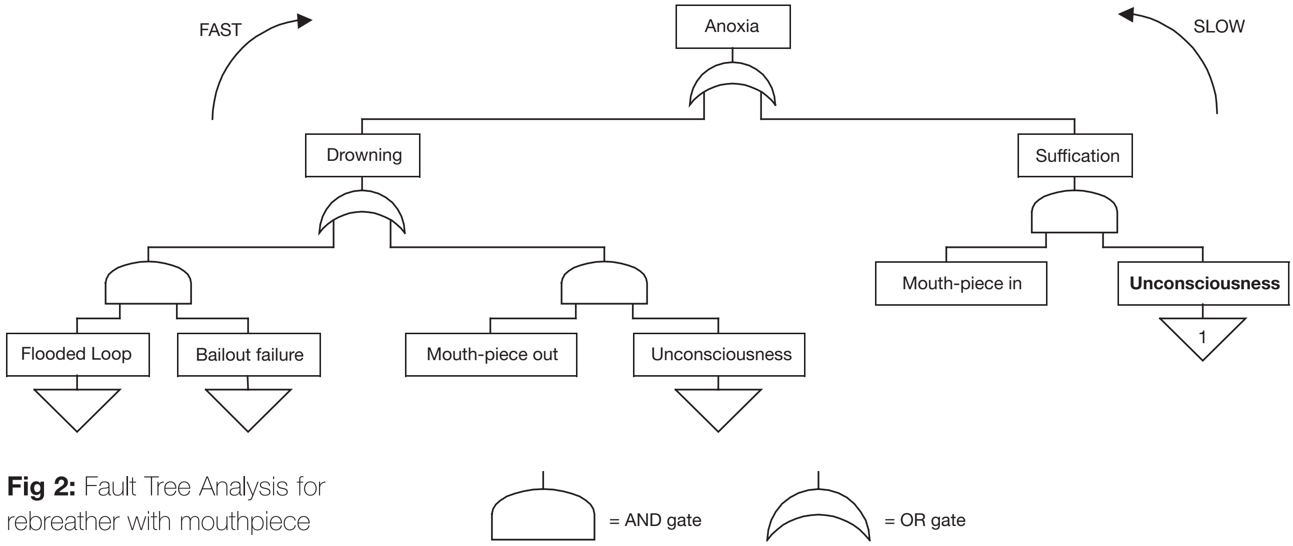


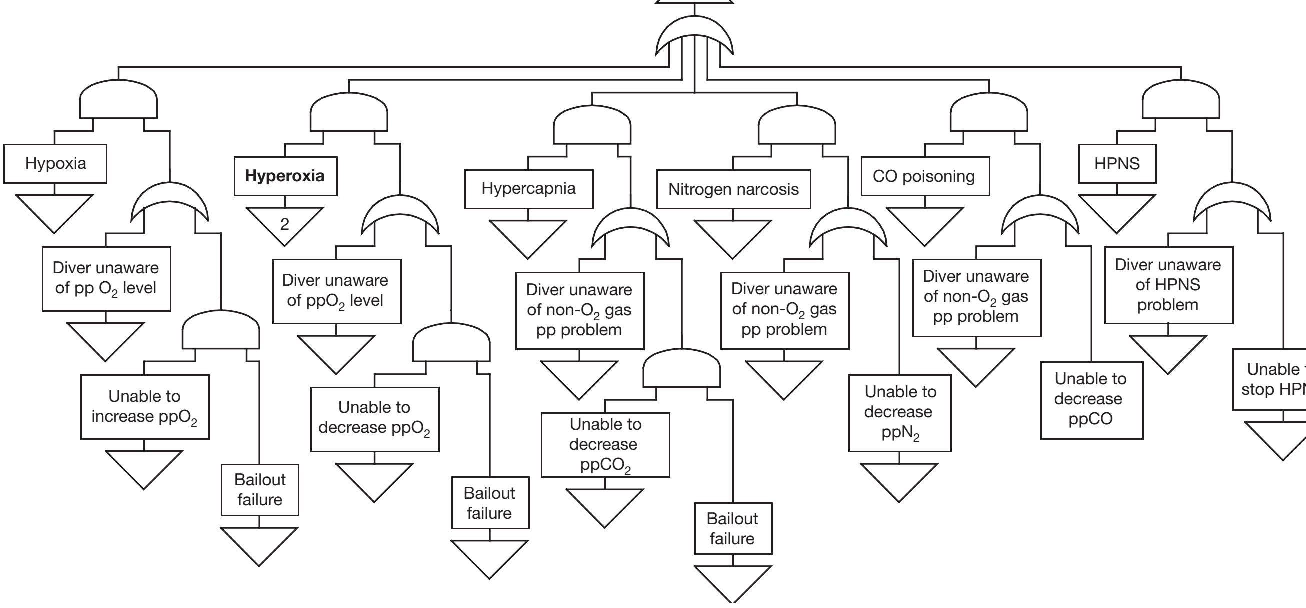
**Fig 2:** Fault Tree Analysis for rebreather with mouthpiece

result in the same ‘cut sets’. Cut sets are a combination of components in a system which, when failed, cause a system to fail. They are usually derived using a Boolean expression once the combination of AND/OR gates for a particular fault tree is known. This paper is not concerned with the Boolean output of the tree but rather the nature of the end events. In this case, it is the process of carrying out a formal risk assessment and seeing the consequences rather than any quantative result that is the main concern.

When undertaken as a student workshop exercise, participants quickly devise a topology that includes the expected dangers with CCR, namely hypoxia, hyperoxia and hypercapnia. Few initial topologies incorporate one of the other major failure mechanisms of CCR, namely partial or full flooding of the loop. In order to introduce flooding of the loop at a high level of the fault tree, the topology shown in Fig 2 was developed. Other topologies are possible and the development of a satisfactory initial topology for such events can be problematic.

It can be seen that the top event of Anoxia can be reached via three pathways. Firstly the diver retains his mouthpiece AND is unconscious because of one of the events below which leads to suffocation. In this case it is assumed that if the diver is unconscious, there is no breathable gas in the loop since all the events below ‘unconsciousness’ lead to that event. Alternatively, the diver is unconscious AND looses his mouthpiece leading to drowning OR the loop floods AND the bailout fails. In common with any fault tree event, time is not considered. For instance, anoxia results from the loop flooding AND the failure of the bailout but in reality a diver might take further actions, which prevent propagation through to the end event (they may be at 3m depth for instance and simply swim up). Finally, it should be noted that in this case a mouthpiece has been used rather than a full face mask (FFM). Use of a FFM, as recommended in the European rebreather standard,[6] would remove the drowning scenario with the mouthpiece out, and illustrates the case-specific nature of the top level topography.

**Fig 3:** Factors leading to unconsciousness



## Unconsciousness

The three events illustrated (Fig 2) – flooded loop, bailout failure and unconsciousness – can be further investigated. For the purposes of this study, only unconsciousness will be considered since it permits the consideration of hyperoxia as one of the causes and illustrates the advantages of carrying out a FTA. The full FTA for the CCR can be found in Hardy.[7]

As expected, the scenarios that every diver trains to avoid are found under unconsciousness, namely, hypoxia, hyperoxia and hypercapnia. However, unconsciousness caused by nitrogen, carbon monoxide and HPNS are also included for completeness, as shown in Fig 3.

It can be seen that that all causes of unconsciousness are similar topologically and since they are independent of each other, they are connected by an OR gate. Unconsciousness caused by hyperoxia occurs if the loop gas becomes hyperoxic and the diver continues breathing from the loop. They are unable to take remedial action if they are unaware of the oxygen partial pressure ($ppO_2$) OR they are unable to come off the loop. The latter would be caused by being unable to decrease the $ppO_2$ AND a failure of the bailout. Each of these latter events can be further analysed but, as described above, only the factors leading to the loop being in a hyperoxic state will be considered further.

## Hyperoxia

The tree for hyperoxia is shown in Fig 4. Overall, it can be seen that hyperoxia results from either a change in partial pressure in the loop because of a change in depth OR an addition of oxygen. The latter can happen either automatically as affected by the controller OR through the manual addition of oxygen by the diver.

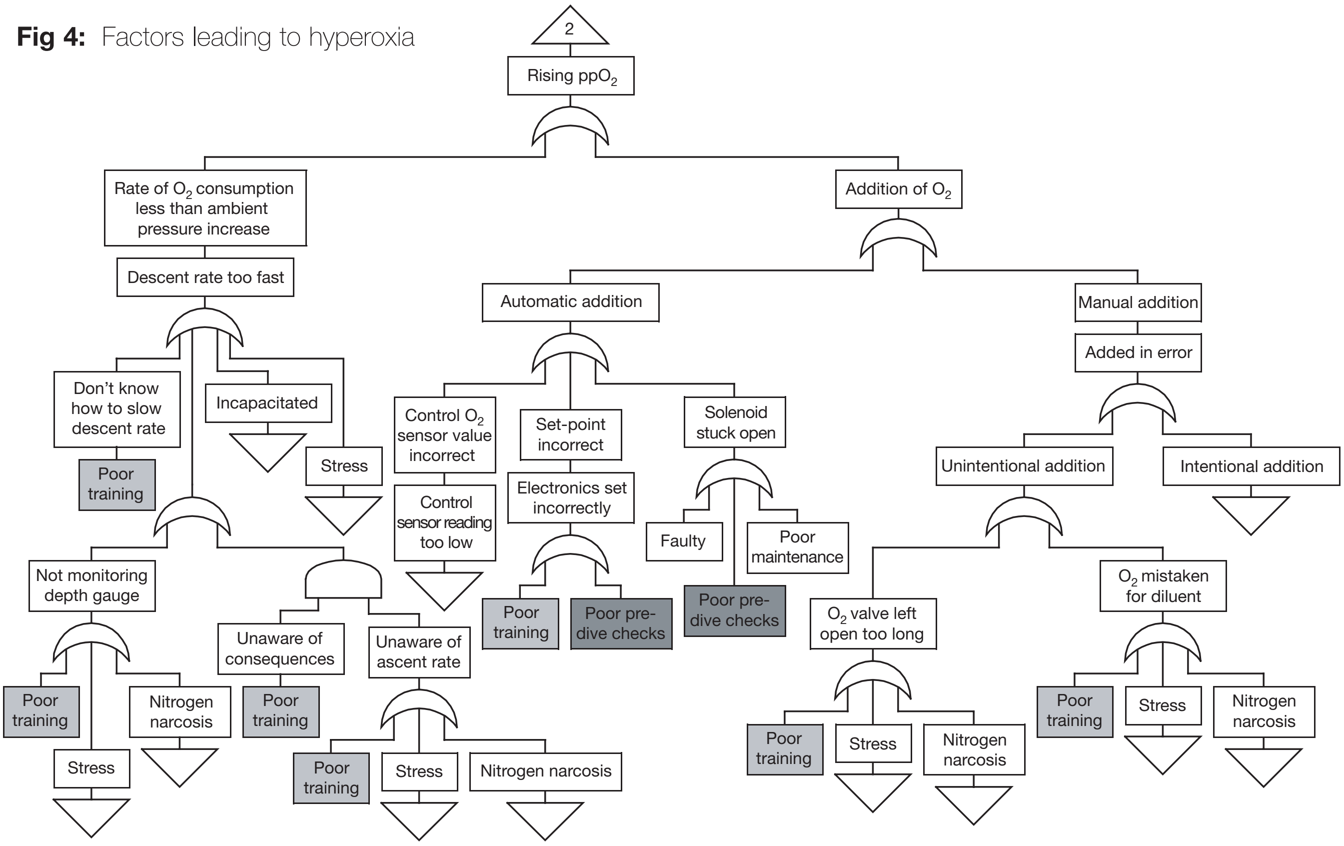
## End events

As seen in the figure, branches are eventually resolved in what can be recognised as human failures with either ‘poor training’, ‘poor pre-dive checks’, or ‘poor maintenance’. It should be recognised that such events can be inter-related. For example, poor pre-dive checks may be the result of poor training but may also be simply because of forgetfulness or lapses caused by time constraints, stress, distractions etc. The different categories will overlap, but here it is important to recognise the difference between adequate training and the ability of the diver to implement what has been learnt in real situations after qualifying.

**Table 1:** Frequency of occurrence of specific end events for the full fault tree

| ***End event*** | ***Total number of occurrences*** |
|---|---|
| Poor training | 180 |
| Poor pre-dive checks | 147 |
| Stress | 78 |
| Poor maintenance | 52 |
| Incapacitated | 42 |
| ‘It will do’ approach | 32 |
| Poor dive planning | 29 |
| Mechanical failure | 24 |
| Other | 16 |
| **Total** | **600** |

**Fig 4:** Factors leading to hyperoxia



## 5. Discussion

In the full fault tree, the distribution of end events can be broken down as shown in Table 1.

It can be seen that over half of the final events for the full FT for a CCR end with poor training or poor pre-dive checks. This emphasises just how important these factors are to safety and it is therefore appropriate to discuss some of the more important aspects in more detail with reference to Fig 4 in particular.

### Poor training

Training has a number of roles for the rebreather diver. Firstly, it is essential that training adequately and sufficiently familiarises the diver with the equipment. Knowing when to replace oxygen sensors, $CO_2$ scrubber material and other worn parts, and how to change set-points and perform calibrations, will prevent dives with performance-diminished components and associated inaccurate status information.

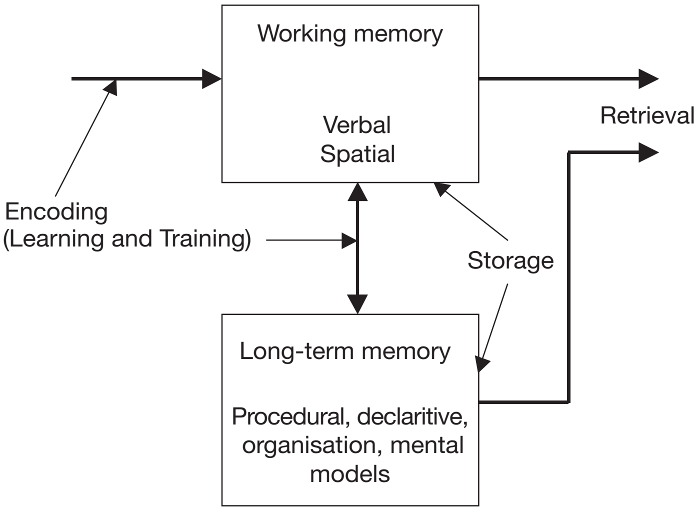
Full familiarity with the equipment will also prevent confusion over which feature to use in a given situation such as the manual addition of oxygen and diluent. Such actions, however, are prone to failure. In human factors terms, such failures, or errors, fall into three categories; slips, lapses and mistakes. Slips and lapses occur in very familiar tasks that are often carried out with little conscious attention. These 'skill-base' tasks are vulnerable to errors especially when attention is diverted elsewhere even momentarily. Mistakes are either knowledge- or rule-based. One of the aims of training is to reduce the probability of making such errors.

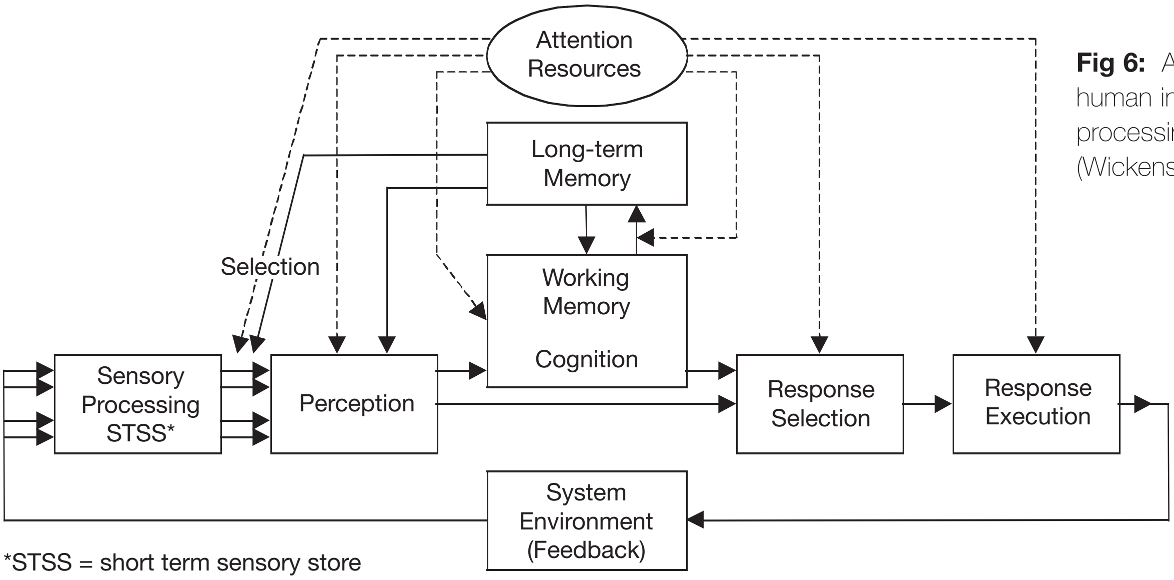
The main aim of training is to maximise the time available to deal with a situation by removing as many processes as possible from working memory. Working memory is a temporary 'storage unit' that retains information until it is used or stored in long-term memory. It is also used as a workspace where information retrieved from long-term memory can be compared, evaluated and examined.[8] Fig 5 shows diagrammatically the relationship between working and long-term memory, storage and subsequent retrieval.

Utilising working memory requires 'attention resources'. These resources are limited and Fig 6 shows how they are theoretically distributed between psychological processes.

The more resources that an individual process requires, the less remain available for other processes and the more resources that are required by sensory processing, perception and response selection, and execution, the less remain available for working memory. Rule-based behaviour requires a hierarchy of rules to be brought into working memory until a decision and response selection is made. Knowledge-based behaviour is even more demanding because of the complete absence of pre-determined rules or response patterns.

**Fig 5:** A representation of memory functions (adapted from Wickens 1992)





*STSS = short term sensory store

**Fig 6:** A model of human information processing stages (Wickens 2000)

For a plan of action to be devised, as much information as possible pertaining to the situation, such as environmental conditions, equipment capabilities, etc, must first be collated into working memory and analysed. As well as taking up valuable attention resources, these two forms of response behaviour also take time, which may not be available in an emergency situation. To minimise the dependency on working memory, behaviour needs to be skill-based, whereby a response stored in long-term memory is triggered automatically by a specific stimuli such as an indicator light on a console display, for example.[9] The degree of automaticity is determined by the amount of practice acquired by the diver in a particular situation as a result of training and experience.

The advantages of this reduced dependency on working memory become particularly apparent in an emergency situation. Just as stress has been shown to have a narrowing effect on perception and selective attention, stress of perceived danger, anxiety and even noise have consistently been shown to reduce the capacity of working memory.[9] This reduction in capacity severely restricts the utilisation of both rule- and knowledge-based behaviour and may also affect the performance of any behaviour that is derived from these processes. Actions may become prone to error and accuracy reduced. This would suggest that simply providing the diver with more response time by changing the warning alarms to activate at slightly more conservative partial pressures would not eliminate the occurrence of stress-induced error. Similarly, retrieval of information (ie, behavioural responses) from long-term memory is also restricted by the effects of stress but only to that information which has not been well- or over-learned.[9]

Wickens[8] identifies a number of studies that have demonstrated the minimal effect of stress in direct retrieval of information from long-term memory, including Wickens, Stokes, Barnett and Hyman,[10] Stokes, Belger and Zhang[11] and Berkun.[12] It follows, therefore, that as stress will be experienced to the greatest extent in the event of a rebreather failure mode, training should ensure that sufficient and adequate attention is paid to emergency procedures. These should be performed to the extent that corrective responses become extremely well learned and firmly implanted into long-term memory. Not only will this ensure that a diver has the greatest possible chance of reacting positively in a given situation but will also increase the diver's confidence in their own knowledge and ability. This will reduce feelings of stress and anxiety in an emergency situation and also help to improve performance.

If a diver is made to experience all potential rebreather failures and can perform corrective measures in conditions of varying visibility, temperature and depth, then the probability of panic occurring during a failure event can be reduced. If training shows a diver to be incapable of dealing with a failure event in less than ideal situations, then thought should be given as to the suitability of the individual for rebreather diving.

## Is training enough?

How many different situations need to be covered during training before the rebreather diver can be confidently judged to be capable of reacting correctly and efficiently in all environmental conditions? Military divers undergo extensive and comprehensive rebreather training and their excellent safety record[13] provides positive support for the argument that training is the solution to preventing failure modes resulting from human error. Unfortunately, the degree of training involved is not realistically possible for the average recreational rebreather diver.

Rebreather divers need to be taught that although their course may be complete, their training is not. Richard Pyle, an ichthyologist at the Bishop Museum, Hawaii and experienced Cis-Lunar rebreather diver, identifies a key characteristic of a rebreather diver as discipline and knowing personal limitations:

> A rebreather diver should be able to recognise the difference between a high level of confidence and a high level of ability. Experienced open-circuit divers are the most at risk as their *confidence* levels may be above their level of *ability* immediately after completing a course.[14]

Pyle famously accepted his own limitations as he 'progressed' from a self-declared expert after 10h experience to a beginner after 100h experience and the realisation that training can not account for every eventuality.

As a final thought on training, both open-circuit and closed-circuit divers rarely practise self- rescue skills in a habitual manner. The exceptions are those who take part in the training of others where the need to impart their skills requires them to reinforce their own. A diver not involved in training should perhaps consider practising some of these skills on a regular basis so that they reinforce reactions to an emergency situation.

## Design

As well as recognising the need for continuous learning through experience, to reduce the amount of required training and yet still maintain or increase user safety, consideration must be given to the design of the rebreather and its ease of use by the diver. Ergonomics plays a vital role in human/machine interaction success and failure modes arising from poor design could be added easily to the FTA to complement or even replace some of those faults currently attributed to poor training. Fig 7 shows an example where poor design could feature in the FT. Although not a human factor usually attributed to the diver, poor design is a human factor of the manufacturer.

On the Cranfield rebreather, the diluent addition valve is a push-valve conveniently placed on one of the

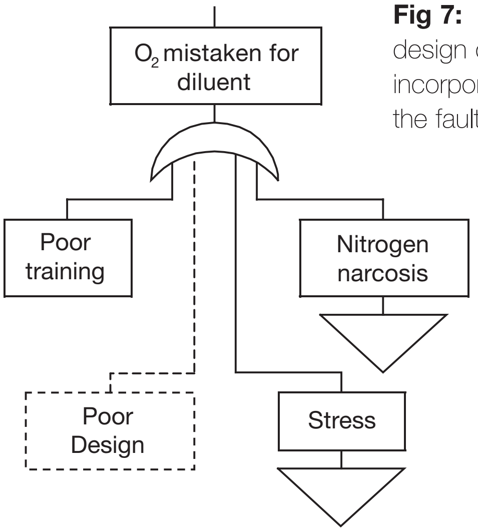


**Fig 7:** How poor design can be incorporated into the fault tree

counterlungs while the manual oxygen valve is an under-arm needle valve. Given the different methods of operation and the different valve locations, the probability of the addition of incorrect gas in error is greatly reduced. The oxygen valve is difficult to access though and one option would be to mount a valve similar to that used for the diluent injection but on the second counterlung. Great care would need to be taken to ensure that the diver was capable of distinguishing between the two. Allegedly, the *Electrolung* rebreather was withdrawn from the market in the 1970s because of incidents and fatalities arising as a result of the diver confusing the two addition valves on the counterlung. This was in spite of the fact that the oxygen addition valve was covered by a spring-loaded cover that needed to be lifted up before the valve could be depressed. These same errors were discussed in the section on training above and the problems with the *Electrolung* emphasises how all these human failures can be related at some level.

Mistakes can be reduced by increasing knowledge through training but slips are prevented by improving both system and task design, which in this case would be ensuring the process of oxygen addition is sufficiently dissimilar to diluent addition to capture a possible error.

Norman[15] identified four key points relating to ideal equipment design as a defence against an error.

- Minimise perceptual confusions
- Make the execution of action and the response of the system visible to the operator
- Use constraints to lock out the possible cause of errors
- Avoid multimode systems.

The *Electrolung* oxygen/diluent addition methods clearly contradicts some of the above.

## Poor pre-dive checks and poor maintenance

Maintenance and pre-dive checks account for one third of all the end events in the fault tree. Interestingly, a half of these were associated with checking and maintaining the primary control unit and the mask mounted display. Rebreather divers know the importance of pre-dive checks but a number of observations should be made. Firstly, a simple solution to ensure pre-dive checks are carried out thoroughly is to use a checklist; these are regularly used in both military and media situations.[16] Although available for recreational divers, checklist use is not widespread. An example from another profession is where airline pilots use checklists regularly as it has been shown that they are a valuable aid to memory even for the experienced.[11]

Checklists are especially useful in rushed situations, common in recreational diving, where important checks can be missed or ignored. The fault tree is useful is ensuring that all essential factors are covered when devising a checklist. Of course, a more integrated approach to this would be to include the checklist in the software of the rebreather. This would require the diver to progress through the routine at each step confirming to the computer that the check in question has been carried out. The danger in this approach is that such a rebreather can be dived while still in this checking mode and thought should be given to this by the manufacturer. It should never be possible to dive the rebreather when the primary control system is not maintaining a breathable mix in the breathing loop, as this is a known cause of fatal accidents.

For the Cranfield rebreather a number of components cannot be checked prior to the dive, including the oxygen cell and the linearity of its response above 1 bar, and the high oxygen alarms for the hand unit and mask mounted display (typically set at 1.6 bar $ppO_2$). These could be addressed with good design. For instance, in order to check the response of the oxygen cells and alarms, the *Stealth* rebreather manufactured by Divex Ltd allows the diver to fit pressure plugs during the pre-dive check so that the rebreather can be pressurised above surface ambient pressure.[17] This is a good example of where the necessity for a pre-dive check has influenced the design of the rebreather. In fact, a risk assessment can be used to develop this idea further in order to identify whether the addition of other sensors in the rebreather can be used to carry out a complete computer-led pre-dive check.[18] With the use of an internal pressure transducer, the controller can pressurise the rebreather and confirm the pressure integrity of the breathing loop.

One of the features of the sub-tree for rebreather floods was a series of mechanical failures. Such failures do not occur spontaneously and the most common mechanical failure mechanism for a rebreather is a worn component. However, it can be argued that good pre-dive checks or a planned maintenance programme for replacement of critical components can counter many in-water mechanical failures. It could be further argued that if maintenance is performed rigorously enough, with adequate training and pre-dive checks, only human failing during the dive will lead to a situation which the diver cannot survive. Indeed, such is the philosophy of the 'Alpinist' approach adopted by some rebreather divers. In this way the potential pitfalls of mitigating against failure by using a second breathing loop for redundancy are avoided.

Finally, an FMECA of the Cranfield rebreather was also carried out although not reported here. In an FMECA, the frequency and criticality of a failure are assessed and this information is used to rank individual risk in a risk matrix. Not surprisingly, if a failure was detected during the pre-dive check it had a low criticality but if it was not detected during the pre-dive check the criticality of failure was significantly higher during the dive.

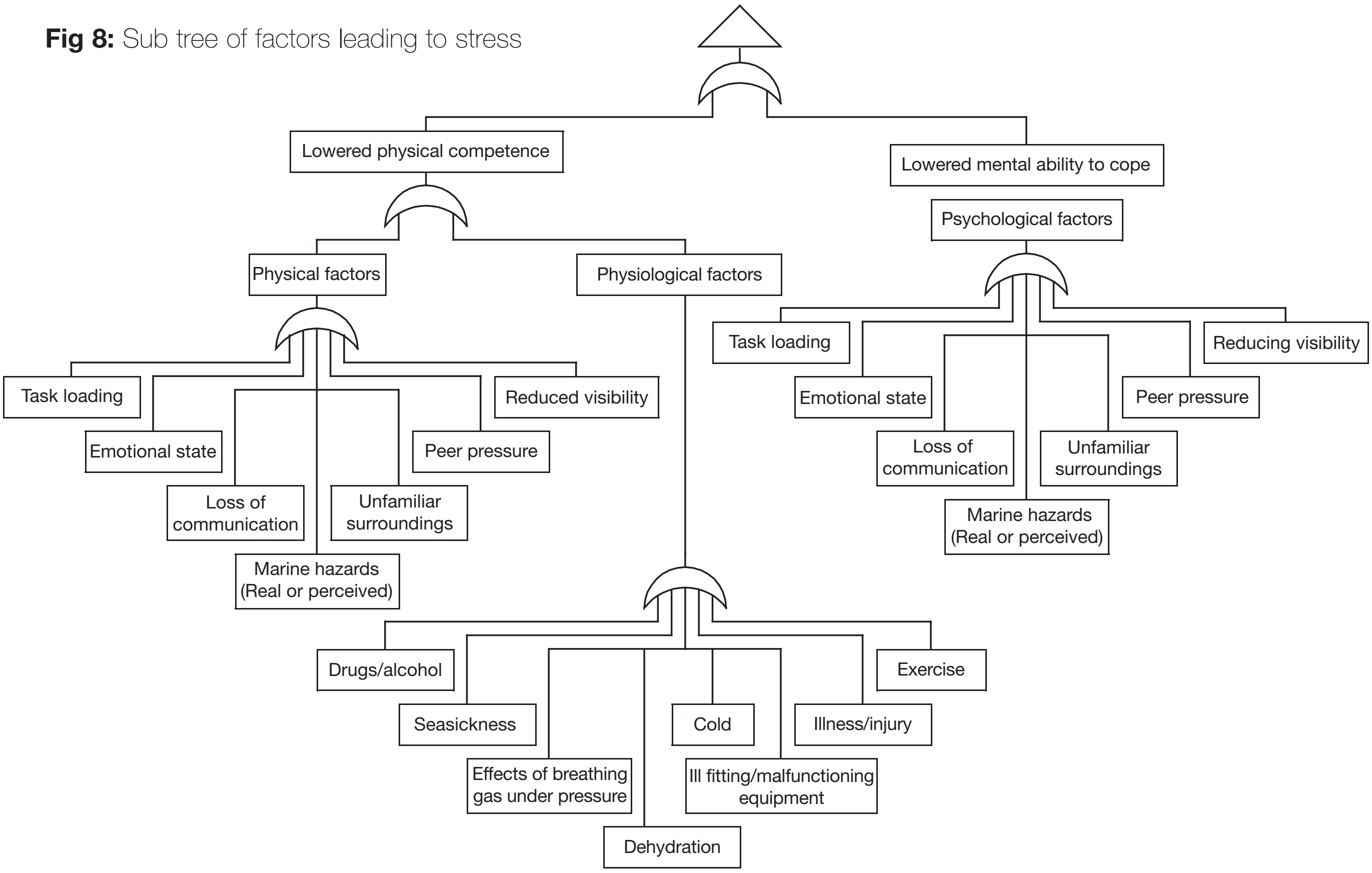
## Further observations from the FTA

The beauty of the FTA (especially when seen as a single but rather large diagram), is that each end event can be reduced to a human factor issue (although not always the diver himself) and the relevance of these can be appreciated by the diver. In a systems-based fault tree, it is possible to use the AND/OR gates to express a Boolean expression for the top event failure. This can be used to derive the cut-sets which reveal the criticality of individual systems. In the fault tree considered, each end event would need to be identified uniquely to allow a meaningful use of any Boolean analysis. However, it can be seen that the OR gate is prevalent throughout the tree. This is problematic since a failure from an end event can propagate up the tree through OR gates until it is arrested by an AND gate requiring another failure.

It can be seen clearly from the above that consideration of human factors are vital to the design and operation of a rebreather in a safe manner. This paper has concentrated on the importance of training, pre-dive checks, maintenance and design as four inter-related aspects of rebreather diving. Stress was another important factor and the sub-tree is shown in Fig 8. At first, it might seem difficult to evaluate the impact of many of the items listed in the stress sub-tree. However, there are techniques that can evaluate the impact of events such as unfamiliarity, task loading and emotional state. HEART (Human Error and Reduction Technique)[19] not only uses the above as 'error promoting conditions' but can also incorporate such things as poor human-system interface, unfamiliarity and time shortage, technique unlearning (rebreather divers with reinforced open-circuit skills) and misperception of risk.

The technique has several failings, one of which is that 'error promoting conditions' are not independent of each other. It has been seen in the above argument that many of the human factors given are not independent and inter-related at many levels. However, it is a useful technique and can, for example, be used to put a quantative figure to whether a diver takes the correct action after responding to an alarm from the rebreather controller.[18] Finally, inert gas narcosis was associated with many stress events as well as occurring in its own right (21 occurrences throughout the tree). Again, there

**Fig 8:** Sub tree of factors leading to stress



are various techniques such as stress strain modelling that can be used to build this seemingly intangible effect into a human reliability model.[20]

## 6. Conclusions

It is possible to carry out a fault tree analysis of a CCR and reduce all the failure modes to human failures. In this paper, only the branch of the tree relating to hyperoxia was considered. However, in common with other branches of the full tree, end events such as poor training, maintenance and poor pre-dive checks were encountered. Training not only instructs a diver how to use his chosen rebreather but also 'hard wires' his brain to operate the rebreather with minimal conscious effort. This is especially important in an emergency situation when decisions can often be wrong and subject to errors in performance. Pre-dive checks are vital to the safety and should be conducted in a methodical manner with a checklist. The 'it will do' approach often seen in divers should be subject to 'unlearning' in the same way that open-circuit buoyancy control must be unlearnt for rebreather diving. Good design can help capture human errors. The diver might make the mistake and there might be nothing physically wrong with the hardware but it should be questioned whether the designer could have helped prevent the mistake, lapse or slip.

The above approach to risk assessment of a CCR provides a visual aid to the diver to allow them to appreciate how human errors lead to failure. A deeper understanding of the value of continued training, good design and rigorous and methodical pre-dive checks should promote safer rebreather diving.

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