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Formal risk identification in professional SCUBA (FRIPS)

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RESEARCH REPORT 436

Formal risk identification in professional SCUBA (FRIPS)

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This report describes how fault tree analysis and failure modes and effects criticality analysis (FMECA) can be carried out on activities and hardware typical of a professional SCUBA diving activity. The methodologies are described and conclusions drawn from each technique. Examples are given of how the techniques can be used to assess diver risk in a quantitative way to aid assessing equipment configurations.

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G. M. E. Little (2004) Professional SCUBA Diving – When does the risk increase?

and

S. L. Hardy (2001) Risk based design considerations for the Cranfield ‘home build’ closed circuit rebreather

CONTENTS

SUMMARY

Fault tree analysis (FTA) and failure mode and effects criticality analysis (FMECA) are two commonly used risk identification techniques. In this report, each technique is used in detail to identify risks encountered by professional SCUBA divers.

The methodology to perform a fault tree analysis (FTA) with the top event being a 'dead diver' is described. The topology developed for this particular FTA is explained. Each branch of the tree is evaluated until an end termination is reached which is attributable to a human factor event such as poor training, poor pre-dive checks or poor maintenance. The value of understanding the significance of these events is then described in detail. In addition, stress, design and accident investigation is discussed in relation to the fault tree.

The full fault tree is not evaluated in a quantitative manner. However, in order to demonstrate this aspect of the technique, a quantitative FTA is carried out for two different SCUBA configurations, namely an octopus regulator and pony cylinder with regulator as an alternative air source. A fault tree is developed for each and the Boolean logic applied with some hypothetical failure rates to show that the probability of failure to provide gas with the octopus configuration is greater than that for the pony configuration.

The methodology to perform a failure mode and effects criticality analysis (FMECA) is also described. Both a high level and low level FMECA are given with associated frequency and criticality estimates, together with the resultant risk matrix. A hardware approach is taken and demonstrates that SCUBA equipment is safe if serviced and maintained properly.

In conclusion, risk can be reduced by using pre-dive checks, maintenance and training to minimise the effects of human failure. It is recommended that checklists are adopted, emergency drills practised routinely and design used to minimise confusion. FMECA provides a way to prioritise risk reduction in SCUBA hardware. Finally, it is noted that these techniques are not appropriate to evaluate the cause of most SCUBA fatalities which are usually a sequence of several often unrelated events.

1 INTRODUCTION

1.1 AIMS

The aim of this report is to show how two formal risk identification techniques can be used for commercial SCUBA operations. Fault tree analysis is used to highlight the influence of human factors and FMECA is used to identify hardware risks.

1.2 BACKGROUND

In the UK, the Health and Safety Executive (HSE) regulate commercial diving through the Diving at Work Regulations (DWR) 1997 (SI 1997 No 2776) and its associated ACoPs (Approved Codes of Practices). There are six ACoPs for professional diving and they are as follows:

1. Offshore Diving (Oil & Gas)
2. Inshore Diving (Civil Engineering, Aquaculture)
3. Media Diving (TV etc.)
4. Recreational Diving (Paid Recreational Instructors) & Guides
5. Scientific and Archaeological Diving
6. Police Diving

All these professional sectors except the Offshore Industry use SCUBA. The other five groups employ open circuit SCUBA systems in different configurations regularly. A standard scuba system and diving method does not exist for commercial purposes. In other words, the SCUBA system worn by a professional recreational instructor would bear no relationship to the system worn by a police diver. This situation is understandable as both divers face different circumstances and risks when at work. However, the police diver and the recreational instructor both face the same hyperbaric and physiological risks irrespective of their SCUBA equipment.

Military SCUBA divers in Britain are not regulated by the DWR 1997 but the BR 2806-Military Diving Manual; however they must comply with the Health & Safety at Work Act 1974.

Assessing the risk to commercial SCUBA divers in Britain is difficult due to few accidents having taken place and the strict regulations that have to be adhered to while diving. This is not the case in recreational diving where there are a large number of fatalities each year across the globe, and in the USA alone there were 83 deaths in 2002 (DAN, 2004).

In 1997, the HSE commissioned a quantitative risk assessment of SCUBA diving, which was carried out by PARAS Consulting Ltd. The data used for this study came from recreational accident reports produced by the British Sub Aqua Club (BSAC) and the Divers Alert Network (DAN). This recreational diving data analysed by PARAS represented Commercial SCUBA by proxy. In all, one thousand diving accidents were analysed of which there were 286 fatalities. The study revealed that the majority of fatalities resulted from two or more sequential events or ‘contributory causes’ where a contributory cause was defined as either a procedural error or an equipment failure. Of the 269 diving fatalities for which cause information is available, only 12 (4.46%) were attributable to a single contributory cause. The remaining two hundred and fifty seven fatalities probably arose as a result of a progressive sequence of events. Since all of the procedural errors are avoidable by a well-trained, intelligent and alert diver, working in an organised structure, it may be concluded that the low accident rate in commercial SCUBA diving, is due to this factor. It would be impossible to eliminate absolutely all-minor contra-indications of SCUBA diving. This would be a hopeless task, would result in overwhelming bureaucracy and would bring all diving to a halt (HSE-PARAS, 1997).

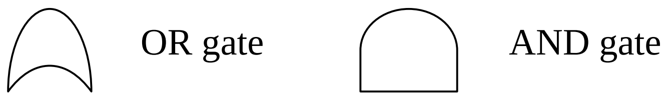
Nevertheless, SCUBA divers are at risk when they are underwater and this report uses two forms of formal risk identification that can be used for SCUBA configurations. Fault tree analysis is used to show the importance of human factors to the ultimate safety of divers. The fault tree is also used to quantify the difference with differing equipment configurations. Failure mode and effects and criticality analysis (FMECA) is used to demonstrate how a formal risk assessment can be carried out on SCUBA hardware.

2 FAULT TREE ANALYSIS (FTA)

2.1 INTRODUCTION

Fault tree analysis (FTA) is just one technique for risk identification and assessment. Other methods include brainstorming, Failure Mode and Effects Criticality Analysis (FMECA), Hazard and Operability Studies (HAZOPS), event tree analysis to name a few, all of which are well documented (Billington 1983). 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 (1999). In this report, only the fault tree and FMECA will be considered.

For the purposes of the fault tree in this report, the top event considered will be ‘death of the diver’. The analyst then asks the question ‘How does the diver end up dead?’ The response might be EITHER by ‘drowning’ OR by an ‘uncontrolled ascent’ (the assumption is made that a rapid uncontrolled ascent leads to death by barotrauma or severe DCS). The analyst then asks how each event occurs in turn and uses AND and OR gates to link the events into a tree until further resolution of the problem is not possible. An AND gate allows progress up the tree if event A AND event B is true. An OR gate allows progress up the tree if event A OR event B is true.



2.1.1 Topology

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 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 and OR gates for a particular fault tree is known.

In this report, we will not be 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 quantitative result that is our main concern. However, a limited application of the Boolean logic will be applied to compare two forms of alternative air source. See section 2.4.

The topology developed in section 2.2 is based on a number of assumptions which effect its logic. For instance, it will be noticed that many items of ancillary equipment do not feature in the fault tree although they are known to lead to the top event of dead diver. The topology has been chosen such that if good maintenance, pre-dive checks and training are rigorously applied, the top event will not occur. It is known that many accidents occur as a result of a cascade of events from a single failure. The fault tree does not deal with this situation but this is discussed further in Section 2.3.6 ‘Accident investigation’. For instance, loss of a fin strap cannot result in a dead diver since there are 2 buoyancy methods available for a well trained diver to use to gain the surface in a controlled manner. Incorrect use of a delayed surface marker buoy (DSMB) can be considered as a sudden buoyancy event but will not be considered since a DSMB is not considered as primary life support equipment. In situations where a DSMB was part of the basic equipment, it might be included. An alternative tree structure incorporating ancillary equipment can be found in Little (2004).

2.1.2 SCUBA configuration adopted

For the purpose of this report, a simple SCUBA configuration typical of a professional diving instructor has been adopted. Hence, the analysis is based on a diver using a half mask and regulator with no communication. The diver is assumed to have a dry suit and a buoyancy compensator device (BCD). A secondary air source is carried in the form of a pony cylinder and associated regulator.

2.2 LIST OF FAULT TREES

Figure 1 Dead Diver

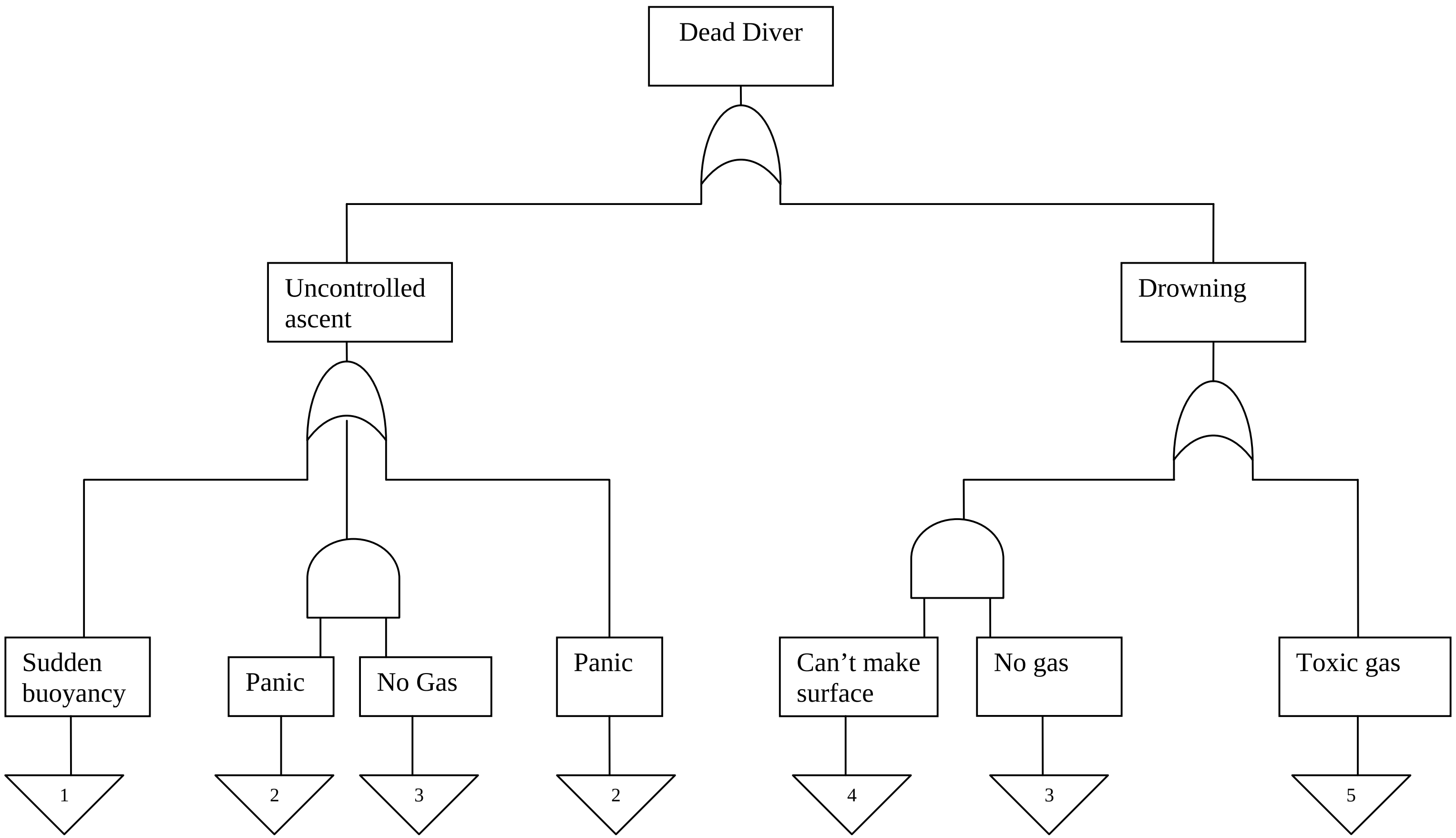


Figure 2   Sudden buoyancy

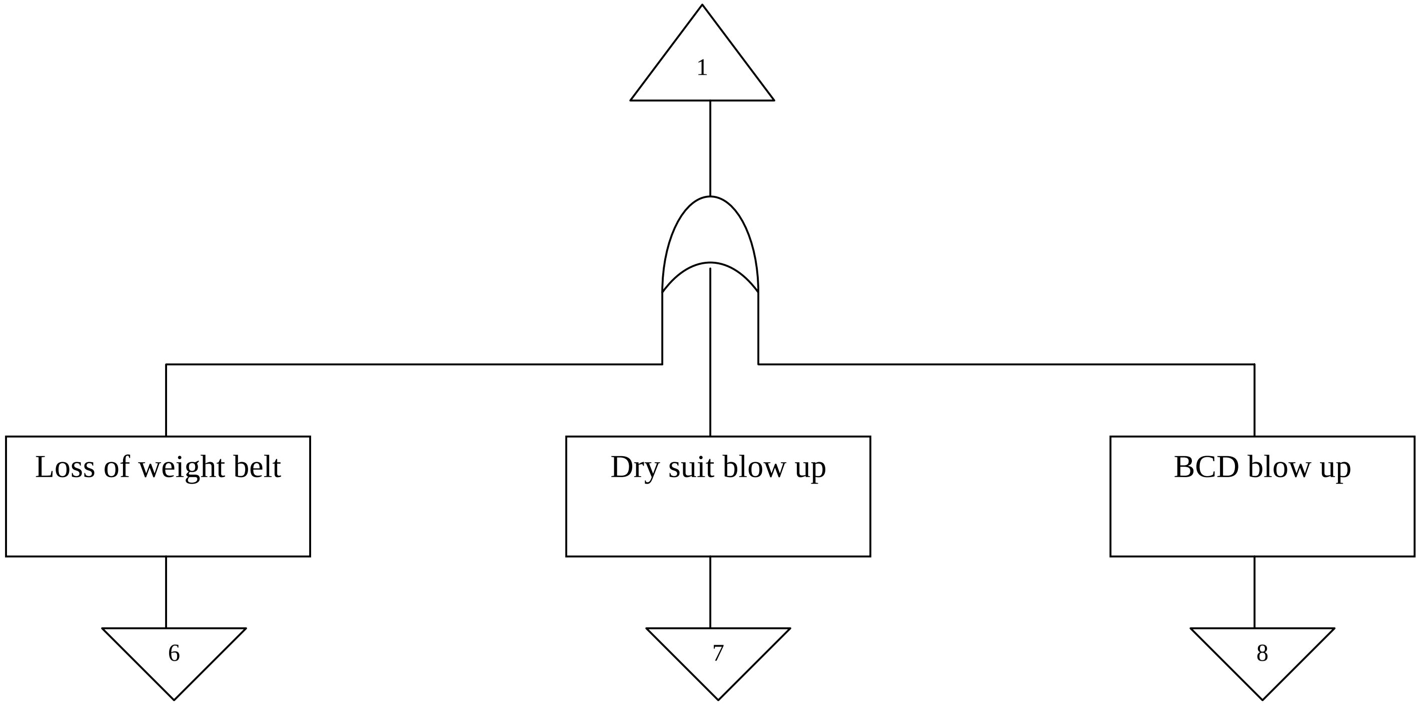


Figure 3 Loss of weight belt

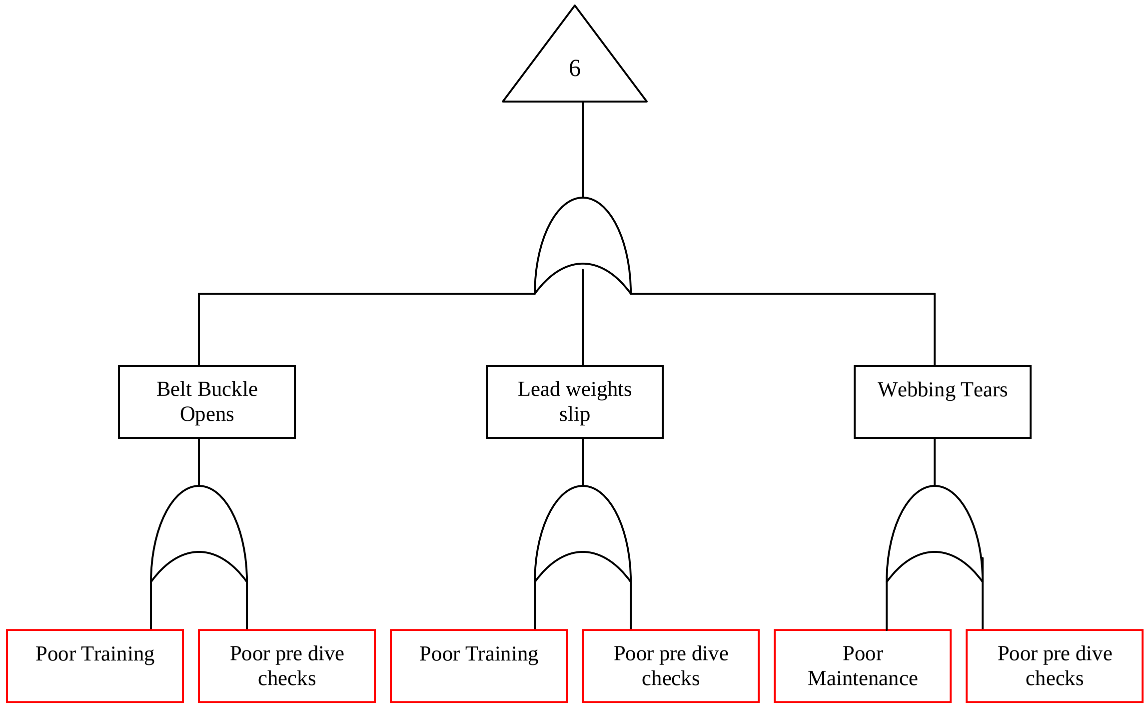


Figure 4 Dry suit ‘blow up’

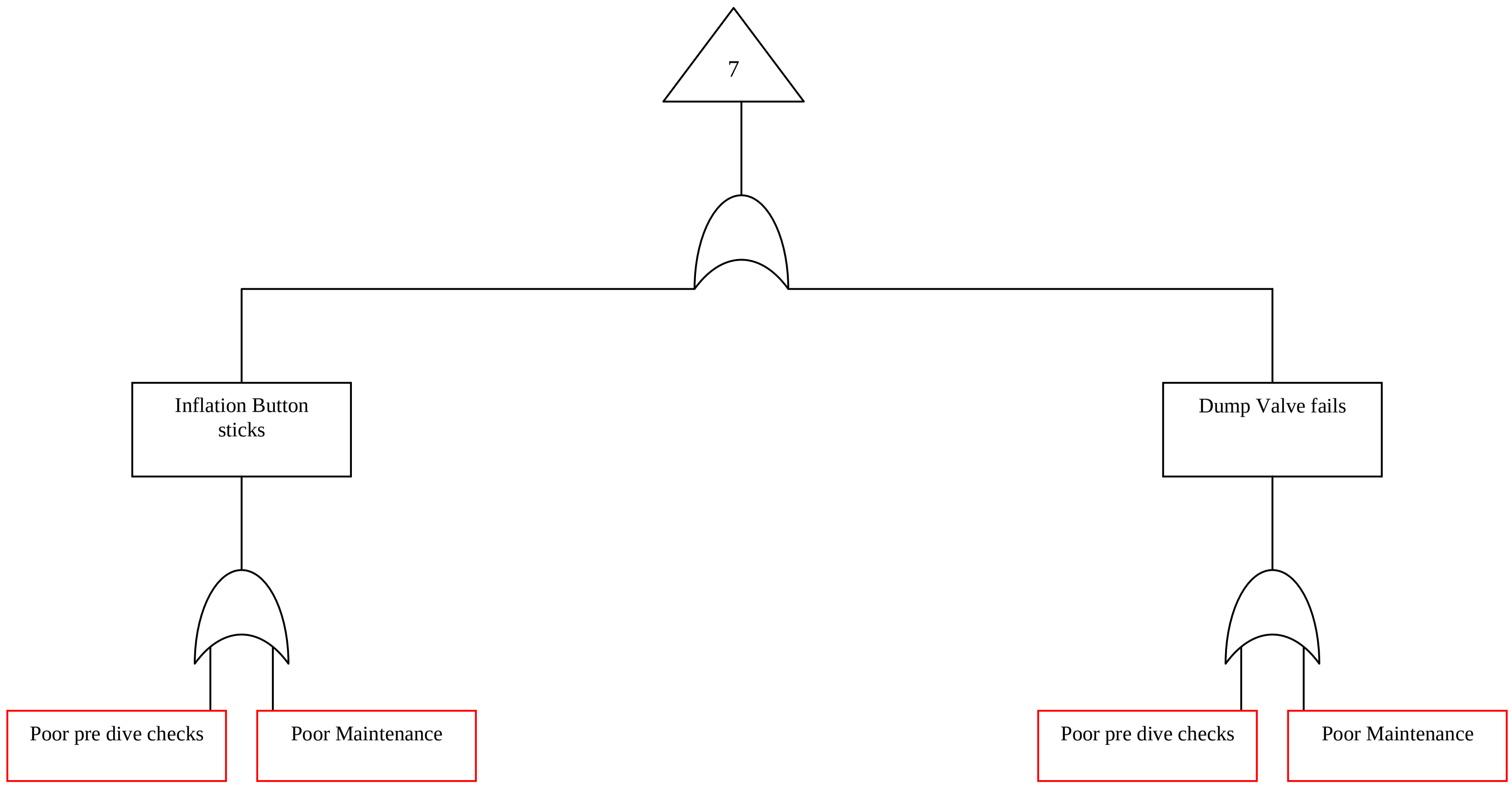


Figure 5   BCD 'blow up'

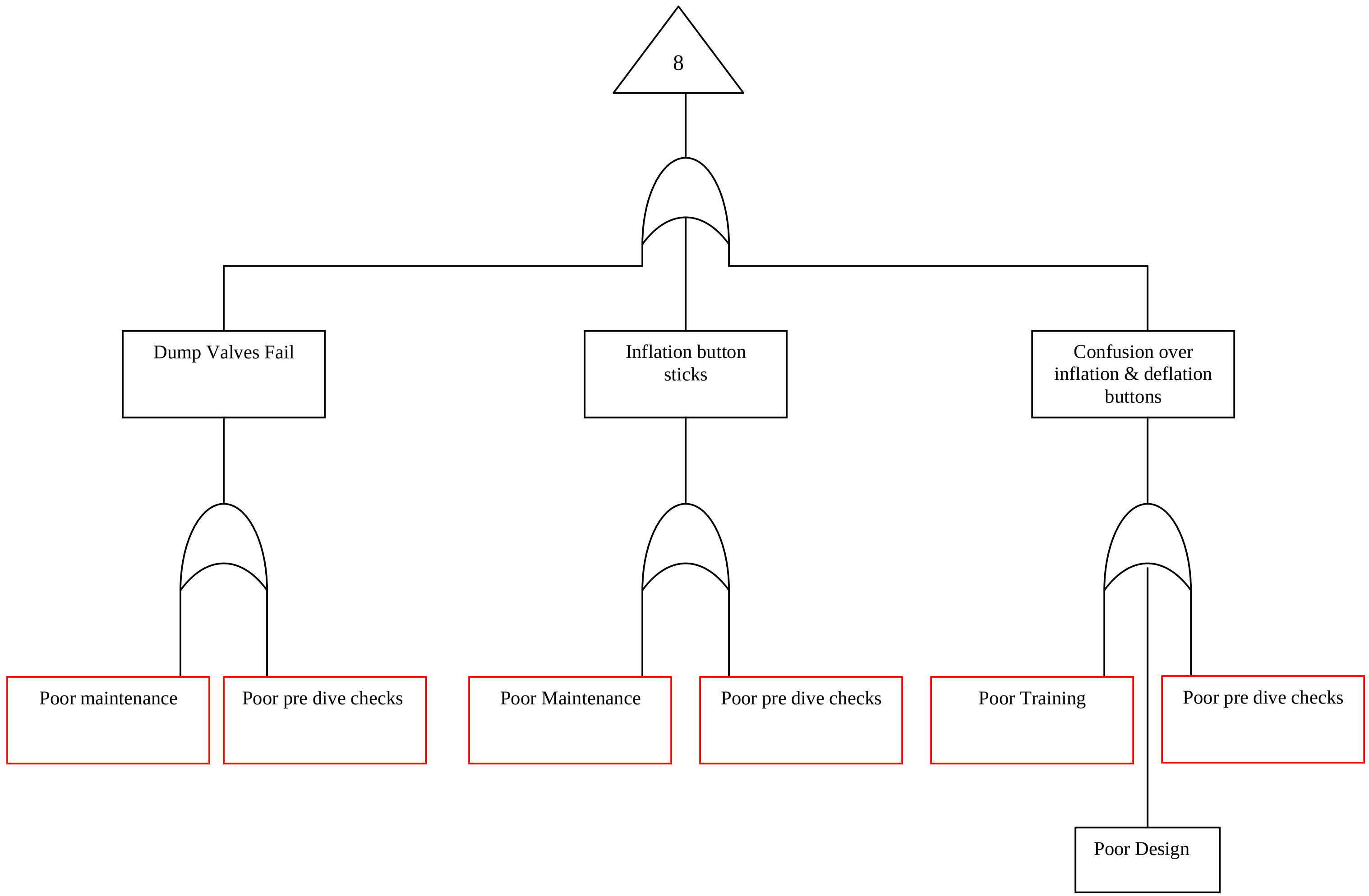


Figure 6 Panic

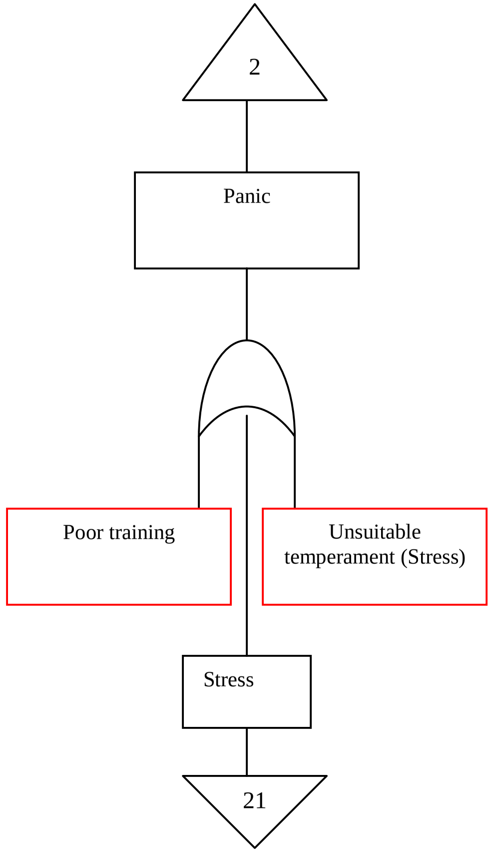


Figure 7 No gas

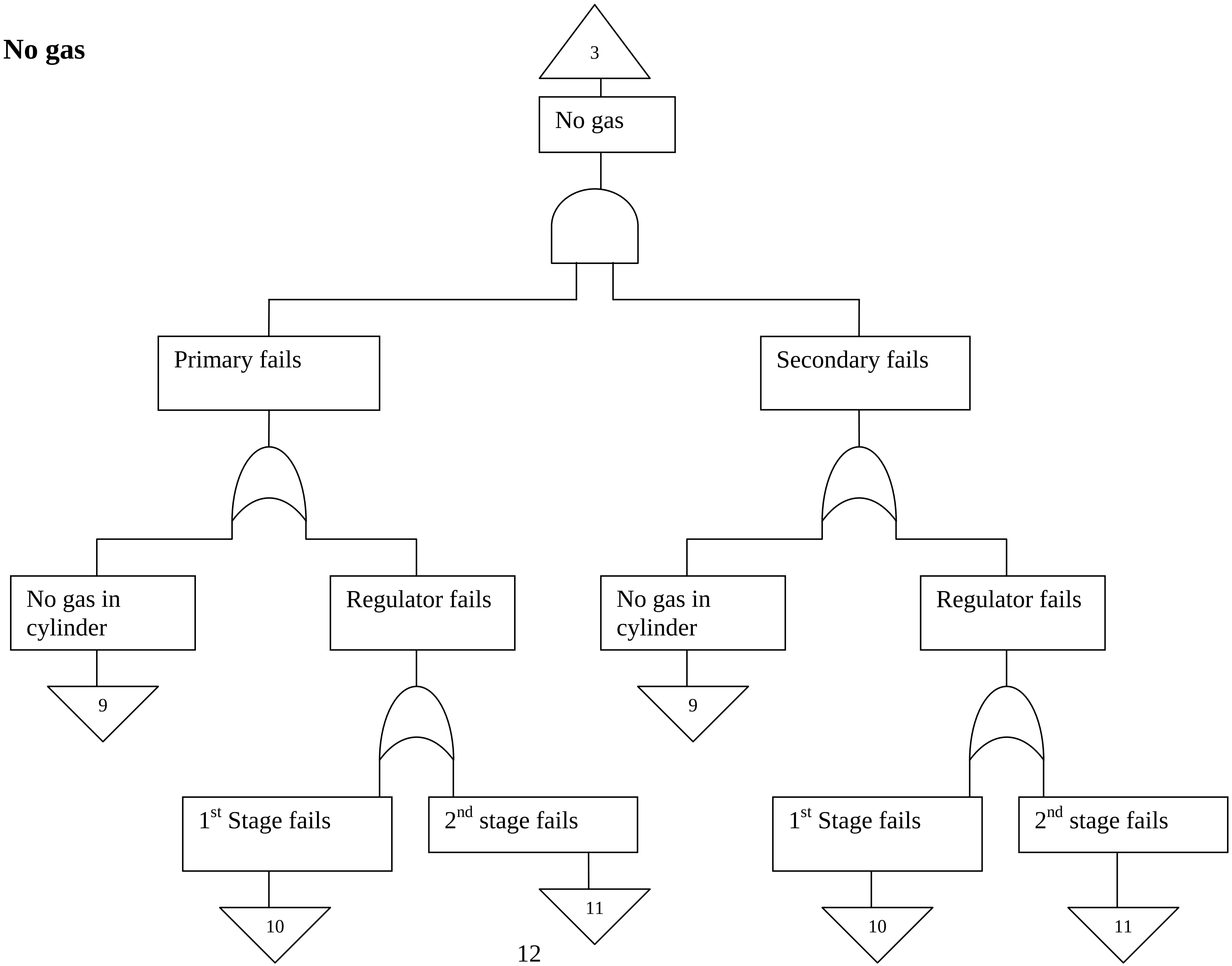


Figure 8 No gas in cylinder

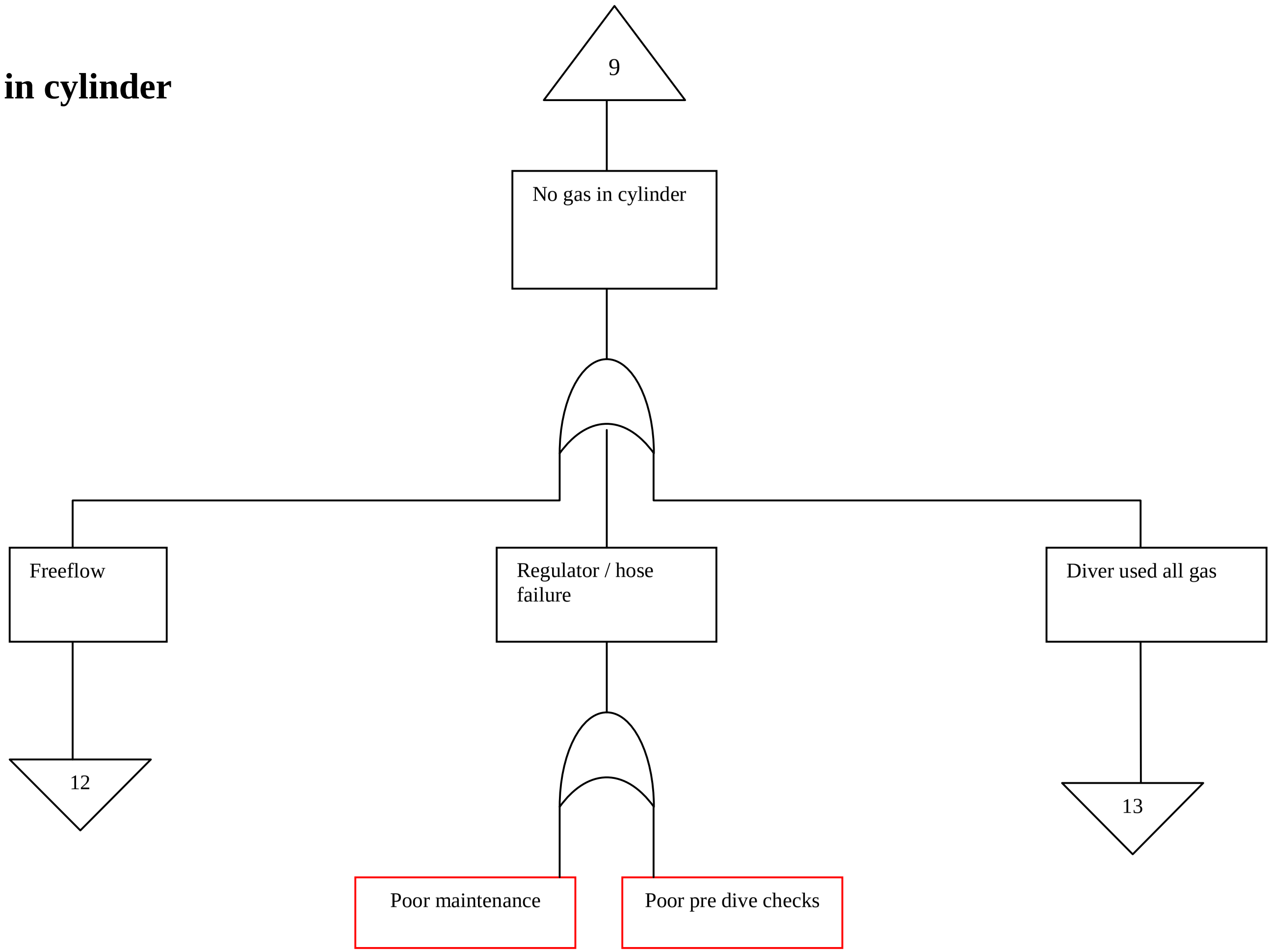


Figure 9 Demand valve free flow

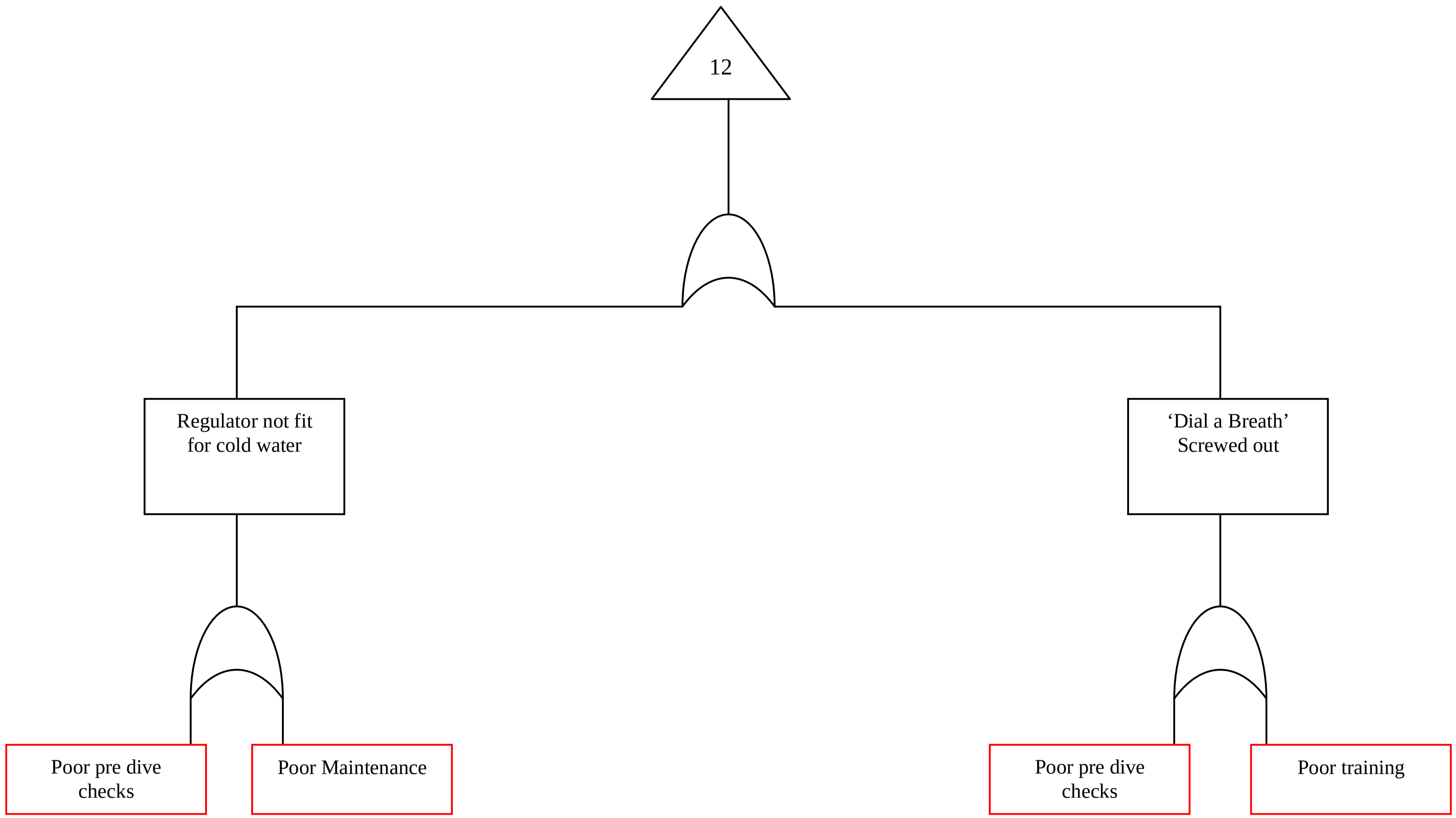


Figure 10 Diver used all gas

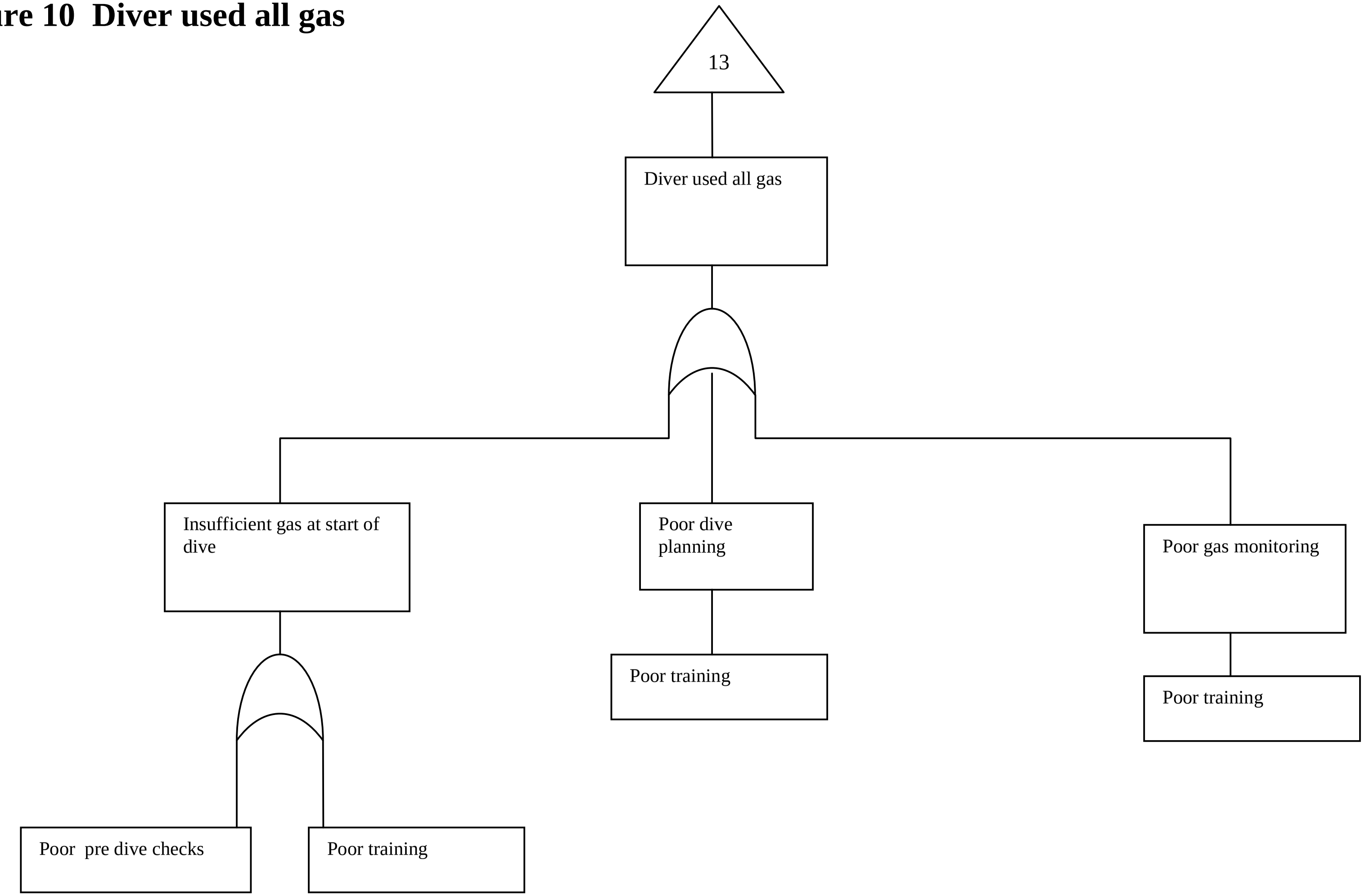


Figure 11 First stage failure

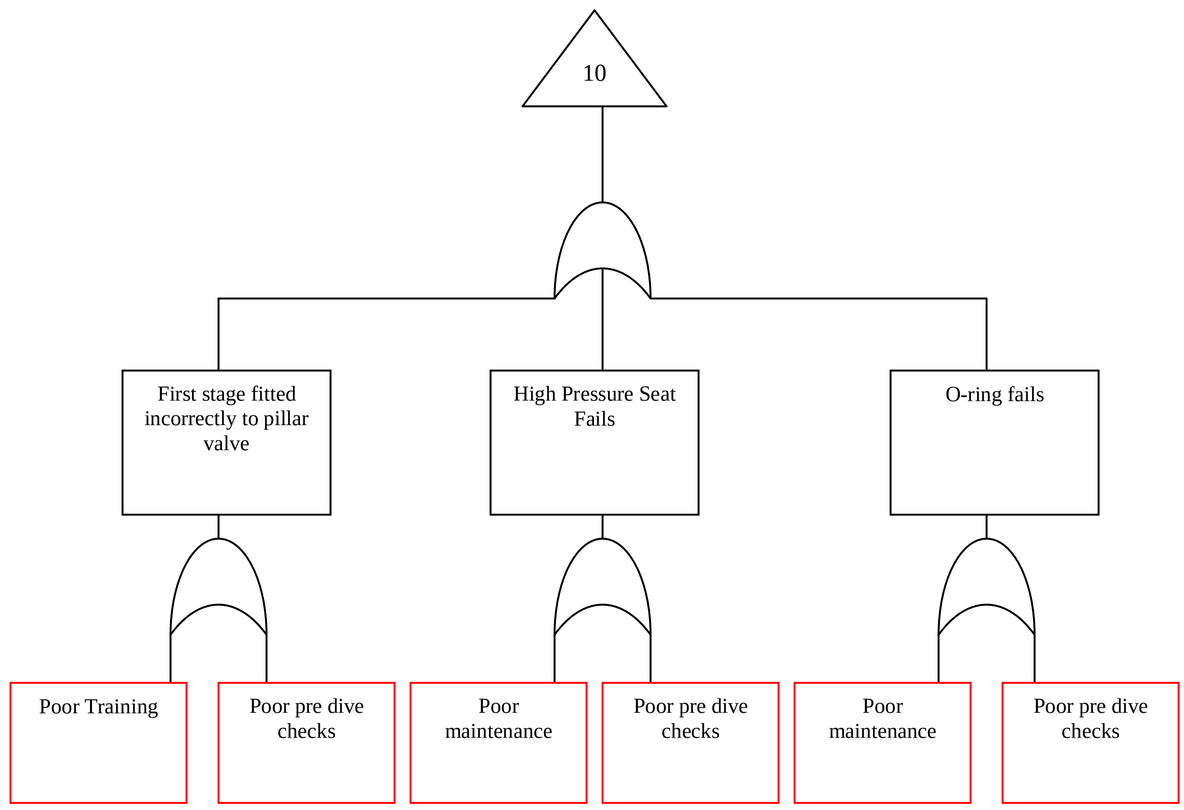


Figure 12 Second stage failure

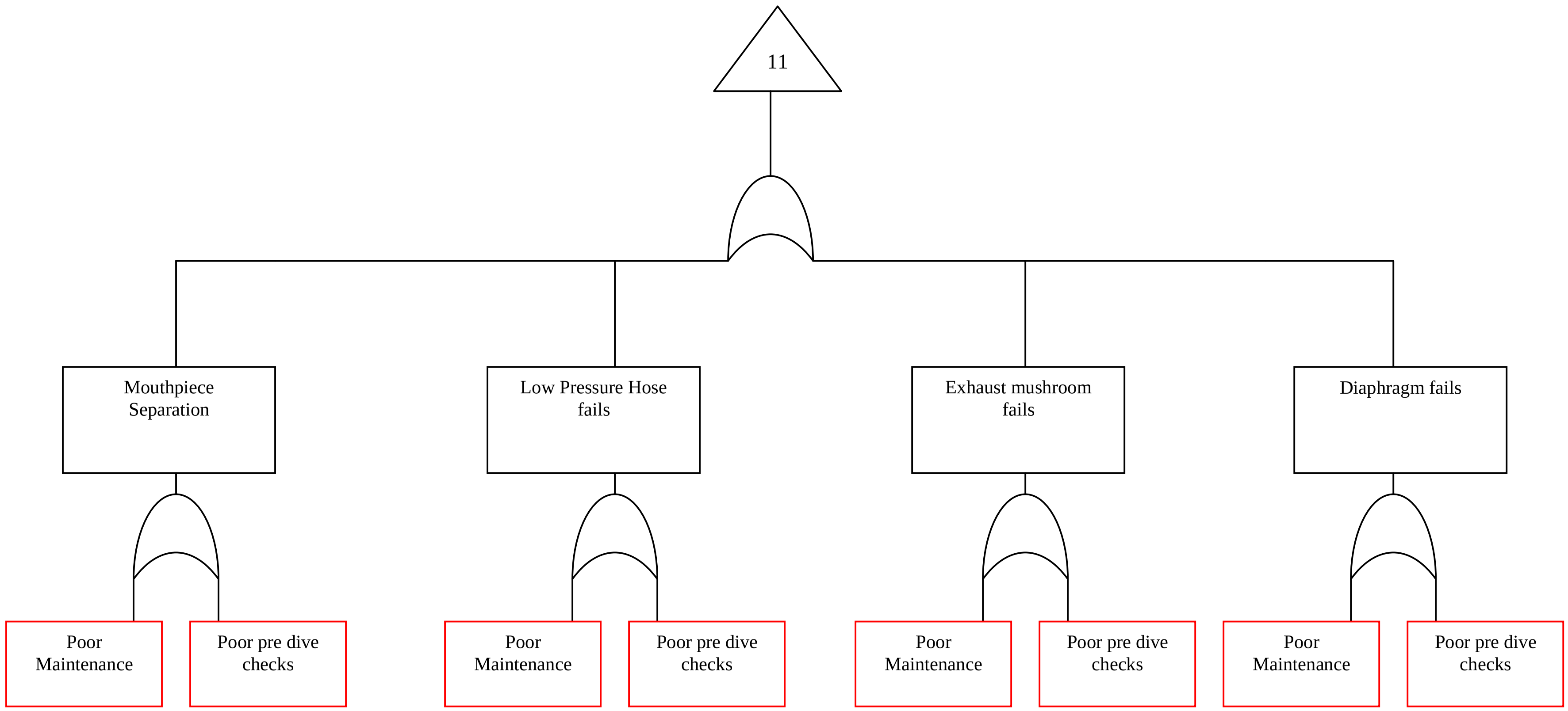


Figure 13 Can’t make surface

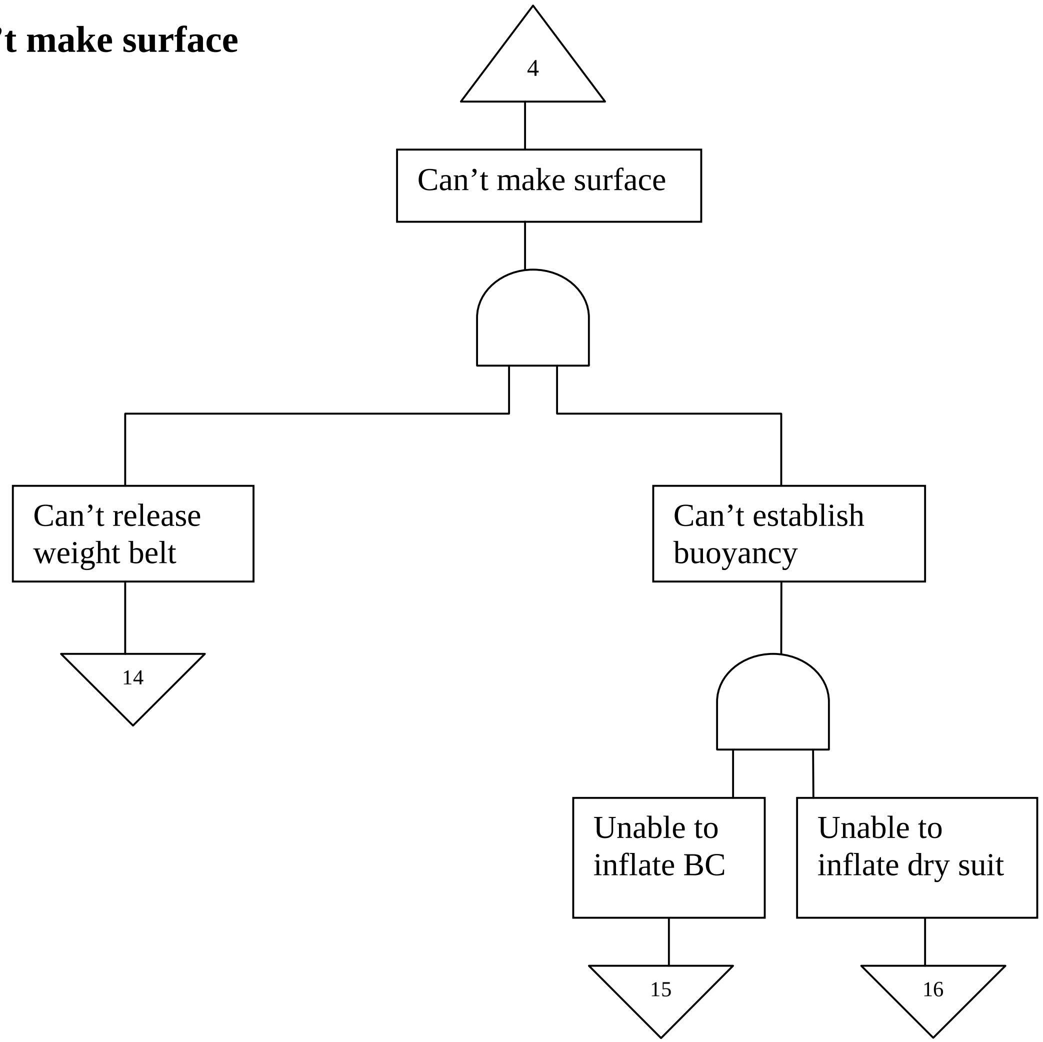


Figure 14 Diver unable to release weights

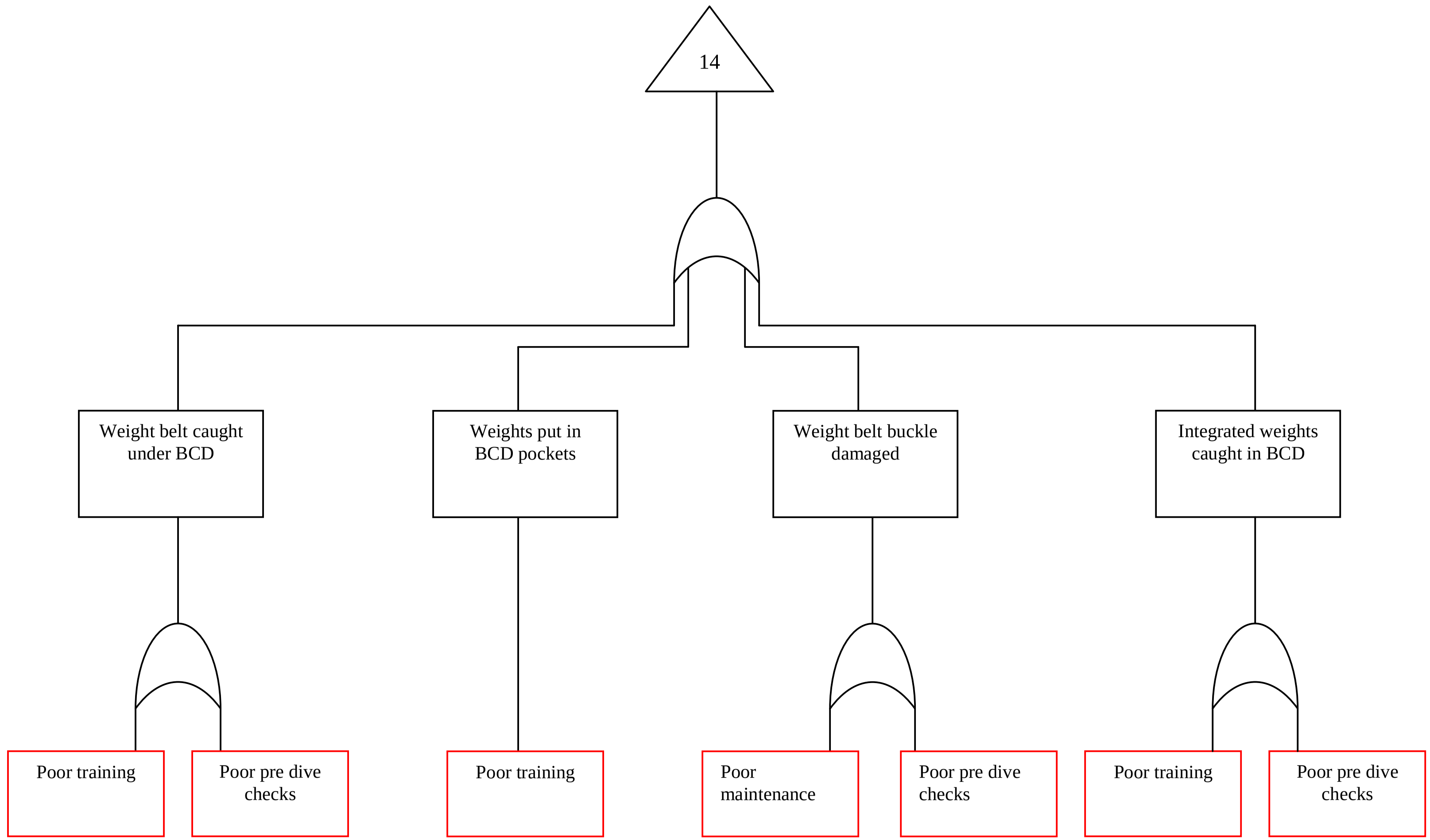


Figure 15 Unable to inflate BCD

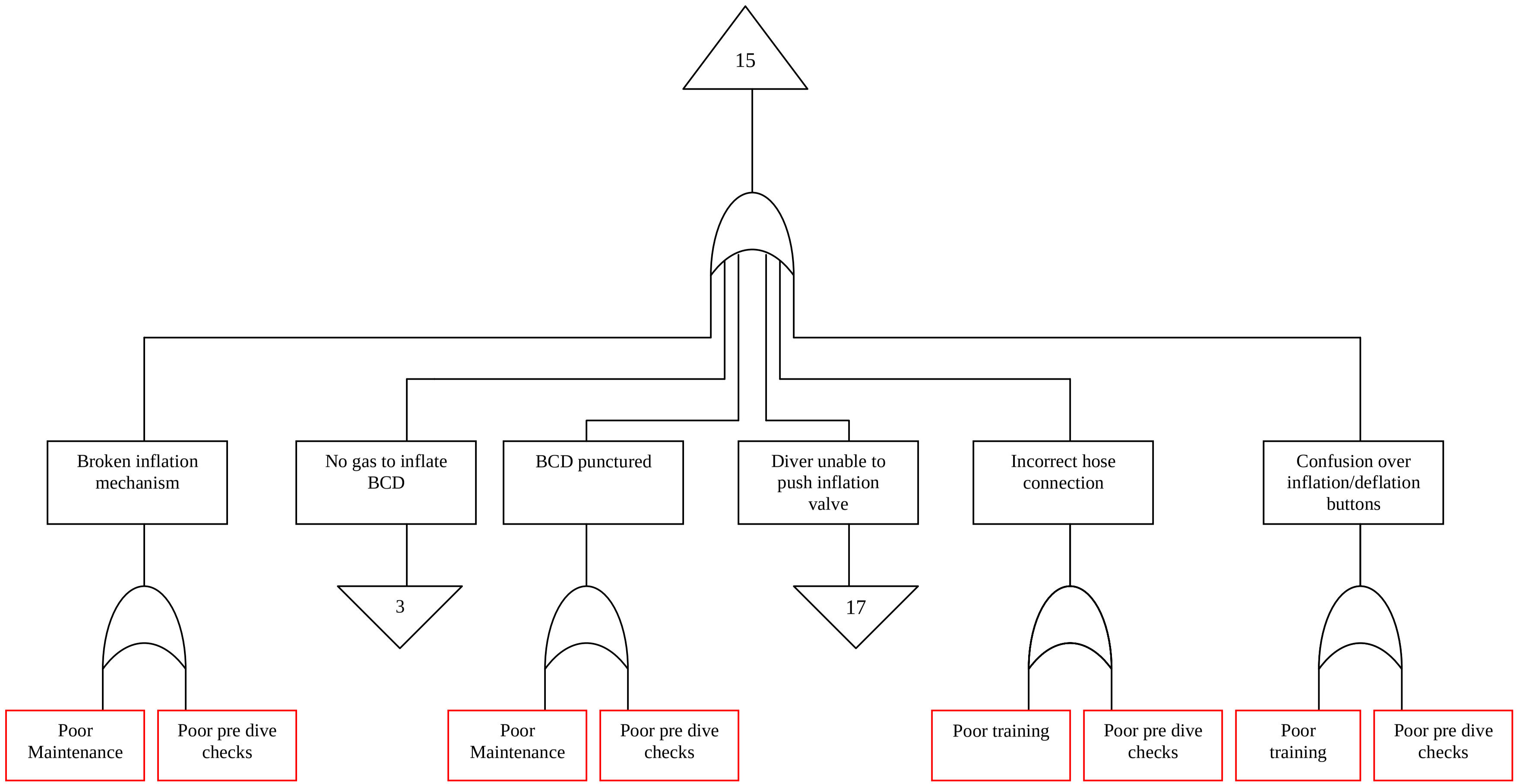


Figure 16 Unable to inflate drysuit

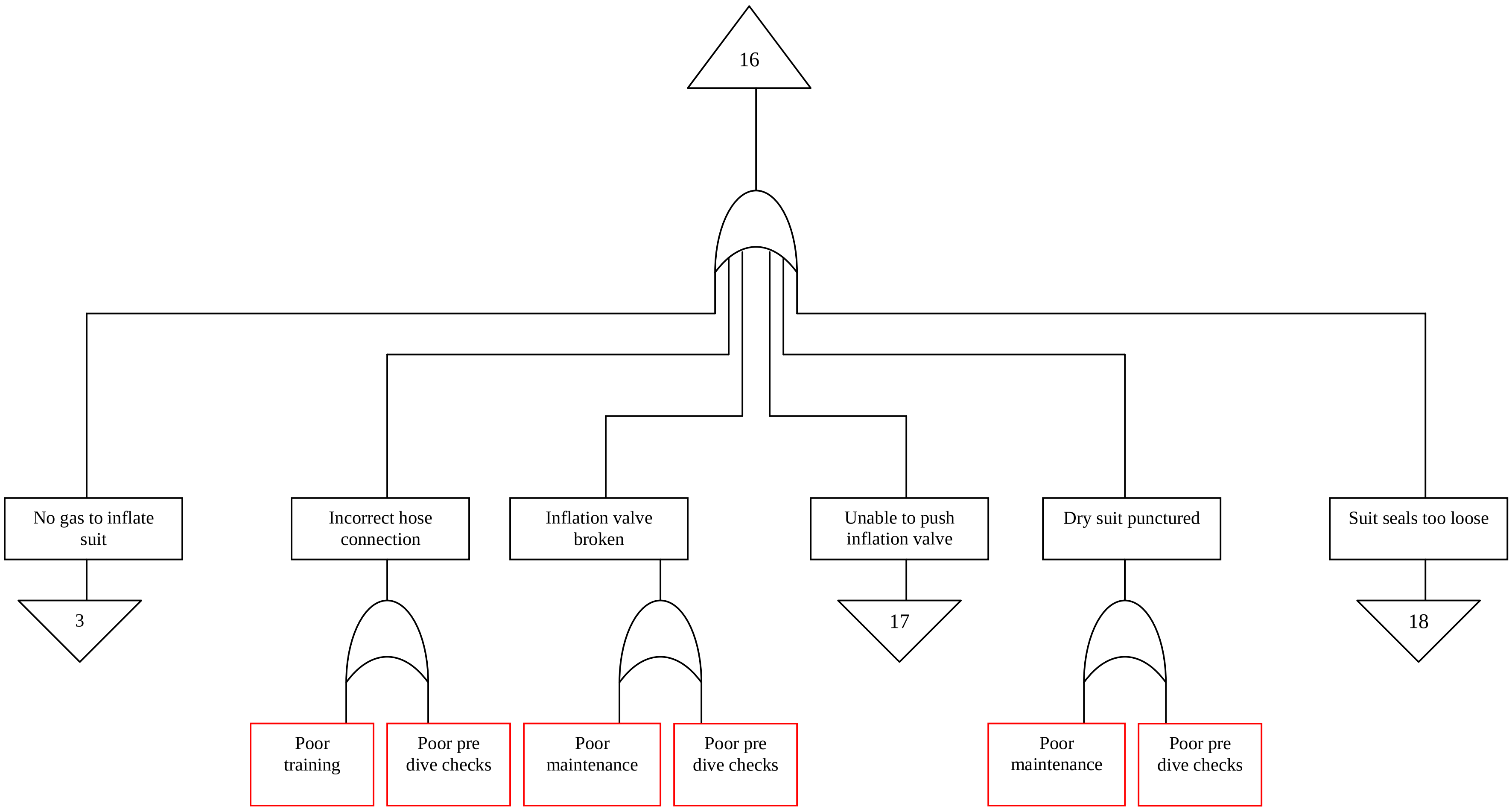


Figure 17 Unable to push dry suit inflation button

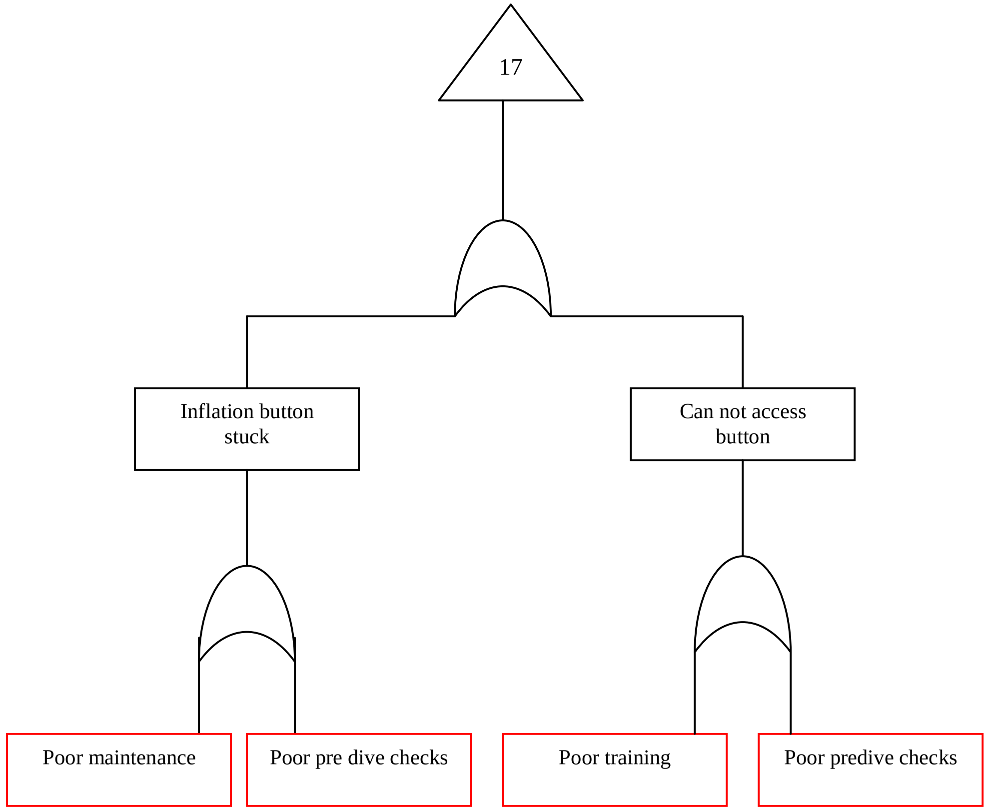


Figure 18 Dry suit seals too loose

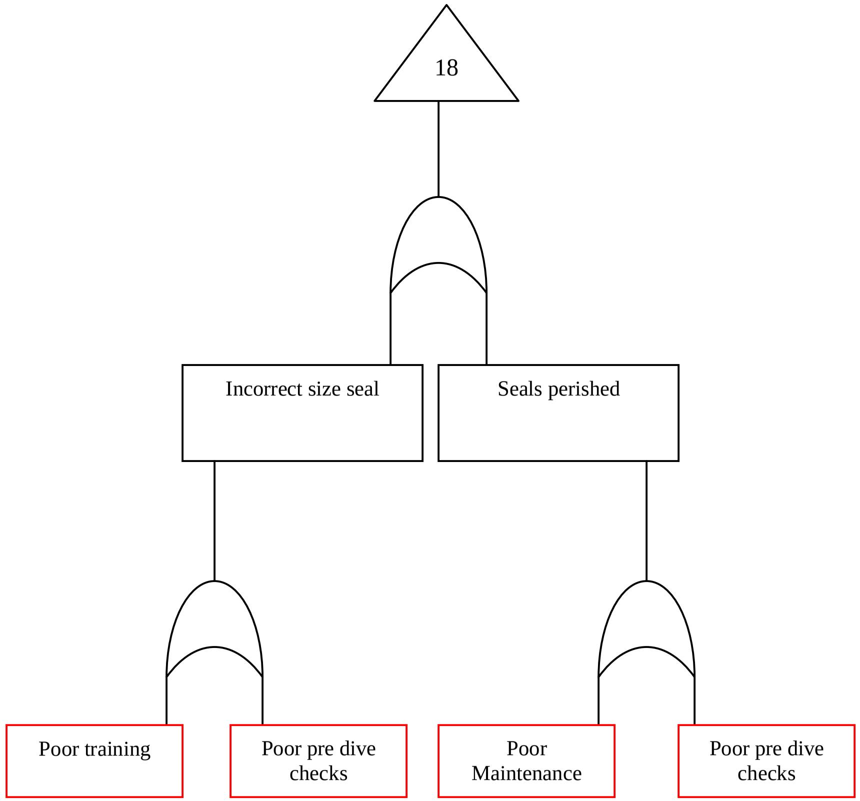


Figure 19 Toxic gas

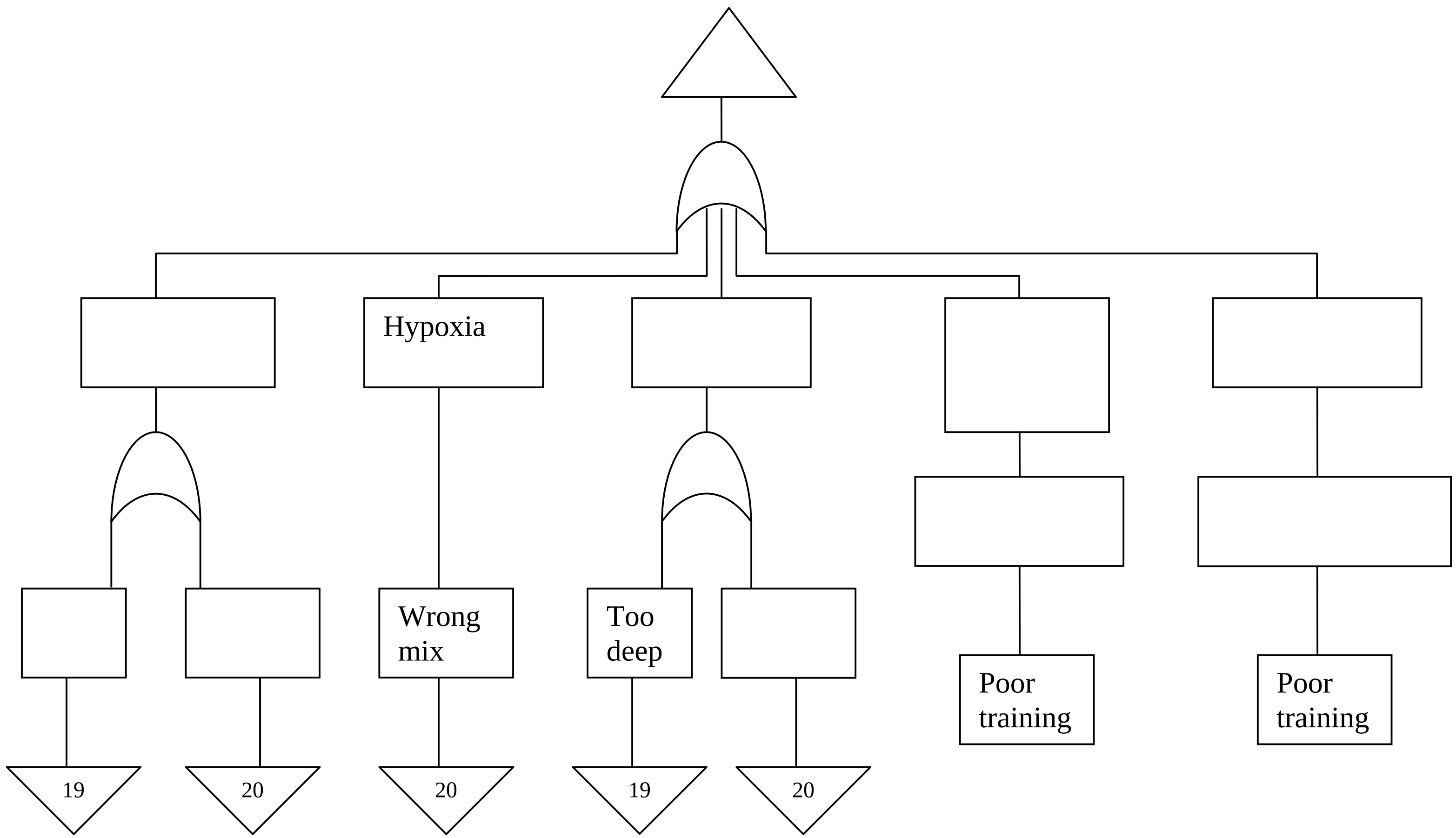


Figure 20 Too Deep, Wrong mix

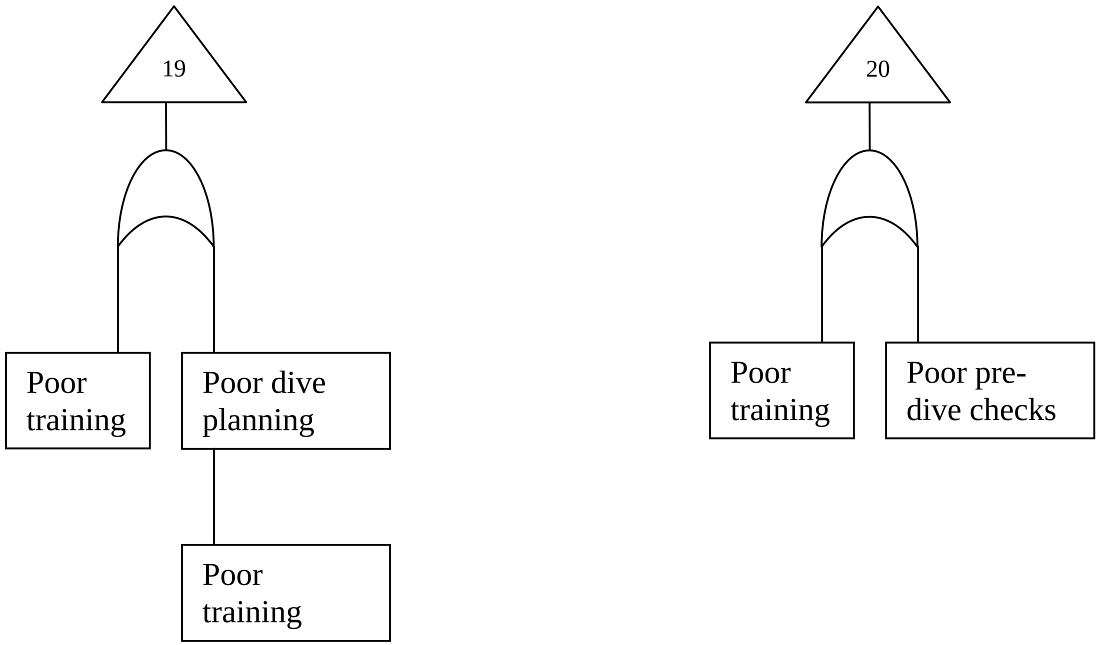
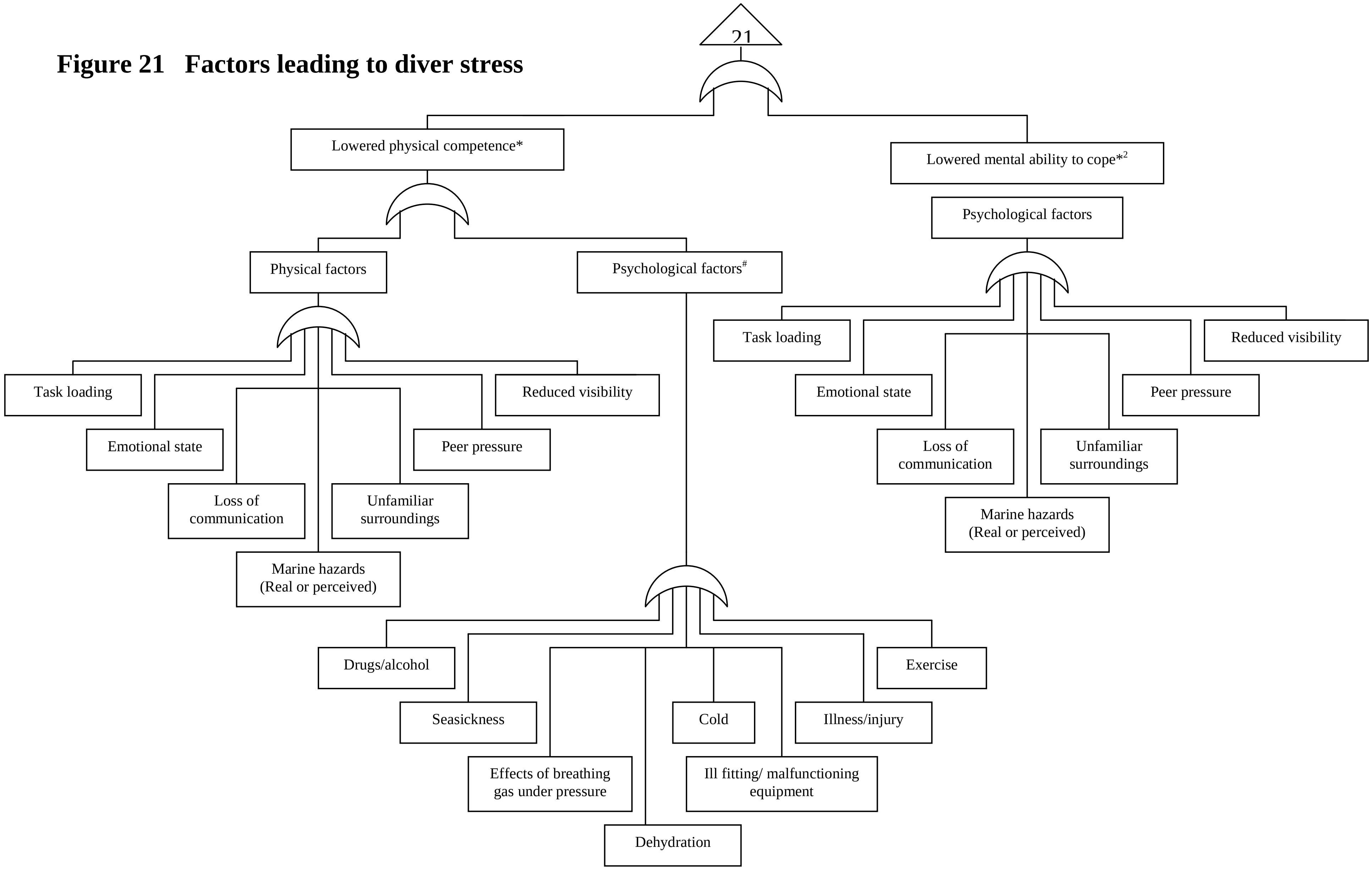


Figure 21   Factors leading to diver stress



2.3 DISCUSSION

It should be appreciated that the OR gate provides no defence to propagation of a failure through the fault tree. Hence, for an event such as 'BCD (or dry suit) inflation button sticks' (due to poor maintenance)(Figure 5), the failure will result in sudden buoyancy and uncontrolled ascent resulting in death as defined. Of course, in most case the maintenance failure is unlikely to lead to the end event but it does illustrate one limitation of the fault tree, namely that it is time independent and does not account for subsequent actions of the diver. Unlike the OR gate, the AND gate will arrest propagation of an event since it requires the failure of 2 or most events simultaneously. It will be noticed that AND gates feature in the 'out of gas' situations shown in the tree because a pony cylinder configuration has been considered.

2.3.1 Human factors

It will be seen that the majority of branches of the tree terminate in either poor dive planning, poor maintenance or poor training. These 3 events often occur together in different combinations but it should be recognized that there are inter-relationships between these events. For instance, poor training will lead to poor pre-dive checks. Nevertheless, some effort has been made to separate them out and in the fault tree shown the end events can be broken down as follows.

Table 1 Summary of end events from the fault tree

End event	Number of occurrences
Poor pre-dive checks	103
Poor maintenance	73
Poor training	47

2.3.2 Pre-dive checks and maintenance

The above table shows the importance of pre-dive checks to open water SCUBA. The following points can be highlighted.

- Although some items end in pre-dive checks, they might not normally be part of a pre-dive check to all divers – an example might be visual inspection of low pressure hoses. This is an example of where maintenance might replace the role of pre-dive checks.
- Some items ending in pre-dive checks cannot be functionally checked such as dump valves.
- The thoroughness of some pre-dive checks might depend on both training and experience. Checks can often depend on how the diver was taught to carry them out and they will be further modified based on his subsequent experiences. For instance, a diver might have experienced a BCD or dry suit inflation hose coming off during a dive and check it is properly connected during pre-dive checks on subsequent dives. One way to overcome some of these problems is to use a checklist as adopted routinely by other professionals such as airline pilots. This would act as a defence not only to failing part of a pre-dive check but would also prevent poor training leading to poor pre-dive checks.

The value of the fault tree is that it identifies items to be checked prior to the dive which could be included on a pre-dive check list and if an item cannot be checked in this way, it should be covered as a maintenance item with a suitable inspection interval or an alternative defense against failure should be put in place.

2.3.3 Training

Training has a number of roles for the diver. Firstly, it teaches the diver an understanding of the environment they are operating in. It is essential that training adequately and sufficiently familiarize the diver with the equipment. Finally, emergency responses are especially important in diving and training prepares a diver by providing the correct response and allowing practise in a safe environment.

One of the main aims of training is to maximize 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 (Wickens, 1992).

Utilizing working memory requires use of limited 'attention resources'. The more resources that an individual process requires, the less that remains available for the remaining processes. The more resources required by sensory processing, perception, response selection and execution, the less remains available for working memory. This can be seen in rule- and knowledge-based behaviors. 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 due to the complete absence of pre-determined rules or response patterns. In order 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 resources, these two forms of response behaviour also take time, which may not be available in an emergency situation. To minimize 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 (Wickens, 2000) such as an out of air situation for example. The degree of automaticity is determined by the amount of practise acquired by the diver in a particular situation as a result of training and experience.

The advantages of this reduced dependency on working memory becomes particularly apparent in an emergency situation. Just as stress has been shown to have a narrowing effect on perception and selective attention (Wickens, 2000), stress of perceived danger, anxiety and even noise have been consistently shown to reduce the capacity of working memory (Wickens, 2000). This reduction in capacity severely restricts the utilization 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. Unless information has been well- or over-learned, retrieval of information (i.e. behavioural responses) from long-term memory is also restricted by the effects of stress (Wickens, 2000). Wickens (Wickens, 1992) 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 (1991), Stokes, Belger and Zhang (1990) and Berkun (1964).

It therefore follows that as stress will be experienced to the greatest extent in the event of a failure, 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 his or her own knowledge and ability. This will reduce feelings of stress and anxiety in an emergency situation also helping to improve performance.

If a diver is made to experience all potential failures and can perform corrective measures in conditions of varying visibility, temperature and depth, then the probability of panic occurring during a real 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 diving.

As a final thought on training, SCUBA 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. For divers not involved in regular training consideration should be given to practising some of these skills on a regular basis so they also derive the benefit of reinforcing a reaction to an emergency situation.

2.3.4 Stress and Panic

For the purpose of this report, the fault tree was developed to emphasis the importance of human factors to the top event. It will be recognized that many external and environmental factors can also contribute to an accident. In this case, these external issues have been included in a sub-tree referred to as 'stress' (Figure 21). In the fault tree, stress can lead to panic. There is no way to completely avoid or prevent stress during diving. The question is how the diver will react when stressful situations do occur (Bachrach, 1982). Most investigators in the field of diving highlight that successfully dealing with stress begins during training. Nevo & Breitstein, 1999, suggested that panic might be prevented in the following ways:

- Improving physical fitness - Divers who are fit and have no medical contra indications may combat cold and fatigue more easily.
- Acquiring solid professional knowledge of diving, diving equipment and 'watermanship' - knowing the real risks of diving prevents unrealistic fears from taking over.
- Practicing responses to emergency situations until this response becomes automatic. Divers should practice emergency response techniques such as buddy breathing, out-of-air scenarios and emergency ascents until they are 'over learned'.
- Improving psychological fitness – Spigolon & Dell'oro (1985) proposed that autogenic training might be useful to divers. This involves learning techniques that break the vicious circle that goes from difficult situation to anxiety to panic. A diver who, when confronted by difficulties, can direct himself to 'Relax-Breathe easily-Think' will be in a better frame of mind to help himself and others. Also, Griffith et al. (1985) showed that, by using techniques, which combine relaxation and cognitive rehearsal, it is possible to reduce state anxiety among diving students and to improve their execution of diving skills.

The reader will recognize that the above can be attributed ultimately to human factors and would be greatly reduced with good training, maintenance, pre-dive checks and diver fitness.

2.3.5 Design

Poor design has not been widely included in the fault trees but is worth consideration. To reduce the amount of required training and yet still maintain or increase user safety, consideration must be given to the design of equipment 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 easily be added to the FTA to complement or even replace some of those faults currently attributed to poor training. For instance, confusion over inflation/deflation of a BCD (Fig 5 and 15) can occur but can arguably be taken away by design as well as training. Similarly, an inadvertent opening of a weight belt buckle could be due to design.

In human factors terms 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. 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 BCD inflation is sufficiently dissimilar to deflation to capture a possible error.

Norman (1988) 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

Some BCD inflation and deflation arrangements clearly contradicts some of the above.

2.3.6 Accident investigation

The fault tree identifies single failures that might propagate to a more serious incident – such as inflation button sticks. In fact, unsurprisingly, the topology of the fault tree used in this report reflects well the finding of the PARAS report for fatalities resulting from a single contributory cause. These are listed in Table 2 and it will be noted that air embolism due to breath-hold ascent is represented as uncontrolled ascent in the fault tree. Hence, despite being 'backward looking' accident investigation can affect both the understanding to produce a fault tree but also allow some degree of checking that all past accidents feature in the fault tree in some way.

Table 2. Fatalities resulting from a single contributory cause (from PARAS 1997).

Air embolism due to breath-hold ascent	6
Loss of consciousness	3
Difficulty with buoyancy control	2
Carbon monoxide poisoning	1
Total	12

As an observation, it should be noted that the fault tree topology was derived by an experienced diver reflecting on what leads to the death of a diver rather than initially using the PARAS data to derive it. It is conforting however, to see PARAS data confirm the topology to some extent.

The limitation of the fault tree is that many fatalities are a result of a number of causative factors as concluded in the PARAS report. When a number of causative factors are involved, other risk techniques might be more appropriate such as the 'Bow tie diagram' (Miles 2005) which can be used to identify defences that can be put in place to minimize escalation of the initial event to further consequences.

2.4 QUANTITATIVE USE OF FAULT TREES

The fault tree shown links a number of actions through a network of logical gates. If the probability of failure of the actions is known, Boolean logic allows the probability of the top event to be calculated. Although this has not been done for the whole tree in this case, it might be useful to consider the technique for a smaller part of the tree.

It should be noticed that loss of gas is critical at both a high and lower level in the fault tree. At a high level it can lead both to drowning and to a rapid ascent to the surface but at a lower level it can result in a failure of buoyancy mechanisms. As a demonstration of the use of Boolean, a situation where the diver has no breathable air is considered with two common scenarios, namely the use of the octopus and the pony cylinder to provide redundancy.

An octopus setup is shown in Figure 22 and the pony setup in Figure 23. Both trees have the same top event of ‘no gas’ and terminate in the same events namely failure of first and second stages or no gas in the cylinder. Obviously the pony configuration has an extra cylinder and first stage and the logic of the tree is slightly different.

Boolean for Octopus setup (Figure 22)

$X = A + Y$
$Y = B + Z$
$Z = C.C$

$X = A + (B + Z)$
$X = A + B + C.C$

Boolean for Pony setup (Figure 23)

$X = Y.Y$
$Y = A + Z$
$Z = B + C$

$X = (A + B + C)^2$
$X = A^2 + B^2 + C^2 + 2AB + 2AC + 2BC$

Note the squared terms are not reduced because they are the different pieces of equipment with the same functionality.

Calculation of probability of out of air situation

If we assume the probability of no gas in cylinder is quite high and for the purposes of this example a value of 0.1 can be adopted (A = 0.1). The probability of a first or second stage failure is less than the above and for the purpose of this example a value of 0.01 will be adopted for both cases (B = 0.01, C = 0.01).

Based on the above probabilities put into the Boolean statements above, the probability of no gas with the Octopus setup is 0.1 while the probability of no gas from the pony setup is 0.01, an order of magnitude less. Of course, great care should be exercised in the use of these numbers. They are for a specific case of providing gas to one diver and do not consider providing gas to buoyancy devices or to a second diver. However, they do provide an illustration of how the Boolean can be used in a fault tree.

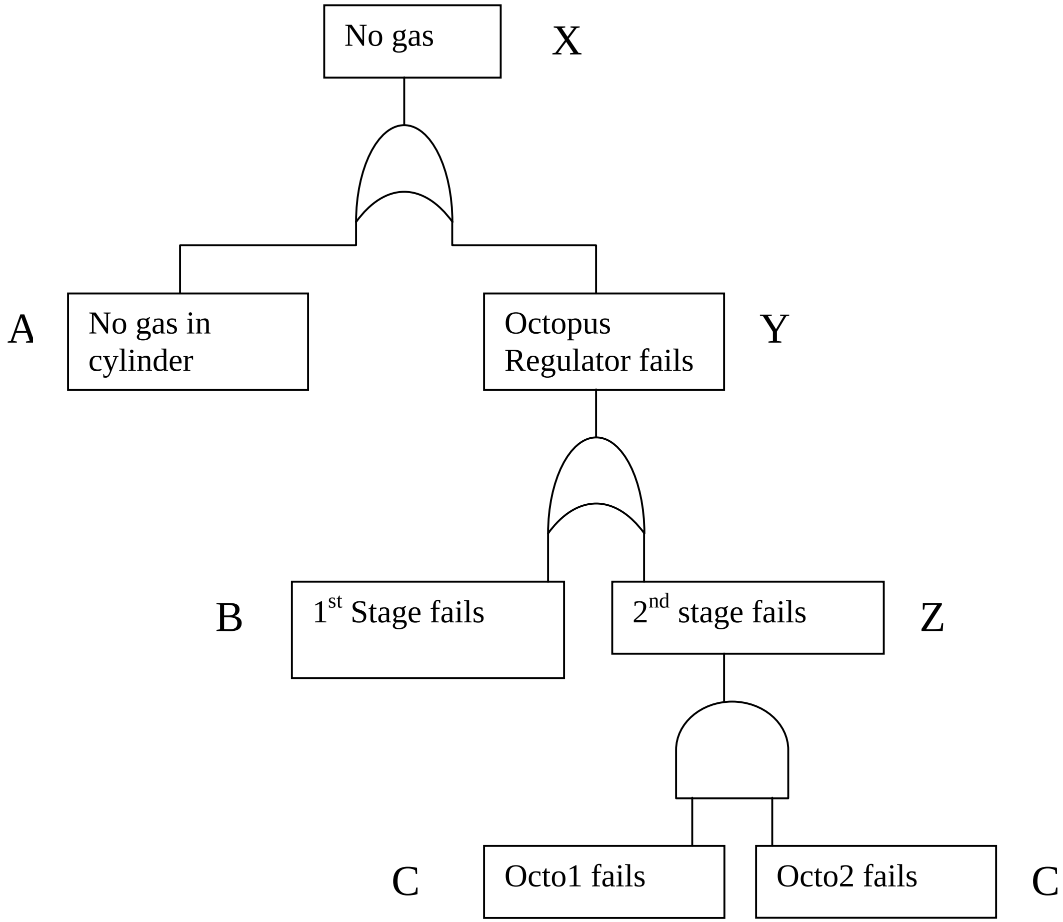


Figure 22 Fault tree for an octopus arrangement

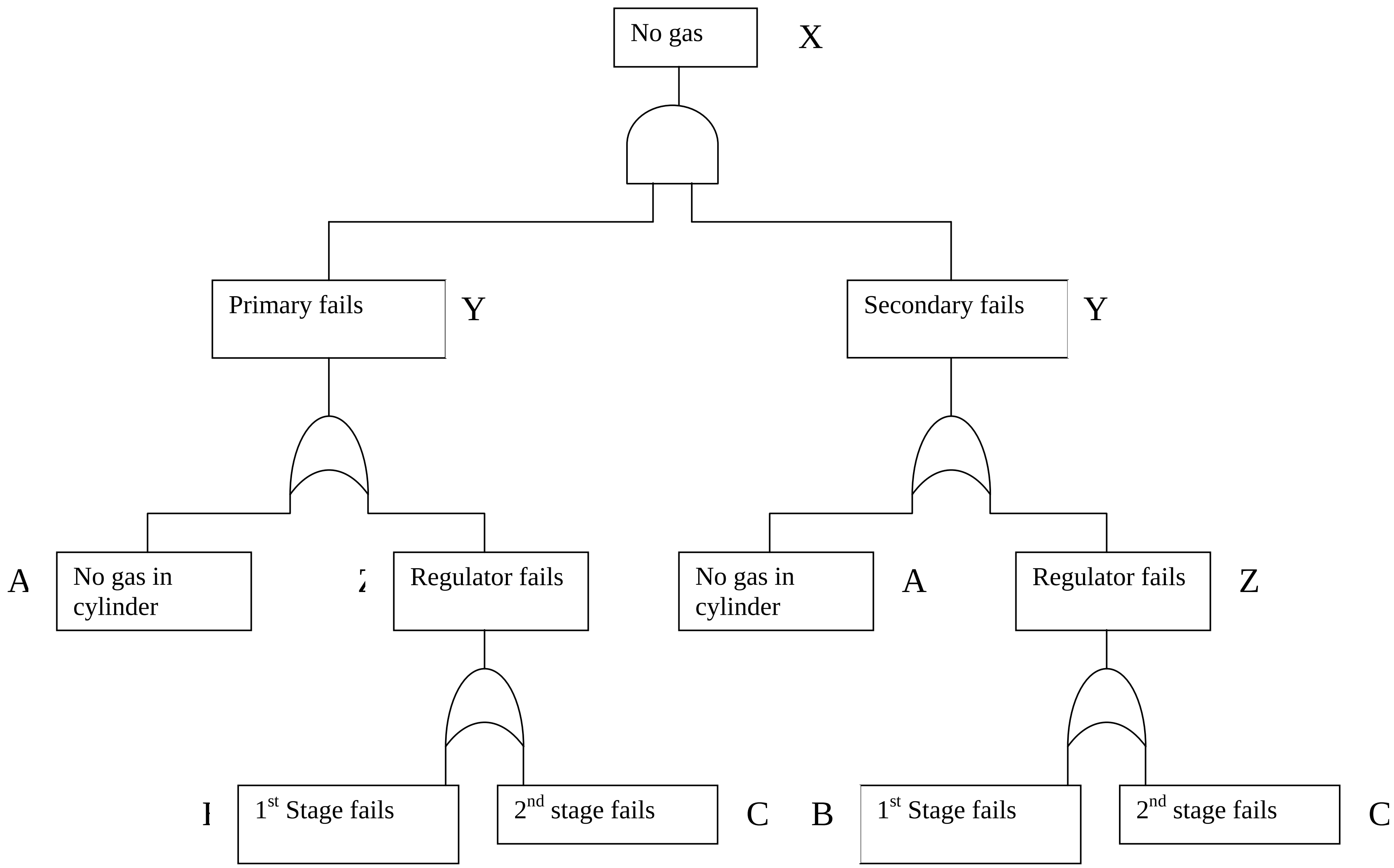


Figure 23 Fault tree for pony arrangement

If quantitative analysis was to be carried out for the whole tree, there are techniques available to derive a value for a human factors based activity. These techniques include HEART, THERP, ASEP, TESEO and SHARP.

3 FAILURE MODES AND EFFECT CRITICALITY ANALYSIS

3.1 HIGH LEVEL FMECA

Failure modes and effect criticality analysis (FMECA) is a widely used risk identification methodology. The three stages to the analysis are self evident perhaps contributing to its wide spread use.

FMECA can be carried out at differing levels of complexity from a high levels system analysis to a low level hardware analysis where individual items are considered. Often a fault tree analysis will be carried out prior to the FMECA to help identify all the risks to be evaluated and whereas the FT in this report was taken down to human factor end events, it could equally have terminated in hardware items that could be used in the FMECA.

The first example shown below is for a high level FMECA. In the first task, the analyst must attribute values to frequency and criticality for the task to be carried out. For the purpose of this study, the following 5 level frequency and criticality values were established.

Table 3 Frequency ranking and definition

Number	**Frequency**
1	Possible but never experienced
2	Occurs once in a divers career
3	Expected to occur 2-5 times in a career
4	Likely to occur 1/year
5	A common event

Table 4 Criticality ranking and definition

Number	**Criticality**
1	No impact on dive
2	Inconvenience
3	Serious incident
4	Diver seriously injured
5	Diver dies

The number of levels and how these are attributed is entirely up to the analyst and will often depend on his experience in a particular field. It will be noted that the above definitions are very general. However, the definitions given for the more detailed FMECA later in this report are more highly focused.

In the second stage of the FMECA process the analyst uses worksheets to consider each hardware component, assess the failure mode and effect of the failure and then attribute a frequency and criticality as defined above. For a high level analysis, equipment is considered at a high level of functionality.

The final stage of the FMECA process is the input of the frequency and criticality values into a risk matrix as shown in Figure 24. The risk matrix provides a graphical view of comparative risk and allows the analyst to identify which items should be considered in order to reduce the risk. In this case items 1.1, 4.1, 6.1 and 6.2 might be considered in priority to the others.

3.1.1 High level FMECA worksheet

Component	Failure Mode	Effect	*Freq.*	*Crit.*
1. Cylinder	1.1 Explodes	Explosive release of gas	1	5
	1.2 Valve comes off	Explosive release of gas	1	4
	1.3 Valve stuck closed	Not able to access gas	2	2
	1.4 Valve stuck open	Cannot remove regulator	3	1
	1.5 Unsecured to BCD	May pull regulator out	3	3
2. Regulator	2.1 Freeflow	Rapidly uses gas, difficult to breathe	3	3
	2.2 Falls apart	May not provide air	3	3
	2.3 Leaks	Air and water mix	3	3
	2.4 Burst hose	Less air provided	3	3
3. Contents gauge	3.1 No reading	Diver unaware of contents	2	3
	3.2 Incorrect reading	Diver misinformed of their air status	2	3
	3.3 Burst hose	Gauge may not function, loosing air	3	2
4. BCD	4.1 Inflation stuck open	Sudden buoyancy	3	4
	4.2 Inflation broken	Cannot use BCD	2	3
	4.3 Cannot retain air	Cannot retain buoyancy	3	3
	4.4 Dump broken	Cannot dump air	3	2
5. Fins	5.1 Strap/buckle breaks	Loose fin, loss of propulsion/stability/lift	4	2
	5.2 Foot pocket ripped	Impaired propulsion/stability/lift	3	2
6. Mask	6.1 Strap breaks	Possible loss of mask and sight	4	3
	6.2 Leaks	Irritation, possible panic with other circumstances	5	2

Frequency	5		6.2			
	4		5.1	6.1		
	3	1.4	3.3, 4.4, 5.2	1.5, 2.1, 2.2, 2.3, 2.4, 4.3	4.1	
	2		1.3	3.1, 3.2, 4.2		
	1				1.2	1.1
		1	2	3	4	5
	Criticality					

Figure 24 High level FMECA risk matrix

3.2 DETAILED FMECA

In the following pages a more detailed FMECA is considered. The frequency and criticality definitions shown below are less general than previously.

Table 5 Frequency ranking and definition.

Number	Frequency
1	Failure 1 in every 5000 dives
2	Failure 1 in every 2000 dives
3	Failure 1 in every 1000 dives
4	Failure 1 in every 100 dives
5	Failure 1 in every 10 dives

Table 6 Criticality ranking and definition.

Number	Criticality
1	No significance
2	Minor discomfort
3	Major discomfort
4	Failure of diving operation
5	Immediate threat to diver's life

In the FMECA considered, equipment was chosen that would be deemed to fulfill a range of HSE ACoPs. It would be impossible to complete a thorough FMECA of all SCUBA used in Britain due to the number of different regulators, dry suits, full-face masks etc. that are available for retail. Components common to all SCUBA hardware were analysed and ranked according to frequency and criticality in worksheets.

3.3 LIST OF FMECA WORKSHEETS

3.3.1	FMECA worksheet:	BCD
3.3.2	FMECA worksheet:	Lifeline
3.3.3	FMECA worksheet:	Fins
3.3.4	FMECA worksheet:	Drysuit
3.3.5	FMECA worksheet:	Full face mask (AGA)
3.3.6	FMECA worksheet:	Full face mask (AGA) Demand Valve (Positive & Negative Pressure Version)
3.3.7	FMECA worksheet:	First stage regulator (Diaphragm) Poseidon or Apeks Part 1
3.3.8	FMECA worksheet:	Communications ‘Hard Wire’ or ‘Thru-water’
3.3.9	FMECA worksheet:	Low pressure hoses
3.3.10	FMECA worksheet:	Submersible Pressure Gauge
3.3.11	FMECA worksheet:	Depth Gauge (Analogue or Digital)
3.3.12	FMECA worksheet:	Diving cylinder
3.3.13	FMECA worksheet:	Bailout side block

3.3.14 FMECA Risk Matrix

3.3.1 FMECA WORKSHEET 1: BCD

Component	Failure Mode	Effect	*Freq.*	*Crit.*
1.1 Bladder	Puncture/Tear	Diver loses control of buoyancy	2	4
1.2 Inflator Unit	Inflator seizes open Inflator seizes closed	Too much gas in the bladder, excessive buoyancy, rapid ascent, DCS, Embolism etc. No gas injected into bladder, no buoyancy provided.	2 2	4 4
1.3 Webbing straps & Quick release buckles	Webbing tears	BCD becomes loose-stress on the diver. BCD could be potentially lost-uncontrolled buoyancy.	2 2	4 4
1.4 Low pressure Inflation hose	Bursts Becomes blocked O-ring fails	No gas supplied from first stage regulator to the buoyancy bladder.	2	4
1.5 Gas Dump Valves	Seize open Seize closed	Gas lost from BCD, no buoyancy, H_2O will enter bladder. Too much gas in the bladder, excessive buoyancy, rapid ascent, DCS, Embolism etc.	2 2	4 4
1.6 Male/Female quick connector between hose and inflator	Fails to connect	No gas to inflate bladder.	2	4

3.3.2 FMECA WORKSHEET 2: LIFELINE

Component	**Failure Mode**	**Effect**	*Freq.*	*Crit.*
2.1 Carabineer	Locking gate screwed open Carabineer metal fails	(i) Physical contact lost with diver (ii) Rope signals (communications) lost	1 1	4 4
2.2 Knot at the carabineer	Knot tied incorrectly Rope material fails	(i) Physical contact lost with diver (ii) Rope signals (communications) lost	1 1	4 4
2.3 Rope Material	Rope not strong enough Rope frayed	(i) Physical contact lost with diver (ii) Rope signals (communications) lost	1 1	4 4

3.3.3 FMECA WORKSHEET 3: FINS

Component	**Failure Mode**	**Effect**	*Freq.*	*Crit.*
3.1 Rubber Strap	Rubber perished Rubber cut/severed	Fin lost, propulsion is lost, and buoyancy may become uncontrollable in sea with currents, tide and swell.	3	3
3.2 Male/Female Quick release buckle	Buckle breaks Fails to keep strap taut	Fin lost, propulsion is lost, and buoyancy may become uncontrollable in sea with currents, tide and swell	3	3
3.3 Fin Blade	Rubber/Plastic breaks factures	Inefficient Propulsion	2	3
3.4 Foot Pocket	Cracked Perished	Fin becomes loose, inefficient propulsion, potential loss of fin.	2	3

3.3.4 FMECA WORKSHEET 4: DRY SUIT

Component	**Failure Mode**	**Effect**	*Freq.*	*Crit.*
4.1 Vulcanised rubber.	Suit punctured	Ingress of water into suit, loss of buoyancy, loss of thermal insulation. Potential problems with hypothermia, DCS, Narcosis and stress. Potential health risk if diver is in polluted water.	3	3
4.2 Neoprene/Latex seals	Tear in seal at the neck or wrist	Water ingress is subject to size of tear	2	3
4.3 Inflation Valve	No inflation	Suit squeeze, loss of buoyancy major discomfort.	2	3
	Seizes while inflating	Over inflation of suit, loss of breathing gas, rapid ascent. Potential for DCS, embolism etc.	2	4
4.4 Dry Zip	Zip breaks, becomes undone or parts from suit material	Water ingress is subject to size of break	2	3
4.5 Deflation Valve (automatic/cuff dump)	Fails to dump gas	Over inflation, rapid buoyancy etc.	3	4
	Leaks water	Water Ingress etc.	2	3
	Leaks gas	Suit squeeze, loss of breathing gas through continual inflation	2	3

3.3.5 FMECA WORKSHEET 5: FULL FACE MASK (AGA) Part 1

Component	Failure Mode	Effect	*Freq.*	*Crit.*
5.1 Strap/Spider	Rubber breaks	Potential for mask loss and flooding. Loss of vision and communications with surface. Unable to read depth/pressure gauge.	3	4
5.2 Strap/Spider Buckle	Clip fails	Mask becomes loose, liable to flood, discomfort for diver	2	4
5.3 Rubber Seal/Skirt	Puncture or tear in skirt, failure of joint between rubber and plastic lens frame.	Leakage of water into the mask, loss of vision, discomfort for the diver, breathing gas consumed in clearing mask	2	4
5.4 Lens	Lens cracked or broken	Leakage of water into the mask, loss of vision, discomfort for the diver, breathing gas consumed in clearing mask	2	4
	Join between lens and frame fails	Leakage of water into the mask, loss of vision, discomfort for the diver, breathing gas consumed in clearing mask	2	4
5.5 Demand Valve stainless steel jubilee clip	Demand Valve lost from mask	Water floods into the mask, loss of vision, discomfort for the diver, breathing gas consumed in clearing mask	2	5

3.3.5 FMECA WORKSHEET 5: FULL FACE MASK (AGA) Part 2

Component	**Failure Mode**	**Effect**	*Freq.*	*Crit.*
5.6 Nose Equalisation Pad	Pad breaks or is lost	Diver has trouble in equalising ears, unable to descend, potential to burst an eardrum etc.	2	4
5.7 Plastic frame moulding around lens	Break/crack	Leakage of water into the mask, loss of vision, discomfort for the diver, breathing gas consumed in clearing mask	2	4
5.8 Plastic Frame securing screws	Lens may fall out of the frame due to lost or loose screws.	Leakage of water into the mask, loss of vision, discomfort for the diver, breathing gas consumed in clearing mask	2	4
5.9 Oral nasal assembly	Mushroom valves fail or tear in assembly	Breathing dead space is increased. Risk of hypercapnia etc.	2	5

3.3.6 FMECA WORKSHEET 6: FULL FACE MASK (AGA) Demand Valve (Positive & Negative Pressure Version) Part 1

Component	Failure Mode	Effect	*Freq.*	*Crit.*
6.1 Low pressure hose	Blocked by debris etc.	Failure of gas supply to demand valve	1	5
	Rupture/leak of hose	Loss of breathing gas and bailout gas depending on FFM bailout system.	1	5
6.2 Valve Seat	Cannot open	Lack of breathing gas	1	4
	Cannot close	Loss of breathing gas to ambient water.	1	4
6.3 Valve Orifice	Blocked by debris or mechanical damage	No breathing gas	1	5
6.4 Counter Pressure Assembly	Excessive opening of valve seat	Too much gas supplied and lost	1	4
	Insufficient opening of valve seat	Insufficient breathing gas supplied	1	4
6.5 Sealing Spring	Excessive force on counter pressure Assembly	Excessive resistance to inhalation, insufficient gas supplied to the diver and potential CO_2 build up	1	5
	Insufficient force on counter pressure assembly	Loss of breathing through free flow.	1	5
6.6 Lever Assembly	Bent/Broken	Continually loss of breathing gas	1	2
	Fails to operate when diver demands gas	Breathing gas not supplied on demand	1	5

3.3.6 FMECA WORKSHEET 6: FULL FACE MASK (AGA) Demand Valve (Positive & Negative Pressure Version) Part 2

Component	**Failure Mode**	**Effect**	*Freq.*	*Crit.*
6.7 Demand Valve Housing	Seal not created against ambient water.	Air cannot be supplied on demand and housing floods, diver may aspirate water.	1	4
6.8 Exhaust Diaphragm	Fails to seal, may be torn, perished.	Air cannot be supplied on demand and housing floods, diver may aspirate water	1	4

3.3.7 FMECA WORKSHEET 7: First stage regulator (Diaphragm) Poseidon or Apeks Part 1

Component	**Failure Mode**	**Effect**	*Freq.*	*Crit.*
7.1 Captured O-ring at male DIN connection.	O-ring is perished/torn etc.	High-pressure gas is lost to ambient water.	1	4
7.2 DIN threads	Threads are damaged/riveted	First stage not connected properly, potential for first stage to blow from pillar valve.	1	4
7.3 Sealing Spring	No pressure on diaphragm due to mechanical failure.	Diaphragm doesn't close, no breathing gas supplied to diver or for buoyancy.	1	5
	Excessive pressure on diaphragm due to debris or freezing.	Inter stage pressure increases, free flow will occur, breathing gas lost.	1	5
	Spring loses mechanical tension	Reduced gas flow to the diver	1	5
7.4 Diaphragm	Diaphragm is split/torn	Gas not regulated which will lead to free flow	2	4
	Diaphragm obstructed by debris	Inter-stage pressure cannot increase with ambient pressure, reduced gas flow to diver	2	4
7.5 Valve Seat	Seat fails due to wear and tear	High inter-stage pressure, free flow	2	4
	Seat fails to open	No breathing gas supplied	1	5

3.3.7 FMECA WORKSHEET 7: First stage regulator (Diaphragm) Poseidon or Apeks Part 2

Component	Failure Mode	Effect	*Freq.*	*Crit.*
7.6 Push Rod	Mechanical failure	Cannot pressurise poppet. No gas supplied to the diver	1	5
7.7 Poppet	Fails to close, valve remains open	High inter stage pressure leads to free flow	1	5
	Fails to open, valve remains closed	Low inter stage pressure, no gas supplied to diver		
7.8 Low pressure ports (x 4)	Blocked by debris	Gas not supplied to diver, BCD or dry suit.	1	4
	Leakage of gas due to failed O-ring	Loss of gas to ambient water	1	4
7.9 High Pressure Ports (x 2)	Blocked by debris	Gas not supplied to SPG	1	4
	Leakage of gas due to failed O-ring	High Pressure gas lost to ambient water	1	5
7.10 Poppet O-ring	Over seal poppet	Poppet is jammed unstable inter stage pressure	3	3
	Under seal poppet due to wear and tear.	High Pressure air leaks into low pressure chamber, free flow	3	4
7.11 UNF Blank ports	O-ring perished or split	Loss of breathing gas	1	4

3.3.8 FMECA WORKSHEET 8: Communications ‘Hard Wire’ or ‘Thru-water’

Component	**Failure Mode**	**Effect**	*Freq.*	*Crit.*
8.1 ‘Comms.’ Rope	Severed/damaged	Voice and physical communication lost to the diver	2	4
8.2 Divers Microphone	Fails due to water ingress	Voice communication lost in one direction	1	3
8.3 Divers earpiece	Fails due to water ingress	Voice communication lost in one direction	1	3
8.4 Marsh Marine Connector	Fails due to water ingress or wires damaged	All communications lost	1	4
8.5 Surface Unit	Fails due electrical damage or power failure	All communications lost	1	4
8.6 Surface Transducer Unit (thru-water comms)	Fails due electrical damage or power failure	All communications lost	1	4
8.7 Divers Transducer Unit	Fails due to electrical damage or power failure Fails due to water ingress	All communications lost	1	4

3.3.9 FMECA WORKSHEET 9: Low pressure hoses

Component	Failure Mode	Effect	*Freq.*	*Crit.*
9.1 Dry suit hose	Hose ruptures, severed, perishes Male/female quick disconnect coupling fails	(i) Low pressure breathing gas lost (ii) Suit cannot be inflated, suit squeeze, loss of buoyancy.	1 1	4 4
9.2 BCD Inflation hose	(i) Hose ruptures, severed, perishes (ii) Male/female quick disconnect coupling fails (see worksheet 1)	(i) Low pressure breathing gas lost (ii) Loss of buoyancy etc. (see worksheet 1)	1 1	4 4
9.3 BCD auto-air hose	(i) Hose ruptures, severed, perishes (ii) Male/female quick disconnect coupling fails (see worksheet 1) (iii) Loss of gas to AAS	(i) Low pressure breathing gas lost (ii) Loss of buoyancy etc. (see worksheet 1) (iii) AAS is made redundant	1 1 1	4 4 4
9.4 Demand Valve hose	See worksheet 6	See worksheet 6		

3.3.10 FMECA WORKSHEET 10: Submersible Pressure Gauge

Component	**Failure Mode**	**Effect**	*Freq.*	*Crit.*
10.1 High Pressure Hose	Hose ruptures, severed, perished, screw threads fail	Catastrophic loss of breathing gas.	1	5
10.2 Swivel Coupling	(i) Mechanical Failure of coupling (ii) O-ring fails	(i) Catastrophic loss of breathing gas.	1	5
		(ii) Breathing gas lost but not catastrophic	1	4
10.3 Analogue Gauge	Not calibrated correctly	Diver unaware of remaining gas supply	2	3
10.4 Analogue Gauge Face	Crack or Mechanical failure of gauge	Catastrophic loss of breathing gas	1	5

3.3.11 FMECA WORKSHEET 11: Depth Gauge (Analogue or Digital)

Component	**Failure Mode**	**Effect**	*Freq.*	*Crit.*
11.1 Rubber wrist strap	Rubber torn/severed	Depth Gauge is lost	2	3
11.2 Buckle (stainless/plastic)	Mechanical failure of buckle	Depth Gauge is lost	2	3
11.3 Battery	Power supply to digital gauge fails	Depth cannot be measured by the diver	1	3
11.4 Depth Gauge Face	Face is cracked/mechanically fails	Diver cannot see depth measurement	1	3

3.3.12 FMECA WORKSHEET 12: Diving Cylinder

Component	Failure Mode	Effect	*Freq.*	*Crit.*
12.1 Steel Vessel	Fracture/rupture of cylinder body	Explosive release of breathing gas	1	5
12.2 Pillar/Cross flow valve	Failure of screw threads on cylinder neck or pillar/cross flow body	Explosive release of breathing gas	1	5
12.3 O-ring at cylinder neck	Failure of seal due to perishing/splitting.	Gas release may slow or explosive	1	5
12.4 Needle Valve	(i) Locks open (ii) Locks closed	(i) Breathing gas supply cannot be accessed	1	4
		(ii) Gas supply cannot be isolated if required	1	4
12.5 O-ring within needle valve	Failure of seal due to perishing/splitting	Gas flow to regulator isn't sealed, gas leaks to ambient water	2	4
12.6 DIN threads in cross flow valve	DIN threads fail due to wear and tear	Explosive release of breathing gas	1	5

3.3.13 FMECA WORKSHEET 13: Bailout side block

Component	Failure Mode	Effect	*Freq.*	*Crit.*
13.1 Non return valve	Mechanical failure of non return valve	Bailout gas may lost through severed primary first stage hose	1	5
13.2 Needle Valve	(i) Needle Valve locks shut	(i) Emergency breathing gas cannot be accessed from bailout bottle	1	5
	(ii) Needle Valve locks open	(ii) Emergency breathing gas cannot be isolated if not required	1	4
13.3 Needle Valve o-ring	Perished or split	Fails to seal gas flow, gas leaks	1	4
13.4 UNF screw threads	LP hoses couplings not gas-tight	Loss of breathing gas	1	4
13.5 UNF Blank Ports	O-ring perished or split	Loss of breathing gas	1	4

3.3.14 FMECA CRITICALITY MATRIX

FREQUENCY OF OCCURANCE	1	2	3	4	5
5					
4					
3			3.1, 3.2, 4.1, 7.10.	4.5, 5.1, 7.10.	
2			3.3, 3.4, 4.2, 4.3, 4.4, 4.5, 10.3, 11.1, 11.2.	1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 4.3, 5.2, 5.3, 5.4, 5.6, 5.7, 5.8, 7.4, 7.5, 8.1, 12.5.	5.5, 5.9.
1			8.2, 8.3, 11.3, 11.4.	2.1, 2.2, 2.3, 6.2, 6.4, 6.6, 6.7, 6.8, 7.1, 7.2, 7.8, 7.9, 7.11, 8.4, 8.5, 8.6, 8.7, 9.1, 9.2, 9.3, 10.2, 12.4, 13.2, 13.3, 13.4, 13.5.	6.1, 6.3, 6.5, 6.6, 7.3, 7.5, 7.6, 7.7, 7.9, 10.1, 10.2, 10.4, 12.1, 12.2, 12.3, 12.6, 13.1, 13.2.

CRITICALITY LEVEL

3.4 FMECA DISCUSSION

FMECA is a useful technique for formal risk assessment of hardware at both a high and low level. At the high level, a single piece of hardware such as a regulator is taken and its failure modes are considered. The obvious high level failure would be failure to provide gas. At a low level as seen in the work sheets, it is possible to take a piece of diving equipment such as a regulator and break it down into its constituent parts.

Several observations of FMECA can be seen from the high level analysis.

- Even though the full range of values for frequency and criticality are used, most failures occupy the mid range.
- The technique does not differentiate hardware and human failures. Although both can be defined in a similar way, in reality there are differences. For instance, a hardware failure may clearly occur once in a divers life time or several times in a divers lifetime. However, a diver can influence a failure rate once he has had the first failure of a particular kind. Awareness and 'experience' may then prevent this happening several times in a life time.
- FMECA does not account for when the failure occurs. Consequences of the dump valve not working are different when on the surface prior to a dive and when making a rapid ascent.
- A failure of an individual item might not in itself have a high consequence. For instance, loss of a fin strap in itself should not be catastrophic, but with a series of other events, the outcome could be significantly different.

The FMECA matrix (Section 3.3.14) clearly shows that SCUBA equipment has a high level of criticality but low frequency of occurrence as one would expect for life support equipment. It is difficult to ascertain the actual failure rates of SCUBA equipment, as manufacturers are very reluctant to divulge such details if they exist at all. Training organizations have incident reporting systems which include equipment failure but this is not the same as evaluation of a piece of equipment by a trained technician.

The main conclusion that can be drawn from the FMECA is that SCUBA hardware is inherently safe if serviced and maintained properly. Groups such as the MoD and Police forces dive SCUBA everyday and have a policy of maintaining their equipment to the highest standards. This practice should eliminate all potential equipment failure modes.

4 CONCLUSIONS

Fault tree analyst and failure modes effect criticality analysis (FMECA) provide an easy to use formal risk identification techniques for diving experts not specialized in risk analysis.

Fault trees can be used to visualise the effects of human factors to a serious end event in professional SCUBA diving. Upon analysis, pre-dive check are the most important issue followed by maintenance and training.

Human factors are inter-related but the following should be considered.

- Checklists can aid pre-dive checks and offset failings in training.
- Emergency drills should be practiced routinely to minimize use of working memory in stressful situations.
- Equipment design can minimize confusion

The Bolean relationship in fault trees can be used to quantitatively compare different SCUBA configurations. The probability of a octopus configuration not providing air was compared with a secondary pony configuration.

FMECA provides a way to risk identification at both a high functional level and a low hardware based level.

FMECA allows the analyst to produce a risk matrix to prioritise failure modes.

One of the weaknesses of both FTA and FMECA is that they do not deal with multiple contributory causes and consequences well. Previous studies based on accidents have found a sequence of events have led to fatal situations. Other risk analysis techniques might be more appropriate to analysing these situations.

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