Health and Safety
Executive

Assessment of manual operations and emergency procedures for closed circuit rebreathers

Prepared by **Cranfield University**
for the Health and Safety Executive 2011

RR871
Research Report

HSE

Health and Safety
Executive

Assessment of manual operations and emergency procedures for closed circuit rebreathers

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Closed Circuit Re-breather (CCR) diving has become increasingly popular as more sophisticated units enable diving for longer and at greater depths. CCR diving is much more complex than traditional open circuit diving in many ways and there is an increased potential for problems and diver errors to emerge. However, formal research examining CCR safety has been rare. To address this, the UK Health and Safety Executive commissioned the Department of Systems Engineering and Human Factors at Cranfield University to conduct a scoping study into the human factors issues relevant to CCR diving apparatus. The scoping study was designed to explore five principal subject areas: accident / incident analysis, unit assembly / disassembly, normal / non-normal diving operations, training needs analysis, interface and display. This scoping study has approached this with a series of studies each addressing separate issues that are relevant to the principal subject areas. These studies can be seen as potentially stand alone, each with its own objectives, method and results. These studies comprise; Accident / Incident Analysis; Human Error Potential Analysis: Assembly and Disassembly; Human Error Potential Analysis of Diving Operations; Training Needs Analysis; Interface and Display Recommendations and Human Error Potential in Non-Normal Operations.

HSE Books

First published 2011

ACKNOWLEDGEMENTS

For their considerable assistance with the various components of this project we would like to thank the following:

AP Diving

- Martin Parker
- Nicola Finn
- Mike Etheredge

BSAC

- Brian Cumming
- Gavin Anthony

HSE

- Richard Martins
- Nicholas Bailey
- Damien Walker
- Steve Field

InnerSpace Systems

- Leon Scamahorn
- Jerry Watley

TDI

- Stephen Philips (UK)
- Sean Harrison (US)

VR Technology

- Kevin Gurr

HM Coroners:

- W. Armstrong (Greater Norfolk District)
- T. Brown (North Northumberland)
- P. McNab (Northern Ireland)
- S.S. Payne (Bournemouth, Poole and Eastern Dorset District)
- D. Pritchard Jones (North West Wales District)
- M.C. Johnstone (Western District of Dorset)

EXECUTIVE SUMMARY

Closed circuit diving rebreather (CCR) technology has progressed significantly over recent years enabling divers to dive deeper and for longer. This type of equipment, which traditionally was used primarily in the military field, is also now used at work in commercial and recreational diving as well as by leisure divers. CCR diving is much more complex than traditional open circuit diving in many ways and there is an increased potential for problems and diver errors to emerge. However, formal research examining CCR safety has been rare. To address the well-documented paucity of empirical research and knowledge in this area the UK Health and Safety Executive commissioned the Department of Systems Engineering and Human Factors at Cranfield University to conduct a unique scoping study investigation of CCR diving apparatus. The scoping study was designed to explore five principal subject areas in separate sub-projects: accident / incident analysis, unit assembly / disassembly, normal / non-normal diving operations, training needs analysis, interface and display. The focus and breadth of the sub-projects had to be expanded in some places to accommodate unexpected developments and discoveries that emerged as the work progressed. Nonetheless, the overall remit of 'scoping' research, to identify key areas in need of further investigation, was maintained throughout.

This scoping study has comprised a series of studies addressing separate issues, each headed by individual members of the project team. After the first introductory chapter, chapters 2-7 of this report will each set out one of the studies. These studies can therefore be seen as a potentially stand alone, each with its own objectives, method and results.

Chapter 2 Accident / Incident Analysis; *Dr Sarah Fletcher*

This first study was designed to analyse accident / incident data. As little reliable data on recreational CCR accidents and incidents is available the study reviewed relevant literature, sought UK coroner reports and incorporated a set of interviews to gather self-reports from current CCR divers. Main findings reveal current deficiencies in: synergy and communication between key CCR organisations, procedure and regulatory oversight over diver training and accident investigation, general awareness of diver behaviours which could be highly advantageous for the development of behavioural based training components.

Chapter 3 Human Error Potential Analysis: Assembly and Disassembly; *Dr Steve Jarvis*

In this study the human error potential for CCR unit assembly and disassembly tasks was analysed using the Systematic Human Error and Prediction Approach (SHERPA) methodology. The study identified eight task errors which could become more likely and safety critical in disorganised circumstances. These errors lead to various recommendations for design modifications to reduce possibilities of inaccurate assembly more rigorous storage and disposal procedures to be educated and reinforced. Mandating the use of simplified checklists is also

recommended, along with supplementary education so that divers fully understand why each checklist point task is important.

Chapter 4 Human Error Potential Analysis of Diving Operations; *Jonathon Pike*

This study also applied the SHERPA methodology to task analyses of 'normal' diving operations, drawing upon Standard Operating Procedures (SOPs). Findings comprise a long list of issues and recommendations including: building the check sequence into controller software, incorporating a degree of human error education into diver training, greater human factors in unit design, making Human Factors analysis of units part of EN standards, adding CO_2 measurement systems directly downstream from the scrubber to warn of rising levels indicative of breakthrough, and further investigation of personal unit adaptations and the potential remedial impact of bespoke training.

Chapter 5 Training Needs Analysis; *Dr John Huddlestone*

The CCR Training Needs Analysis (TNA) study was conducted using analyses produced in the previous chapter / study, and a set of semi-structured interviews with representatives from manufacturing and training organisations. A broad set of recommendations for training was generated, these include: Advanced Nitrox training as standard, trainee minimum entry and instructor currency requirements, optimising course length and content incorporating Human Factors theory, specifying attitude goals, mandating UK courses are delivered by unit manufacturers with more emergency situation training and manuals with checklists for emergency situations, using alternative assessment models e.g. independent assessors or graduated learning progression, recurrent training and feedback mechanisms.

Chapter 6 Interface and Display Recommendations; *Jonathon Pike*

This individual study set out to assess best practice and identify key design principles which should be applied to the design of CCR interfaces and displays. This analysis was conducted using the FAA Human Factors Design Standard (FAA, 2003) as the main reference and guide. The study's findings primarily highlight the need for review of EN standards to cover specification of interfaces and controls, plus further research to identify and develop design guidance and, once again, to gain better understanding of personal adaptations to units.

Chapter 7 Human Error Potential in Non-Normal Operations; *Dr Sarah Fletcher*

This study undertook analysis and evaluation of 'non-normal' or emergency CCR diving procedures. The SHERPA method was partially used but the complexity and uniqueness of emergent situations made prediction very difficult. Key findings and suggestions were produced, however, including: the feasibility of designing units to reduce or eliminate the possibility of making adaptations, develop training that better addresses emergency procedures and drill practice including unit variations / adaptations, update standards to cover emergency procedures and personal adaptations, conduct further work to examine individual differences.

CONTENTS

GLOSSARY OF TERMS

Pnenamics	*high pressure supply*
BCD	*buoyancy control device*
CCR	*closed circuit rebreather*
DSV	*dive / surface valve*
FO2	*fraction of oxygen*
PO_2	Partial Pressure of Oxygen
SPG	submersible pressure gauge

1. INTRODUCTION

1.1 OVERVIEW

This document reports a ground-breaking Human Factors project carried out by Cranfield University to investigate Closed Circuit Re-breathing (CCR) diving safety. The original research proposal describes this as an *"initial scoping study"* commissioned by the Health and Safety Executive (HSE) to address that there is *"little (or no) directly-applicable previous Human Factors-related research in this particular area"*.

This scoping study therefore set out to expose unknown or undocumented safety issues related to CCR diving. Whilst it may not cover all existing or potential problems it provides a first broad sweep of exploration using formal and empirical Human Factors methods, to identify key areas that are worthy of further investigation. Importantly, it is the first impartial and academic study to research this subject area in such depth and, therefore, is highly valuable in circumventing commercial sensitivities and biases that currently exist.

This report will describes the series of individual studies that were undertaken within the overall project in turn. First, the background to this work is briefly summarised.

1.2 BACKGROUND

In recent times, there has been a significant progression in mixed-gas re-breather technology and the development of CCR diving apparatus (Levett and Millar, 2008). As these systems are more gas-efficient, allowing extended diving to greater depths and for longer periods underwater, there has been a growth of 'technical diving' in both professional, occupational diving as well as in recreational / sports diving activities (Shreeves and Richardson, 2008). Figure 1 depicts a summary of 80 fatal CCR diving incidents occurring between 1998 and 2006 produced by the Diver Alert Network (America) which demonstrates the likely scale increase of the problem.

The problem emerging from the growth in CCR diving is an apparent resultant increase in serious accidents and incidents when diving using these units. CCRs have several, significant drawbacks: they are far more complex to set up, operate, break down and maintain, require a greater and more in-depth level of training and may induce an exaggerated sense of simplicity and diver ability (Shreeves and Richardson, 2006). In addition, emergency and non-normal CCR diving procedures (especially manual) are more complex and any errors made are more likely to lead to an accident compared to simpler, open-circuit systems. This means there are generally many more opportunities for operational error and risk with CCR use than in the use of older-technology open circuit systems.

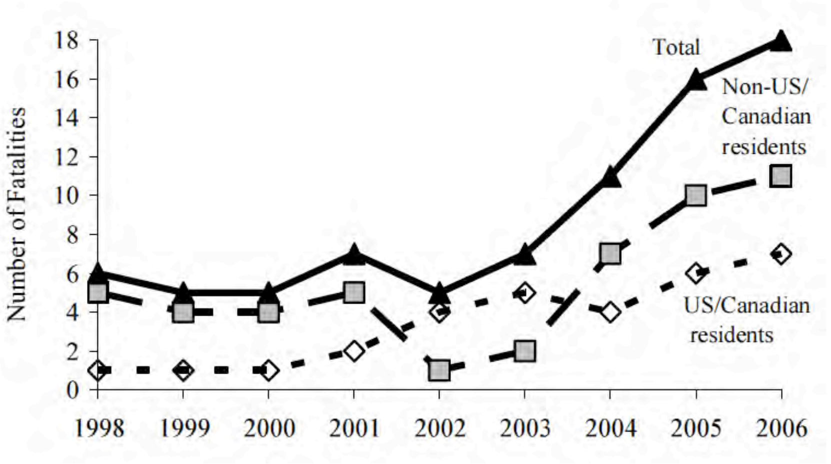

FIGURE 1 DIVER ALERT NETWORK SUMMARY OF GLOBAL FATAL CCR INCIDENTS (VANN, POLLOCK AND DENOBLE, 2006)

CCR diving requires much greater monitoring and brings higher physiological demands / consequences. The HSE are concerned with the situation for occupational CCR divers as this is where they are able to directly contribute to regulation and oversight. However, HSE are also concerned that as the cost of CCR units decreases over time it is likely that they will become even more popular with sports divers, thereby increasing non-occupational accident risk. Thus, the research project set out in this report was commissioned to address the current paucity of empirical knowledge and the need for greater awareness to plan for remedial strategies and interventions – for both occupational and recreational users.

1.3 STRUCTURE OF WORK

The original proposal for this scoping study set out that the HSE's required aims included a need to identify where short-term gains may be achieved to improve safety but primarily to identify longer-term research and development needs in respect of the following:

- Reduce the potential for human error when using CCRs
- To alert CCR users to potential problems
- Assist CCR training organisations in CCR procedures
- To help develop national and international standards

To achieve these aims, discussions between HSE and Cranfield established some key areas regarding CCR diving that needed priority attention in this scoping study. Firstly, due to a recognised paucity of available accident data there was a need to try to bring together reliable evidence for evaluation. Second, due to the complexity of CCR systems there was a need to review the potential for error in planning and preparation tasks. Third, also due to the complexity of CCR systems there was a need to also evaluate the error potential in actual diving operations. Fourth and lastly, there was a need to review training needs and make recommendations for improvements based on the design of current training in relation to current design / interfaces.

The key areas identified as requiring priority investigation translated into a set of primary deliverables; as set out in the original proposal and outline of the work:

- Summary report on rebreather accidents/incidents and ‘violations’
- Human Error Identification analyses (including comparative analyses) for CCR assembly/preparation/maintenance errors
- Human Error Identification analyses (including comparative analyses) for CCR use and ‘non-normal’ use
- Best practice for training and human interface design to minimise risk of human error

The latter two dual-component deliverables were split into two parts and, therefore, into six individual pieces of work and this forms the structure for the rest of this report, as follows.

1.4 STRUCTURE OF REPORT

The six individual pieces of work described were undertaken by different project team members, and these provide individual chapters that structure this report as follows:

Chapter 2	Accident / Incident Analysis; *Dr Sarah Fletcher*
Chapter 3	Human Error Potential Analysis: Assembly and Disassembly; *Dr Steve Jarvis*
Chapter 4	Human Error Potential Analysis of Diving Operations; *Jonathon Pike*
Chapter 5	Training Needs Analysis; *Dr John Huddlestone*
Chapter 6	Interface and Display Recommendations; *Jonathon Pike*
Chapter 7	Human Error Potential in Non-Normal Operations; *Dr Sarah Fletcher*

In each of these chapters an Introduction to the individual study will explain its rationale and remit, with reference to the original proposal. Each chapter’s sections will then provide details of the Method taken, with any significant developments, and a summary of Results, with recommendations where appropriate. Auxiliary data is to be found in Appendices.

It is important to note that the individual studies within the project have each looked at individual CCR units along with associated literature and expert guidance. However, in the aim of providing general findings and generic indications this report does not refer to individual makes or models of apparatus and attempts to review the key issues in a generic way.

2. ACCIDENT / INCIDENT ANALYSIS

DR SARAH FLETCHER

2.1 INTRODUCTION

One of the most important problems reported to the Cranfield team at the outset of this project was an apparent lack of real accident / incident data. Without this, the HSE had not been able to draw sound conclusions or even indications as to what factors are contributing to CCR-related accidents and incidents. Therefore, this individual study was originally intended to be the first stage of work conducted, aimed to find and acquire "accident and incident and 'violations'" data such that a formal analysis could be undertaken to inform subsequent work packages. The proposal stated this deliverable as:

> *"A structured analysis of accidents and incidents (taken from accident investigations, coroner's reports, etc) will also be undertaken. This will be used to help inform and validate the formal error analyses performed (associated with both the preparation and the use of the CCR units) and to provide any additional insights into the potentially dangerous use of CCRs."*

Unfortunately, the very premise for this individual study – lack of available data – soon proved to be an obstacle that meant the intended short term preliminary analysis could not be undertaken. To compensate, this project phase was delayed and redesigned to seek the lacking information via a systematic search for formal incident reports on fatal accidents. Additionally, a supplementary small-scale interview study was arranged to explore current CCR divers' accounts of incidents and violations. Section 2.2 and 2.3 now describe these two extended parts of this study, in turn.

2.2 ACCIDENT DATA SEARCH

At the start this project assumed a pool of accident data would be identified or developed which could be analysed. However, as described, an adequate set of reliable and empirical accident data was not found. In order to satisfy the goal of this study, the search for information was extended in an attempt to locate suitable data. The following sections describe various approaches that were taken and resources that were found as a result. The 'key points' in each case are summarised in individual boxes. A synthesis of findings is presented later in the overall summary of this study, Section 2.4.

2.2.1 INTERNET

As described, the project began with efforts to try to find a pool of real and reliable data that would indicate the conditions surrounding diving accidents and incidents. This was first approached using lengthy internet searches, exploring a wide range of websites to seek potential leads. Information made available by manufacturers, suppliers and training companies was not considered where the impartiality of content could not be ascertained. Information available from diving organisations did not distinguish CCR-related incidents specifically. Private websites and public forums generally only contained personal views or assumptions. One database of global fatalities emerged, but as the information was not empirically derived or evaluated it was discounted as unreliable. No other databases were found and, overall, there was little directly relevant information to be found anywhere from formal / credible sources. The electronic search did generate some potentially useful and reliable sources of general background information (see Bibliography). However, for the purposes of this study the focus was on finding material specifically related to Human Factors CCR issues particularly in relation to accidents and incidents. Two publications deemed sufficiently formal and impartial that were selected for review are now described.

2.2.1.1 CMAS (2000): REPORT ON CCR-RELATED FATALITY IN SOUTH AFRICA

This report describes a non-legal investigation into a CCR diver fatality involving a training diver with a diving team; it was undertaken by the Confédération Mondiale des Activités Subaquatiques (CMAS), the international 'world underwater federation' for diver training organisations. Their investigation was conducted using a series of interviews with key witnesses. The report states that inspection of the equipment showed no signs of fault.

KEY POINTS

- Insufficient cross-team dive planning / understanding
- Lack of cross-team technical diving and depth experience and training
- Resultant lack of critical pressure calculation ability
- Suggested: diving with low cylinder pressures continued to 'not disappoint the group'?

2.2.1.2 NEDU (2009): US NAVY TECHNICAL EQUIPMENT INSPECTION REPORT

The US Navy Experimental Diving Unit was able to begin early inspection of the equipment after the incident so this reduced the possibility of problems and contaminations due to time lag and decay. However, indications are that the unit itself was suffering from age.

KEY POINTS

- Fault: 'nonlinearity in the oxygen sensors'
- Fault: 'improper assembly of the solenoid controlled oxygen add-valve'
- Configuration of apparatus may have inhibited emergency remedial actions (closed O2 isolation valve, possibly to avoid free-flow caused by the faulty add-valve)

2.2.2 SUBJECT MATTER EXPERTS

Various Subject Matter Experts (SMEs) were approached for guidance and as potential sources of reliable data. This section sets out positive responses received and information acquired.

2.2.2.1 HEALTH AND SAFETY EXECUTIVE (HSE)

As the project's commissioners the HSE / HSL (Health and Safety Laboratory) was visited for background information and provided a set of formal reports from HSL investigations into occupational CCR fatalities between 2001 and 2008: 8 CCR equipment investigation reports and 1 wider occupational fatality investigation report were received. These provided a pool of directly comparable documents. As these were from the HSE there is no need to provide in-depth summary here; instead key points from all 9 cases are collated and set out below.

KEY POINTS

1	• No evidence of diver experiencing oxygen 'hit' • Diluents connector not correctly fixed leading to rapid sink and breathing loop flood leading to incapacitation
2	• Diver surfaced but removes mouthpiece without closing leading to loop flooding and sink • Equipment appears in working order but length of time in water obscures analysis
3	• Lack of evidence: length of time equipment was in water obscured analysis
4	• Poor maintenance of kit • Modification of wedging batteries appear to have contributed to pin seizure in the battery box • Diving solo prevented early alert / assist
5	• Entanglement in buoy ropes initiated difficulties • Interface issues (position of flow-stop, ADV diaphragm position) due to apparent modifications and / or incorrect placement appear to have limited remedial actions
6	• Home-build unit design – several design weaknesses identified • Scrubber quantity would have obstructed diver's breathing
7	• Under-filled scrubber canister appears to be key factor • Diver experienced but lacked RECENT experience • Diving solo prevented early alert / assist
8	• No indications – equipment seemed all in good working order
9	• Deviation from various standards and procedures • Lack of cross-team joint planning and understanding • Design concerns re: manual oxygen inject; possible confusion with similar button • Bail-out requirements require better gas consumption levels guidance

2.2.2.2 DIVER ALERT NETWORK (DAN)

DAN (US) and DAN (Europe) were both contacted and expressed considerable interest in the work being conducted and for potential future collaboration and data-sharing. Within the time scope of this project DAN could not provide any data to assist with this particular study; contact details for further use can be passed on. NB: Two fatality data summaries from DAN that were found in other literature are summarised later in Section 2.2.4.

2.2.2.3 BRITISH SUB-AQUA CLUB (BSAC)

BSAC representatives also indicated that they lack reliable data on accidents and incidents. However, of the data that they do hold BSAC assisted greatly by providing non-confidential / public domain information to widen the search. BSAC provided copies of UK newspaper articles concerning CCR-related fatalities on the basis that as the articles had already been in – and retrieved from – the public domain this would not contravene any confidentiality / data protection issues. The provision of these articles enabled an additional line of enquiry to be undertaken in the aim of trying to boost the pool of reliable information being retrieved – to pursue coroners' inquest reports for analysis. Section 2.2.3 below describes how this emergent piece of work was developed.

2.2.3 CORONERS' REPORTS

Given the extreme lack of data suitable for formal analysis, the media articles from BSAC led to a new direction and possibility. The detail provided by the media articles could be used to identify the location of fatal accidents such that the local coroner jurisdiction for each case could be identified also. With this information coroners could be approached to supply inquiry reports. These reports would provide the degree of formality and empirically-derived information required. One drawback was that BSAC could not confirm that all of the fatalities concerned a CCR unit – i.e. the CCR involvement could be due to the fact the accompanying 'buddy' diver was using a CCR. However, as these instances would emerge within the search, each identified coroner's office was contacted individually by letter to briefly describe the nature of this study and request the relevant formal inquest reports.

A total of 16 UK and Channel Islands coroners offices were contacted concerning a total of 28 fatalities reported in the media articles. Out of these, 11 coroners replied but invariably the initial responses stated problems and queries requiring further information and follow up, for example:

- Incorrect identification of appropriate coroner (adjacent boundaries)
- Non-identification of deceased (not named in the media articles)
- Redirection (offices have different systems)
- Deferral of request (resource-led delays in dealing with request)
- Unable (limited resources + in one case an assertion that it was not permissible)
- Non-CCR incident (deceased was not using re-breather)

Only one coroner provided a full inquest report documents in time for the production of this report. This comprised two documents covering the main inquest hearing and the supplementary technical equipment report.

2.2.3.1 CORONER'S INQUEST REPORT AND EQUIPMENT INVESTIGATION REPORT

The equipment investigation was conducted by Defence Evaluation and Research Agency (DERA) in the weeks following the accident. Exact causes were not established and tests showed that the unit was performing within acceptable parameters. Damage to the apparatus is thought to have occurred during recovery rather than pre-existing as the unit was almost new. Evidence suggests that the diver deliberately inflated his dry suit around maximum depth which exhausted gas supply and caused "rapid uncontrolled ascent" (p.21).

The coroner's report provides a complete verbatim account of the inquest hearing regarding a CCR diver's death that occurred in 1999. Overall, it concurs with the DERA report view that the deceased had deliberately inflated his dry suit but there was no obvious explanation of this accident. It was unclear whether the diver took this action to ascend to the surface as quickly as possible when experiencing difficulty, or whether the deceased diver was actually attempting to gain a suitable degree of buoyancy but the valve stuck. As there was no apparent fault with the valve mechanism the coroner was unable to opt for one of these scenarios and therefore recorded an open verdict. There were no other significant findings or indications from this or the accompanying DERA report to inform this study.

KEY POINTS

- Death due to rapid uncontrollable ascent; diver appears to have deliberately inflated dry suit around the point of the dive's maximum depth, exhausting inflation supply gas (argon)
- Suggestion that valve may have stuck but this, and no other significant contributing technical fault, was found

2.2.3.2 CORONERS' COMMENTS

Contact with coroners was limited in this study, however the following are a few statements given in written communications which underline concerns and experiences:

> *"Many of the cases I have dealt with in the past are people who have little practical experience in English coldwater conditions. Many have done a week's PADI course whilst on holiday somewhere like the Red Sea and seem to think this rather basic qualification will enable them to dive in English conditions."*

> *"[I]t may well be that the delay between the fatal incident and the laboratory investigation has allowed the equipment to change or that vibration or transport of it has allowed the fault to rectify itself. I am fairly certain that the only explanation in a*

> *number of these fatalities is that something went wrong with the rebreather although this simply could not be proved."*
>
> *"...in my view the sports divers using rebreather units are incredibly casual in their approach. I have dealt with cases where they have dived even though the alarm had been sounding on the rebreather unit and they had only stopped it by banging it on the side of the boat."*

These comments make generalised points about behaviours and attitudes of recreational 'sports' divers which, although 'off the record', provide insight into the wider issues that need to be addressed. This scoping study was originally designed with a firm focus on technical CCR issues. However, the above comments indicate that further exploration of the attitudes and behaviours of CCR divers and the various professionals involved in providing training, advice and investigations would be a worthwhile venture.

Given the effort taken to search for this information surplus to the original remit for this study, the end returns were disappointing. However, this could be addressed in future work as in many cases coroners simply needed more time and contact. Some coroners eventually issued solid offers but unfortunately these came too late to be followed up and for the reports to be retrieved within the time limitations of this project. All communications with coroners have been retained so that leads can be followed up in subsequent work.

2.2.4 ACADEMIC LITERATURE

An additional academic literature search (peer reviewed, research based journals and relevant 'scientific' conference proceedings) was undertaken to explore the extent to which previous Human Factors work may have already been conducted in relation to CCR diving. Once again, although a range of literature has addressed diving issues *per se*, little was found in association with real CCR accident and incident data. It is perhaps indicative of the current dearth of scientific knowledge in this area that even within the key subject area journal *Underwater Technology* only one article was found that directly addressed the Human Factors of CCR diving. Nonetheless, in order to boost the data available in this study a small number of relevant articles were selected for review from medical, forensic and underwater science publications. The key points of these articles are now summarised.

2.2.4.1 TETLOW AND JENKINS (2005)

This paper directly explores how to approach a risk assessment of a CCR unit using a fault tree analysis (FTA). The authors report FTA to be a successful method of identifying the Human Factors related to CCR risk but the paper is limited to only reporting one part of the overall analysis of the CCR (for hyperoxia events). No other related or similar work was found to support the findings. However, the paper provides the full FTA analysis breakdown of frequencies for occurrences of 'end events' (causal factors); these are set out in Table 1.

TABLE 1 FREQUENCY OF OCCURRENCES OF SPECIFIC EVENTS FOR THE FULL FAULT TREE

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

The authors admit there is overlap between the categories but Table 2 shows, ‘human failures’ are by far mostly linked to poor training (30%) and pre-dive checks (24.5%). It is also interesting to note that the authors highlight that stress is also an important causal human factor (13%) that interferes with performance, and that can be reduced by improved design.

KEY POINTS

- Training would condition divers to follow procedures
- Pre-dive checks need to be methodical and use checklists
- Design improvements reduce risks

2.2.4.2 TRYTKO AND MITCHELL (2005)

This paper is also highly relevant to the study, as a case report on the events surrounding a real CCR diver’s fatality. The report provides a summarised but detailed chronology of events and conclusion. A range of suggested likely causes for the accident are given and the need for high training standards is stressed – standards that are supported by regulations and *“impeccable credentials*” of instructors (p.26).

KEY POINTS

- Poor maintenance and condition of unit, particularly ‘exhausted scrubber material’ and ‘incorrectly packed scrubber canisters’ (p.25)
- Improper preparation and assembly: scrubber-counterlung ‘centre section’
- Incomplete pre-breathe
- Effects of long descent and depth

- Refusal to enact bailout operations; resistance to mouthpiece swap

2.2.4.3 MITCHELL, CRONJE, MEINTJES AND BRITZ (2007)

This is another case report of a CCR diver fatality, providing a detailed summary of events. The most likely cause of death is cited as most likely to be respiratory failure and CO2 toxicity although the apparatus appeared to be in working order. Thus, it is suggested that increased environmental pressure was augmented by the diver’s increased physical exertion, particularly when entangled, and that fresh scrubber material had not been packed correctly. The authors emphasise that the gas-efficiency benefits of CCR systems are *“at the cost of greater technical intricacy and additional breathing resistance”* (p.84).

KEY POINTS

- Respiratory effects of increased breathing resistance when using CCR systems at depth and other environmental conditions, and impacts of incorrect assembly, may be a key Human Factors issue to address
- Exact causal factor(s) are unclear but authors stress that the planning of deep dives divers especially requires better understanding and consideration of physiological limitations

2.2.4.4 LÜDERWALD AND ZINKA (2008)

This article provides two case reports, with a focus on forensic aspects, relevant to this study because one of these involves a diver who used fraudulent credentials to obtain the materials to construct a home-made CCR system without due training.

KEY POINTS

- Lack of training and experience – fraudulent acquisition of materials needed
- Wrong gases used in breathing loop system (argon) and no controls
- CCR apparatus in poor condition and incorrectly assembled
- Diving solo – no opportunity for assistance in identifying problems or remedial actions

2.2.4.5 SHREEVES AND RICHARDSON (2006)

The paper provides a set of accident data analyses already conducted, some by notable SMEs. The analyses derived from the International Professional Association of Diving Instructors and the Divers Alert Network have been selected as adequately credible for this review.

Professional Association of Diving Instructors (PADI)

This article cites the work of Caney (2005) who reviewed PADI UK data on 19 CCR fatalities between 1998 and 2005. Figure 2 below depicts the attributed contributory factors showing that 17 of these fatal dives went beyond recreational limits (130 ft, no-stop, open water diving), 6 went deeper than 200 ft, 7 were solo dives, ‘at least’ 6 were beyond the scope of their training, and 1 case appears to have involved overuse of the carbon dioxide scrubber.

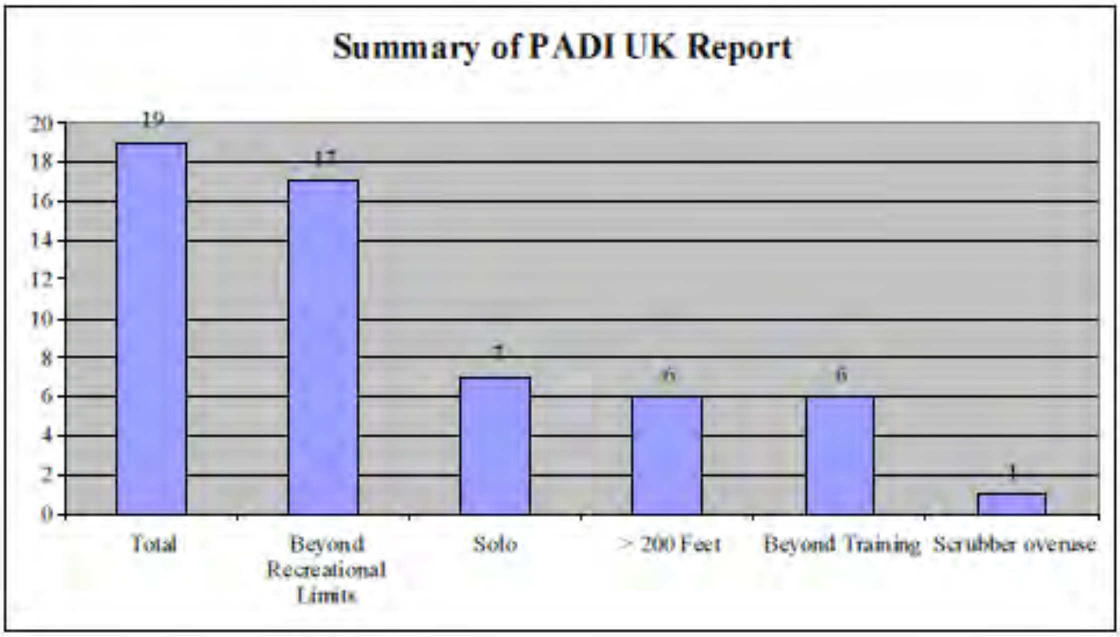

Figure 2 UK CCR fatality data analysis 1

Outside of the UK, PADI Americas data was used to analyse 11 CCR and SCR incidents for the period of 2001 to 2005 (presented in Figure 3). Out of these, 5 cases were fatal – all of which (plus 3 non-fatal events) involved the diver becoming unresponsive. In 1 incident the water in the breathing loop was found to have a ‘caustic cocktail’ delivery of CO_2 absorbent chemicals to the diver’s mouth.

Divers Alert Network (DAN)

As mentioned in Section 2.2.2.4, although DAN were unable to collaborate with Cranfield for this scoping study project some of their data was found within this article for review. Denoble (2006) analysed DAN data on 13 fatal CCR/SCR cases occurring between 1998 and 2003. In 5 of the cases diving went beyond recreational limits, 4 involved solo diving, in 3 the gas exhausted, in 2 the units were incorrectly assembled and 1 case concerned a solo dive to test a homemade unit. However, 3 of the cases were attributed to entirely non-CCR causes and the overlap between these factors is unclear, so this confuses the summary breakdown which is shown in Figure 3 below. Nonetheless, as with the PADI data analysis – evidence clearly suggests that exceeding ‘recreational limits’ and diving solo are the most common key factors linked to CCR fatalities.

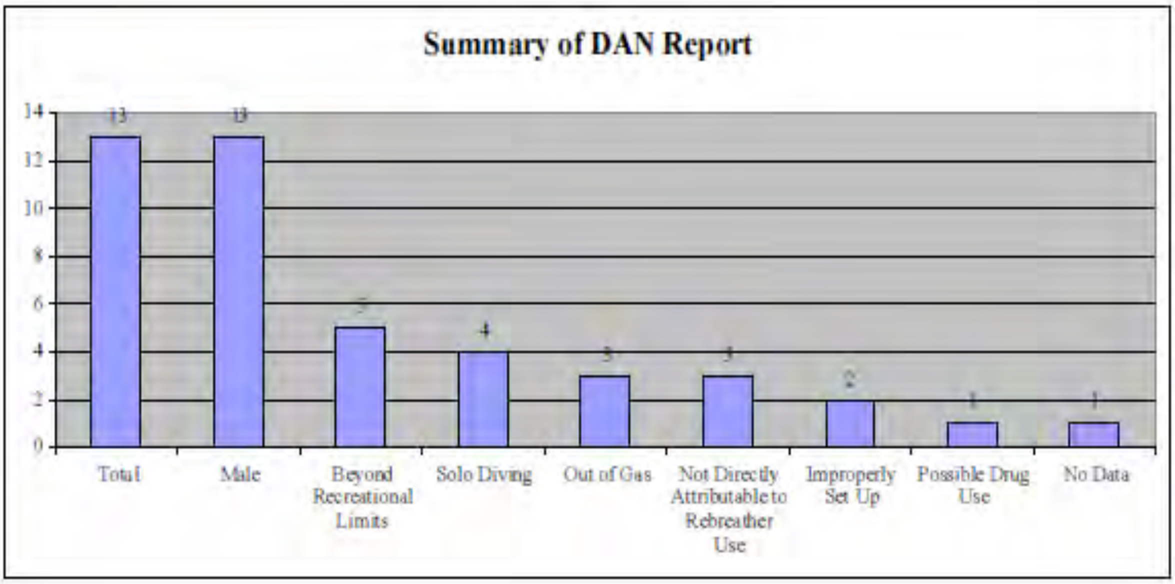

FIGURE 3 UK CCR FATALITY DATA ANALYSIS 2

2.2.4.6 VANN, POLLOCK AND DENOBLE (2007)

This article also includes DAN data, comparing 964 open-circuit diving fatalities (1992-2003) with 80 CCR cases (1998-2006). However, this analysis is an extension of the data summary already presented in the previous section and tells little more about the Human Factors involved in CCR diving. However, the article goes on to make some useful points

KEY POINTS

- Fatal accident investigation requires greater rigour and systematic recording of procedures
- Standard 'black box' data recording on all CCR units would assist inquiry and future interventions
- As solo diving is so strongly associated with CCR fatalities training needs to address this more directly and provide 'buddy' training
- Police need to be involved in development of the protocol for CCR death investigations
- Accident investigation procedures would benefit from multi-agency collaboration

2.2.5 RESULTS

With no raw data available for analysis in this study, it was only possible to contribute a review of documents found to contain details of CCR fatalities and associated investigations. Therefore, rather than a set of results, a set of key points from these articles has been presented. As discussed, with this scarcity of available real data a supplementary interview study was arranged so that real data could be acquired from CCR users; this now follows.

2.3 INCIDENT / VIOLATIONS INTERVIEW STUDY (ELIZABETH HUMM)

When it became apparent that reliable accident data was not available for analysis in the early stages of this study, another idea for securing relevant information was generated: to speak directly to current CCR users. Whilst searching for data it was found that most reports (reliable or not) had been made in relation to fatality cases – but obviously this is where the very person to explain the circumstances, the deceased, was unable to. Indeed, often the only available information about an incident could be found in informal comments and conjecture on unofficial internet sites and forums. As there were unavoidable concerns over the reliability and validity of this sort of information it could not be used for analysis.

Instead, it was considered a useful exercise to investigate accounts from current CCR users to explore their personal experience of incidents and 'violations' as opposed to simply focusing on fatalities. However, this valuable supplementary study had not been planned and was beyond the boundaries of the overall scoping project. Thus, to achieve the analysis a Cranfield Masters student, Elizabeth Humm, undertook a short interview study to gather an insight into CCR divers' personal experiences. This section will provide a brief synopsis of this thesis project work, focusing simply on key aspects of method and results.

2.3.1 METHOD

This short study aimed to "identify Human Factors that may influence the safe use of closed-circuit rebreather units" as part of a limited Masters thesis project. Although an independent body of work, its inception was designed to support the wider Cranfield CCR project. The method involved conducting a series of semi-structured, one-to-one interviews using a sample of 12 civilian UK CCR divers. Audio recordings of the interviews were transcribed and analysed using 'Template Analysis', which involves developing themes in the response data. Themes in this study include: nature of use; training and experience; preparation, cleaning and maintenance; operations; user interface; and environmental stress management. Novel factors associated with safety to emerge in the data include attitude to safety, trust in technology, and vigilance, amongst others.

2.3.2 RESULTS

Of the 12 divers interviewed, 10 reported at least one significant event that had compromised their safety when using a CCR unit. A total of 9 divers reported having to bail out at least once because of a significant problem and 4 said they had experienced exposure to a build-up of CO_2 or other gas disturbance of some kind on at least one occasion, some citing more than one such event. Despite the alarming severity of incidents reported, all participants reported that they continued to dive and generally all seemed to hold positive views about CCR diving.

The Template Analysis of the 12 interviews generated a long list of themes that may indicate potentially relevant areas that may warrant further research. These are presented below, for the purposes of indication but this work has yet to be finalised, as the thesis is still under construction / revision until final academic marking later in 2010.

TABLE 2 EMERGENT THEMES IN CCR USER INTERVIEWS

- Attitude
- Adherence to instructions and recommendations
- Anthropometrics
- Cleaning and Maintenance
- Confidence and trust in oneself
- Diving with Others
    - Solo diving
    - Self sufficiency
    - Buddies In Setting Up
    - Buddying in action
    - Defining Buddying
- Environmental Stress
- Finances
- Gaining experience
    - Practice
    - Level of Experience
    - Increasing knowledge
    - Experience of Accidents
- Gender
- Hierarchy and Organisational
- Interface design
- Investigating Problems
    - Location when problem solving
    - Not resolving problems
- Modifications
- Motivation
- Passage of information and knowledge
- Past experience
- Personal readiness and wellbeing
- Post-event reaction
- Preparation
    - Pre-dive preparation
    - Time for preparation
- Pre-release testing and testing after modifications
- Procedural, Regulatory and Legislative
- Reacting to a problem
    - Time in reacting
    - Ability to react
    - Vigilance
- Redundancy in the system and single point of failure
- Rescue/emergency
- Safety and Risk
    - Approach to Safety
    - Understanding of Safety and Risk
- Skill based Performance
- Support services
- Technical Problems during Operation of the Equipment
- Technology Advancement
    - Technology maturity
    - Reliability of system
- Training
    - Instructor
    - Training Method
    - Level of Training
    - Training Content
    - Individual Differences
    - Training Standards
- Trust in others
- Trust in the technology
- User Error
- Void in Knowledge
- Ways of working
- Workload

As the work has yet to be finalised the themes in these results cannot yet be relied upon as adequately representative because:

a) the sample size is too small – only 12 participants is too limited to be representative of the wider CCR diving fraternity and to have captured a reliable set of data

b) the sample consisted of volunteers– this self-selection could mean they volunteered because they had a ‘tale to tell’ about a prior incident and, again, a wider sample would be necessary to provide more representative and reliable results

Nonetheless there is much to be gained from qualitative in-depth interview studies of this kind, and many of the themes generated do accord with findings and key points found in the wider literature. A more definitive analysis that will demonstrate the relative importance and magnitude of each theme is ongoing, to be submitted and assessed later in 2010.

2.4 SUMMARY

The two parts to this particular study provide very different approaches and sets of information. The development of both was made difficult by limitations of the project and in gaining accident to key information and individuals. However, this study provides some clear indications and illustrates how further work in this area might proceed for more comprehensive evaluation of Human Factors in CCR accidents and incidents.

Training and accident investigation are clearly areas where tighter procedure and regulatory oversight are needed. Although links between different organisations no doubt exist, the research in this part of the study was unable to ascertain the degree to which there is international unity across organisations (e.g. TDI, CMAS, DAN, BSAC etc). It is clear that there are pockets of collated evidence being held by various organisations, including the HSE / HSL (e.g. HSE, 2006). However, it is unclear how far these are shared and reviewed for validation purposes. It would therefore be useful for such relationships to be ascertained, for data and analysis to be shared and pooled, and where appropriate, for unity and collaboration to be sought. Greater accord across the impartial advisory and regulatory bodies is likely to reduce the negative effects of competitive sensitivity between the less partial organisations who supply CCR goods and services.

In the accident data analysis part of the study, the hunt for coroners’ reports was disappointing but this could be continued in further work. However, it would be beneficial to first review the one report (and technical report) that was acquired for this study to evaluate how useful this type of resource actually is as it may not be efficient to distil the level of verbatim detail this sort of document contains.

Amongst the HSE cases it was disappointing to see that one case involved a professional diver who strayed from formal protocol and regulation in a training situation. The unofficial coroners’ comments in Section 2.2.2.2 referred to an “incredibly casual” approach observed amongst recreational CCR users. The recent PADI analysis, shown in Figure 2, suggests that exceeding 'recreational limits' and 'diving solo' are the most common key factors linked to CCR fatalities. These cases demonstrate that any diver may be prone to deviate from the correct level of formal planning and procedure. Thus, this may be a matter of attitude and motivation, perhaps related to experience-based complacency.

We know from research in other contexts that those with experience and training (and with authority) may be more prone to deviate from formality and protocol because they feel disproportionately safe and in-control. Indeed, European research showed that professional divers tend to fear factors and situations over which they have no personal control, but are at the mercy of others (e.g. foremen) because they will not understand the problems inherent to diving work (Honkasalo, 2000). Therefore, further work should explore not only the attitudes and behaviours which make recreational divers "incredibly casual" but also the wider psychosocial factors that may make any individual diver deviate from safety measures and protocol that they may have learned and understand well. For example, in 2.2.4.2 it seems we can never know why the diver refused to swap his mouthpiece to follow the bail-out procedure with his buddy and can only assume that this action was resisted. A wide and in-depth interview study of CCR users' perception could reveal attitudes and beliefs that explain such an event which could be enormously helpful for future training content.

As the remit for this study was to conduct accident data analysis, it was fundamental to seek objective and reliable data from credible and formal sources. However, the interview study illustrates the value of this alternative type of research approach. Despite its limitations, the interviews revealed a wide range of potentially important issues and lends support to the need to expand the current focus of research which is mainly evaluating technical aspects of CCR diving. It is important to consider the psychology of CCR diving and possible individual differences – between people and groups / types. It is this sort of anecdotal, subjective evidence that can direct future work towards finding out exactly what lies behind human performance decisions and errors in CCR diving as Shreeves and Richardson (2006) believe.

A summary of key points and recommendations from this individual study are as follows:

- Greater links between impartial advisory and regulatory bodies (e.g. TDI, CMAS, DAN, BSAC etc) and commercial organisations (manufacturers and training providers) is likely to reduce the negative effects of competitive sensitivity and improve safety through collaborative analysis; this could be promoted by the HSE through a data pooling initiative to build on this scoping study
- Training and accident investigation are clearly areas where tighter procedure and regulatory oversight are needed; the HSE could initiate new standards (advisory or legislative)
- The utility of the detail contained in coroners' reports should be evaluated through analysis of the single report (+ technical report) obtained in this research; it might be that the information gathered currently in coroners' investigations is not of use, and might benefit from HSE review
- Divers' behavioural violations are a major causal factor in accidents, and appear to be sometimes related to experience-based complacency. Clearly this holds implications for CCR diver training as behavioural-based training is likely to provide an effective educational component that would complement the technical side of training. Further

research would accurately identify ideal syllabus components for CCR diver behavioural training

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- 1999 HM Coroner’s Inquest Report, Bournemouth
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3. HUMAN ERROR POTENTIAL ANALYSIS: ASSEMBLY AND DISASSEMBLY

DR STEVE JARVIS

3.1 INTRODUCTION

CCR units are more complex than traditional open circuit systems and require a much greater degree of preparation and maintenance. There are simply more opportunities for CCR units to afford human error. For this reason it was necessary to examine and consider the human error potential for assembly and disassembly tasks. The proposal stated this study's deliverable as:

> *"A basic hierarchical task analysis (HTA) will be performed for all common preparation tasks... The HTAs will also be supplemented with a formal error identification analysis... to identify potentially problematic steps in the dismantling and re-assembly process. From these analyses the relative error potentials for common aspects of CCR preparation and maintenance will be ascertained for the selected makes and models."*

3.2 METHOD

To undertake analysis of assembly / disassembly and maintenance, Subject Matter Experts (SMEs) were employed to assist in a walk-through methodology analysis of one unit type. This involved all of the tasks being set out and deconstructed, step by step, so that each of the primary tasks and secondary tasks necessary for the assembly of unit and scrubber refill were mapped out to the lowest level, and no task components were missed. This process was written up on a whiteboard from where it could be reviewed and amended iteratively with the SMEs. Digital photographs were taken of each element and task stage; Figure 1 below illustrates an example of how this procedure took place.

A task analysis and error prediction of scrubber refill and re-assembly specifically was carried out on one specific system (and looked at in parallel with two other systems). This is shown in Figure 2. In order to assess the likelihood of serious errors being made by the diver during the assembly process, a Systematic Human Error and Prediction Approach (SHERPA) taxonomy was applied to the task analysis (see Appendix 2). Firstly, all possible SHERPA error modes applicable to the task analysis operations were identified (Figure 3). Next, these were practically applied to the assembly of the re-breather in question to see if they were appropriate. All appropriate error modes were identified and the probabilities and consequences were considered. Eight serious error modes emerged from this process and are detailed last.

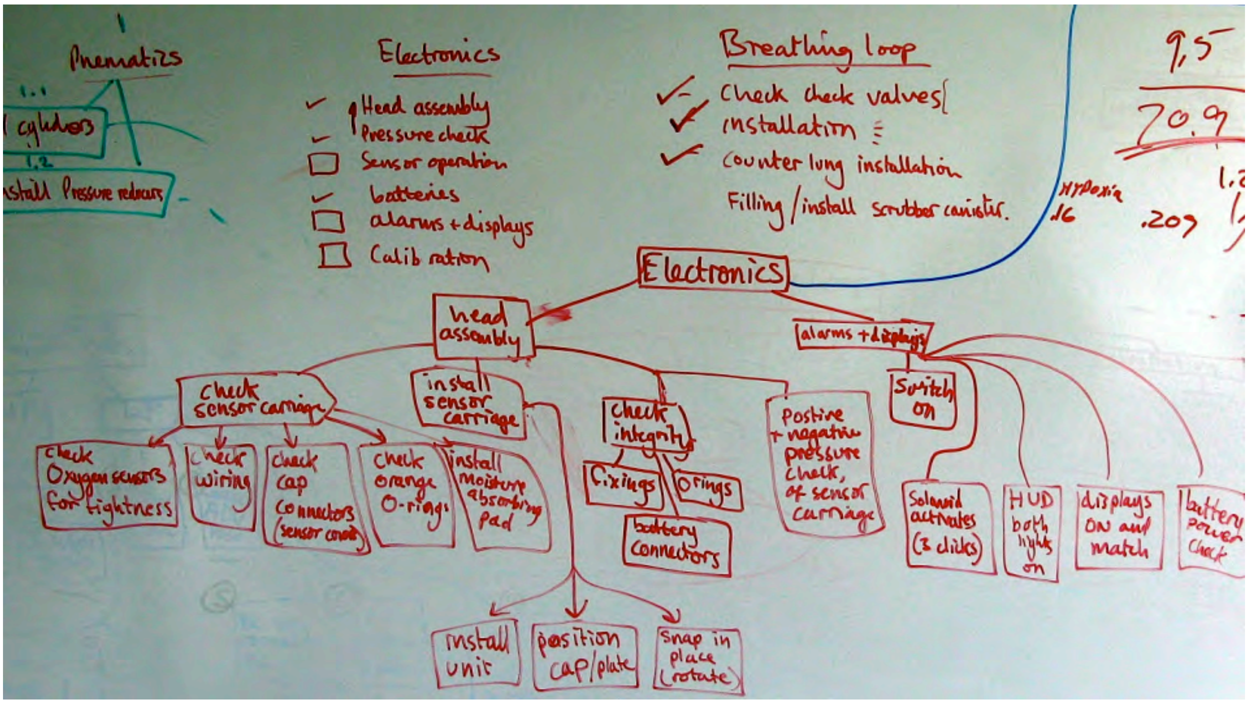


FIGURE 4: PHOTOGRAPH SHOWING HTA CONSTRUCTION PROCESS

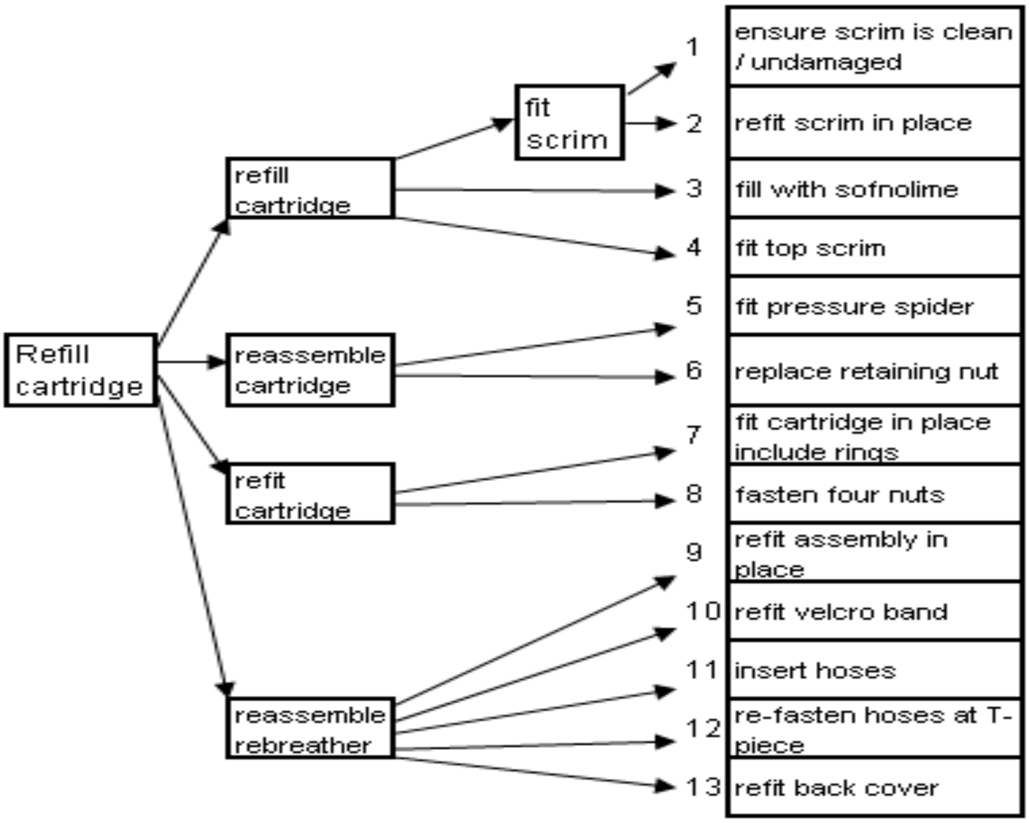


FIGURE 5. TASK ANALYSIS OF SCRUBBER FILLING AND FITTING, LEADING TO 13 OPERATIONS

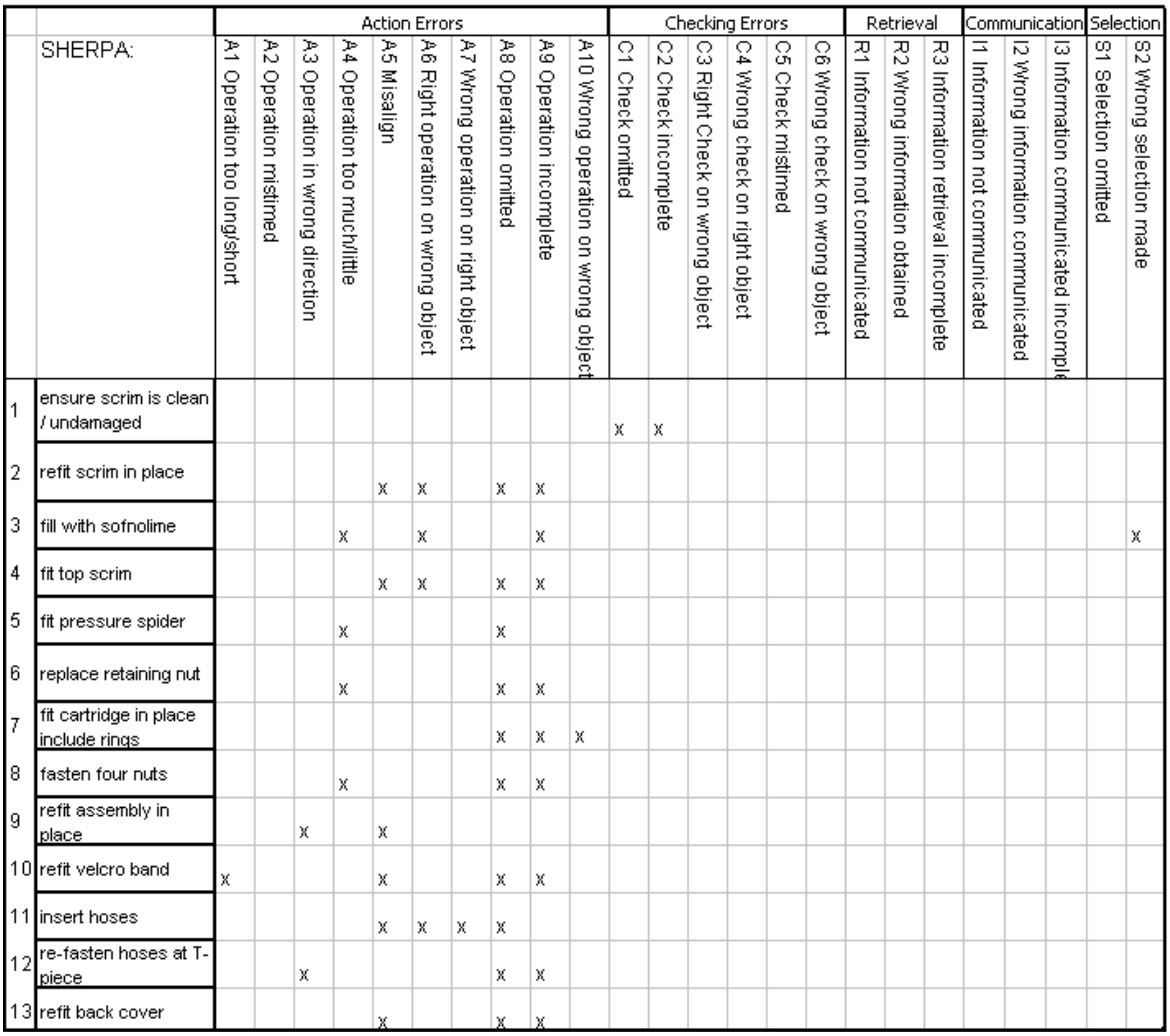
3.3 RESULTS

This area is not where the most specific dangers lie within this diving system, although being very complex, there are infinite ways that it could assembled wrongly, more so than traditional diving apparatus. Installation is an area which could easily suffer from inattention caused by lack of interest and repetition, and hence serious errors and mistakes. All assembly tasks become more likely to error when the situation is not ideal, and unlikely when the situation is right and the diver affords the appropriate level of attention, discipline and care. Tools such as checklists are recommended, and practice in the use of such tools would be appropriate. There are several specific areas of concern listed below. In general however, because the assembly can take place at a time convenient to the diver, and without the necessity of other concurrent tasks, it is possible to minimise distractions and concentrate ones' attention on the singular tasks properly.

Assembling the unit and refilling the scrubber are tasks which are assumed to be done under the full attention of the operative, and under low cognitive workload. As stated, there is no concurrent task which will make errors more likely to occur; the operative can give their full attention to the assembly process. However if attention is elsewhere (time pressure to dive, physiological needs such as hunger / fatigue, other people conversing, etc) then errors become far more likely (skill-based errors are particularly likely: slips / lapse because when distracted the diver will be less effective in monitoring their skill-based routines). In such circumstances, many important procedures could be missed or mis-ordered. Hence the diligence of the diver is important, and the use of a checklist or written procedure is highly recommended when doing these tasks. It is also recommended that divers choose appropriate conditions under which to complete these tasks (minimise distraction and social interaction).

Mistakes (knowledge-based errors) are likely when the diver is not in current practice, or is new to the tasks. Because many recreational divers will dive infrequently, there is a danger that the assembly / cleaning / scrubber refill will have components that have been forgotten, and are hence equivalent to novel tasks. If the diver does not take time to look up the correct methods, or the information is unavailable or poor, then the diver might proceed inappropriately.

The sequence and types of tasks required during assembly of the units and refilling of the scrubber cartridges are completed by a sequence of straightforward tasks. Much of the sequencing order is important in order to correctly assemble the unit. There are a number of areas where the order can be violated, but in most cases this is not critical. In other critical areas it is impossible to complete the assembly if not done in the correct sequence. There are however several areas where the order can be violated and the results may be critical. These are listed below. The types of tasks required are all capable of being easily completed with minimum / no tooling and no excessive force is needed to complete them.



		Action Errors										Checking Errors						Retrieval			Communication			Selection	
	SHERPA:	A1 Operation too long/short	A2 Operation mistimed	A3 Operation in wrong direction	A4 Operation too much/little	A5 Misalign	A6 Right operation on wrong object	A7 Wrong operation on right object	A8 Operation omitted	A9 Operation incomplete	A10 Wrong operation on wrong object	C1 Check omitted	C2 Check incomplete	C3 Right Check on wrong object	C4 Wrong check on right object	C5 Check mistimed	C6 Wrong check on wrong object	R1 Information not communicated	R2 Wrong information obtained	R3 Information retrieval incomplete	I1 Information not communicated	I2 Wrong information communicated	I3 Information communicated incomple	S1 Selection omitted	S2 Wrong selection made
1	ensure scrim is clean / undamaged											x	x												
2	refit scrim in place					x	x		x	x															
3	fill with sofnolime				x		x			x															x
4	fit top scrim					x	x		x	x															
5	fit pressure spider				x				x																
6	replace retaining nut				x				x	x															
7	fit cartridge in place include rings								x	x	x														
8	fasten four nuts				x				x	x															
9	refit assembly in place			x		x																			
10	refit velcro band	x				x			x	x															
11	insert hoses					x	x	x	x																
12	re-fasten hoses at T-piece			x					x	x															
13	refit back cover					x			x	x															

FIGURE 6. IDENTIFICATION OF APPLICABLE SHERPA ERROR MODES ON THE THIRTEEN OPERATIONS IN THE TASK ANALYSIS (CROSSES INDICATE AN APPLICABLE MODE).

The error prediction process found no areas where, under normal (non-distracting) conditions, there was a high probability that the diver would make a highly-critical error during assembly or scrubber refill. This does not mean it cannot happen, but that no highly critical error was found to be likely given a normal time and task environment. This does not take into account violations and knowledge-based malpractices that may emerge from the diver's (or others') own experience. In general the units tested were found to have features that prevented the most obvious / likely and serious kinds of assembly errors (e.g. connecting the breathing tubes to the wrong tanks).

3.4 SUMMARY

There were eight areas of concern identified, where an error (although not highly likely) might become likely in disorganised circumstances, and would be critical and without recovery:

- Before step one of the task analysis it is possible that the softnolime may not be emptied out (lapse) and hence the diver may forget to replace it.
- The softnolime material itself. Used softnolime looks the same as fresh softnolime. Putting used rather than fresh softnolime into the cartridge would be a critical error with no recovery through the assembly process and no flag to alert the diver to the issue. Hence the procedure by which divers keep and dispose of softnolime must be very rigorous, and it is recommended that manufacturers and trainers develop and pass on effective (foolproof) practices for divers.
- The O-rings (seals). On the unit there are two black O-rings (one plastic, one thin rubber), that are fitted over the cartridge once it has been lowered into the container (prior to screwing the top on). Either could easily be omitted, without noticing. There would be no obvious recovery flag other than a component left-over at the end. However in many circumstances this could not be relied upon (e.g. the o-ring could have fallen off the table unnoticed and underneath a piece of furniture, or into grass, etc). Equally the hard plastic ring and the soft rubber one could be switched round, since it is not obvious which way round they should be. This would mean no component would be left over at the end to flag up the error. Either of these errors would probably leave an insufficient seal, meaning that used CO2 could leak round the scrubber.
- Insufficient tightening of hoses (at T-Piece, and at the connections to the scrubber). These errors would be noticed only if diligent checks were done. They are likely due to interruptions occurring, or the diver leaving them partly connected for some reason (with no visible sign). It is recommended that the inner thread be brightly coloured so such errors are immediately obvious, or other design modifications such as snap connections might be more suitable. Such errors could cause disconnection in the water or leakage, which would prove hard to diagnose given the situation that would arise.
- Insufficient tightening of the four retaining nuts. This would not be immediately obvious, and once the cover was fitted would not be spotted. This might also not be picked up until the dive itself. Such errors are likely due to interruptions occurring, or the diver leaving them partly connected for some reason. As before, it is recommended that the inner flange of the cylinder cap be brightly coloured so such errors are immediately obvious.

- The softnolime cartridge could be placed in the container the wrong way up, without the pressure spider in place (by lowering it in using the retaining nut to hold on to). Such an error would require a combination of errors to occur (i.e. replacing the retaining nut but not the pressure spider). However this is possible and the diver may simply replace the retaining nut without concentrating. Such an error would not be flagged unless the pressure spider was visible after the assembly (showing that it had been omitted). The consequence would be that the system would have severe leakage and possibly not work.
- The bottom scrim (fitted second) could be misaligned (or damage go unnoticed), sufficiently to hold in enough softnolime to not be noticed. The softnolime would begin leaking out after it was lowered into the cartridge. This would lead to softnolime leakage into the breathing tube, as well as spoiling the integrity of the scrubber.
- Fitting the back cover of the unit in place could result in pinching any one of the hoses, leading to difficulties. Again this would not be visible or obvious and would only be picked up in a check. This could also cause damage to a hose, and if the problem was noted and the cover refitted, unless the unit were re-tested an assumption may be made by the diver that the problem was fixed.

It is recommended that the use of a checklist be mandatory. The checklist should not be driven by ‘legally protective’ phrases, and should instead be a very simple aide memoir, with each key point being necessary to the assembly / integrity safely. The points should not be overly informative in terms of imparting knowledge, but simply be statements of what is required to be completed at each step. It should take the form of a list that the experienced diver would find useful as an aide-memoir, and contain the absolute minimum of information and points. The more information is included, the less chance there is that the diver will use it and the higher the chance that the diver will learn to ignore parts of it. Importantly the diver must learn why each checklist point is critical, in order to protect against experienced divers determining for themselves that points are unnecessary, based on incomplete knowledge.

The full task analysis for the evaluated CCR unit is shown in Appendix 1.

4. HUMAN ERROR POTENTIAL ANALYSIS OF DIVING OPERATIONS

JONATHON PIKE

4.1 INTRODUCTION

The original proposal set out that a similar approach to that employed in the previous section would be utilised in this phase involving tasks analyses for 'normal and selected non-normal operations when using a CCR unit' drawing upon Standard Operating Procedures (SOPs) contained in the user manuals and structured interviews and walk through/talk through analyses with Subject Matter Experts (SMEs):

> *"As before, the HTA output will then be supplemented with a formal error identification analysis. The formal error identification analyses using SHERPA will allow the comparison of the likely error potentials for certain selected normal and non-normal tasks between the different selected CCR units."*

In this section the potential for human error during dive operations is analysed and discussed in successive sub-sections pertaining to the following specific dive phases:

- Pre-dive Checks and pre-Breathe
- Entry and Descent
- The Main Dive
- Dive Planning

Note that these phases are what are typically considered to be 'normal' diving phases. Due to the complexity of 'non-normal' emergency situations, the analysis of the human error potential of these was undertaken separately and is presented later in Chapter 7. The rest of this section will discuss the 'normal' phases in turn, following an initial section to describe the general Human Error Potential Analysis method that was employed.

4.2 METHOD

The analysis was conducted using the Systematic Human Error Reduction and Prediction Approach (SHERPA). The SHERPA method was selected as it is acknowledged to be one of the most successful in terms of accuracy of error predictions (Stanton, Salmon, Walker, Baber and Jenkins, 2005). It was conducted using the following the seven step procedure adapted from Stanton et al (2005):

- STEP 1: HIERARCHICAL TASK ANALYSIS (HTA)

An HTA is conducted to determine the task steps required to complete the task.

- STEP 2: TASK CLASSIFICATION

Each of the terminal task steps is categorised into one of the following task categories:

- Action (e.g., pressing a button, pulling a switch, opening a door)
- Retrieval (e.g., getting information from a screen or manual)
- Checking (e.g., conducting a procedural check)
- Selection (e.g., choosing one alternative over another)
- Information communication (e.g., talking to another party)

- STEP 3: HUMAN ERROR IDENTIFICATION (HEI)

The viable errors that could be made at each task step are then identified using the SHERPA error taxonomy (see Appendix 2).

- STEP 4: CONSEQUENCE ANALYSIS

The consequences of each viable error that has been identified are determined and described.

- STEP 5: RECOVERY ANALYSIS

The recovery potential for the error is determined by identifying future task steps at which the error could be recovered.

- STEP 6: ORDINAL PROBABILITY ANALYSIS (P)

The probability of the error occurring is estimated using a scale of Low (L), Medium (M) and High (H)

- STEP 7: CRITICALITY ANALYSIS (C)

The final step is an assessment of the criticality of each error. Often a scale of low, medium and high is used but for the CCR diving case it was felt that the following scale was more appropriate:

Criticality
"-" = non critical
"!" = critical, potential injury or death
"!!"= immediately critical, potential immediate/instant injury and/or death.
"B" = condition applies to bailout only.

Once the HTAs and SHERPA tables were complete they were circulated to five of the Manufacturer and Training Agency SMEs for comment and also internally reviewed. Detailed feedback on every HTA and SHERPA table was provided by at least one of the SMEs; they were then revised in accordance with the feedback received (see Appendices 3-7). The results for each of the five dive operations' analyses are now presented in separate sections, in turn.

NB: Solo diving rules out a large number of checks which must increase the risk of an error not being picked up. All of the HTAs assume a buddy is present. This is what all training agencies recommend / mandate.

4.3 RESULTS: PRE-DIVE CHECKS AND PRE-BREATHE

The pre-dive checks and pre-breathe sequence (often simply referred to as the "pre-breathe") is a comprehensive set of checks of the functionality of the CCR system, which includes a period of time spent breathing on the unit. The task steps are split into the following groups:

- CCR Electronics Checks
- Breathing Loop Checks
- O_2 and Diluent Supply Leak Checks
- O_2 and Diluent Supply Connection Checks
- Pre-Breathe
- Check of Pre-Dive Configuration of CCR and External Decompression Computers
- Bailout and Buoyancy
- Pre-Dive Buddy Checks

The results of the SHERPA analysis for the generic pre-breathe are shown in Appendix 3. The supporting HTAs are in Appendix 7.

4.3.1 CCR ELECTRONICS CHECKS

Twelve credible errors were identified for the electronics checks, three of which were unit specific. Of these, eight were checking errors and four were action errors (three being unit specific). The highest level of error was not switching the unit on, which in fact represented missing the entire section of checks. This was considered to be an immediately critical error because if the unit was dived in this state it could rapidly lead to hypoxia and death with no PO_2[1] warnings. Missing this check could be captured during the pre-breathe itself and during the recommended buddy check procedure. An engineering solution would be to design the unit to switch on automatically when immersed in water, or when the unit detected a drop in PO_2. Missing the check for O_2 cell warnings was considered to have equally severe consequences, as compromised PO_2 readings could have a similar outcome. This should elicit a "No Dive" warning on the handset and training should reinforce the importance of following such warnings. An audible alarm associated with O_2 cell warnings would be a useful addition.

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[1] PPO_2 and PO_2 were found to be used synonymously in the literature. As PO_2 appears to be used increasingly as convention, it is adopted and used throughout this report.

Of the remaining checks, two were considered to have severe consequences if missed, these being the low battery warning and the CCR electronics self-test warning, as failure of the electronics would result in the loss of PO_2 monitoring and control. Both of these should result in a "No-Dive" caption and would be picked up during the pre-breathe and during buddy checks. The entry of the atmospheric pressure and the calibration of the O_2 sensors were considered to have severe consequences if conducted incorrectly since they could affect PO_2 readings, though these were units specific and the likelihood of these errors was considered to be low (these were unit specific as some units sense atmospheric pressure and some would reject an incorrect calibration and record a no dive caption).

4.3.2 BREATHING LOOP CHECKS

Nine credible errors were identified for the breathing loop checks. Omitting to inspect the mushroom valves was considered to have immediately severe consequences and to be high in probability. If the mushroom valves are damaged the unidirectional nature of the breathing loop is compromised; CO_2 may mingle with the upstream (inhalant) breathing mixture in the loop and result in hypercapnia requiring immediate bailout. This may be captured during the pre-breathe itself, but emphasis on the importance of this check is required in training. Omission of the positive and negative pressure checks was also considered highly likely though less severe, as leaks not identified as a consequence of these omissions should become apparent during the subsequent bubble check on descent. In addition a small but continuous leak in the breathing loop will be obvious to the user and will be recoverable through open circuit bail-out and dive termination. That said, the importance of buddy checks during the bubble check also needs to be emphasised, as not all leaks may be visible to the unit wearer.

4.3.3 O_2 AND DILUENT SUPPLY LEAK CHECKS

Both the O_2 and diluent supply leak checks could be missed. Missing the O_2 supply leak check was considered to have potentially severe consequences as gradual loss of O_2 could ultimately require bailout. Diluent loss was considered not as important as less diluent is required. These omissions could be captured during the bubble check and emphasis on their importance should be underlined during training.

4.3.4 O_2 AND DILUENT SUPPLY CONNECTION CHECKS

Credible SHERPA errors were identified for four check items and five action items during the gas supply check phase of the pre-breathe procedure. Of these, not watching the submersible pressure gauge (SPG) for needle bounce or flicks during the check was considered to have potentially immediate severe consequences, as partially closed O_2 valve may lead to hypoxia and death if insufficient O_2 can be supplied to maintain the required PO_2, this problem manifesting in the worse situation on ascent where O_2 valve is the rate determining step for O_2 addition into the loop. Missing the equivalent check on the diluent supply was considered equally severe, as it could lead to an inability to maintain positive buoyancy or supply adequate loop volume, this issue most likely to manifest on descent as diluent needs to be added to the loop to maintain loop volume as pressure increases. It was also noted that slider (flowstop) valves might not be opened. Development of flow stop valves that provide a visual indication of their state (so a buddy can recognise the potential error) and that cannot be closed by accident is recommended.

4.3.5 PRE-BREATHE

Credible errors were associated with two actions and six checks in the pre-breathe. Not wearing a mask or blocking the nose was considered to be both highly likely and of potentially having immediate severe consequences. If this is not done then it is possible that the diver will unconsciously start breathing through the nose to compensate for abnormally high levels of CO_2 in the breathing loop if present, thus negating the test. This is an important issue that should receive particular emphasis during training as there is no possible recovery strategy[2].

Assessed to be of equal severity in consequence was conducting the pre-breathe for less than five minutes as this compromises the effectiveness of the test. Using a timing device and conducting pre-breathes with a buddy are recommended. Of the remaining checks, only missing the check that the PO_2 level was maintained at the set point was considered to have a severe consequence.

4.3.6 CHECK OF PRE-DIVE CONFIGURATION OF CCR AND EXTERNAL DECOMPRESSION COMPUTERS

For dives with a decompression obligation, six activities/checks were identified where credible errors could be made in checking the configuration of the CCR and the external decompression computers. Errors made in the configuration of diluent and decompression mixes, the high and low set points not matching the dive plan and the absence of back-up decompression tables could all lead to decompression sickness.

4.3.7 BAILOUT AND BUOYANCY CHECKS

Seventeen credible checking errors were identified in the bailout and buoyancy checking task. Not checking the off-board bailout valve was open or checking off-board-bailout contents, not breathing from the bailout regulator and not confirming that the bailout regulator was subsequently secured in where it was immediately available were considered to have immediate severe consequences in the event of a bailout. Emphasis during training on the importance of these checks and the need for buddy checking of bailout is recommended. Omitting checks of BCD inflation and deflation were considered to have severe consequences, as was omitting to check that the breathing loop pull dump (where fitted) was free of obstruction. Pull dump toggles and pull dump cords should be marked with a high visibility

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[2] It should be noted that whilst one SME stressed this practice was critical, another SME had not encountered it before. This section highlights this as a credible and critical potential source of error.

distinguishing colour that contrasts with the BCD and counterlung material. Dumps can easily get trapped under straps, hoses or under the arm and end up in the "pulled position" meaning they continually vent when the diver enters the water. Clearly distinguishing pull dump toggles and cords would make this error easier to spot by a buddy.

4.3.8 PRE-DIVE BUDDY CHECKS

Eighteen viable checking errors (all missed checks) were identified for the list of buddy checks that were formulated. The SMEs considered that there was a high probability that buddy checks would not be carried out at all. Emphasis on the value of these checks is necessary during training.

4.3.9 DISCUSSION

There was a universal agreement amongst the SMEs that the pre-breathe was a critical and essential stage in any CCR dive. Whilst the individual actions and checks required are not complex, with over seventy items it is improbable that all of the checks could be memorised even if chunked into the groups in which they are reported here. Therefore the use of a checklist is considered imperative and it is recommended that, as a minimum, manufacturers should provide waterproof checklists for this purpose. However, this of itself may not be sufficient to guarantee completion of the pre-breathe in its entirety. Apart from the possibility of the checklists being mislaid or lost, the context of use has to be considered.

It is unlikely that the pre-breathe will be conducted in a situation where there are no distractions or interruptions. Frequently, they will be conducted on a dive boat where there is much other activity going on. In the event of an interruption, one of the most common errors that can occur is for the checklist to be re-entered at the wrong point. This will be spotted if it is at an earlier point in the checklist but not necessarily if it is re-entered at a point further down the list, with intermediate items being missed.

The diving context also presents other factors that may influence the safety of CCR divers' behaviour. Reason and Hobbs (2003) distinguish between "errors" which they define as being unintentional acts, and "violations" which are intentional departures from accepted or mandated procedures and safe practice. They suggest that when a person commits a violation they mentally weigh up the costs and benefits of not complying with the procedure.

Table 3 shows the mental “balance sheet” that an individual may weigh up when deciding whether or not to violate a procedure (Reason & Hobbs, 2003). Often the benefits are immediate whereas the perceived costs occur in the future.

TABLE 3 THE MENTAL "BALANCE SHEET" DETERMINING WHETHER OR NOT A PERSON WILL VIOLATE A PROCEDURE IN A PARTICULAR SITUATION (REASON AND HOBBS, 2003)

Perceived Benefits	**Perceived Costs**
Easier ways of working	Accident
Saves time	Injury to self or others
More exciting	Damage to assets
Gets the job done	Costly to repair
Shows skill	Sanctions/punishments
Meets a deadline	Loss of job/promotion
Looks Macho	Disapproval of friends

Reason and Hobbs (2003) also contend that personal beliefs such as illusions of control (over-estimating the extent to which they can control the outcome of risky situations), invulnerability (underestimates of the chances that rule-breaking will lead to bad outcomes), superiority (violators believing that they are more skilful than other people), "there's nothing wrong with it" (not perceiving that their behaviour is more unsafe that others following safe practice) and "everyone else does it" (explaining their behaviour by saying they are simply doing what everyone else does, often overestimating how many others violate in a particular way).

One factor that can precipitate violations in the diving context is time pressure. As one SME put it "the first person in the water sees the most fish". A possible scenario in UK waters is a skipper having difficulty locating a wreck, and with tides being critical, there could be a case of 'get in now' or you aren't going to get to the wreck at all. Both situations may lead to the temptation to omit checks to save time and meet a deadline. Boat skippers telling CCR divers the slack window and providing a "30 minutes before the dive to prepare" warning may help mitigate this.

Another factor is perceived or actual peer pressure. This is likely to be a significant factor when diving with open circuit divers, as the preparation of the CCR unit and the conduct of the pre-breathe may take up to 20 minutes longer than preparation and checking of an open circuit unit, according to one of the SMEs. One of the recreational divers participating in the study reported a reticence to spend a long time checking his equipment if there were a lot of people around, which suggests that there was a concern about looking skilful or "macho".

An engineering solution that would mitigate some or all of these issues is the inclusion of the pre-breathe checklist within the software of the CCR unit so that it has to be stepped through prior to the dive (noting that there has to be a bypass in case of emergency such as a fire on the boat where missing the pre-breathe is safer than remaining onboard).

The prevention of violations is a well recognised challenge in all high risk industries. Ultimately a robust safety culture has to be developed if violations are to be reduced. This is particularly difficult in a recreational activity, especially where people can participate without supervision. Safety related training interventions in high risk industries typically include training on Human Factorsissues to raise awareness and inform behaviour. We would recommend that this should be mandated for inclusion in all CCR courses.

4.4 RESULTS: ENTRY AND DESCENT

The results of the SHERPA analysis for the entry and descent phases are shown in Appendix 6 with supporting HTAs in Appendix 5. The task steps are split into the following groups:

- In-Water Checks
- Surface Swim
- Initial Descent to Bubble Check
- 6m Bubble Check
- Main Descent
- Arrival at the Target Depth

4.4.1 IN-WATER CHECKS

Eight potential check omissions were identified associated with the checks of all the CCR controls, valves, inflators and displays. These represent the last opportunity to check the functionality of the system before the descent commences. It is recommended that divers are taught to locate all CCR controls, valves and inflators by touch and that these checks are well drilled.

4.4.2 SURFACE SWIM (OPTIONAL)

The electronics may have been affected by the diver jumping into the water so a PO_2 check is required to ensure that the PO_2 has not been dropping. This needs to be trained.

4.4.3 INITIAL DESCENT TO BUBBLE CHECKS

Five credible errors were identified for the twelve checks and actions required. Omitting checking the initial PO_2 in the case where the descent was to be direct without a surface swim and checking the SPGs were all considered to have potentially severe consequences. Regular monitoring of the SPGs has to be emphasised in training.

4.4.4 6M BUBBLE CHECK

Twelve credible errors were identified that could occur during the bubble check. Missing the check that the O_2 cells can read over the high setpoint was considered to be potentially critical. If the cells are unable to read over the high setpoint it suggests that the cells are reading lower than the loop PO_2 with the potential for hyperoxia to occur leading to CNS toxicity, convulsions, drowning and death. The immediacy of the effect would depend on the degree of error on the readings displayed, which is in turn related to the age of the O_2 sensors. If cells cannot read over the setpoint the dive must be aborted. Missing the other checks may mean that leaks of diluent and O_2 are not detected and ingress of water into the scrubber canister is not spotted. These may all have severe consequences; however they are likely to generate noticeable symptoms. Conduct of bubble checks has to be drilled in training and the importance of buddy participation emphasised.

4.4.5 MAIN DESCENT

The principle action on the main descent is the regular checking of the PO_2 readings from each cell. Missing these checks could lead to potential hyperoxia not being spotted. On units where the high set point has to be switched to manually, missing this change at 15-20m may lead to higher decompression obligations and ultimately decompression sickness if the diver is forced to surface by insufficient decompression gas quantities. Some sets change their set point shallower than 15 m during descent, this is configurable and may also occur on ascent.

4.4.6 ARRIVAL AT THE TARGET DEPTH

Seven credible errors were identified that could occur in the actions required at the target depth. Missing the check that the PO_2 was not above 1.6 was considered to be highly probable. The danger associated with missing the check, is that the next time the check would be performed the PO_2 could potentially be dangerously high due to the greater depth (for example getting a PO_2 reading of 4.0 at 30 m).

4.5 RESULTS AND ANALYSIS: MAIN DIVE

The results of the SHERPA analysis for the main dive are shown in Appendix 5. The supporting HTAs are in Appendix 7. The task steps are split into the following groups:

- Monitor Continually
- Monitor Every Minute
- Monitor Every 5 Minutes
- Ascent

4.5.1 MONITOR CONTINUALLY

Four viable checking errors were identified in the continual monitoring category. Arguably the most challenging aspect of the monitoring activity of CCR diving is the monitoring of the diver's own physical and mental condition. Unfortunately hypoxia, hyperoxia and hypercapnia may all cause diver disabling symptoms without warning; hypoxia causing unconsciousness, hyperoxia causing convulsions and hypercapnia causing irrationality, confusion, panic and unconsciousness making diver self-rescue impossible. Hypercapnia in high PO_2 environments may not present the diver with symptoms such as dyspnea, may cause convulsions (a symptom of carbon dioxide narcosis) and may also cause fatal secondary effects such as a central nervous system oxygen toxicity convulsion.

If warning instrumentation fails or is absent, the passive failure modes involved in these conditions (especially hypercapnia and hypoxia), coupled with the insidious and incrementally compromising nature of physiological symptoms, makes diver self-rescue extremely unlikely. Diving in a buddy team is a potential extra safety measure (especially in hypoxic and hypercapnic scenarios). In buddy diving situations, an additional LED display, where an additional back mounted LED that duplicates the diver's own HUD is visible to the buddy, would provide a potential extra safety measure (this design capability has already been introduced into one CCR unit system, so could be developed and incorporated into other models). Instrumentation to measure CO_2 directly at the point downstream from the scrubber would potentially warn a CCR diver of rising CO_2 levels indicative of breakthrough.

4.5.2 MONITOR EVERY MINUTE

Three viable checking errors were identified in the task to be conducted every minute. Failing to monitor the PO_2 readings on the handsets was considered to be critical as the diver could miss high or low PO_2 readings indicating that a hyperoxic or hypoxic breathing mix was present in the breathing loop, both of which are ultimately lethal. Emphasis on these checks during training is essential. It should be noted that audible alarms and HUD systems provide some additional warning mechanisms to the diver, however diver vigilance is essential.

4.5.3 MONITOR EVERY 5 MINUTES

Two viable retrieval and checking errors were identified with the 5 minute checks of the O_2 and diluent SPGs. The consequence of missing these checks was considered severe as O_2 or diluent leaks may not be spotted, each of which would necessitate terminating the dive.

4.5.4 ASCENT

Three viable checking errors and two viable action errors were identified for the ascent task elements. Checking the PO_2 against the setpoint before ascent, not monitoring the PO_2 on ascent and not correctly managing buoyancy to control the ascent were all considered to have critical consequences. As the PO_2 decreases on ascent, hypoxia may occur if the PO_2 is not monitored and corrected as required. A rapid ascent can ultimately lead to decompression illness or arterial gas embolism.

4.6 RESULTS AND ANALYSIS: DIVE PLANNING

The results of the SHERPA analysis for dive planning are shown in Appendix 6 and supporting HTAs in Appendix 7. The dive planning task was split into the following stages:

- Diluent Selection
- Bailout Selection

- Decompression Calculations – closed circuit
- Decompression Calculations – bailout
- Oxygen Toxicity Considerations
- Scrubber Endurance
- Gas Consumption – Closed Circuit
- Gas Consumption -Open Circuit Bailout
- Cross-check of Dive Plan with buddy (recommendation for additional task)

4.6.1 DILUENT SELECTION

Five errors were identified as viable in the diluent selection stage. Of these, incorrect calculation of the diluent FO_2 and incorrect calculation of the minimum operating depth for the diluent gas were considered to have immediately critical as these errors could lead to hypoxia. Using air a diluent below 40 m brings other issues most noticeably narcosis and increased work of breathing.

4.6.2 BAILOUT SELECTION

Five errors were identified as viable in the bailout selection stage. Of these, incorrect calculation of the bailout FO_2 and incorrect calculation of the minimum or maximum operating depths for the bailout gas were considered to have immediately critical consequences if bailout were needed. These errors could lead to hypoxia or hyperoxia when using the bailout mix.

4.6.3 DECOMPRESSION CALCULATIONS – CLOSED CIRCUIT

Seven viable errors were identified associated with closed circuit decompression calculations, focussed mainly on decompression planning not being undertaken. The need to identify decompression requirements and appropriate safety margins and plan accordingly to avoid decompression injury has to be emphasised.

4.6.4 DECOMPRESSION CALCULATIONS – BAILOUT

Four viable errors were identified with decompression calculations for bailout. If the bailout calculations do not assume that bailout can occur at the last minute of bottom time, or if inappropriate bailout decompression mixes are selected, or the decompression schedule is not calculated correctly then decompression injury may result.

4.6.5 OXYGEN TOXICITY CONSIDERATIONS

Four viable errors were identified in connection with oxygen toxicity calculations. If oxygen toxicity were ignored or incorrectly calculated, the potential immediately severe consequence of CNS convulsions leading to drowning could occur. Cross checking the dive plan with a buddy is recommended along with the use of dive planning software to reduce the possibility of these errors. A number of the SMEs cited instances of divers ignoring oxygen toxicity limits. We would recommend that manufacturers and training agencies make a clear statement concerning the risks of ignoring oxygen toxicity limits.

4.6.6 SCRUBBER ENDURANCE

Four viable errors were identified in connection with scrubber endurance calculations, all of which were considered to have potentially immediate consequences when the dive commenced and were considered highly likely to occur. The central issues identified were the diver not following the manufacturer's published guidance on scrubber endurance and not factoring in the use of the scrubber on previous dives. The potential consequences of all of these errors would be the scrubber endurance being exceeded leading to CO2 breakthrough and subsequent hypercapnia, requiring bailout.

We recommend that emphasis during training is placed on always being conservative when calculating scrubber duration and always using fresh scrubber material for deep and/or cold water dives. Also it is essential to make divers aware that they can be incapacitated without any warning symptoms in high PCO2, high PO_2 environments (i.e. no opportunity to bailout). The teaching of CO2 narcosis dangers should be incorporated into CCR diving courses.

CO2 narcosis is a physiological situation well understood in anaesthesia but not well published in the CCR field or in training manuals. It involves 3 phases (Lomholt, 1980):

- Analgesia stage (which includes loss of memory)
- Excitation stage - loss of consciousness with uncontrolled convulsions (may be mistaken for an hyperoxic event in a CCR diving scenario), at this point the CCR diver if not wearing a full face mask will probably lose the mouthpiece and start drowning
- Anaesthesia stage results in relaxation with intact respiration and circulation.

Victims of CO_2 narcosis are likely to have little or no recollection of the event (Poulsen, 1952). The physiological anaesthetic mechanism of action is severe and rapid such that it is possible to lose consciousness without being cyanosed. Further hyperbaric research on the anaesthetic effects of high PCO_2 in high PO_2 environments is needed to improve our understanding of potential instant diver incapacitation due to scrubber break through.

4.6.7 GAS CONSUMPTION – CLOSED CIRCUIT

Four viable errors were identified concerning the gas consumption calculations for the closed circuit dive case. Three would result in insufficient O_2 being carried and one would lead to insufficient diluent being carried. That said, although insufficient on-board Oxygen to complete the dive is a very serious situation, a mistake on litres of O_2 consumption per minute is unlikely to cause an error resulting in running out of O_2 (due to so much excess O_2 capacity carried). Diluent usage calculations have typically been based on prior usage and rules of thumb. We recommend that CCR diluent calculations are performed and recorded during CCR training courses so that novice divers have a reference guide for their own diluent consumption.

4.6.8 GAS CONSUMPTION – OPEN CIRCUIT BAILOUT

Five viable errors were identified related to the calculation of gas consumption, four of which were considered to have immediately severe consequences in terms of DCI or drowning if bailout were required. The use of dive planning software with gas volume calculation functionality is recommended, along with the checking of the dive plan with a buddy and the carrying of laminated tables for open circuit bailout.

4.6.9 CROSS-CHECK OF DIVE PLAN WITH BUDDY (RECOMMENDATION FOR ADDITIONAL TASK)

The thirteen viable errors that were identified in relation to cross checking the dive plan with a buddy reflect missed opportunities to trap errors previously made in the dive plan. Emphasis on the value of buddy checks in planning should be emphasised in training.

4.6.10 DISCUSSION

Dive planning for CCR diving is more complex than that for open circuit diving by virtue of the fact that both the closed circuit case as well as open circuit bail out has to be taken into account. Whilst an *ab-initio* CCR diver would not be introduced to mixed gas diving on an introductory course, this additional complexity still has to be taken into account in subsequent training. It is therefore recommended that emergency drills are practiced routinely in safe conditions to maintain skill and procedural familiarity.

4.7 SUMMARY

The purpose of conducting the various SHERPA analyses reported in this section was to identify the scale and nature of the potential for human error in CCR diving. This work has identified a range of individual problems which represent generic issues that may be relevant across CCR unit models. A summary of key points and recommendations from this individual study are as follows:

- As CCR diving is substantially more complex than open circuit diving the criticality of pre-dive checks and the pre-breathe process cannot be overstated
- Also the potential engineering solution of building the check sequence into the controller software would seem to be highly desirable
- As a substantial number of procedures have to be recalled from memory, it would seem wise to provide training and education to all CCR divers about human error mechanisms, including both errors and violations, so that they are better placed to make informed judgements about their actions and to understand the value of recommendations such as

the use of buddy checks and the importance of manufacturers' recommendations about such issues as scrubber life and packing procedures

- Training also should be considered to address unsafe attitudes / behaviours such as overconfidence, lack of preparation, inadequate skills and a lack of equipment maintenance. Drill practice needs to be emphasised more – this could be incorporated to complement attitude / behavioural training
- More consideration could be given to changes in design to make human error less likely and there are clear improvements to be made to some CCR handset interfaces, flow stop valves, etc.
- Current EN standards includes nothing on Human Factors analysis / testing for CCRs. It is recommended that this area should be included in the standard so that rather than just identifying individual design issues with units, formal human factors analyses could be undertaken to show manufacturers how to correct these in future. Regulatory authorities should take the lead rather than leave responsibility to individual manufacturers
- As set out in 4.5.1., instrumentation to measure CO_2 directly at the point downstream from the scrubber would potentially warn a CCR diver of rising CO_2 levels indicative of breakthrough
- Personal adaptations to units can make them unique and reconfigure the procedural steps needed in any given diving situation, meaning they cannot be predicted by generic analyses as in this study. Further work investigating these effects and the potential remedial impact of bespoke training might therefore be advantageous

4.8 REFERENCES

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5. TRAINING NEEDS ANALYSIS

DR JOHN HUDDLESTONE

5.1 INTRODUCTION

The purpose of the Training Needs Analysis (TNA) was to determine if any additions were required to CCR training and to make recommendations for training practice.

> "*A high level Training Needs Analysis will be derived from data obtained from the HTA, CTA and accident/incident analyses. Material in the extant training curricula will be compared with the analyses undertaken to assess if the safety critical aspect of CCR operation identified are being addressed*".

Unfortunately, as it was found that there was no source of accident data with which analysis could be undertaken (see Chapter 2 'Accident / Incident Analysis), it was not possible to conduct the TNA as had been originally planned and set out in the above project proposal text. Instead, data analysis conducted within the 'Human Error Potential Analysis of Diving Operations' study (Chapter 4) was used combined with a set of semi-structured interviews with representatives from manufacturing and training organisations.

5.2 METHOD

Since effective training depends not only on course content, but also the overall set of processes that are involved in the development, delivery and evaluation of training, a simple training lifecycle model was used as the analytical framework. The model chosen was the Analyse, Design, Develop, Implement and Evaluate (ADDIE) model adapted from Gagne, Wager, Golas and Keller (2005). This model is shown Figure 7 and the key components are now described in turn.

The Analysis step is concerned with the identification of the knowledge, skills and attitudes required to conduct the task to be trained and the existing levels of knowledge of potential students. The difference between the two, the training gap, determines the overall content of the training course required.

The Design phase is concerned with the determination of the overall training strategy including course structure and methods to be used. This strategy is translated into detailed lesson plans and practical exercise descriptions that can be delivered to trainees during the development phase.

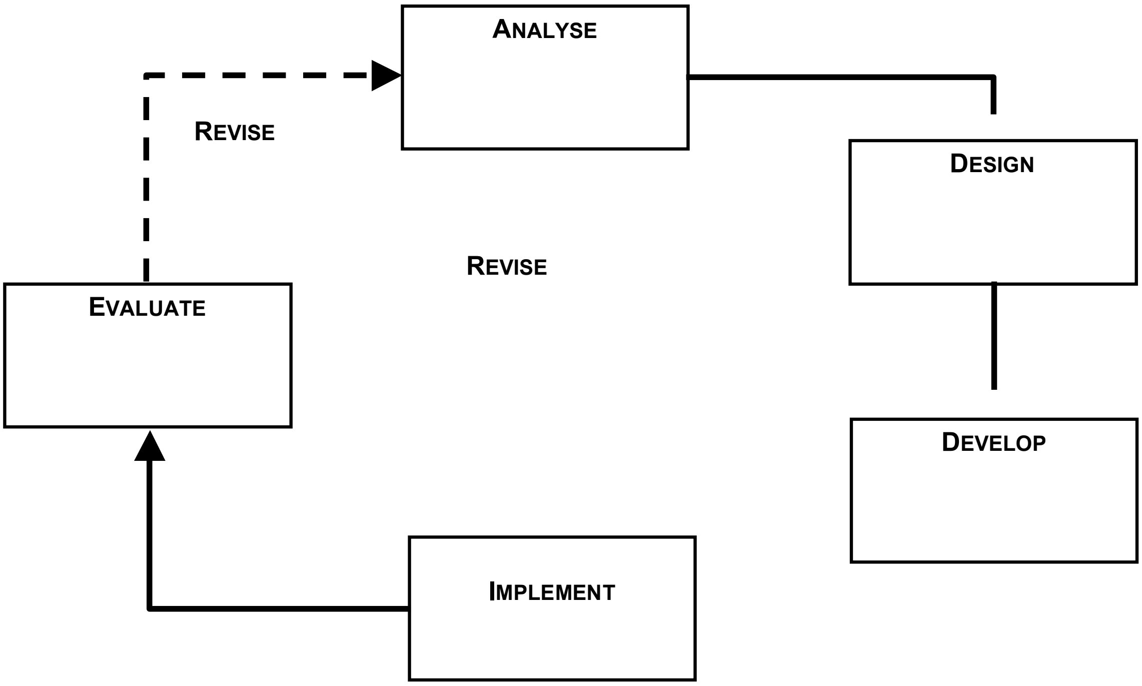

FIGURE 7 THE ADDIE MODEL ADAPTED FROM GAGNE ET AL (2005)

The implementation phase is concerned with the actual instructional delivery of the course. Evaluation of the course is the final phase of the training cycle. This embraces not only the evaluation of the students' satisfaction with the course content and their performance at the end of the course, but also the determination of the effectiveness of the training in the longer term (is the end of course performance level sustained post-course for example).

A significant feature of the ADDIE model is that the evaluation phase feeds back into all preceding phases. If it is determined that the training course is not producing the required training output, changes may be required in any one or more of the preceding phases.

Data to inform the training research were drawn from the SHERPA analyses (Chapter 4). In addition a series of semi-structured interviews were conducted with a representative selection of manufacturers and training agency representatives which included discussion about course content and training standards. The interview schedules with these 'subject matter experts' (SMEs) are shown in Table 4.

Table 4 Semi-structured interview schedules for interviewing manufacturer and training agency SMEs.

Interview Schedule for Manufacturers
• What is the process for determining the content of CCR courses? • What influence do you have on the design of CCR courses? • What input do you have to CCR course materials? • What involvement do you have in instructor selection and training? • What do you consider should be the currency requirements for instructors? • What influence do you have on student evaluation? • What feedback do you get about training courses? • What issues affect the use of accident data to inform training content? • What could be done to improve the training process?
Interview Schedule for Training Agencies
• What is the process for determining training requirements with manufacturers? • What is the process for designing courses and developing course materials? • How do you select and train instructors? • What are the currency requirements for instructors? • How do you evaluate students? • How do you quality assure training delivery? • What issues affect the use of accident data to inform training delivery? • What could be done to improve the training process?

5.3 Results

Results are presented according to the stages of the ADDIE model, in turn.

5.3.1 Analyse

5.3.1.1 Input standards

There was universal agreement amongst the SMEs that an entry level CCR candidate should have some minimum level of open circuit SCUBA experience and have completed a Nitrox course.

The underpinning logic for open circuit experience was that experience of the underwater environment (including aspects such as visibility, currents, boat procedures and navigation) and of such skills as controlling buoyancy and rates of ascent and descent were critical. The other significant factor was that being able to undertake open circuit bail-out was a critical skill which the candidates should be proficient at. The precise amount of open circuit SCUBA experience recommended varied from 20 to 50 dives. This raises the question as to whether the experience level should be defined both in terms of a minimum amount of dive time as well as the minimum number of dives completed.

The justification for the Nitrox course requirement was that CCR candidates needed to be familiar with such concepts as the partial pressure of oxygen. It was noted that some agencies offer the opportunity to combine a Nitrox course with an initial CCR course. This raises the question as to how well the concepts will have been assimilated in an operational context if they have not been applied practically. Given that a Nitrox course may have been taken some time before a CCR course is undertaken, consideration should be given to mandating some level of experience of Nitrox diving and associated currency prior to undertaking a CCR course. Given that with CCR diving there is a risk of death due to PO_2 over 1.6, an Advanced Nitrox qualification would appear to be an appropriate minimum standard (noting it also has a requirement for more dives to be completed on higher fraction O_2 mixtures).

5.3.1.2 KNOWLEDGE REQUIREMENTS

From the inspection of the course standards for a number of courses, it could be seen that, for the courses reviewed, all of the theoretical subjects that one might expect to see were included in the syllabus. Based on the SHERPA analysis, one subject that we would recommend be included in the knowledge training would be an introduction to Human Factors, with a particular focus on human errors and violations and performance shaping factors. In addition, given the significant risk posed by high levels of CO_2, an expansion of the coverage of this topic, including the anaesthetic properties of CO_2, and potential masking of symptoms in high O_2 hyperbaric environments may be warranted.

5.3.1.3 SKILLS REQUIREMENTS

Inspection of a number of course standards indicates that, at least at a high level, all the appropriate skills are included in the courses for which the standards were viewed. However, one area that may need strengthening is the handling of emergency situations, particularly where there may be a number of casual factors. For example, a Low O_2 warning may be caused by a number of factors identifying the correct cause is vital in effecting a resolution. Such situational problems would require a student to diagnose the problem and select the appropriate drill.

5.3.1.4 ATTITUDE GOALS

Whilst attitude goals are not usually specified for CCR training courses (and are relatively uncommon in general), there was universal agreement amongst all the SMEs that a disciplined approach to CCR diving was a critical attitude that had to be fostered to ensure safe diving. Terms such as “fastidiousness” and “maturity” and “attention to detail” were also used in a similar vein. The other attitude that was commonly mention was that of having a positive attitude to safety. From the SHERPA analysis it could also be seen that a positive attitude to buddy diving and the conduct of buddy checks both in planning and diving would be highly desirable

5.3.1.5 THE ANALYSIS PROCESS

A significant issue that was identified during the study was that the actual analysis process that occurs in the genesis of any CCR course is a matter of negotiation between manufacturers and training agencies. Furthermore, this process is subject to a number of commercial pressures and is dependent on the development of a good working relationship between the manufacturer and training agency concerned.

The manufacturers wish to ascertain that the agencies will deliver good quality training such that divers completing a given agency’s course will be safe divers of their equipment. In the case of all the manufacturers that participated in the study, they stated that they would not approve an agency’s course unless they were satisfied with the training that the agency would provide. The significance of this is that they would not sell a unit to an individual unless they completed an approved course. The training agencies wish to ascertain that the manufacturers are producing safe equipment that is well supported and has an appropriately comprehensive set of documentation, such that they are happy to support the purchase of that type of unit by their clients. Ultimately both parties also wish to ascertain that the other has sufficient liability insurance in the case of the unfortunate event of an accident or fatality.

The commercial tension that exists is that the training agencies represent a route to market for the manufacturer, in that they cannot sell units unless training is available for customers to complete, and equally, the training agencies cannot supply training unless they have manufacturers that are happy to approve their courses. It should be noted that the manufacturers and training agencies that participated in the study were well established and had robust processes in place. However, there is a potential risk that where new manufacturers and new agencies enter the market place such a robust approach may not be taken and the consequent risk to the consumer may be increased.

A further commercial pressure exists in that the longer the course, the more expensive the overall CCR unit purchase which may cause the user to consider both a different unit and an alternative training provider.

One area of concern is the second-hand market for CCR units. If a diver buys a second hand unit they are not obliged to take an approved course (indeed they can potentially dive the unit with no training at all) and may therefore be put at risk by being provided by substandard training by a non-approved agency. Manufacturers can exert some influence buy refusing to supply consumables, spares and the recommended, periodic manufacturing servicing unless a user has taken an approved course. However, this situation presents the manufacturers with a dilemma, in that such a user is then likely to seek alternative sources of components and consumables and to not have their units serviced which would be highly detrimental to safety. Whilst this cannot be controlled world-wide, this issue could potentially be addressed to some extent within the UK by mandating that all CCR training courses delivered within the UK be approved by the appropriate manufacturer, though of course this cannot cater for the user that chooses to dive a unit untrained or not to ensure that their unit is appropriately maintained in line with the manufacturer's recommendations.

Another area of concern is the use of modified units. Given that CCR units are highly sophisticated pieces of life support equipment that take considerable knowledge and expertise to design and manufacture, and undergo extensive laboratory testing, it might seem remarkable that some users choose to modify them, with all the attendant risks. However, this situation does occur. Instances of individuals modifying units and testing them by diving them to significant depths have been reported in the study. The manufacturers we spoke stated that their policy was not to approve training on modified units, and the agencies similarly stated that their policy was not to conduct training on modified units. However this is potentially difficult to police at the point of training delivery and there is nothing to stop unapproved training taking place.

Again, the manufacturers can have some influence in choosing not to supply parts and servicing for modified units. However, this is only effective if it is known that a unit is modified and this may only come to light if a unit is returned to the manufacturer for servicing. Also once again, there is the dilemma of such actions causing users to source alternative components or dive un-serviced units. It would appear that the only control that could be exerted would be to mandate that all courses taught in the UK have to have manufacturer's approval. One avenue that could be explored from a training perspective is to mandate that all CCR courses contain an element of education about the design, manufacture and testing processes that are involved for CCR units and the dangers of making amateur modifications, in the hope that better educated users would and subsequently less tempted to make such modifications if they had a better understanding of the risks involved.

5.3.2 DESIGN

The design phase is concerned with the identification of the teaching methods to be used, the selection of types of activities to be employed, the time to be spent on each of the activities and the overall duration of the course. Typically, CCR courses comprise classroom-based theory lessons, land-based practical lessons and a mix of confined water and open water dives. The exact pattern for any given course is based on negotiation between the manufacturers and the training agencies. All of the courses examined had of the order of two days classroom/land based training combined with approximately 500-600 minutes of confined water and open water dives. The number of dives is important as some skills can only be practised once per dive. Ascent is the main example, if one does 8 dives you are only going to get to practice 8 ascents to the surface. The greatest variation was noted in the split between confined water and open water diving. One manufacturer mandated 4 hours of confined water (swimming pool) diving compared with 2 hours for other courses on the basis that it was easier to see the students in the pool and that this time was required for rehearsing drills before moving to open water.

One of the more challenging aspects of course design is determining how much time should be devoted to any given learning point and its associated instructional activities. A useful tool to assist this analysis is Difficulty, Importance and Frequency (DIF) analysis. DIF analysis uses combinations of subjective ratings of the difficulty, importance and frequency of individual tasks to identify the level of training that should be conducted, ranging from no training required to over–training. An example of a flowchart to guide DIF analysis is shown in Figure 8.

Within CCR training there are few, if any tasks, which are unimportant and infrequent and would therefore be judged as requiring no training. The critical tasks to be identified are those that are difficult, important and infrequent as these require overtraining. A strong case can be made for emergency procedures to be placed in this category. Whilst it could be debated as to whether the procedural steps in emergency drills are difficult, the fact that they have to be conducted when the individual is placed in challenging and possibly frightening circumstances i.e. an emergency situation, categorising such drills as difficult seems reasonable. The fact that they are important and, one would hope, infrequent is probably beyond dispute.

Typical introductory CCR courses are seen to have between 40 and 50 skills that have to be successfully mastered by the student. This makes for a busy time in the water for the 9 hours of training. Typically, each emergency drill might be practiced in 2-4 of the dives conducted. Whilst this can be supplemented by rehearsal of emergency drills on land, on balance this would not seem to offer the opportunity for overtraining.

Whilst more detailed analysis of the content of training courses is required, consideration should be given for greater opportunity to practice emergency drills in the water. The lack of clarity of procedures and the absence of complete sets of checklists in user manuals serves to confound this situation. One SME suggested that consideration should be given to doubling the length of CCR courses because of the volume of material to be taught. Of particular concern is the training of handling emergency situations.

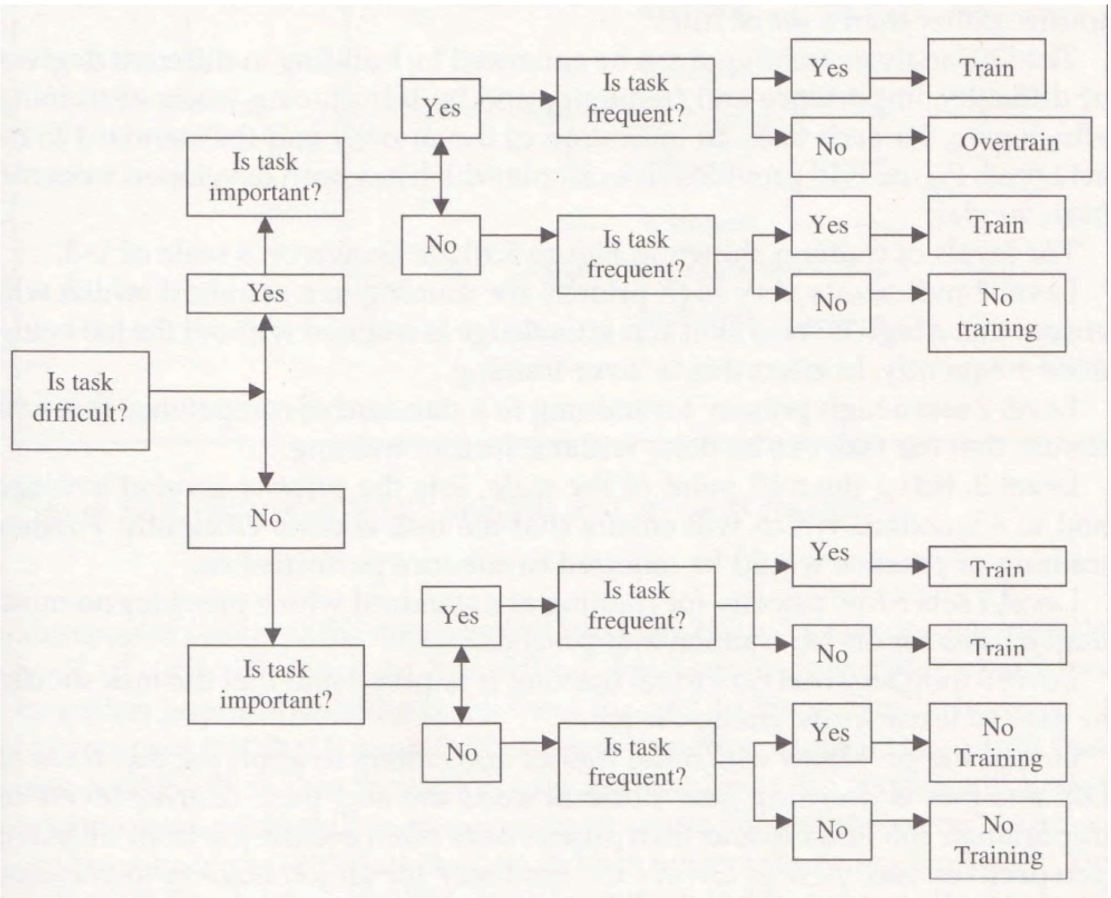

FIGURE 8 DIF ANALYSIS FLOWCHART (BUCKLEY AND CAPLE, 2004)

5.3.3 DEVELOPMENT

The development of detailed lesson plans and course materials sits mainly with the training agencies. In some agencies instructors have to buy the slide deck from the training agency. There is also manufacturer input to varying degrees; one of the manufacturers we spoke to provides a training video, most provide a skills list that has to be signed off, and some provide the training manual or review the training manual written by the training agency. One of the manufacturers commented that they sometimes have to put considerable time into rewriting training agency materials to ensure they are technically correct.

5.3.4 IMPLEMENTATION

It is not possible to make informed comment about the quality of training provision as currently implemented without the opportunity to witness/participate in a range of training courses, and this was beyond the scope of this study. However, the SMEs that participated in the study universally agreed that instructor selection, training and currency were factors that could have a fundamental impact on training quality.

5.3.4.1 INSTRUCTOR SELECTION

There was broad agreement between the manufacturers and training agencies with regard to the required input standards for instructor candidates. Typically they are required to be qualified and have previous experience of instructing open circuit scuba and Nitrox courses and to have a minimum of 100 hours experience of CCR diving. These requirements seem sensible as the open circuit environment provides a simpler environment in which to acquire basic instructional skills, and Nitrox instruction embraces the more theoretical underpinnings required for CCR teaching. Where there was a difference was that one of the agencies required CCR instructor candidates to have logged at least 100 hours of Nitrox diving.

5.3.4.2 INSTRUCTOR TRAINING

Based on a comparison of standards documents [BSAC (2008) and TDI (2008)] and discussions with training agency SMEs, it could be seen that the training agencies which they represented had broadly equivalent instructor training processes. These include a written examination and demonstration of teaching skills in both the practical and theoretical elements of the CCR course the instructor is qualifying to teach. The standards documents from both agencies also provide detailed guidance on how the training is to be conducted. Differences were noted in the requirements mandated by the various manufacturers, with each manufacturer having a different approach. One manufacturer required that instructors attend training conducted by the manufacturer in addition to the training agency course. Another mandated that instructor trainers must be trained by factory personnel. Whilst the third chose to leave instructor training entirely to the instructor trainers within the training agencies, having agreed the training standards. Some of the manufacturers expressed concern that some agencies have multiple layers of instructor trainers, believing that this type of hierarchy would lead to dilution of knowledge and reduction in standards.

One potential gap that was identified in the instructor training process concerned the development of the attitudes that all believed were important. Certainly, the example set by the instructor is an important factor in this process, and it was noted that both training agencies specify that the instructor candidate has to demonstrate safe diving practices and a mature, responsible attitude to the diving and training process. However, Cranfield University's experience in the domain of driver training has demonstrated that positive outcomes can be achieved with regards to attitudinal training by ensuring that instructors are taught specific techniques and by employing simple to administer tests that provide a profile of individual's attitudes and perceptions of risk. Such an approach may have value in the CCR diving domain.

5.3.4.3 INSTRUCTOR CURRENCY

Given that CCR diving is complex and that the associated skills are perishable, it is reasonable to expect that there should be requirements on instructors to achieve an ongoing level of currency. This applies both to the instructional task and to the use of the units themselves. There appeared to be more variation between manufacturers and training agencies as to what was mandated in this regard. In terms of frequency of teaching, the baseline levels specified by the training agencies were slightly different. One requires that instructors should deliver a course at least once every two years, requiring instructors to take a refresher course if this was not achieved, whilst the other requires that instructors conduct 3 training events over a three year period. One of the manufacturers required instructors to deliver at least three courses per year to be considered current. There were no specific requirements from the agencies as regards to the amount of time that had to logged annually on a CCR unit, although one SME expressed a personal opinion that 30-40 hours would be an appropriate amount of time. One of the manufacturers mandates a minimum annual logged time of 25 hours to be achieved. A related issue that emerged in the discussion with SMEs was the number of units on which an instructor could be considered current. Some manufacturers considered that an instructor could only be considered current on one type of unit, whereas the training agency viewpoint tended to it being feasible to be current on as many as three different units (predicated upon being able to dive at least 30 hours per year on each unit). There is possibly a commercial factor involved as well as a safety factor involved here, in that the manufacturers would prefer to have their unit alone being championed by any given instructor, whereas the training agencies would prefer to have as much flexibility as possible in the variety of courses their instructors can offer to reach the widest possible market.

Whilst this requires further discussion and consultation, there does seem to be a need for more comprehensive guidelines to be determined which cover both the annual logged dive time/number of dives conducted by an instructor on any given unit, the minimum number of courses to be taught annually, refresher requirements if these minimums are not met, and the maximum permissible number of unit types that an instructor can hold a current instructional category on. From the discussions with the SMEs, it would seem that 30-40 hours of logged time on a unit and a minimum of two courses taught per year might provide a basis for discussion for appropriate guidelines.

5.3.5 EVALUATION

Evaluation is a critical phase in the training cycle. It is concerned not only with determining is the student has reached an acceptable performance standard at the end of the course but also if the training is effective and identifying if any changes are required.

5.3.5.1 STUDENT PERFORMANCE ASSESSMENT

The evaluation of students' performance and the decision as to whether or not a student has reached an acceptable standard rests with the instructor running the course. They have the responsibility of deciding if the student is competent and safe to dive the unit. This can place the instructor under significant pressure if they deem that the student has not met the required standard, particularly in the commercial situation where the student has paid a significant amount of money for the training. One of the agencies advises its instructors, quite sensibly, to take payment at the start of the course, rather than leaving it to the end to avoid payment disputes if a candidate does not make the grade. An example of unacceptable performance cited by one of the SMEs was a candidate that missed four screws in the assembly of the scrubber on the final dive. The candidate disputed the suggestion that his approach was 'lackadaisical'. It requires a degree of strength of character to handle such challenges. One of the manufacturers made the suggestion that the assessment should be conducted by someone independent from the instructor running the course. Whilst this has logistical and cost implications, we would suggest that this avenue should be explored. Fewer assessors assessing a broader range of candidates may have the benefit of producing more consistent standards being applied. In the club environment the financial issue is removed from the equation to a greater degree but then there is also the possibility that an instructor is confronted by having to fail someone they know, which introduces another potential pressure. Again, independent examiners could reduce such an effect. An alternative training model that might be explored is that used in Accelerated Free-Fall (AFF) parachuting. AFF training is based on a sequence of jumps of progressive difficulty. Each jump is paid for separately (you can by a bundle of jumps as a "course") but there is not necessarily any expectation that the student will progress automatically to the next level. Progression to the next level is conditional on achieving a satisfactory standard at the previous level, which may necessitate multiple repetitions of a jump until sufficient mastery of the required skills at that level is demonstrated.

An additional factor that should be considered is the way in which performance goals are specified. For example, one might express the requirement for buoyancy control as "maintain effective control of buoyancy". The limitation of such a specification is that it is ambiguous and requires subjective judgement in its assessment. Performance specification couched in terms of objective, observable standards such as "maintain a stable position 3 ft from the bottom of the pool for a period of 1 minute to an accuracy of +/- one foot" would reduce the scope for dispute about performance standards achieved. We would encourage the review of performance standards along these lines.

5.3.5.2 EVALUATING THE TRAINING PROCESS

The issue of central concern with regard to the evaluation of the training process is whether or not the training that is delivered is leading to candidates being capable of diving safely on completion of training. The two key factors that affect this are the appropriateness of the training content, including the degree of practice provided, and the performance of the instructor delivering the course. Poor content will not lead to good skills being learnt, but equally good content delivered badly will have the same effect.

5.3.5.2.1 MONITORING TRAINING STANDARDS

It is imperative that training standards are monitored. In one of the interviews conducted with divers it was reported that the instructor had taught he students how to bypass the inbuilt warning on a system that indicated that the scrubber needed replacing, clearly a potentially dangerous practice. Such lapses in standards need to be trapped.

A potentially useful source of information about training is student feedback. Both of the agencies that were involved in the study have systems in place to achieve this. BSAC requires all candidates to complete a feedback form in order to receive their certificate. This has the advantage that feedback will be received but there is the risk that candidates will report what they think is what is wanted and avoid negative feedback in order not to jeopardise receipt of their qualification. TDI have a voluntary sampling process, which includes checks but response rates have historically been about 5%, although a recent initiative to take feedback online produced much higher response rates of up to 30%. Such initiatives are to be encouraged.

Whilst monitoring student feedback has its place, it is not sufficient on its own. We would contend that there is a need to periodically audit training delivery to ensure that the training that is delivered in line with the design and policies laid down by the training agency.

Simply capturing data about training delivery is insufficient on its own. The data needs to be analysed and appropriate actions taken. To close the feedback loop as shown in Figure 9, this has to involve communicating information back to the manufacturers as they are involved in determining training course content , methods and assessments. A number of the manufacturers participating in the study expressed concern that it can be very difficult to get any feedback from some of the training agencies that they are involved with, with issues only coming to light when customers contact customer support with queries about the use of the unit they have been trained on. One of the training agency SMEs characterised the operation of the current training cycle as having “strong local eddies” rather than rather than being an effective large scale loop. That said, both agencies involved in the study had robust quality assurance systems in place, as did the manufacturers.

The current training system is modelled in

Figure 9. In any multi-party system such as this, the potential weak spots are the interfaces between the different parties particularly where there is no direct control.

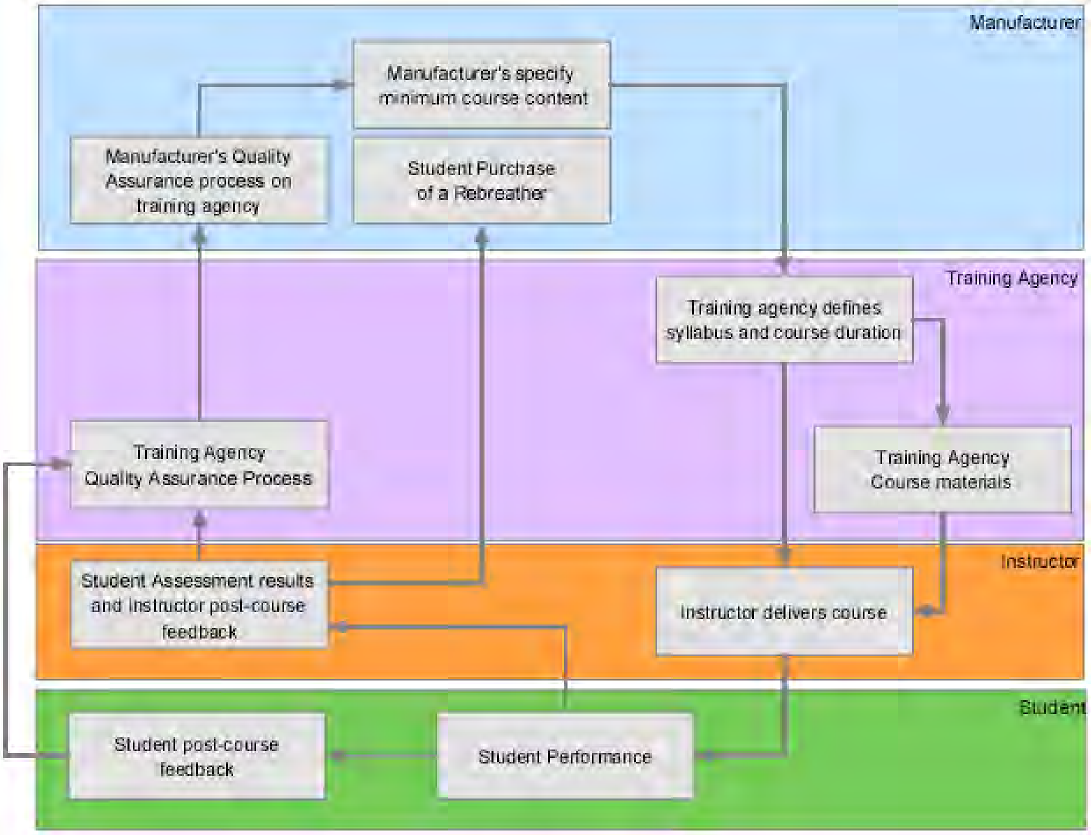

FIGURE 9 MODEL OF THE CCR TRAINING SYSTEM

The challenge for the industry is to ensure that information flows effectively across these interfaces to ensure that best practice for safe CCR diving is always at the focus of the training system and that deviations from best practice are identified and eliminated expediently.

An example of such an issue that may still need to be addressed is that of instructors teaching students how to extend a scrubber canister beyond the manufacturer's recommendations. This was reported both as an issue at a forum of experts held in 2006 in the US reported by Vann, Pollock and Denoble (2007) and as an occurrence experienced by one of the recreational diver interviewees in this study. Similar data from different sources would seem to suggest that this is a problem that may be widespread. It certainly constitutes a divergence from safe practice.

5.3.5.2.2 EVALUATION OF ACCIDENT AND INCIDENT DATA

Another potentially useful source of information to inform the revision of training would be the analysis of accident and incident data. One of the issues that has already been identified in this report has been the difficulty in obtaining reliable accident data and the need for an UK national (CCR) accident database has been highlighted. A number of the SMEs participants in the study raised the point that one of the confounding factors is a lack of knowledge in first responders to incidents as to how to effective lock down a CCR Unit and preserve the evidence for subsequent investigation. Their recommendation was that there should be protocols available for first responders' use and that there was potentially a training requirement in this area. This issue has been raised previously at a CCR seminar (Vann et al, 2007). This issue is complex, not only because there are necessarily unit specific requirements as well as generic principles, and confounding legal issues such as the preservation of the chain of evidence.

A number of the SMEs provided protocols which they had devised for this purpose and these are included at Appendix 8. The generic guidance shown in Appendix 8 section 8.1, devised by Qinetiq and the Health and Safety Laboratory, has been published on the British Diving Safety Group Website (www.bdsg.org). We would recommend that a working party is formed to develop a protocol to be used nationally, containing both generic and unit specific guidance, and that the provision of training for first responders is considered. SMEs have suggested the following parties as potential recipients of such training:

a. Marine Police
b. Dive Boat Operators
c. Instructors
d. Inland Diving Centre Operators

Whilst more accidents occur than anyone would wish, with zero accidents being the ideal, there are many more minor incidents than accidents. This evidenced by the fact that every diver participant in the study had experienced at least one incident whilst using a CCR unit. This could be a very rich source of data but there is no formal mechanism for capturing it. One type of system that has been used across the aviation community embracing both commercial and recreational flying, is the use of an anonymous Human Factors reporting system. An online system for reporting “near misses” could provide the opportunity to share experience in such a way as to allow formal analysis to the benefit of all in the CCR diving community.

5.3.6 SUMMARY

The key findings from the training needs analysis study were:

- Consider specifying student input standards for open circuit experience in terms of minimum dive time as well as number of dives completed
- Consider Advanced Nitrox training as the input standard
- Human Factors training, specifically covering human error and violations should be included in the theory section of CCR courses
- Consider increasing the level of training in emergency situations and emphasising the need for recurrent practice of emergency procedures
- Attitude goals should be specified for CCR courses and instructor training provided on how to foster attitude goals
- Consider mandating that all CCR courses delivered in the UK be approved by the manufacturer of the unit being taught
- Consider the inclusion on CCR courses of education about the development and testing process for CCR units
- A detailed study should be conducted to determine appropriate course durations with particular reference to the number of dives conducted, the content of such dives and the repetition of skills across those dives
- Consider mandating that CCR User Manuals should have a complete set of checklists for handling emergency situations
- Instructor currency requirements should be reviewed and consideration given to specifying them in terms of numbers of hours dived on the unit per year as well as numbers of courses taught per year (30 hours diving per year and 2 courses taught per year is suggested as a starting point for discussion)
- Consider alternative assessment models such as using independent assessors or introducing a pay per dive system where progression to the next dive level is dependent on achievement of set performance criteria; recurrent training may also be advantageous to maintain skills and abilities
- Where possible, performance standards should be expressed in terms of observable performance criteria.

- Methods to increase student feedback on courses, such as online feedback systems should be encouraged
- The development of a generic protocol with unit specific annexes for locking down units in the event of an accident in order to preserve evidence more effectively should be considered along with training in its use for first responders
- Diving with personally adapted units may negate the efficacy of training that has been designed for manufacturer specifications. Training standards need to address this problem and further work to examine effects may be highly advantageous for this purpose

5.4 REFERENCES

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6. INTERFACE AND DISPLAY RECOMMENDATIONS

JONATHON PIKE

6.1 INTRODUCTION

This individual study was originally set out in the proposal to be combined with the work in the previous chapter on training needs analysis and presented as the fourth and final deliverable: "Best practice for training and human interface design to minimise risk of human error". However, due to differences between the work that is involved in analysing training needs, and that which is required to analyse interface issues, the final work package was split into two separate work pieces. Nonetheless, the aim remained consistent with the original proposal:

> *"...derived from the HTAs and CTAs (and their associated formal error analyses) generic human-machine interface design requirements to assist in avoiding design-induced error will be derived. This will relate to both the design of the user interfaces on the CCR computer (including any Head Up Displays) and other controls to the CCR (e.g. diluent / oxygen buttons; valves, etc)*[3]*."*

The design of the user interface for a system can have a fundamental impact on its usability and therefore its safety. A simple example of where a design oversight can lead to human error is when a door that has to be pushed open has a handle on it which one would naturally pull. The consequence is a good deal of frustration as users attempt to pull the door open instead of pushing it. Whilst the example is simplistic it does capture the central principle of concern in this section. The purpose of this section is to identify key design principles which should be applied to the design of CCR interfaces and displays.

6.2 METHOD

The main reference that is used throughout is the FAA Human Factors Design Standard (FAA, 2003). The reason that this was chosen is that it is widely recognised as an authoritative guide in the field and draws widely on Human Factors research and is extensively referenced. Reference is also made to the UK Ministry of Defence Standard 00-250 Issue 1 (MoD, 2008) which is a

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[3] While the functional purposes of the controls and display interfaces will be common to all CCR, comment passed on the adequacy of the design and procedures for manual and automatic operation is likely to be specific to a make and model of CCR

recent revision of an established Human Factors design standard which is applied to the interfaces of military equipment.

6.2.1 CCR HANDSETS AND HEAD UP DISPLAYS

CCR handsets function as the primary interface into the oxygen monitoring and control system of CCR units. Information displayed on the handset during a dive generally includes:

- Controller status (Master or Slave)
- Battery status
- PO_2 setpoint
- 3 independent PO_2 readings from each of the three PO_2 sensors in the scrubber lid
- Diluent selected
- Dive depth
- Dive time
- Decompression information / No stop time

Other information that may be displayed by specific units:

- CO_2 scrubber temperature display (a proxy for scrubber usage)
- HP contents for diluent and O_2
- CNS Information
- Ascent Rate
- Menu options to alter brightness and contrast of the screen
- Alarm and Fault displays (such as O_2 Cell failures and Low battery warnings)

In electronically controlled CCRs automation through software control will monitor and maintain O_2 levels in the breathing loop through solenoid function. Majority voting rules will poll the three O_2 sensors and calculate a single output, which the value that the unit then refers to the selected setpoint. If the calculated PO_2 is below the setpoint the solenoid will function to bring the PO_2 levels up to the setpoint.

CCR units generally have two handsets, one which functions as a Master which controls the oxygen solenoid, the other that is a slave that displays calculated PO_2 levels but does not actually control the oxygen solenoid. System redundancy allows a Slave controller to be promoted to a Master, in the event of a fault.

Many CCR units are also fitted with a Head Up Display (HUD). Unlike aircraft HUDs, which project data and instrument displays onto a glass screen which the pilot looks through to see the outside world, HUDs on CCR units are typically a small group of LEDs, often of different colours, mounted on a small unit that is fastened to the mouthpiece. These LEDs are used to provide warning signals and system state information by means of coded flashes (for example, a flashing red led might signify the need to abort the dive and bailout), and are supplementary to the handsets.

6.2.2 DESIGN RECOMMENDATION CATEGORIES

For the purposes of this study, Human Factors design recommendations are considered for the following three areas:

- **Automation** – general Human Factors guiding principles for automation and the alignment of access of function with potential diver tasks. Major considerations in Automation as related to electronically controlled CCRs are divided into (1) General considerations and Control Automation, (2) System Response and Feedback and Information Automation (3) Automation Interface and System Modes, (4) Monitoring (5) Fault Management
- **Display of information to the CCR Diver** - to enable decision making, this covers the physical aspects of screen displays including legibility and screen brightness. In addition relevant system information needs to be displayed to the diver – enabling the diver to assess that PO_2 automation is functioning correctly. The CCR diver needs to have a mental model of system operation; the interface is critical in enabling relevant information to be displayed in a way that is instantly understandable by the diver
- **Handset controls** - that enable the diver to select relevant information and execute control actions; such as setpoint selection, promoting a slave controller to a master controller (this may occur automatically in the event of a system fault, but can also be user selected).

6.2.3 SCOPE

Interface and display recommendations cover the design of controls and displays on CCR handsets. Recommendations for other CCR controls and indications such as audible alarms, buzzers, inflators, over pressure relief valves, auto diluent valves, flow stop valves or gas switching blocks were beyond the scope of this report but merit further investigation.

6.3 AUTOMATION

6.3.1 TYPE, CRITICALITY AND LEVEL OF AUTOMATION

Automation is the independent accomplishment of a function by a device or system (FAA, 2008). Electronically controlled closed circuit rebreathers (CCRs) regulate the partial pressure of O_2 (PO_2) in the breathing loop by monitoring the PO_2 through three independent oxygen sensors. The CCR control system uses voting logic to calculate an averaged PO_2 value from the three values received from the oxygen sensors. This averaged value is compared to an established PO_2 setpoint, and a computer controlled solenoid valve is opened if the PO_2 has dropped too far below the setpoint. PO_2 must be maintained in a range of 0.21 to 1.6, below 0.16 hypoxia, unconsciousness and death result; above a PO_2 of 1.6 a hyperoxic convulsion caused by CNS oxygen toxicity may result, usually resulting in drowning.

In terms of classification the FAA (2008) defines Control Automation as "when an automated system executes actions or control tasks with some level of autonomy" (section 3, page 34), CCRs regulate PO_2 in the breathing loop so use Control Automation. The FAA defines a Critical Function as a "function that can cause system failure when a malfunction is not attended to immediately" (section 3, page 34). As a CCR is a life support system, system failure will involve the potential death or injury of the wearer. PO_2 regulation is a critical function of life support. CCRs also use Information Automation where system information (such as PO_2 values) are filtered, transformed and provided to the user usually with supporting data to enable the user to estimate confidence in system presented values and system integrity checks.

Automation system human computer interfaces should support the user's understanding of processes underlying system operation (i.e. the user's mental model of system operation). The FAA (2003) defines a number of automation levels shown in Table 5. For ease of reference the levels have been numbered. Electronically controlled CCRs are level 1 systems (Control Automation systems embrace level 1 to level 5). It should be noted that there are manually controlled CCR units commercially available. Manual control CCRs use Information Automation, but not Control Automation; depending on system interface and information presented, manual control CCRs will be level 6 to level 10 systems.

TABLE 5 LEVELS OF AUTOMATION

Level	Description
1	The system acts autonomously without human intervention
2	The system informs the user after executing the action only if the system decides it is necessary
3	The system informs the user after executing the action only upon user request
4	The system executes an action and then informs the user
5	The system allows the user a limited time to veto before executing an action
6	The system executes an action upon user approval
7	The system suggests one alternative

8	The system narrows the selection down to a few
9	The system offers a complete set of action alternatives
10	The system offers no assistance

6.3.2 HUMAN FACTORS CONSIDERATIONS AND RECOMMENDATIONS FOR AUTOMATION

The FAA (2008) splits requirements, recommendations and considerations for automation into a number of areas, not all of these apply to personal life support systems used underwater. In the section that follows specific statements are quoted directly from Chapter 3 of the FAA Human Factors, with discussion of the implications as relate to electronically controlled CCRs following.

This section is divided into four areas relating to Automation, these are:

- General considerations and Control Automation,
- System Response and Feedback and Information Automation
- Monitoring
- Fault Management.

It should be noted that not every recommendation in FAA (2003) is covered in this report. The intention is to highlight elements that appear to be particularly pertinent to CCR design and briefly discuss their application. The reader is referred to FAA (2003) for a full discussion of the considerations that should be taken into account.

6.3.2.1 GENERAL CONSIDERATIONS AND CONTROL AUTOMATION

- *"**3.1.1 Minimum automation Human Factors requirements.** An automated system should;*
  - *a. provide sufficient information to keep the user informed of its operating mode, intent, function, and output;*
  - *b. inform the user of automation failure or degradation;*
  - *c. inform the user if potentially unsafe modes are manually selected;*
  - *d. not interfere with manual task performance; and*
  - *e. allow for manual override [Source: Veridian (AHCI), 1998; Billings, 1997]" (p3-1)*

CCR divers are kept informed on the system's function through the primary handsets with some CCR units offering HUD functionality. Audible alarms, buzzers and HUD also offer means of alerting the diver to a system fault. CCRs only offer the user a small number of selectable modes which may cause the user death or injury if improperly selected underwater (either deliberately or accidently):

  - O_2 sensor calibration underwater, which will result in all O_2 cells mistranslating sensor voltages into PO_2 figures. This is likely to lead to a hyperoxic environment, diver seizure and drowning. It is recommended that this mode be unavailable to the user underwater.
  - Inadvertent promotion of slave controller to master when slave controller is unserviceable or receiving inaccurate or incomplete data.
  - Low set point maintained at depth – this will lead to excessive decompression requirements, if a dive plan has been made for the high setpoint and the system does not have integrated decompression tracking this may result in DCI. Many CCR units have a facility to enable automatic setpoint modification, and may also display decompression information. It is recommended that handsets display current setpoint value and setpoint switching mode (Manual or Automatic) next to this figure. If the system has decompression tracking the user should be alerted to entering the mandatory decompression envelope.
  - O_2 sensor disablement – some CCR units offer the ability to lock out manually readings from specific O_2 cells which may be reading erroneously high or low; if this potentially useful function is improperly used good readings may be cancelled and calculated setpoint may be based on inaccurate data. Where cells have been cancelled from the voting logic this should be indicated to the user.
  - Selecting “Open Circuit Decompression” by accident when on closed loop, this will alter decompression calculations, so ideally would require a “confirm” and would be a reversible operation.

- *“**3.1.2 Place user in command**. Automated systems shall prevent the removal of the user from the command role. [Source: Billings, 1997]. Discussion. The reasoning behind this rule is twofold. First, it is ultimately the user who is responsible for the task. Second, automation is subject to failure. Therefore, it is the user, not the automation who must be in control of the system with the automation.” (p3-1)*

In electronically controlled CCR the user is in the command role as only the diver can ultimately be responsible for their own life. The issue that accompanies life support automation is that of potential diver complacency, skill fade and the lack of user monitoring. Training and regular practice of “manual flight” life support is of the greatest importance. CCR manual override is allowed through manual addition of diluents and O_2 into the breathing loop.

- *“**3.1.6 Provide a clear relationship with user tasks**. The relationships between display, control, decision aid, and information structure and user tasks and functions shall be clear to the user. [Source: Nuclear Regulatory Commission (NUREG-0700), 1996; Nuclear Regulatory Commission (NUREG/CR-6105), 1994] Discussion. The user needs to be able to* *see clearly how the display or decision aid, and so on, facilitates the completion of the necessary task." (p3-2)*

In terms of CCR handset displays information that one would want to see is:

- Indication of Master or Slave display (i.e. control information vs. information for display only).
- Setpoint value, and whether the setpoint was Automatically or Manually altered.
- System calculated PO_2 (i.e. the single output of system voting logic)
- 3 individual O_2 cell values, including captions relating to cells disabled (whether by a fault or by the user) or cells excluded from majority voting calculations.
- Depth and units
- Depth trend (i.e. diver ascending or descending – as this will have an impact on PO_2)
- Dive Time
- No stop time
- Reference flush predictions – so that when a reference diluents flush is performed the diver can directly compare calculated PO_2 values with actual PO_2 readings
- Master / Slave comparison – so the diver can compare PO_2 readings on both the master and slave handsets.

- *"**3.1.7 Ensure active user involvement in operation**. Users shall be given an active role through relevant and meaningful tasks in the operation of a system regardless of the level of automation being employed. [Source: AHCI, 1998; Billings, 1991] Discussion. User awareness of system state cannot be sustained passively. Active involvement is essential for operators to exercise their responsibilities and be able to respond to emergencies. Reducing active involvement may be detrimental to the user's understanding of important information, may lead to longer response times in case of emergencies, or, in the long term, may lead to loss of relevant knowledge or skills. [Source: Galster, Duley, Masalonis, & Parasuraman, 2001; Garland & Hopkin, 1994; Hopkin, 1988; Sarter & Woods, 1992 (as found in Scerbo, 1996); Wickens, 1992 (as found in Scerbo, 1996)]" (p3-2)*

It is a difficult to see how the user can be kept actively involved in the PO_2 maintenance task without removing automation completely, one theoretical approach to this problem might be to allow automation to maintain a lower than optimal PO_2 setpoint (say 0.8), but then prompt the user to add O_2 into the loop to bring PO_2 up to 1.3. (a value which will maximise no stop time and act to minimise any decompression obligations).

- *"**3.1.18 Make it error resistant and error tolerant**. Automation should be error resistant and error tolerant. [Source: Billings, 1991] Discussion. To make a system error resistant is to make it difficult for a user to make an error. Simplicity in design and the provision of clear* *information are tools to improve error resistance. Error tolerance is the ability to mitigate the effects of human errors that are committed. Error tolerance can be improved by adding monitoring capabilities to the automation. Electronic checklists also have the potential to improve error resistance by providing reminders of items." (p3-4)*

Given the complexity of CCRs, electronic checklists in support of pre-dive checks are to be recommended.

- *"**3.1.20 Ensure safe operations are within human capacity**. Systems shall not be so reliant on automation or on human skills degraded by automation use that human users can no longer safely recover from emergencies or operate the system manually if the automation fails. [Source: Billings, 1996; NRC, 1998]" (p3-5)*

Training and regular practice of emergency drills with a dive buddy in appropriate conditions are to be recommended. Refresher training is recommended after an interval of 6 months not diving.

- *"**3.1.21 Provide means of user override**. The automation should not be able to veto user actions leaving the user without means to override or violate the rules that govern the automation unless there is not enough time for the user to make a decision. [Source: Garland & Hopkin, 1994; Inagaki, 1999]" (p3-5)*

The CCR diver always has the manual override option through diluents or oxygen manual addition, the only situation where the automation might have to override manual flight is a rapid ascent situation where PO_2 would be expected to drop rapidly and the diver may have their hands full with other tasks and so unable to respond in a useful timescale.

- *"**3.1.23 Make systems easy to understand and use**. Automated systems and associated integrated information displays should be intuitive, easy to understand, and easy to use. [Source: Billings, 1991; Sarter & Woods, 1994; Woods, 1996] Discussion. System operations that are easily interpretable or understandable by the user can facilitate the detection of improper operation and the diagnosis of malfunctions. [Source: Wiener & Curry, 1980] (p3-5)*

Handset warning screens should be carefully designed to inform the user of the specific problem and potential remedies. For example if a Cell fails, inform the user which cell has failed and the appropriate action rather than providing a generic warnings which the user has to interpret.

- *"**3.1.25 Provide means to check input and setup data**. Automated systems should provide a way to check automation setup and to check information used as input for the automated system. [Source: Wiener & Curry, 1980; Wickens, 2000] Discussion. Automation failures are often due to setup error. Although the automated system itself could check some of the setup, independent error-checking equipment or procedures may be needed. The user needs to be* *able to distinguish whether a failure occurred due to the automation setup or due to an inaccuracy in the input information. An automation failure could have been caused by a malfunction of an algorithm or by the input of inaccurate data. For example, if the automated system relies on primary radar and secondary radar as inputs and uses an algorithm to predict conflicts, a failure could arise from faulty data from either the primary or secondary radar or from the algorithm that combines this information. [Source: Wiener & Curry, 1980; Wickens, 2000]" (p3-6)*

System configuration, calibration and setup are all potential areas where diver mistakes can be made – system based pre-dive checks and electronic checklists are all useful in minimising these. A reference diluents flush facility that allows divers to rapidly compare calculated PO_2 to expected PO_2 enables a sanity check on cells that may be deviating, especially in the "one cell good, two cells bad" situation.

- *"**3.15.4 Provide immediate feedback**. To promote successful situation awareness of the automated system, the user shall be given immediate feedback to command and control orders. [Source: Morris & Zee, 1988]" (p3-33)*

It is recommended that solenoid function is accompanied by an audible tone and has a visual indicator on the handset that allows the user to see that such an action has taken place or has taken place in the recent past (a segmented bar which shrinks over time is one common interface motif used in this situation). Automatic setpoint changes and other command activities performed by the CCR should also be indicated to the user by audible and visual means.

- *"**3.15.6 Make available override and backup alternatives**. Override and backup control alternatives shall be available for automation controls that are critical to the integrity of the system or when lives depend on the system. [Source: Billings, 1991] "(p3-33)*

As discussed earlier, manual backup through manual diluents and oxygen inflators is available.

- *"**3.15.7 Make backup information easy to get**. Information for backup or override capability shall be readily accessible. [Source: Billings, 1991] " (p3-33)*

If summary information is displayed at the main dive screen and the detailed PO_2 information is held elsewhere, this information must be immediately presented to the user in the event of one PO_2 reading not being incorporated into majority voting logic, or a PO_2 cell failure.

6.3.2.2 SYSTEM RESPONSE AND FEEDBACK & INFORMATION AUTOMATION

- *"**3.3.1Visualize consequences of decisions**. The user should be able to visualize the consequences of a decision, whether made by the user or the automated system. [Source: Billings, 1996]" (p3-7)*

This mainly applies to functionality that the CCR offers in Dive Planning or Dive Simulation, where a user is inputting a number of variables and seeing what overall impact they make to output variables such as decompression times, CNS percentage, or gas volumes required.

- *"**3.3.2 Provide brief and unambiguous command response**. Automated system responses to user commands should be brief and unambiguous. [Source: Billings, 1997] "(p3-7)*

System commands – i.e. commands which will change the parameters used by the CCR in life support functional control should be accompanied by audio and visual confirmation that such a change has been made.

- *"**3.3.3 Keep users aware of function**. The automated system should keep the user aware on a continuing basis of the function (or malfunction) of each automated system and the results of that function (or malfunction). [Source: Billings, 1996]" (p3-7)*

The use of LED based HUDs fulfils this function, in CCRs not fitted with HUDs an intermittent tone and confirmatory handset caption would satisfy this recommendation.

- *"**3.3.4 Provide effective feedback**. Automation should provide the user with effective feedback on its actions and the purpose of those actions". (p3-8)*

System calculated PO_2 value, confirmation of solenoid function and Cell indicators for O_2 sensors not included in voting logic are three examples of feedback. Likewise simple captions such as LOW OXYGEN accompanied with recommended diver action are examples of effective feedback.

- *"**3.12.1 Indicate if data are incomplete, missing, uncertain, or invalid**. The automated system should provide a means to indicate to the user that data are incomplete, missing, unreliable, or invalid or that the system is relying on backup data. [Source: AHCI, 1998]" (p3-23)*

This applies to the cell PO_2 readings; divers must be able to see on what basis the control system is making calculations. From a presentation perspective it is quicker and easier for divers to compare numerical values when they are aligned vertically, this is a function of visual field covered by the eye and numeral shape similarity with the decimal point acting as frame of comparison. The reader can experience this effect by comparing the time it takes to read and compare the values horizontally...

1.12 1.29 1.30

...with the time to read and compare the values arranged vertically:

1.12
1.29
1.30

Given that divers will also have to reference Setpoint and System Calculated value for PO_2 it is recommended that values are arranged vertically where possible:

1.30 SET
1.29 CALC
1.12 CELL 1
1.29 CELL 2
1.30 CELL 3

Voting logic rules should be displayed so that divers can see which cells are being used as the basis for the PO_2 calculation – if for example a unit takes the nearest two cell values and averages them, and disregards the third cell the diver should be aware of that fact. One would also need to distinguish in some way desired values, calculated values, and raw values. A possible approach for doing this is shown below; the rectangles show the cell on that line is included in the calculations.

1.30 SET
1.29 CALC
1.12 CELL 1
1.29 CELL 2 []
1.30 CELL 3 []

- *"**3.12.4 Show accurate status**. Information presented to the user should accurately reflect system and environment status in a manner so that the user rapidly recognizes, easily understands, and easily projects system outcomes in relation to system and user goals. [Source: Endsley & Kiris, 1995; NUREG-0700, 1996]" (p3-24)*

Reflection of accurate system status is especially important in automation failure situations. The aim is draw attention to the system component that has failed, and the implication of that failure to the diver. For example if a cell has failed we want the user to be aware of this immediately; this can be achieved with a warning and a highlight:

1.30 SET
1.29 CALC
0.00 CELL 1 FAILURE

1.29 CELL 2 []
1.30 CELL 3 []

- *"**3.12.8 Present information consistent with task priorities**. Both the content of the information made available through automation and the ways in which it is presented shall be consistent with the task priorities. [Source: Billings, 1996] "(3-24)*

Visual consistency is very important for users, as is the method of presentation of emphasis, highlighting, and reversing out text is useful for immediately drawing attention to the thing that needs to be dealt with. Warning captions and recommended diver actions should be the most prominent text on the screen when required. CCR manufacturers should follow standard recommendations relating to system alarm prioritisation, and display the most severe alarm consequence to the user first, for example; a low oxygen warning has priority over cell failure. This could be achieved with a high priority highlight using a different colour (e.g. red) than for a lower priority situation (e.g. black, as used above)

Care should be taken not to overwhelm the diver with colour or visual emphasis as this detracts from the piece of information that needs to be processed in what is probably a very stressful situation. Large saturated blocks of colour also have a tendency to overwhelm other forms of emphasis, in this case the differences in text formatting.

- *"**3.12.14 Integrated displays**. Integrated displays should combine various information automated system elements into a single representation. [Source: Billings, 1996; Parasuraman et al., 2000]" (p3-25)*

Ideally information that needs to be compared and referenced should be presented and integrated in such a way that quick visual comparison is possible without memorisation or having to flick between screens. This applies with reference flush prediction screens, and comparison of primary and secondary controller PO_2 values.

6.3.2.3 MONITORING

- *"**3.7.1 Allow users to monitor automated systems**. The system shall be designed so that users are able to monitor the automated systems and the functionality of its hardware and software, including the display of status and trend information, as needed. [Source: Billings, 1991] Discussion. One way that this can be accomplished is by providing the user with access to raw data that the automation processes." (p3-12)*

As has been mentioned previously, it is important to display individual oxygen cell information (or at very minimum make such information available at a single step), and show the user how

PO_2 calculations are being made. It would also be useful for divers to be able to access the sensor voltage values directly.

- *"3.7.2* ***Display changing data as graphic****. Changing data that must be monitored by the users should be displayed in a graphic format. [Source: Smith & Mosier, 1986]" (3-12)*

Given that there are only five pieces of PO_2 information to display this is probably not necessary, and would be difficult on an LCD screen with the limitations of screen size. However it is important that cell PO_2 values are seen to change when the user breathes while holding the handset (i.e. diver can judge speed of cell response), and for this reason two decimal places should be displayed for PO_2 readings.

- *"3.7.3* ***Make users active in control and monitoring****. Automation should be designed so that users are involved in active control and monitoring rather than just passive monitors. [Source: Hilburn, Jorna, & Parasuraman, 1995; Wickens & Kessel, 1979] Discussion. Automation failures may be easier to detect when users are involved in both active control and monitoring, than when they are just passive monitors. [Source: Hilburn, et al., 1995; Wickens & Kessel, 1979] "(p3-12)*

This issue relates to the previous point under General automation requirements "Ensure active user involvement in operation." It is difficult to see how the user can be made more involved in the automation without either fundamentally lowering the level of automation provided (i.e. remove the solenoid and make the CCR diver manually responsible for PO_2 maintenance), or designing in arbitrary limitations to the automatic control system (for example limiting the CCR setpoint to 0.8, and making divers manually inject O_2 to maintain a value above this).

6.3.2.4 FAULT MANAGEMENT

- *"3.8.2* ***Make failures apparent****. Automation failures shall be made unambiguously obvious to the user. [Source: AHCI, 1998; Billings, 1991]. Discussion. Stress, preoccupation, and distraction may reduce the user's ability to detect faults. [Source: Rogers et al., 1996]" (p3-16)*

Users will be much less familiar with system fault / failure screens and so it is critical that error displays are not potentially confusing or ambiguous to the user. For example, if a display cell is producing an erroneous reading it needs to be drawn to the user's attention exactly which cell is producing the erroneous reading. In the display below cell one is under-reading but it is not clear which cell is actually producing an erroneous reading.

1.00 1.29 1.30
CELL FAILURE

This type of display could be improved by highlighting the cell reading that is incorrect to leave no ambiguity with the situation where two cells are reading incorrectly. However, this display can be made even easier to read by highlighting the cell value and attaching a failure label in line with the cell reading so there is no ambiguity about the meaning of the highlight and attention is drawn to the inaccurate cell reading, as below.

1.30 SET
1.29 CALC
0.00 CELL 1 FAILURE
1.29 CELL 2 []
1.30 CELL 3 []

- *"**3.8.3 Provide adequate early warning notification**. Early warning notification of pending automation failure or performance decrements should use estimates of the time needed for the user to adjust to task load changes due to automation failure. [Source: Morrison, Gluckman, & Deaton, 1990. Discussion. In situations where automation failure would require user intervention, it is useful for the user to be warned that he or she will need to take manual control before the automated system fails. Ideally, this warning needs to come in adequate time to allow the user to adjust to the new task load. There may, however, be cases where it is not possible to provide advance notification of pending failure or where the estimate of time needed for the user to take control is unknown. [Source: Morrison et al., 1990]" (p3-16)*

Areas of potential application would include all system elements which are consumable; batteries, O_2 cells, scrubber material, diluent and O_2 contents. For example if O_2 cells fail over time in a specific manner (such as losing the ability to read high PO_2 values and becoming slower to respond), then an indication of that fact would enable the user to perform preventative maintenance.

- *"**3.8.5 Automate diagnostic aids**. Fault isolation, inspection, and checkout tasks shall be automated to the extent practical. [Source: National Aeronautics and Space Administration (NASA-STD-3000A), 1989]" (p3-16)*

It is recommended that automated CCR preflight procedures are driven through an electronic set of checklists with user prompts at each stage.

- *"**3.8.7 Provide capability for on-demand system check**. On-demand system checkout shall be available. [Source: NASA-STD-3000A, 1989]" (p3-17)*

CCR monitoring systems should have a self-check facility available during the dive.

6.4 DISPLAY OF INFORMATION TO THE CCR DIVER

6.4.1 GENERAL PRINCIPLES

Chapter 8 of FAA (2003) covers Human Factors requirements for human computer interfaces and recommends that the following general principles be applied:

- Simplicity (information should be presented in a consistent and orderly manner) – screen structures should be consistent as should screen elements.
- Information should be presented in consistent and predictable locations
- Language used should be simple
- Navigation controls should be implemented in a consistent manner
- Only information that is essential should be presented at any specific time
- Screen density should not exceed 60% (ratio of filled vs. unfilled character places)
- Information presented should be in a directly usable form.
- Allow the user access to complete datasets
- Minimise short term memory load for the user
- Context Support - context should be provided for displayed data – for example where values of variables are displayed, data units should be displayed alongside data values. This is important where different units (metric and imperial) may be selected by the diver.

The following recommendations with regards to format are also made:

- Avoid visual competition between screen elements
- Differentiate between instructions and data
- Align layout to task
- Priority of displayed information – information should be prioritized so that the most important information is displayed at all time
- Grouped Information – groups of data items should be separated by blank space, lines or use of colour

The following specific guidance for the design of displays on aircraft flight decks is provided in FAA (2003) Section 5 (while the context of use is different from CCR diving, the general points of guidance remain valid):

General

- Visual displays will function under operational conditions. Visual displays should function under any circumstance corresponding with the operational and use philosophies [MIL-STD-1472F, 1999]

- Visual displays shall be legible under all conditions. This includes consideration of the properties of the display, ambient light and viewing distance. [MIL-STD-1472F, 1999].
- Avoid unnecessary markings on the panel face. [MIL-STD-1472F, 1999].
- Provide adjustable contrast and brightness [Vanderheiden & Vanderheiden, 1991]

Location and Arrangement

- Group task-related displays together. [MIL-STD-1472F, 1999]
- Arrange according to function and sequence. [MIL-STD-1472F, 1999]
- Arrange displays consistently, arrangement of displays within the system shall be consistent from application to application. [MIL-STD-1472F, 1999]

6.4.2 LCD DISPLAYS

FAA (2003) makes a set statements relating to different display types – liquid crystal displays are used in CCR handsets. LCD displays offer excellent contrast, long life, are rugged, low voltage and have low power consumption (except when backlit). LCDs are more suited to high ambient light conditions, however back lighting is often used in situations where low ambient light conditions can be expected (FAA, 2003 pp.5-15)

Guidance for LCDs

1. Use LCD with adequate levels of ambient illumination – reading performance improves as illumination increases over 20-1500 lx range. [DOE HUMAN FACTORSDG ATCCS V2.0, 1992].
2. Screen Polarity – transmissive LCDs (which can be backlit) should use dark characters on a light background.
3. Minimise backlighting – LDC reading errors increase as backlighting increases over the range of 0 to 122 cd/m^2.
4. When LCDs are used in low ambient illumination situations users should be able to adjust the amount of backlight. Backlight luminance should be 35 cd/ m^2.

6.4.3 MINIMUM SIZE OF TEXT ON HANDSET DISPLAYS

The American national standard for Human Factors engineering of visual display terminals (CRT type) gives a preferred size of text on screen for readability is 20-22 arc minutes, which is also that used by the FAA Human Factors in aircraft flight deck design. However this is at resting focal (tonic accommodation) distance of 590mm, with a minimum contrast of 3.5 cd/ m2. At CCR handset reading distance (400mm), 22 arc minutes translates in size to text that is 2.5 mm high. Def Stan 00-250 Part 3 Section 15 gives 2.3 mm as a minimum (20 minutes of arc).

Under lower light conditions (as potentially found underwater) visual acuity decreases as level of illumination drops and vision moves from the photopic to mesotopic system (mesotopic vision comes into play at luminance levels of 10-3 cd/ m2 and 10 cd/ m2).

For CRT displays viewed at a luminance below 3.5 cd/m2 critical information in variable positions (e.g. numerals on moving scales/counters) should be 4.25-6.75 mm high assuming a distance of 600 mm (DEF STAN 00-250 Part 3 Section 15, page 459). These heights translate to characters 2.83 to 4.5 mm at a CCR handset reading distance of 400mm; however given the lower contrast ratio of LCD displays (contrast is the difference between characters and their background), and potential lowlight /low visibility situations encountered underwater - we would recommend that character displays are at the larger end of this range for critical information such as PO_2 information (6mm or more in height).

6.4.4 Character Formation

Of equal importance to the size of characters are the relative proportions of the characters. FAA (2003) provides clear guidance on this. Characters in vertical orientation should be formed from a matrix of at least 9 x 13 pixels. Character stroke width should not exceed minimum and maximum values given in Table 6. In conjunction with this, the width of characters of a given height should not exceed the minimum and maximum width values given.

Table 6 Stroke width for pixel generated characters, numbers in pixels. (FAA, 2003, p5-14)

Upper case character height	**Minimum stroke width**	**Maximum stroke width**
7 to 8	1	1
9 to 12	1	2
13 to 14	2	2
15 to 20	2	3
21 to 23	2	4

Table 7 Height-width relationship for upper-case pixel generated characters, all numbers in Pixels (FAA, 2003, p5-14)

Character height	**Minimum width**	**Preferred width**	**Maximum width**
7	4	5	5
8	4	6	7
9	5	6	8

10	5	7	9
11	6	8	10
12	6	9	11
13	6	9	12
14	7	10	13
15 or 16	8	11	14

6.4.5 HEAD UP DISPLAYS

CCR Head Up Displays (HUDs) fall outside the guidance provided in FAA (2003) in that they are quite different from conventional aircraft HUDs with their projected symbology. The use of led indicator lamps is also different as the guidance provided in FAA (2003) assumes indicator lamps are mounted on an instrument panel in a cockpit, not directly in front of the eye. Helmet mounted displays in aircraft also tend to rely on data projection onto a clear monocle. Therefore, further research is required to identify or develop appropriate guidance for the use of LEDs on CCR HUDs.

6.5 HANDSET CONTROLS

Physical aspects of interface control include size and type of buttons suitable for use underwater by divers with cold hands and potentially wearing thick neoprene gloves. Given that the interface is actually a control system, as well as allowing the diver to call up specific information; consideration of potential inadvertent operation should be made. Worst case scenario would be to switch the unit off underwater by accident and not notice (and not check the handsets); other possibilities would be inadvertent selection of set point, or accidently swapping master and slave and then motioning a handset which was not the primary oxygen controller. Diver training and vigilance are critical in emphasising monitoring of CCR system information through the handsets.

System control operations and user actions that impact on system control operations should be notified to the user by a confirmatory audible tone and visual caption confirming that the operation has been completed successfully.

Handset buttons should be shielded from inadvertent activation where possible, with the handset ideally secured to the wrist so that the handset is let likely to come into contact. It is recommended that the risk of CCR units being inadvertently switched off underwater by diver action is mitigated as far as possible through design. Example diver actions including jumping into the water, handsets subjected to accidental forces such as dragging or catching on object, or through diver error.

If CCR units are to have the functionality to enable the PO_2 monitoring and control system to be switched off underwater, it is recommended that this is a failsafe design such as a “soft reset” function accompanied by secondary alarms (audible and tactile), and a countdown period during which a ‘Cancel’ function can be invoked, prior to system switch off. This would allow a diver to be alerted and respond to a potential accidental system shut down. [A fail-safe design shall be provided for systems in which failure could cause catastrophic damage, injury to personnel – FAA (2003) pp.2-4]

Human Computer Interaction Design Process

Given that a flawed HCI design for a CCR unit could have potentially fatal consequences when the unit is dived, it is reasonable to expect that there should be a robust process for conducting the design. MoD (2008) details a set of activities that have to be conducted when HCIs are developed where ”the HCI Operational Risk Assessment indicates that aspects of the HCI design represent a significant risk to system objectives”. The set of activities that are recommended in such circumstances include the production of:

- An HCI Risk Identification Report
- An HCI Development Plan
- An HCI Requirements Specification
- An HCI Design Rational and Specification
- A User Evaluation Report

CEN (2003), the current standard for the approval of CCR units, does not currently address Human Factors issues in general or specifically the development of the HCI. We would recommend that EN14143 should be extended to cover the specification of interfaces and controls on CCR handsets that monitor and control CCR life support. This work should be based on best practice in automation human interface design as contained within FAA (2008) Chapters 3,5,6 and 8 and MoD (2008) and other relevant HCI / human factors guidance.

6.6 SUMMARY

Electronically controlled close circuit rebreather handsets are the interfaces to a Control Automation system which performs a Critical Function (life support) to the user. Human Factors design standards should be applied to Control Automation interfaces performing Critical Functions to ensure that they meet minimum industry standards of user operability. The design of automation, presentation of information to the diver and the functionality of handset controls all need to be considered from a Human Factors perspective if a CCR unit is to be designed in such a way that the risks associated with its use of its HCI and controls are minimised. To this end we make the following recommendations:

- EN14143 should be extended to cover the specification of interfaces and controls on CCR handsets that monitor and control CCR life support. This work should be based on best practice in automation human interface design as contained within FAA (2008) Chapters 3,5,6 and 8 and MoD (2008) and other relevant HCI / human factors guidance.
- Further research is conducted to identify/develop appropriate guidance for the design of CCR HUDs.
- Personal adaptations to units cause different permutations of the kit that may seriously affect performance of the overall unit. Further work would provide better understanding of such effects and could be helpful in informing new design standards.

6.7 REFERENCES

CEN (2003), EN 14143 Respiratory equipment - Self-contained re-breathing diving apparatus, CEN , Brussels

FAA (2003), Federal Aviation Authority Human Factors Design Standard (Human Factors) for Acquisition of Commercial-off-the-Shelf (COTS) Subsystems, Non-Developmental Items (NDI), and Developmental Systems, FAA, Atlantic City

MoD (2008) Ministry of Defence Defence Standard 00-250 Issue 1 Human Factors for Designers of Systems Part 3: Technical Guidance (Section 15 Work Equipment), Defence Procurement Agency, Glasgow

7. HUMAN ERROR POTENTIAL IN NON-NORMAL OPERATIONS

DR SARAH FLETCHER

7.1 INTRODUCTION

The remit of the original proposal specified that task analyses were to be conducted on both 'normal and selected non-normal operations when using a CCR unit' using the Systematic Human Error Reduction and Prediction (SHERPA) methodology:

> *"The formal error identification analyses using SHERPA will allow the comparison of the likely error potentials for certain selected normal and non-normal tasks between the different selected CCR units."*

This chapter describes the work component that applied a SHERPA based analysis to selected 'non-normal' CCR diving procedures, beginning with a full description of the adapted Method.

7.2 METHOD

7.2.1 THE PROBLEM OF NON-NORMAL OPERATIONS

The original project proposal stated that the intended analysis for normal and non-normal operations was intended to be the same SHERPA formal error identification approach. However, during analysis it became apparent that non-normal operations could not be approached in the same way as normal operations had been analysed in Chapter 4. As normal diving operations are highly procedural it had been fairly straightforward to deconstruct them into generic steps and construct a full Hierarchical Task Analysis (HTA) structure and subsequent SHERPA evaluation matrix. However, 'non-normal' diving operations are essentially emergency situations, where operational circumstances are more complex, non-procedural, and unpredictable for various reasons as will now be described.

First, when a normal dive starts requiring the diver to perform operations that are not normal it will usually reflect the emergence of unexpected circumstances – and therefore an emergency situation. Emergencies demand immediate action but inevitably entail a multitude of quickly unfolding influential factors. This means that there is often not one single and absolute course of action to follow as the events unfold. Thus, it is far more difficult to accurately predict and map out generic procedural steps for a non-normal situation than it is for normal situations.

Second, despite that trained divers will have learned some standard operating procedures to apply in certain emergency circumstances, training will to some extent be specific to the design of the CCR unit and associate training company and instructors being used. There may also then be various inconsistencies between individual divers as they go on to gain experience and practice their emergency drills differently, and particularly amongst those who go on to make personal modifications to their units which may significantly affect procedural steps.

Third, predicting divers' non-normal procedures and reactions is made so much more difficult because the inherent complexity of emergency situations is exacerbated by the vast number of possible unit designs – and particularly so due to the potential for unique permutations from personal modifications. This made it extremely difficult to satisfy the overarching project remit of deriving generic findings and to not conduct analysis relevant only to specific unit designs.

For all these technical and behavioural reasons there will be considerable variations in the way individual divers perform procedures in response to emergencies. It was therefore far more difficult to break procedures down into generic task steps and to forecast actions that would commonly be taken by divers as there are simply too many possibilities. So, in the interests of providing some indications that would satisfy the scoping project remit but without jeopardising the neutrality and objectivity needed, an alternative approach was taken. Still using the SHERPA methodology as a guiding analytical framework, non-normal procedures have been analysed as far as possible where experts considered the task steps to be more predictable and important. However, there are many gaps in the evaluation matrices (Appendix 10) which signify where the experts deemed the task step not predictable, not attributable to a single classification, or sufficiently important.

7.2.2 ADAPTED SHERPA METHOD

The first task involved in a typical SHERPA analysis is to construct the HTA structure, as this will illustrate the composition of task steps. Then, in a further six steps a series of evaluations are made to assign error potential. To apply specialist understanding to this analysis of non-normal procedures a team of CCR 'subject matter experts' (SMEs) was assembled. The method steps that were taken are now described along with explanations of any adaptations and limitations.

7.2.2.1 HIERARCHICAL TASK ANALYSIS

An initial set of 9 non-normal diving procedures had been identified and HTAs for those had been produced; this was done alongside the analyses of normal operations (Chapter 4). Using an iterative approach in group discussions the SMEs went through each HTA together, to check accuracy and genericism. This involved deconstructing task procedures to eliminate steps which were considered too specific to individual units, to ensure the structures would be generically representative.

The unpredictability and complexity of non-normal operations made the analysis difficult, as SMEs found that there would be too many potential factors and scenario variations to produce definitive generic representative procedures. The non-normal diving operations HTA structures produced (Appendix 9) are therefore a representation of general procedures and principles *but product / unit variations must be considered individually and additionally.*

7.2.2.2 TASK CLASSIFICATION

As set out in Section 4.2, categories to which task steps are assigned in the 'Error Mode' columns of the evaluation matrices (Appendix 10) are: Action, Retrieval, Checking, Selection, or Information Communication. When analysing the set of 9 non-normal CCR diving procedures SMEs were unable to classify all task steps due to the extent of potential procedural variations across different unit variants.

7.2.2.3 HUMAN ERROR IDENTIFICATION

Errors that could be made at the various task steps are identified in the 'Error Description' columns. The very complex and indeterminable nature of emergent situations outlined also meant that the SMEs found considerable limitations in identifying certain errors at this stage. Having produced more generic and simplified HTAs the SMEs felt it was unfeasible and potentially unsafe to predict errors definitively for all task steps due to there being so many potential factors and scenario variations. Thus, there are also some gaps in these columns signifying the task step lacks importance / is indeterminate.

7.2.2.4 CONSEQUENCE AND RECOVERY ANALYSIS

The consequences that could be identified by the SMEs are listed in the Consequence columns of the evaluation matrices. Again, the extent of possible unit and situation variables prevents a complete analysis in all cases. Due to SME concerns over variability they did not assign recovery steps.

7.2.2.5 ORDINAL PROBABILITY ANALYSIS AND CRITICALITY ANALYSIS

The probability of the error was evaluated using the traditional SHERPA scale of Low (L), Medium (M) and High (H). Then, the final evaluation of error criticality was undertaken using the scale developed for analysis of normal CCR diving procedure as set out in Chapter 4:

"-" = non critical
"!" = critical, potential injury or death

"!!"= immediately critical, potential immediate/instant injury and/or death.
"B" = condition applies to bailout only.

7.2.3 DISCLAIMER NOTE

Given the difficulties listed above the SMEs assisting in this project endeavoured to use the SHERPA method as a framework as far as possible but found it necessary to adapt and omit certain elements for their analysis of non-normal operations and emergency situations. **It is important to note:**

> ***The analyses of non-normal operations undertaken in this study reflect predictive evaluations made by Subject Matter Experts of what they considered to be most generic. However, these analyses are not to be viewed as wholly reliable and the results are not definitive, but are merely a guide to most likely scenarios. There will inevitably be variations in the procedures and actions employed by individual CCR divers due to their individual background experiences, unit design variants, and emergent circumstances.***

With this caveat in mind, the results of the non-normal procedure analyses are now presented.

7.3 RESULTS

A brief summary of the results for each of the 9 non-normal CCR task analyses are presented in turn. Full details of the error potential analyses are to be found in Appendix 10.

7.3.1 OPEN CIRCUIT BAILOUT

A set of errors in connection with the open circuit bailout procedure were identified. Firstly, the diver could encounter difficulties locating, selecting and deploying the open circuit regulator which would lead to wrong gas and related impacts on breathing and making bail out manoeuvres. After this step there are a range of other potential errors that could be made for other task steps, from those directly attributable to the diver such as forgetting to close the DSV or remove it before the open circuit regulator is available, to more subsequent event errors such as no gas or free flow and possible mouthpiece loss.

7.3.2 LOST MOUTHPIECE / LOOP FLOOD

Errors identified in relation to connection with lost mouthpiece / loop flood situations were generally found difficult to attribute to single classifications due to the potential variations in situational variables. However, the greatest recommendation was that the key remedial strategy for this type of procedure would be to practice via training drills.

7.3.3 SEMI-CLOSED CIRCUIT MODE

The semi-closed circuit mode situation task steps were considered too straightforward and subject to unit variation to assign single error classifications.

7.3.4 DILUENT FLUSH

The diluent flush operation is confined and straightforward. The identified errors comprise one action error (omission) and one selection error (incorrect). The principal remedial strategies recommended involve learning and familiarising with the procedure via practice drills, and implementing assistive design features where an audible alarm or heads up display.

7.3.5 HIGH PO_2 ALARM

Potential errors identified in the situation of a high PO_2 alarm are varied action, checking and retrieval errors. The predicted consequences of errors across most of the task steps would be hyperoxia. The SMEs did not assign remedial strategies other than addressing the problems via practice drills.

7.3.6 PHYSIOLOGICAL / AFFECTIVE DISORDER

The procedural steps taken when the diver experiences physiological / affective disorders – i.e. where the diver experiences any manner of negative physical or psychological reactions to the dive situation – is considerably limited. SMEs felt the extent of situational variability was too great to classify potential errors and other classifications. Again, training, education and practice drills were considered the primary remedial strategy needed to address these type of errors.

7.3.7 LOW PO_2 ALARM

The low PO_2 alarm errors identified involve action, checking and retrieval errors. The predicted consequences of errors across most of the task steps would be the diver experiencing hypoxia or hyperoxia due to the gas levels. Once again SMEs felt situational variability was too great to classify errors. Only training, education and practice drills were again recommended as remedial strategies to address these type of errors.

7.3.8 HIGH PRESSURE / INTERMEDIATE PRESSURE FAILURE

High pressure / intermediate pressure failure situations involve action and checking errors and in cases where there the task requires ‘signal buddy’ actions then the SMEs assigned an information error ‘information not communicated. As before, much of the classification process was not completed due to concerns over the variability of the situation and apparatus involved.

7.3.9 RETURNING TO THE LOOP

Errors associated with returning to the loop involve action and checking errors and deemed to involve the diver failing to check displays and gauges effectively and fumbling / physically not taking correct action. The consequences of these errors would be that the PO_2 reaches dangerous levels and the ever-present potential for drowning without corrective action. Remedial strategies for various points of the procedure are to potentially check displays effectively, diluents flush, return to open circuit, and to get assistance from the dive buddy.

7.4 SUMMARY

The limitations of the analyses in this study of non-normal CCR diving operations have been emphasised throughout this chapter. This is to caution against relying on these results without further investigation. However, this is not a negative or worthless outcome. This study has been able to fully underline the problem of CCR unit variation and situational variables which it is hoped will be used to inform further research and the development of unit design, training, and safety standards (which in particular appear lacking in advisory documentation).

Although this study has addressed a set of 9 key emergency procedures it is likely that there are others yet to be analysed, e.g. complete electronics failure and fast ascent emergency situations were cited by SMEs. There are also the inevitable variations within each to consider, e.g. the great difference made by depth where greater depths naturally bring greater complexities to the situation and appropriate procedures.

From other project work it has been identified that not all manuals give a clear checklist of fault-finding actions and there is a need for all manuals to have a clearly identified section dealing with emergency situations incorporating comprehensive procedural checklists. It was also found that system warnings may reflect a range of causal problems (e.g. low O2 warning may have 5 different causes). Therefore, there is also a need for a well defined set of problem diagnostic skills to be developed.

Additionally, to capture all interests there will inevitably be further opinion to be sought from experts in the CCR diving fraternity. The SMEs taking part in this research took different approaches and had different ideas about emergency / remedial actions. These differences in opinion first emerged during the first round of analysis, where the 9 non-normal procedures were first identified. Alternative views were found in relation to the most basic rules, e.g. whether it is “If in doubt, bail out” or “If in doubt after a diluent flush, bail out”, or whether off-board or on board bail out should be used. Views also differed on more situationally specific issues such as whether it was right to return to the loop after an open circuit “sanity breath” if there was doubt about the breathing mixture, and whether it was wise to use a semi-closed circuit mode especially when PO_2 readings are unavailable. This difference of opinion serves to highlight that part of the variability problem comprises differences between individual divers – due to previous experience or simply personal preference. This study and the overall project has largely captured these differences and synthesised them. Future work to develop unit design, training and safety standards would benefit from taking a similarly eclectic approach.

The SMEs who undertook the SHERPA analyses for non-normal procedures were keen to stress their overriding recommendation – that the key to preventing many of these errors is through effective training and education programmes. There is much anecdotal evidence that points towards some individuals being over-confident to the point where, for example, they do not check handsets. Training would of course help address this sort of problem by reinforcing good practice across all divers, despite their personal differences.

A summary of key points and recommendations from this individual study are as follows:

- It should be questioned whether units could be designed so that the ability for individuals to adapt features to the detriment of safety and procedural compliance is 'designed out' – i.e. the potential for modifications is eliminated
- Training programmes need to address emergency procedures and reinforce the need for drill practice; they might also better address the problems of unit variations / adaptations which significantly affect emergency procedures
- Formal standards (ISO) always lag behind innovation because standards take years to develop and rely on the state of the art to be in place before they can address that state. However, it would seem that standards covering emergency procedures (and general safety) in CCR diving are out of step with the current state so it might be advisable for standard development to be encouraged, and to look at the issue of personal adaptations to units
- Having examined this subject area to establish generic findings, future work should instead take account of a wider range of potential variables and variations in circumstances. It also needs to address the wide range of different expert opinions, ideally with an approach that can relate individuals to their previous experience and personal biases so this can be accounted for in analysis

8. GENERAL REFERENCES

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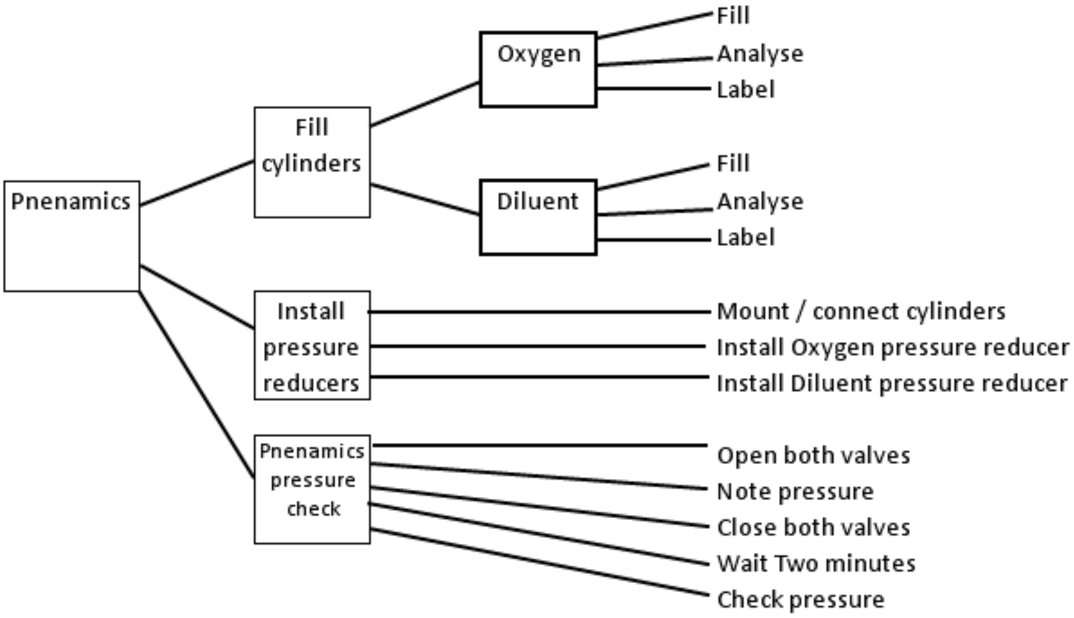
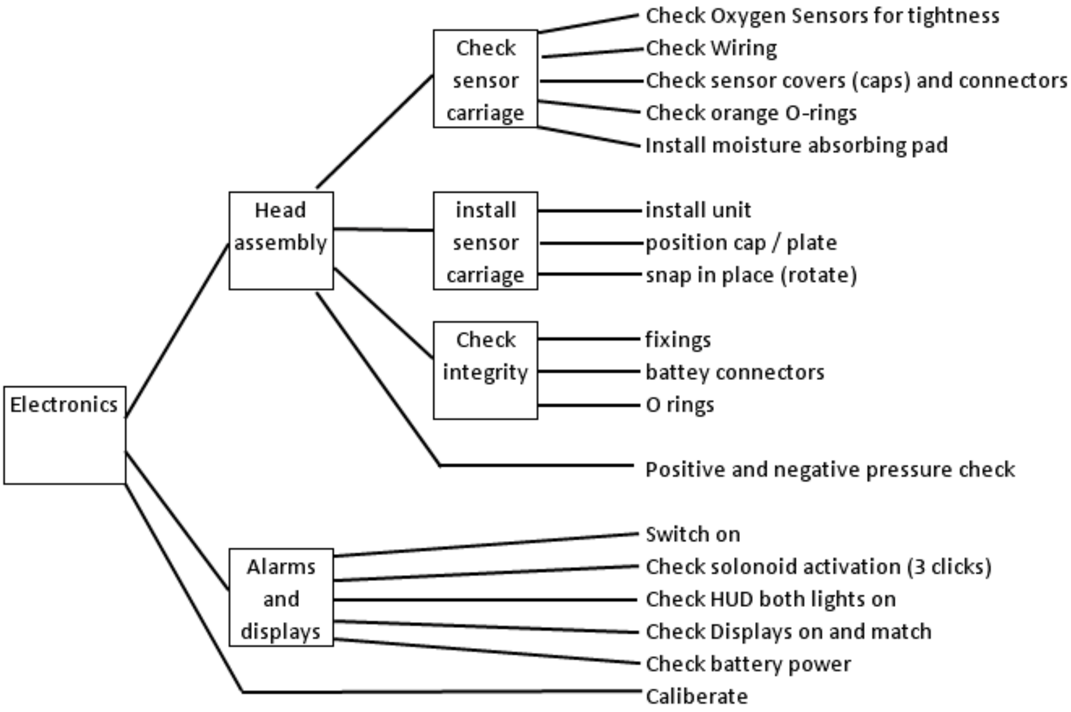
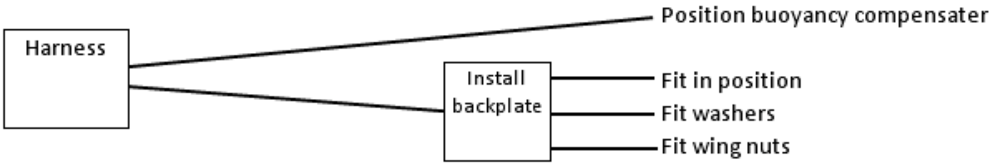
9. APPENDICES

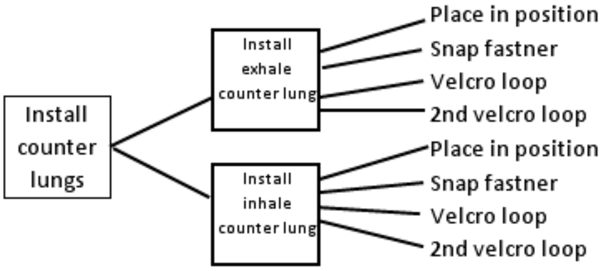
APPENDIX 1: CCR UNIT TASK ANALYSIS (ASSEMBLY)

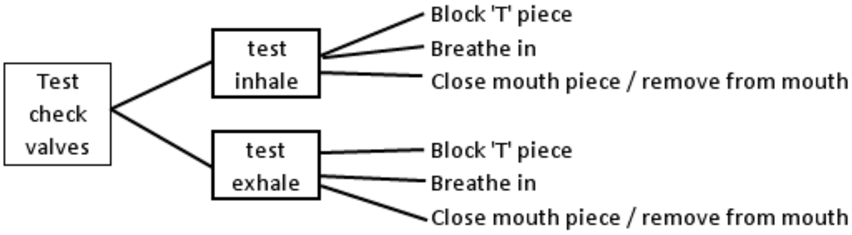


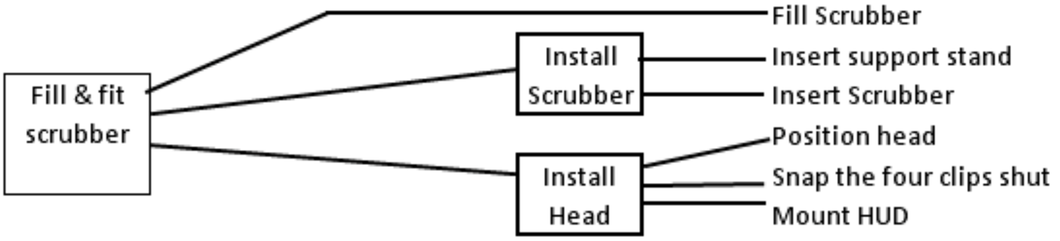
NB: Here the term 'pnenamics' refers to 'High Pressure Supply'

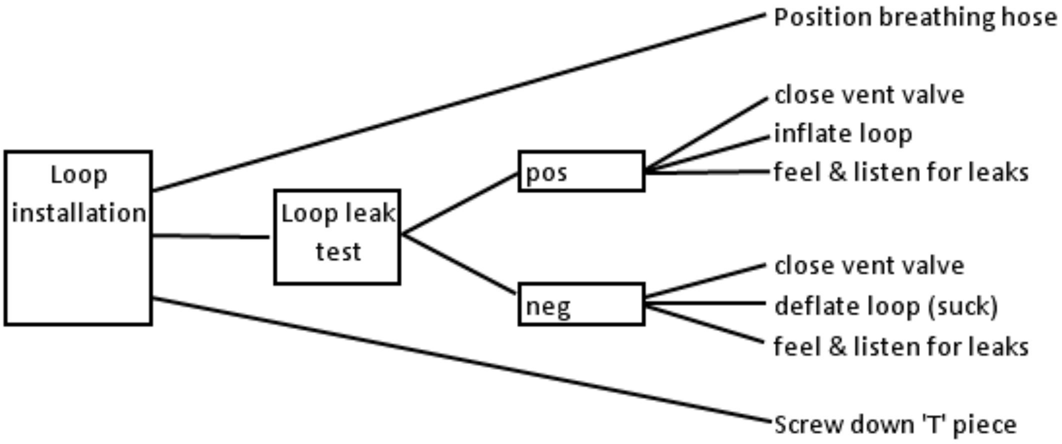

Electronics
Head assembly
Check sensor carriage
Check Oxygen Sensors for tightness
Check Wiring
Check sensor covers (caps) and connectors
Check orange O-rings
Install moisture absorbing pad
install sensor carriage
install unit
position cap / plate
snap in place (rotate)
Check integrity
fixings
battey connectors
O rings
Positive and negative pressure check
Alarms and displays
Switch on
Check solonoid activation (3 clicks)
Check HUD both lights on
Check Displays on and match
Check battery power
Caliberate

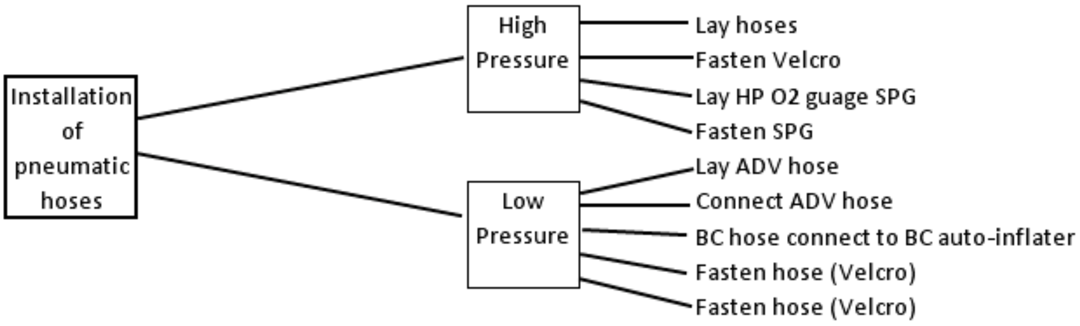

Harness
Position buoyancy compensater
Install backplate
Fit in position
Fit washers
Fit wing nuts

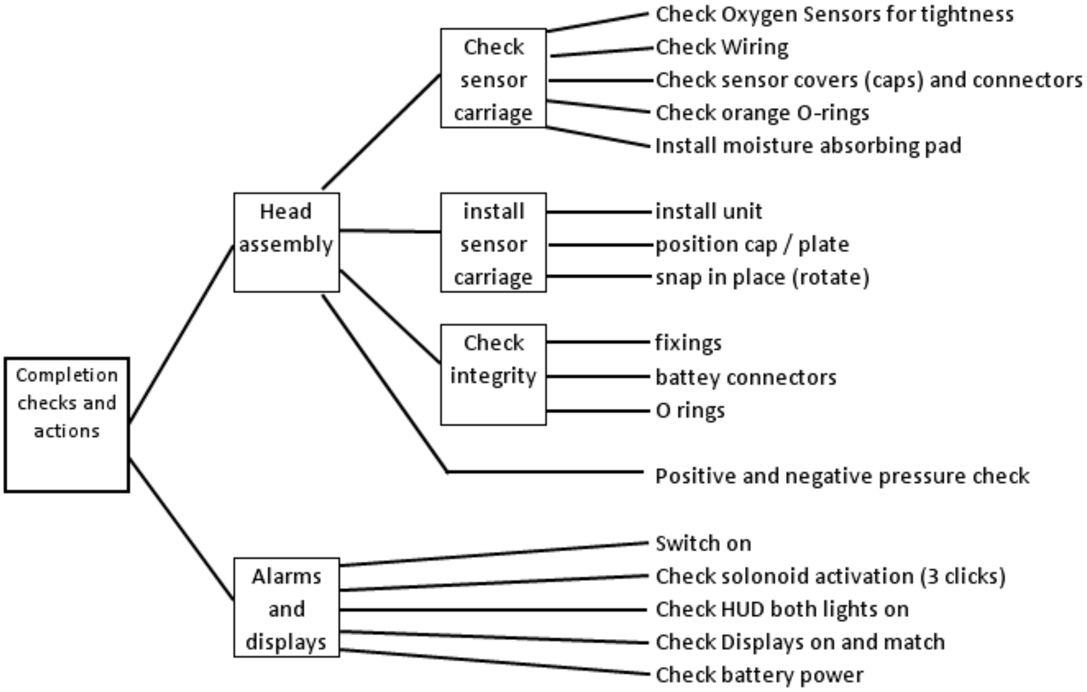

Install counter lungs
Install exhale counter lung
Place in position
Snap fastner
Velcro loop
2nd velcro loop
Install inhale counter lung
Place in position
Snap fastner
Velcro loop
2nd velcro loop

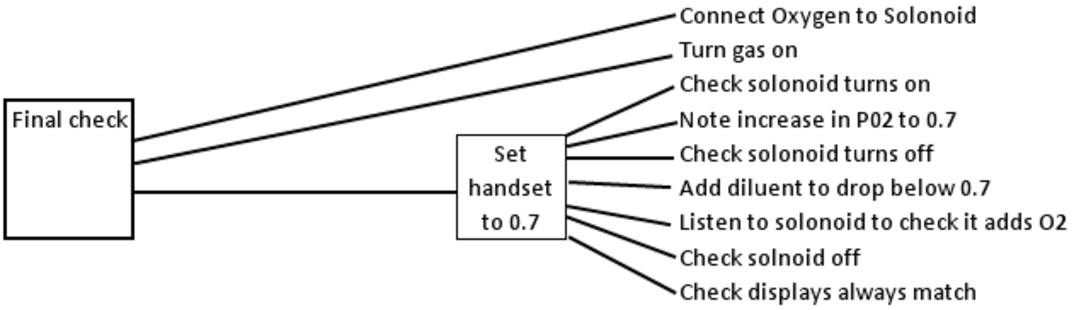

Test check valves
test inhale
Block 'T' piece
Breathe in
Close mouth piece / remove from mouth
test exhale
Block 'T' piece
Breathe in
Close mouth piece / remove from mouth


Fill & fit scrubber
Fill Scrubber
Install Scrubber
Insert support stand
Insert Scrubber
Install Head
Position head
Snap the four clips shut
Mount HUD


Loop installation
Position breathing hose
Loop leak test
pos
close vent valve
inflate loop
feel & listen for leaks
neg
close vent valve
deflate loop (suck)
feel & listen for leaks
Screw down 'T' piece


Installation of pneumatic hoses
High Pressure
Lay hoses
Fasten Velcro
Lay HP O2 guage SPG
Fasten SPG
Low Pressure
Lay ADV hose
Connect ADV hose
BC hose connect to BC auto-inflater
Fasten hose (Velcro)
Fasten hose (Velcro)


Completion checks and actions
Head assembly
Check sensor carriage
Check Oxygen Sensors for tightness
Check Wiring
Check sensor covers (caps) and connectors
Check orange O-rings
Install moisture absorbing pad
install sensor carriage
install unit
position cap / plate
snap in place (rotate)
Check integrity
fixings
battey connectors
O rings
Positive and negative pressure check
Alarms and displays
Switch on
Check solonoid activation (3 clicks)
Check HUD both lights on
Check Displays on and match
Check battery power


Final check
Connect Oxygen to Solonoid
Turn gas on
Set handset to 0.7
Check solonoid turns on
Note increase in P02 to 0.7
Check solonoid turns off
Add diluent to drop below 0.7
Listen to solonoid to check it adds O2
Check solnoid off
Check displays always match

APPENDIX 2: SHERPA TAXONOMY

ACTION ERRORS

A1 Operation too long/short

A2 Operation mistimed

A3 Operation in wrong direction

A4 Operation too much/little

A5 Misalign

A6 Right operation on wrong object

A7 Wrong operation on right object

A8 Operation omitted

A9 Operation incomplete

A10 Wrong operation on wrong object

CHECKING ERRORS

C1 Check omitted

C2 Check incomplete

C3 Right Check on wrong object

C4 Wrong check on right object

C5 Check mistimed

C6 Wrong check on wrong object

RETRIEVAL ERRORS

R1 Information not communicated

R2 Wrong information obtained

R3 Information retrieval incomplete

COMMUNICATION ERRORS

I1 Information not communicated

I2 Wrong information communicated

I3 Information communicated incomplete

SELECTION ERRORS

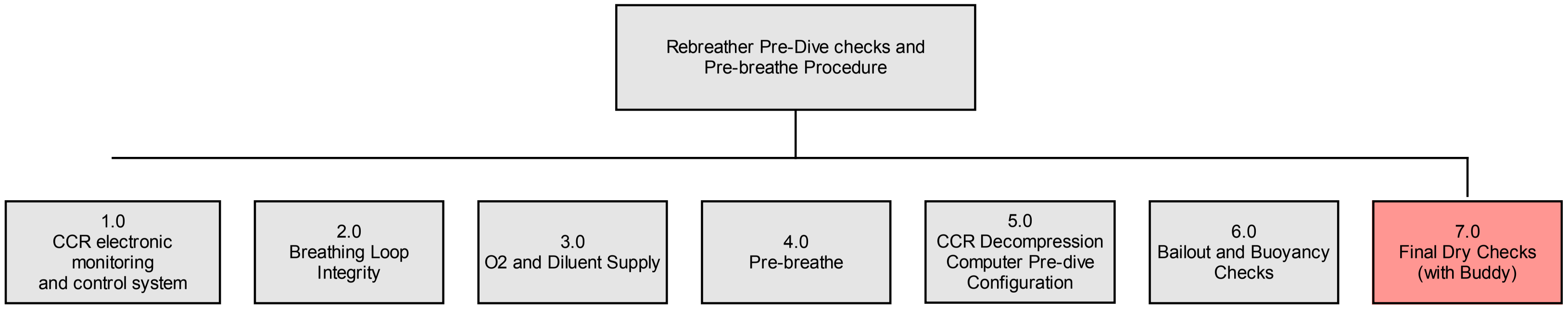
S1 Selection omitted

S2 Wrong selection made

APPENDIX 3: TASK ANALYSES FOR PRE-DIVE CHECKS AND PRE-BREATHE

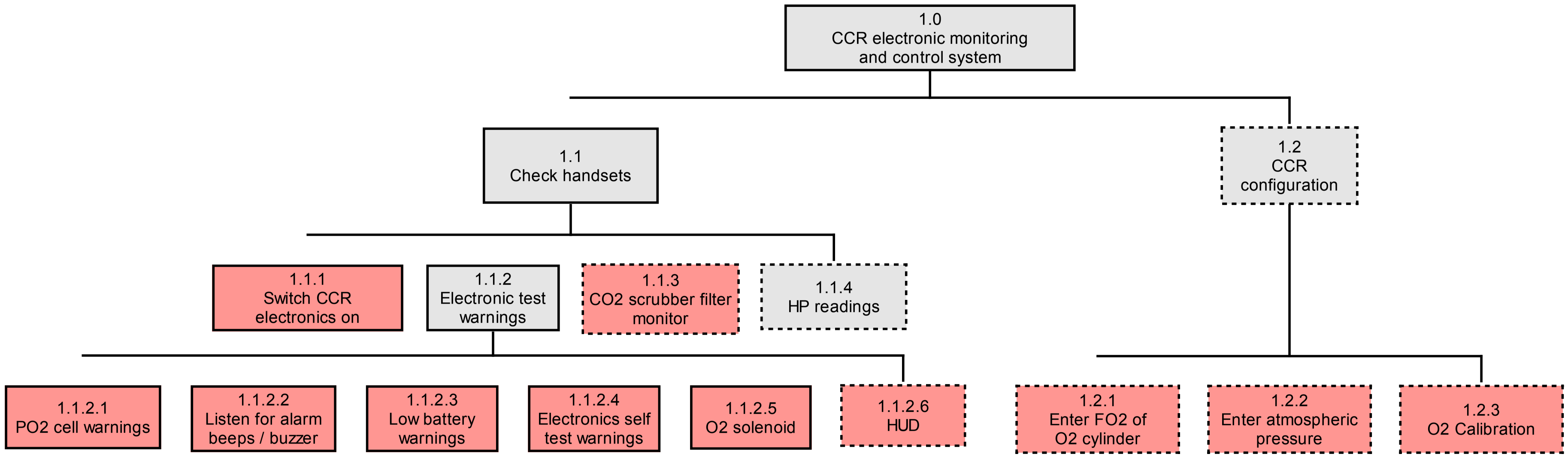
Key:

▢ Task step with no error identified ⬚ Unit specific task step 🟥 Task step with viable error identified

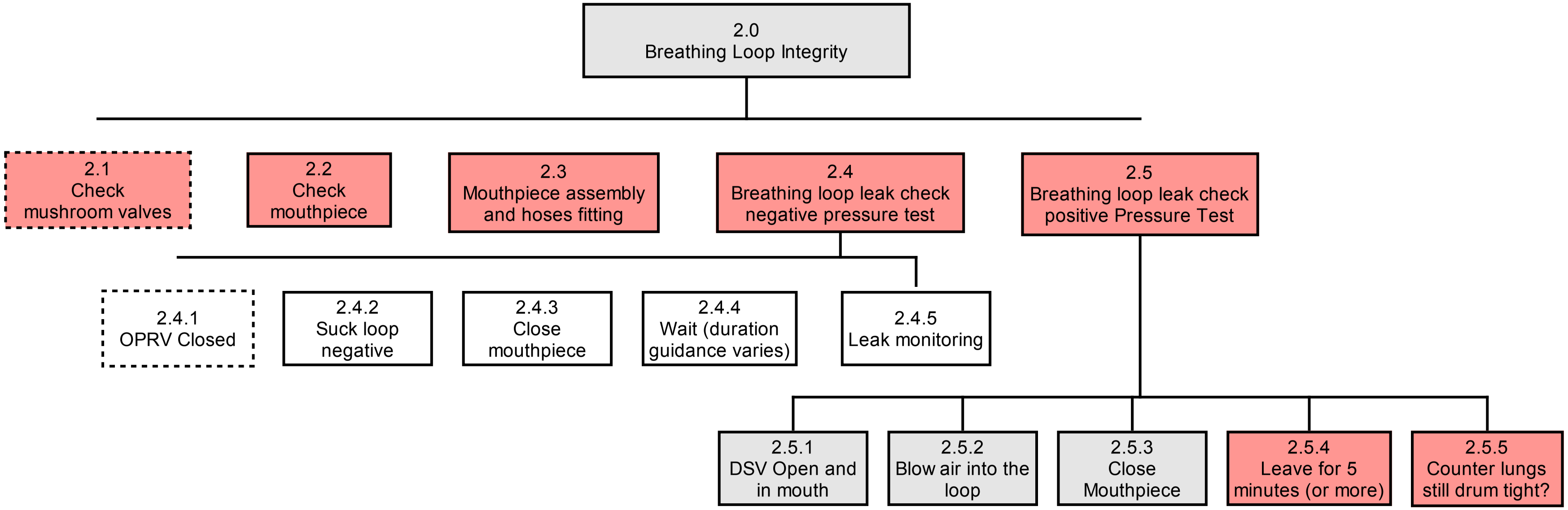


Recommendation of buddy check at the completion of the pre-breathe sequence

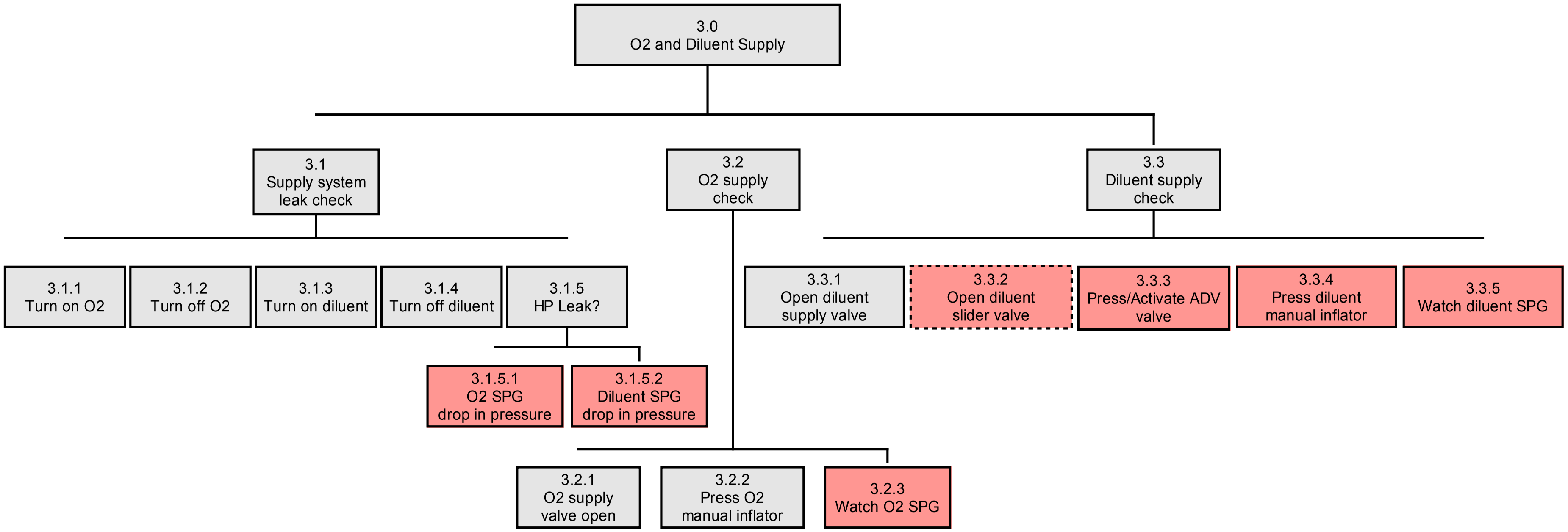
PRE-DIVE CHECKS AND PRE-BREATHE HTA 0



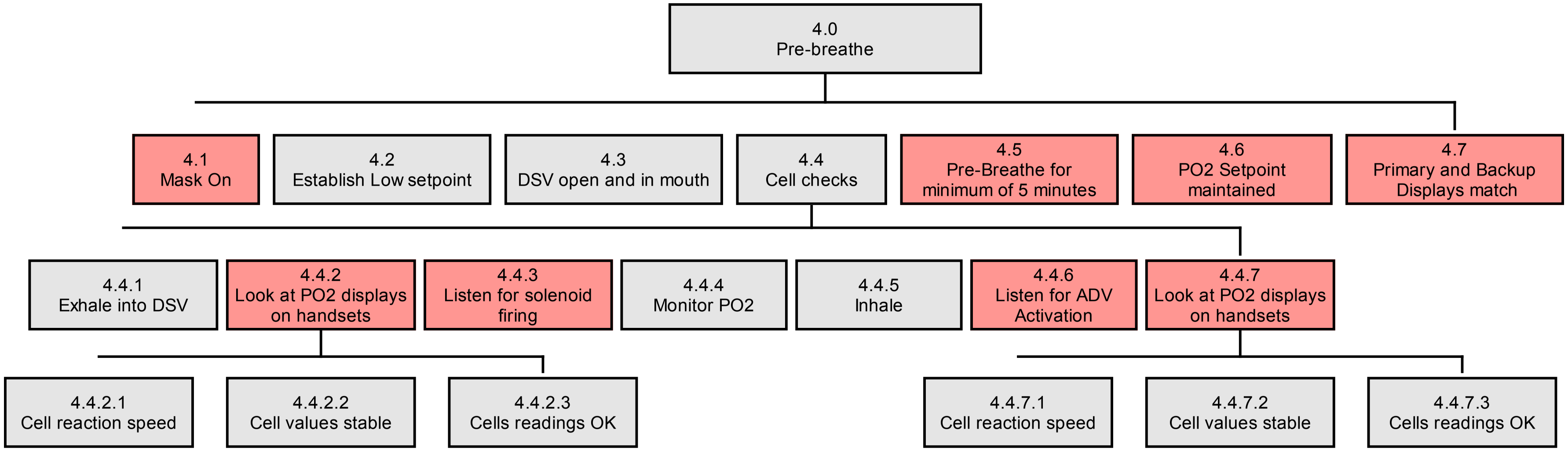
PRE-DIVE CHECKS AND PRE-BREATHE HTA 1



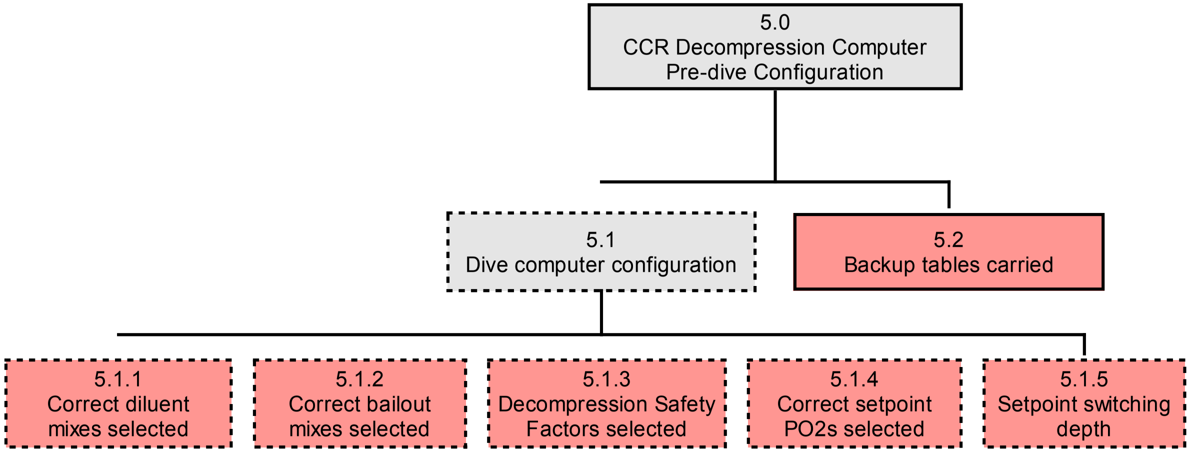
PRE-DIVE CHECKS AND PRE-BREATHE HTA 2



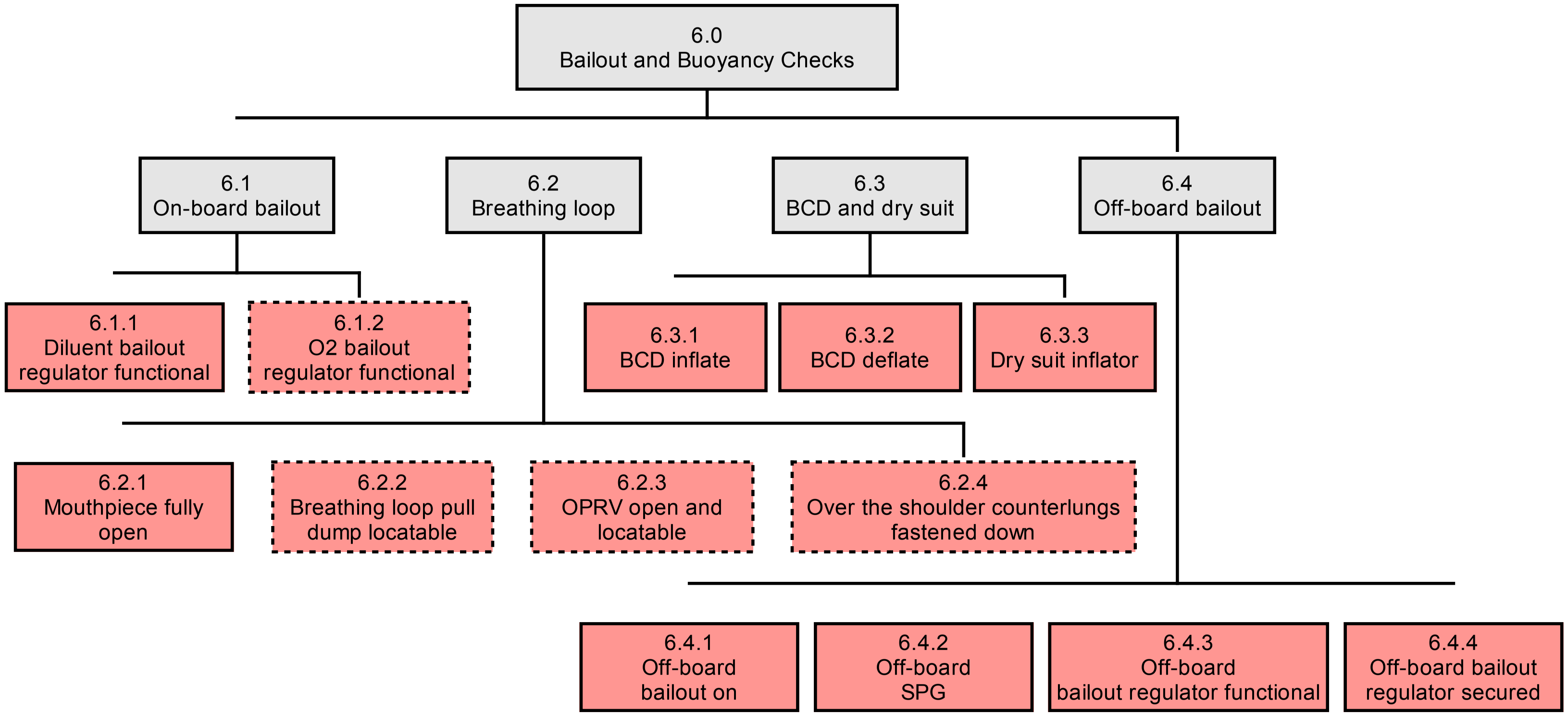
PRE-DIVE CHECKS AND PRE-BREATHE HTA 3



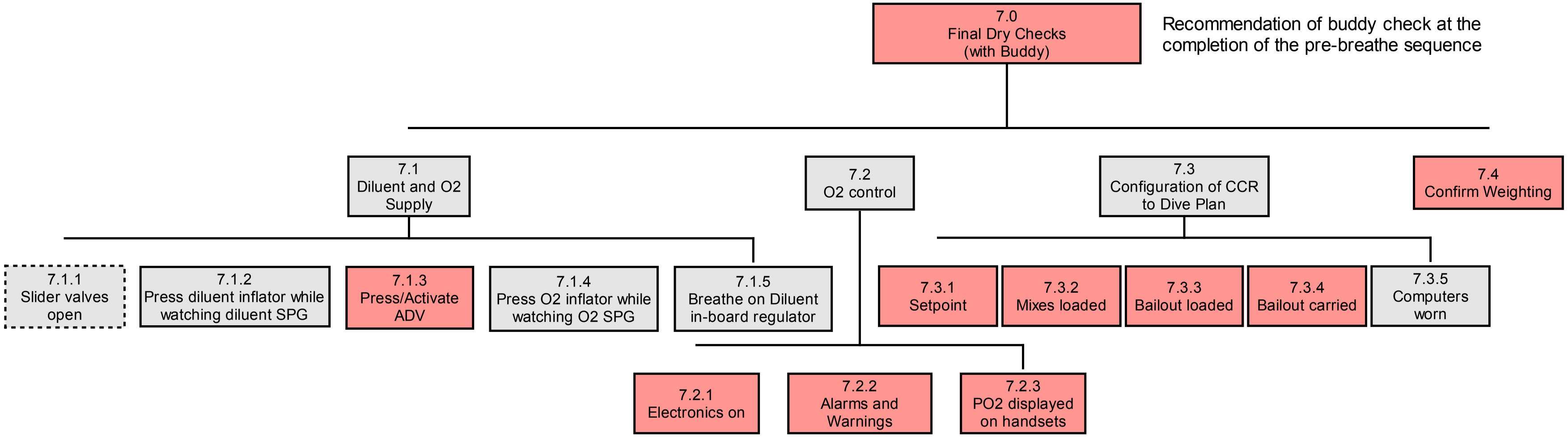
PRE-DIVE CHECKS AND PRE-BREATHE HTA 4



PRE-DIVE CHECKS AND PRE-BREATHE HTA 5



PRE-DIVE CHECKS AND PRE-BREATHE HTA 6



Recommendation of buddy check at the completion of the pre-breathe sequence

Pre-Dive Checks and Pre-breathe HTA 7

APPENDIX 4: SHERPA ANALYSIS FOR THE PRE-DIVE CHECKS AND PRE-BREATHE

Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
CCR electronics monitoring							
1.1.1 Switch electronics on	A8	Unit not switched on	No electronics control, PO_2 not displayed, no oxygen addition. If dived switched off, hypoxia and death with no PO_2 warnings.	7.2.1	M	!!	Buddy checks will establish that the unit is switched on prior to entering water. Design - unit switches on handset immersion.
1.1.2.1 Check for PO2 cell warnings	C1	O2 Cell warnings ignored	Compromised PO_2 readings, potential hypoxia or hyperoxia. Death.	7.2.2	M	!!	Audible alarm for no dive situation. Training – follow any handset "No Dive" instruction if displayed.
1.1.2.2 Monitor for alarm beeps /buzzer	C1	Buzzer / Audible alarm test not listened to	Buzzer, audible alarm potentially not functional. HUD and handsets will display alarms.	7.2.2	M	-	CCR self-diagnostics on buzzer and alarm. Diver training to emphasise importance of regular user monitoring of PO_2 during the dive.
1.1.2.3 Check for low battery warnings	C1	Low battery warning ignored	Unit electronics fail underwater. Loss of PO_2 monitoring and control. Hypoxia, death	7.2.2	M	!	Training – follow manufacturer's recommendations on battery replacement. Training – follow any handset "No Dive" instruction if displayed.
1.1.2.4 Monitor for electronics self-test failure warning	C1	CCR electronics self-test failure warning ignored	Unit electronics fail underwater. Loss of PO_2 monitoring and control. Hypoxia, death	7.2.2	M	!	Training – follow manufacturer's recommendations on servicing. Training – follow any handset "No Dive" instruction if displayed.
1.1.2.5 Check for O2 solenoid failure warning	C1	CCR unit self-test of solenoid fails and user ignores the warning caption	Automatic addition of O_2 under system control not functional. PO_2 will drop and a low PO_2 alarm generated.	4.5	M	-	Training – follow any handset "No Dive" instruction if displayed. Monitor PO_2 regularly and be aware of solenoid action. Always conduct a pre-breathe.
1.1.2.6 Monitor HUD	C1	HUD not checked during unit self test	HUD may have completely or partially failed	4.6	M	-	Training - during the pre-breathe monitor all forms of PO_2 displays (handset(s) and HUD)
1.1.3 Check for scrubber filter caption	C1	Scrubber filter caption not checked	Scrubber monitoring may not be functional, or scrubber filter defective	4.4	M	-	Training - the pre-breathe will capture some scrubber errors but not all, emphasise importance of scrubber duration awareness and monitoring.
1.1.4 Check HP readings	C1	HP readings (where facility exists) not checked	HP monitoring may not be functional	7.2.2	M	-	Training – ensure that HP SPGs are monitored intermittently to verify handset readouts for O2 and Diluent pressures.
1.2.1 Enter FO2 of O2 cylinder	A4	O2 supply FO2 entered incorrectly	CCR Unit specific - self checks may reject this and result in 'No Dive' if value is out of range. Calibration might be affected.	CCR self monitoring	L	-	Training - Emphasise the importance of correct gas analysis and labelling, and implications of not doing this properly. Consider building gas analysis into CCR unit self-check.

1.2.2 Enter atmospheric pressure	A8	Atmospheric Pressure entered incorrectly	CCR Unit specific – some units will detect pressure and apply. Calibration could be affected in others.	CCR self monitoring	L	!	Training – emphasise calibration procedures in training.
1.2.3 O2 Calibration	A4	O2 calibration incorrect	CCR Unit specific – self checks may reject incorrect calibration and result in ‘No Dive’, alternatively PO_2 readings will be incorrect	CCR self monitoring	L	!	Training – teach when and under which conditions calibration should be performed.

Breathing Loop Checks							
2.1 Check mushroom valves	C1	Mushroom valves not visually inspected	High CO2 exhalant may mingle with inhalant causing hypercapnia, Bailout.	4.4	H	!!	Perform 5 minute pre-breathe. Emphasise importance in training
2.2 Check mouthpiece integrity	C1	Mouthpiece not visually inspected	Water may enter mouthpiece and breathing loop, potential loop flood. Bailout	None	M	-	Training – subsequent pressure tests will not detect this so visual inspection essential.
2.3 Check integrity of mouthpiece assembly and hose fittings	C1	Mouthpiece assembly and hose fittings not checked	Water may enter the loop, potential loop flood. Bailout	2.4 and 2.5	M	-	Perform negative and positive pressure test. Training to emphasise correct assembly of rebreather unit.
2.4. Conduct breathing loop negative pressure test	C1	Breathing loop leak negative pressure test not performed	Potential breathing loop leak. Excessive gas consumption, water in system, increased work of breathing. Possible TLF. Bailout.	Bubble Check	H	-	Perform buddy bubble check. Your leak may be indicated by bubbles underwater which may be spotted by your buddy.
2.4.4 Wait	A1	Negative loop test is not performed for long enough	Leak may remain undetected	Bubble Check	M	-	Follow manufacturer's or training agency guidance on how long the negative loop test should be performed for (guidance varies).
2.4.5 Monitor for leaks	C2	Leak test performed but leak not detected.	Small breathing loop leaks may not be spotted. Bubble check may indicate source of problem.	Bubble Check	M	-	Perform buddy bubble check. Your leak may be indicated by bubbles underwater which may be spotted by your buddy. Follow manufacturers and training agency guidance relating to CCR leaks.
2.5 Conduct breathing loop positive pressure test	C1	Breathing loop leak positive pressure test not performed	Potential breathing loop leak. Excessive gas consumption, water in system, increased work of breathing. Possible TLF. Bailout.	Bubble Check	H	-	Perform buddy bubble check. Your leak may be indicated by bubbles underwater which may be spotted by your buddy.
2.5.4 Wait	A1	Positive pressure loop test is not performed for long enough	Leak may remain undetected. The positive loop test is a more demanding test than the negative loop test so will potentially detect smaller leaks.	Bubble Check	H	-	Follow manufacturer's or training agency guidance on how long the positive loop test should be performed for (guidance varies).

2.5.5 Monitor for leaks	C2	Leak test performed but leak not detected.	Small breathing loop leaks may not be spotted. Bubble check may indicate source of problem.	Bubble Check	M	-	Perform buddy bubble check. Your leak may be indicated by bubbles underwater which may be spotted by your buddy. Follow manufacturers and training agency guidance relating to CCR leaks.

O2 and Diluent Supply Leak Checks							
3.1.5.1 Monitor O2SPG for drop in pressure	C1	O2 supply leak check not performed	O2 first stage may not be connected to O2 Supply. O2 unavailable. Possible loop flooding. PO_2 alarm may trigger if electronics are still functional. Bailout.	7.1.4	M	!	Use a check-list to aid assembly, and assemble the CCR in a situation where one is not under time pressure.
			O2 first stage may not be fully connected to O2 supply. O2 leaking. Possible flooding of the loop. PO_2 alarm may trigger if electronics are still functional. Bailout.	Bubble check	M	!	Monitor handsets and O2 SPG (Training)
			O2 hoses may not be connected to first stage properly, or may be leaking. O2 SPG could be leaking. O2 supply may become exhausted.	Bubble check	M	!	Monitor O2 SPG (Training)
3.1.5.2 Monitor Diluent SPG for pressure drop	C1	Diluent supply leak check not performed	Diluent first stage may not be connected to Diluent supply. Diluent unavailable. Possible loop flooding, diluent addition to loop volume and buoyancy not available. In-board bailout not available	7.1.2	M	-	Use a check-list to aid assembly, and assemble the CCR in a situation where one is not under time pressure.
			Diluent first stage may not be fully connected to Diluent supply. Diluent leaking. Possible flooding of the loop. Bailout.	Bubble check	M	-	Monitor Diluent SPG (Training)
			Diluent hoses may not be connected to first stage properly, or may be leaking. Diluent SPG could be leaking. Diluent supply may become exhausted.	Bubble check	M	-	Monitor Diluent SPG (Training)

O2 and Diluent Supply Connection Checks							
3.2.2 Press O2 manual inflator	A8	O2 manual inflator not pressed	O2 manual supply check cannot be performed	4.6 7.1.4	M	-	Ensure final dry checks with a buddy are performed.
3.2.3 Monitor O2 SPG for pressure rise	C1	O2 supply check not performed (by pressing O2 inflator while watching O2 SPG)	O2 LP supply may not be physically connected to O2 inflator. Manual O2 inflator does not add O2 into the breathing loop	4.6 7.1.4	M	-	Ensure final dry checks with a buddy are performed.
3.2.3	C1	O2 SPG not watched during O2 supply check	O2 supply may be almost empty. Low PO_2 alarm when O2 supply exhausted, if alarm ignored hypoxia and death. Bailout.	7.1.4 and Bubble check	M	!	Final SPG check prior to descent. Check SPGs during the dive.
3.2.3	C1	O2 SPG not watched during O2 supply check (i.e. needle dips/bounces)	O2 valve may be only fractionally open. Potential for valve to be closed inadvertently on dive. Low O2 alarm which, if ignored leads to hypoxia and death.	7.1.4	L	!!	Emphasise potential issue during training, especially significance of issue on ascent (solenoid may not be able to add sufficient O2 into breathing loop to maintain PO_2 within breathable limits)
3.3.2 Open diluent slider valve if fitted	A8	Diluent slider (flow stop) valve not opened [if slider valve fitted to ADV supply].	Diluent supply to ADV inhibited (both automatic and manual mode of operation). User will have to press diluent manual inflator to add diluent into breathing loop.	3.3.3 7.1.1	M	-	This error will be trapped by the ADV valve test. Recheck all slider (flow stop) valves fitted prior to entering water. Design - consider fitting slider valves that have a visual indication of valve status, and valves that cannot be closed accidentally.
3.3.3 Press/Activate ADV valve	A8/ C1	ADV valve not pressed (or activated by inhalation) to confirm functional ADV.	ADV may be non-functional, or diluent supply to ADV may be inhibited (flow stop valve closed or diluent supply turned off)	7.1.3	M	-	Emphasise importance of maintenance of breathing loop volume on descent and how ADV and manual diluent inflator can be operated to achieve this. Consider incorporating CCR descents without using the ADV into training.
3.3.4 Press diluent manual inflator	A8	Diluent manual inflator not pressed	Diluent manual supply check cannot be performed	7.1.2	M	-	Ensure final dry checks with a buddy are performed.
3.3.5 Monitor Diluent SPG	C1	Diluent SPG not watched during Diluent supply check	Diluent supply may be almost empty. Potentially critical on descent (loss of loop volume and inability to establish positive buoyancy)	7.12 and Bubble check	M	!	Ensure final dry checks with a buddy are performed. Carry out final diluent SPG check prior to descent.
3.3.5	C1	Diluent SPG not watched during Diluent supply check (i.e. needle dips/bounces)	Diluent valve may be only fractionally open. Potential to be closed inadvertently on dive. Potentially critical on descent – ADV or diluent inflator may not be able to add sufficient diluent to maintain loop volume.	7.1.2	L	!	Emphasise potential issue during training.

Pre-breathe on the Unit							
4.1 Put on mask	A8	Mask not worn (or nose not blocked) during pre-breathe	Diver may subconsciously start to breathe through nose to compensate for elevated CO2 in the breathing loop – pre-breathe potentially not effective.	None	H	!!	Training - encourage buddy pairs pre-breathe together. Emphasis on importance of blocking nose during pre-breathe
4.4.2 Check PO_2 readings for stability, reaction time and agreement	C1	Cells displays on handset not monitored during exhalation	Slow cells, cells with unstable readings and cells disregarded will not be picked up. Potential cell issues (such as moisture on a cell not picked up)	7.2.3	M	-	Training – cell reaction speed, stability of cell values and cell readings being close to each other
4.4.3 Listen for solenoid firing	C1	Solenoid not listened for or solenoid not heard	If the solenoid does not operate then PO_2 will not be maintained in the pre-breathe and a low PO_2 alarm will be generated. If the CCR electronics are not turned on then symptoms of hypoxia will be apparent within 5 minutes.	4.6	M	-	Training - encourage CCR divers to listen for the solenoid and watch PO_2 levels during the pre-breathe. Design – consider a unit that turns itself on automatically if PO_2 drops in the loop. Design – ensure solenoid operation is audible to the diver.
4.4.4 Monitor PO_2	C1	PO_2 not monitored in the pre-breathe	PO_2 levels may not be being maintained / increased to the chosen low set point.	4.6	M	-	As above.
4.4.6 Listen for ADV operating	C1	ADV not listened for	If the ADV is not functional then on initial inhalation on the pre-breathe breathing loop volume will not be added, so breathing in will be difficult/impossible if the breathing loop is properly sealed.	Cannot proceed.	L	-	Diagnose problem, unlikely to occur if loop negative pressure test (2.4) and ADV supply test (3.3.3) have been performed correctly.
4.5 Pre-breathe for 5 minutes	A1	Pre-breathe is less than 5 minutes	Shorter pre-breathes are less effective at picking up potential CO2 issues which are manifested at the start of the dive.	None	M	!!	Use timing device or pre-breathe built into CCR system checks. Training - encourage buddy pairs pre-breathe together. It is important to emphasise that a pre-breathe will not pick up all scrubber related issues (such as old scrubber material which will be pushed beyond its ability to absorb CO2 because of previous dives), so scrubber packing and awareness of scrubber durations are also critical survival skills.
4.6 Monitor et point maintenance	C1	PO_2 levels maintained at setpoint not confirmed at end of pre-breathe	CCR unit PO_2 management may not function properly under water.	None	M	!	Consider cross checking with buddy at the end of the breathe sequence.
4.7 Compare primary and backup handset readings	C1	Primary and Backup handsets not referenced against each other	Handsets not in agreement, one handset may be displaying an error. Secondary handset may have promoted to primary.	7.2.3	M	-	Due to redundancy in systems design unlikely to be critical. Cross check handsets with buddy prior to dive.

Pre-Dive Configuration of CCR and External Decompression Computers							
5.1.1 Check correct diluent mix selected	A8/A 9/C1	Correct diluent mix/mixes not configured to reflect dive plan	Incorrect decompression information. Potentially CNS toxicity or DCS	7.3.2	M	!	Make a written plan of the dive details and gas configuration prior to getting on the boat. Cross check details with buddy.
5.1.2 Check bailout mix(s) match dive plan	A8/A 9/ C1	Correct bailout mix/mixes not configured to reflect dive plan	Incorrect decompression information. Potentially CNS toxicity or DCS	7.3.3	M	!	Make a written plan of the dive details and gas configuration prior to getting on the boat. Cross check details with buddy.
5.1.3 Check decompression safety factors are appropriate	A8/A 9/ C1	Decompression safety factors / gradient factors not appropriately conservative	Decompression schedule may not be appropriately conservative for dive conditions and diver personal health factors. DCS.	None	M	-	Training and education – dive conservatively and factor in appropriate safety margins to decompression calculations.
5.1.4 Check High and Low set points reflect dive plan	A8/A 9/ C1	High and Low set points not configured to reflect dive plan	Decompression information will be incorrect. Potentially CNS toxicity or DCS.	7.3.1	M	!	Make a written plan of the dive details and gas configuration prior to getting on the boat. Cross check details with buddy.
5.1.5 Check set point switching depth matches dive plan	A8/A 9/C1	Setpoint switching depth not selected to reflect the plan	Decompression information will be incorrect, potential DCS.	None	M	-	Follow the written plan made in the dive planning stage.
5.2 Check backup tables prepared	A8	Backup tables not prepared	Decompression information not available if dive instrumentation fails. Potential DCS.	None	M	!	Ensure that two independent sets of Decompression information are available, such as CCR decompression electronics and either other decompression computer or decompression tables.
Bailout and Buoyancy Checks							
6.1.1 Check inboard diluent bailout regulator functional	C1	Failure to check that in-board diluent bailout regulator is functional	Second stage may be inoperable, potential to cause diver panic and drowning in an emergency situation requiring bailout.	Alternative bailout regulator	M	!	Check the functioning of the first bailout regulator with care, especially if a flow stop valve is fitted (also applies to inbuilt BOVs). Follow manufacturer’s guidance on regulator servicing.
6.1.2 Check in-board O2 bailout regulator functional	C1	[optional item] Failure to check that in-board O2 bailout regulator is functional	Second stage may be inoperable, potential to cause diver panic, drowning in a bailout scenario. However this is not likely to be the chosen bailout regulator due depth limits of pure O2.	Alternative bailout regulator (unlikely)	M	!	Bailout to Oxygen only applies shallower than 6 msw.

6.2.1 Check mouthpiece	C1	Mouthpiece not checked	Partially open mouthpieces can leak underwater. Diluent flushes, loop flood recovery drills, excessive gas consumption.	None	M	-	Consider software-driven check-list or written / laminated check-list. Consider the preparation and following of a check-list as part of the CCR unit training.
6.2.2 Locate breathing loop pull dump (if fitted)	C1	Breathing loop pull-dump not checked to be free of obstruction. The breathing loop pull dump may be trapped under other equipment and perpetually venting.	On descent this could cause gas to vent from breathing loop, and flood the breathing loop. Bailout and buoyancy stabilisation required.	None	M	!	Consider colour coding cord and pull dump so that a trapped pull dump is more visible. Consider building the check procedure into pre-dive check with buddy.
	C1	Breathing loop pull-dump not located and confirmed to be free of obstruction to movement.	In a fast ascent situation not being able to reach the pull dump to vent expanding breathing loop volume might lead to an irrecoverably fast ascent. Potential omitted DCS and lung expansion issues.	None	M	!	Consider colour coding cord and pull dump so that a trapped pull dump is more visible. Consider building procedure into pre-dive check with buddy.
6.2.3 Check OPRV open and locatable	C1	OPRV not checked to be operable	OPRV may be damaged, or stuck either closed or open. An OPRV stuck closed means that breathing loop volume expansion needs to be managed manually. Potential ascent issues and potential higher risk of lung expansion injuries. OPRV stuck open means that loop integrity pressure tests cannot be performed.	None	M	-	Follow maintenance instructions, consider adding this item into a pre-dive check-list..
	C1	OPRV not checked to be open	Really only an issue on ascent, there are several descent checks that should trap this error.	On descent OPRV check	L	-	Training – consider adding rapid ascent management theory into training courses and actions to perform in situations with jammed inflators and/or venting not occurring.
6.2.4 Check over-shoulder counter lungs adjusted correctly	C1	[optional item] Over the shoulder counter lungs not checked to be adjusted correctly (if unit has OTSCL)	Work of breathing not optimal	Bubble check	M	-	The bubble check should allow this potential issue to be corrected
6.3.1 Check BCD inflation	C1	BCD inflation not tested	Buoyancy control issues, serious if no alternative means of buoyancy such as a dry suit or dual bladder BC can be used to establish positive buoyancy. Could ultimately lead to Drowning, Death.	Plug bailout supply into BCD	M	!	Carry bailout supply with compatible hose to plug into BCD (consider interoperability with dry suit as well). Consider adding this item into a pre-dive check-list.

6.3.2 Check BCD deflation	C1	BCD deflation not tested	BCD deflation will be tested on descent so unlikely to be an issue if the dive is started with diluent in the BCD.	None	M	!	Training – consider adding rapid ascent management theory into training courses and actions to perform in situations with jammed inflators and/or venting not occurring.
6.3.3 Check dry suit inflation	C1	Dry suit inflation not tested	Buoyancy control issues. Suit squeeze - diver discomfort, restricted movement, compromised thermal protection	None	M	-	Plug bailout BCD supply into dry suit
6.4.1 Check off-board bailout valve open	C1	Off-board bailout valve closed	Bailout gas not available when desperately required. Possible diver panic and drowning	6.5.3	M	B !!	Emphasise importance of bailout and bailout checks prior to starting the dive.
6.4.2 Check off-board bailout SPG functional	C1	Off-board bailout SPG not checked	Off-board bailout contents may be almost empty. In an a bailout situation potentially DCS or drowning.	7.1.5	M	B !!	Emphasise importance of bailout and bailout checks prior to starting the dive.
6.4.3 Check off-board bailout regulator functional	C1	Off-board bailout not breathed from	Off-board bailout may be empty, not connected. Bailout not available, potential diver panic and drowning.	7.1.5	M	B !!	Emphasise importance of bailout and bailout checks prior to starting the dive.
	C1	Off-board bailout not breathed from	Off-board bailout regulator not functional. Bailout not available, potential diver panic and drowning.	None	M	B !!	Emphasise importance of bailout and bailout checks prior to starting the dive.
	C1	Off-board bailout not breathed from	Bailout gas may not have suitable FO2. Potential hypoxia if breathed underwater (a more severe hypoxia would be expected during the test on the surface, but the lesser of two evils.)	None	M	B !!	Emphasise importance of bailout and bailout checks prior to starting the dive.
6.5.4	C1	Primary Bailout regulator not confirmed to be secured in a place where it is immediately available.	Diver cannot locate bailout regulator when they need it most. Potential panic and drowning	7.3.4	M	B !!	Emphasise importance of bailout and bailout checks prior to starting the dive.
Pre-dive Buddy Checks (*recommendation for additional task*)							
7.0 Conduct buddy Checks	C1	Buddy checks are not performed (or no buddy)	Cross-checks do not occur; many potential errors described above would be caught by cross checks.	None	H	!	Encourage CCR divers to operate as a team prior to entering the water. Emphasise the advantage of cross checking prior to starting the dive. CCR divers would be advised to use a waterproof version of the manufacturer’s written check-list. Consider teaching buddy checks as part of CCR diving courses.

							Course materials and manufacturer's guidance should outline a clear position on CCR solo diving, and should contain a buddy check procedure.
7.1.1 Check slider valves open (if fitted)	C1	Slider valves closed error not trapped	Diluent supply to ADV inhibited (both automatic and manual mode of operation). User will have to press diluent manual inflator to add diluent into breathing loop.	None	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
7.1.2 Press diluent inflator whilst watching diluent SPG	C1	Diluent supply problem not trapped	Diluent supply may be almost empty, or valve may be almost closed. Potentially critical on descent (loss of loop volume and inability to establish positive buoyancy)	Bailout to off-board bailout, use alternative diluent supply for buoyancy.	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
	C1	Diluent supply problem not trapped	Diluent valve may be only fractionally open. Potential to be closed inadvertently on dive. Potentially critical on descent – ADV or diluent inflator may not be able to add sufficient diluent to maintain loop volume.	Bailout to off-board bailout, use alternative diluent supply for buoyancy.	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
7.1.3 Press/ Activate ADV	C1	ADV functionality error not trapped	ADV may be non-functional, or diluent supply to ADV may be inhibited (flow stop valve closed or diluent supply turned off)	Use manual diluent inflator	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
7.1.4 Press O2 inflator whilst watching O2 SPG	C1	O2 supply problem not trapped	O2 supply may be almost empty. Low PO_2 alarm when O2 supply exhausted, if alarm ignored hypoxia and death. Bailout.	Bailout	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
	C1	O2 supply problem not trapped	O2 valve may be only fractionally open. Potential for valve to be closed inadvertently on dive. Low O2 alarm which, if ignored leads to hypoxia and death.	Bailout	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.

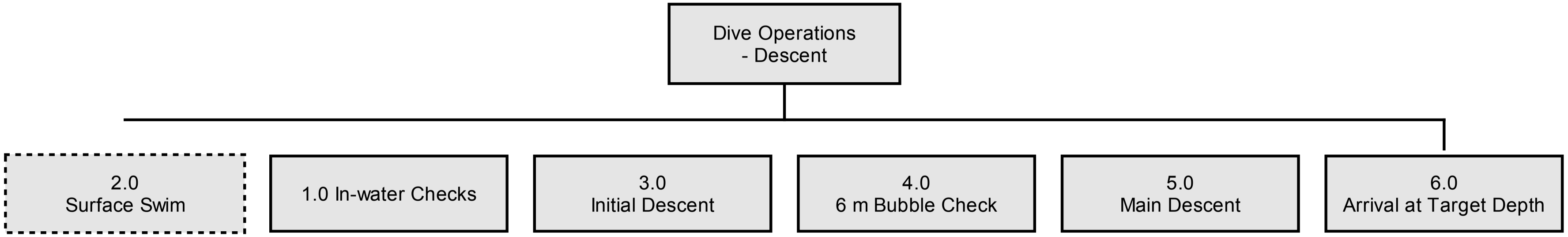
7.1.5 Breathe on diluent inboard regulator	C1	Diluent inboard second stage regulator error not trapped	Off-board bailout contents may be almost empty. In a bailout situation potentially DCS or drowning.	None	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
	C1	Diluent inboard second stage regulator error not trapped	Off-board bailout may be empty, not connected. Bailout not available, potential diver panic and drowning.	None	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
7.2.1 Check electronics on	C1	Electronics off not trapped	No electronics control, PO_2 not displayed, no oxygen addition. If dived switched off, hypoxia and death with no PO_2 warnings.	None	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
7.2.2 Check for alarms and warnings	C1	Alarms and warnings not trapped	One would hope that a CCR diver would not ignore (or not check) handsets displaying “No Dive”	None	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
7.2.3 Check PO_2 readings whist breathing on loop	C1	PO_2 on setpoint not trapped (i.e. not breathing on the loop while displaying handset to buddy)	Slow cells, cells with unstable readings and cells disregarded will not be picked up. Potential cell issues (such as moisture on a cell not picked up)	None	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
7.3.1 Check setpoint matches dive plan	C1	Configuration of CCR with the dive plan – setpoint error not trapped	High and Low set points not configured to reflect dive plan. Decompression information will be incorrect. Potentially CNS toxicity or DCS.	None	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
7.3.2 Check diluent mix matches dive plan	C1	Configuration of CCR with the dive plan – diluent mix error not trapped	Correct diluent mix/mixes not configured to reflect dive plan. Incorrect decompression information. Potentially CNS toxicity or DCS.	None	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
7.3.3 Check bailout mix matches dice plan	C1	Configuration of CCR with the dive plan – bailout mixes error not trapped	Incorrect decompression information. Potentially CNS toxicity or DCS	None	M	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check themselves.
7.3.4 Check bailout carried	C1	Bailout not carried	CCR diver forgets bailout. Diver cannot locate bailout regulator when they need it most. Potential panic and drowning	None	L	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check for themselves.
7.3.5 Check dive computer worn	C1	Computers not worn	CCR diver forgets dive computer	None	L	!	This buddy check item is a failsafe check if the CCR diver has failed to perform this check for themselves.

7.4 Check weights carried are appropriate	C1	Weight not checked, diver could be under or over-weighted	An under weighted diver will not be able to descend. In an over weighted diver this will lead to buoyancy control issues and excessive gas consumption, increased task loading and is a potential contributor / complicating factor in other emergency situations.	None	M	!	Build this item into a pre-dive check, consider a check dive if diving in new conditions or with new equipment which may affect buoyancy.

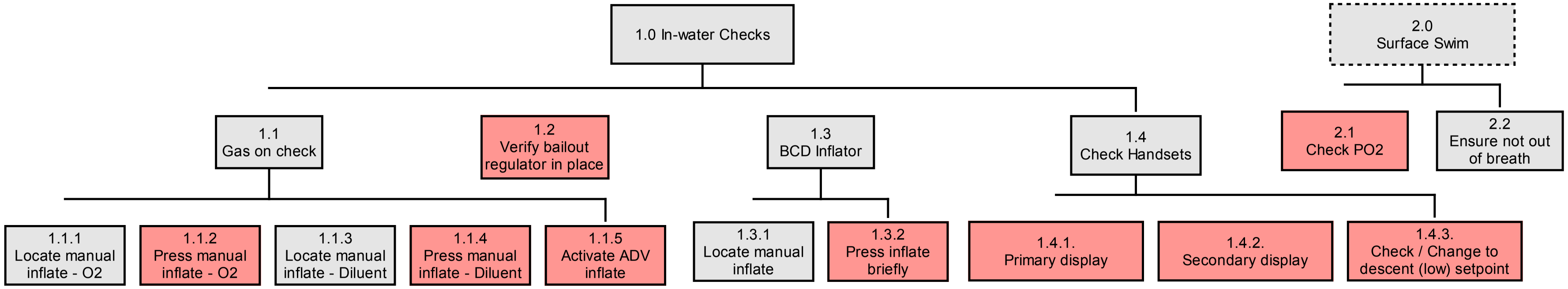
APPENDIX 5: HIERARCHICAL TASK ANALYSES FOR ENTRY AND DESCENT

Key:

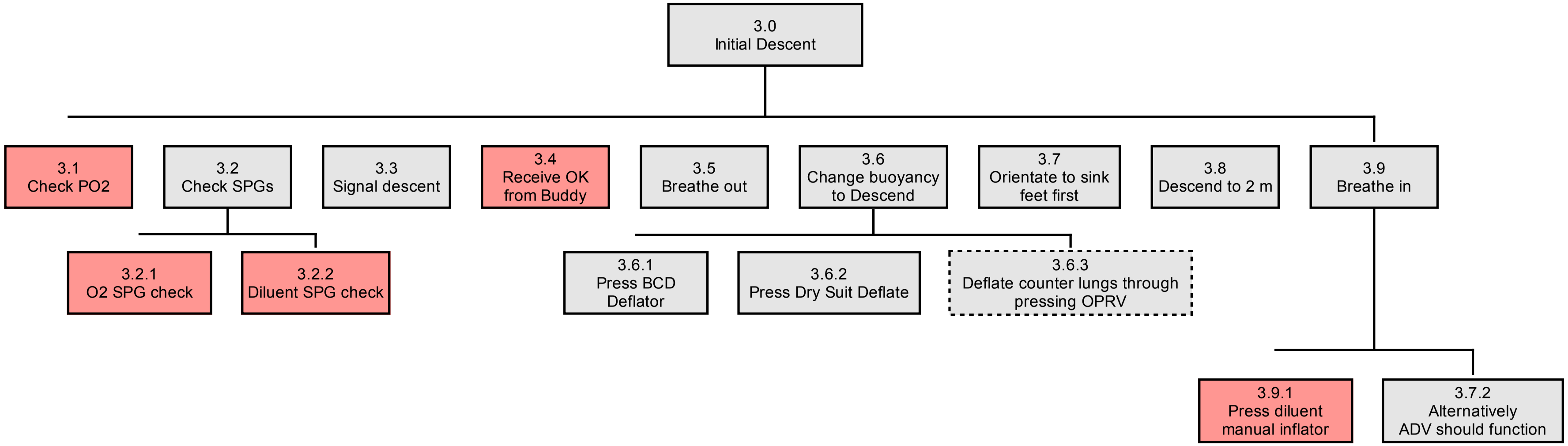
⬜ Task step with no error identified ⬚ Unit specific task step 🟥 Task step with viable error identified



ENTRY AND DESCENT HTA 0



ENTRY AND DESCENT HTA 1 & 2



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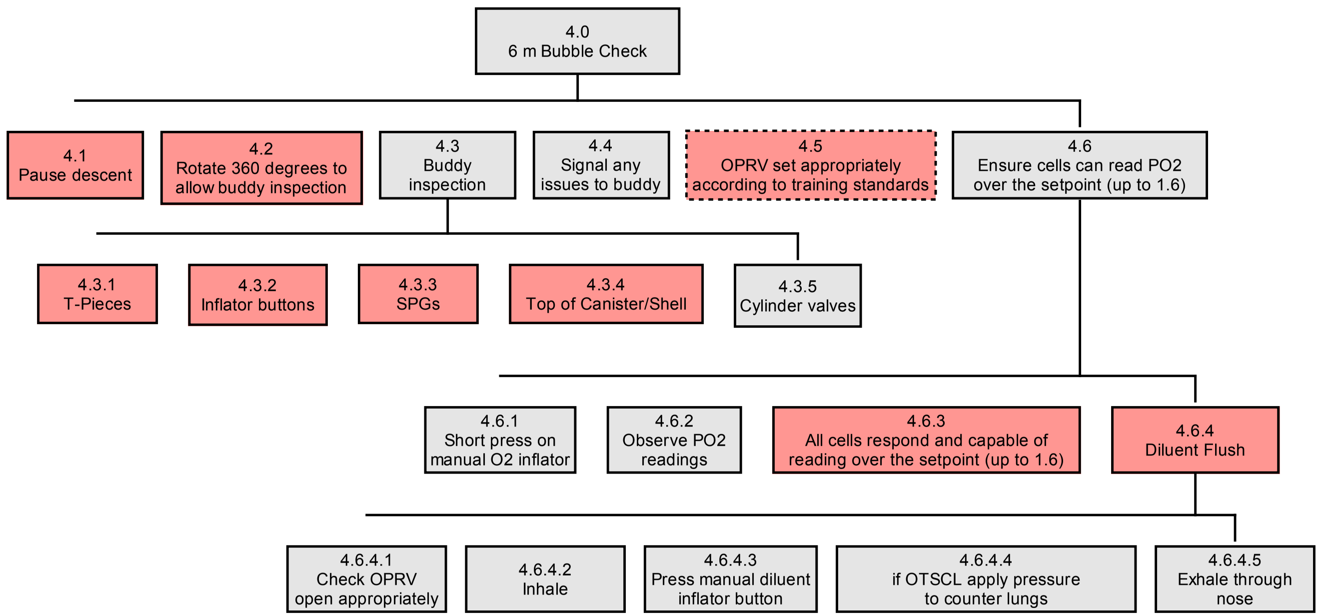

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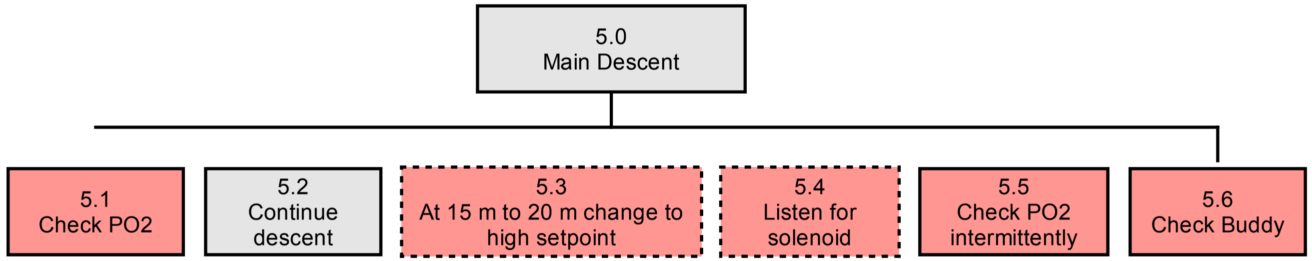
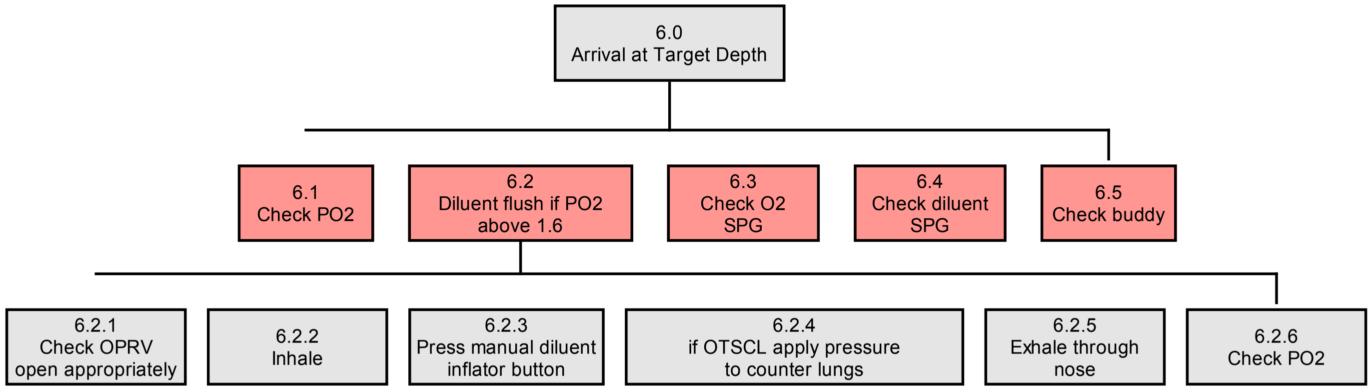


ENTRY AND DESCENT HTA 5



ENTRY AND DESCENT HTA 6

APPENDIX 6: SHERPA ANALYSIS FOR ENTRY AND DESCENT

Entry & Descent Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
In-water Checks							
1.1.2 Press manual inflate – O2	C1	Manual O2 inflator not tested	Potential for O2 supply to have been switched off. Low PO_2 alarm. Hypoxia, Death.	Monitor PO_2 every minute. Turn on O2 supply. Bailout.	M	!	Ensure that rebreathers are not touched once the pre-breathe has been completed. Monitor PO_2 at all times.
1.1.4 Press Manual Inflate - diluent	C1	Manual Diluent inflator not tested	Potential for diluent supply to have been switched off. Loss of loop volume and buoyancy on descent.	Turn on diluent supply. Bailout and use alternative means of buoyancy	M	!	Ensure that rebreathers are not touched once the pre-breathe has been completed. Train CCR divers to react to loss of diluent supply on descent.
1.1.5 Press ADV inflate	C1	ADV flow stop valve not checked to be in the open state	Loop volume will not be automatically maintained. Potential for loop flood due to ADV diaphragm rupture. Loss of Loop volume and buoyancy on descent.	Press Manual Diluent inflator. Open flow stop valve. Bailout.	M	!	Ensure that all flow stop valves can be reached and operated in event of an emergency. Ensure the flow stop valves are positioned such that they cannot be inadvertently closed. Train CCR divers to react to loss/interruption of diluent supply on descent, and actions to remedy.
1.2 Verify bailout regulator in place	C1	Bailout regulator location not verified.	Bailout regulator may have moved on entry and this may have gone unnoticed. In a bailout emergency situation potential diver panic and drowning	None, however Buddy may notice issue on Bubble check	M	!	Training / Practice. It is absolutely critical that bailout regulators are immediately locatable and operable.
1.3.2 Press BCD inflator	C1	Manual inflator not located and operated	BCD inflator may have shifted under other equipment / be difficult to locate.	None	M	-	Training - ensure equipment configuration and streamlining is taught. Train divers to locate all CCR controls, valves and inflators by touch.

Entry & Descent Task Step	**Error Mode**	**Error Description**	**Consequence**	**Recovery**	**P**	**C**	**Remedial Strategy**
1.4.1 Check primary display	C1	Primary handset not checked	Electronics may have been affected by diver entering the water (leak or impact), in worse case electronics may not be functional	Check PO_2 every minute	M	!	Training - monitor PO_2 at all times. Design - Consider an independent power circuit monitoring device to indicate sensor power failure linked to buzzer. Redundant power supplies. Protect electronics and battery housings.
1.4.2 Check secondary display	C1	Secondary handset not checked	Secondary (Slave) handset not ON and in Dive mode	Check PO_2 every minute	M	!	Training - monitor PO_2at all times. Design - Consider a power circuit monitoring device to indicate sensor power failure, or redundant power supplies. Protect electronics and battery housings.
1.4.3 Check/Change to low setpoint	C1	Set point not changed to low setpoint (this is unit specific in that some CCRs have a manual setpoint setting)	Dive Decompression plan not followed, potential DCS.	None	M	!	Training - plan the dive including set points and monitor PO_2 against that plan.

Surface Swim							
2.1 Check PO_2	C1	Initial (post surface swim) PO_2 check not performed	O2 supply or delivery (unlikely) or electronics may have been affected by diver jumping into water. PO_2 may be dropping and diver may not be aware of that fact.	3.1 and PO_2 alarms	M	!	Training - monitor PO_2 at all times. Listen for solenoid firing.

Initial Descent to Bubble Check							
3.1 Check PO_2	C1	Initial PO_2 check if direct descent (i.e. no surface swim)	PO_2 may be dropping below setpoint and diver may not be aware of that fact. Set point may not have been set appropriately.	5.1	M	!	Training - monitor PO_2 at all times.
3.2.1 Check O2 SPG	C1	O2 SPG not checked	O2 supply system may be leaking	4.3.3	M	!	Training - monitor SPGs every 5 minutes
3.2.2 Check diluent SPG	C1	Diluent SPG not checked	Diluent supply system may be leaking	4.3.3	M	!	Training - monitor SPGs every 5 minutes

3.4 Agree descent with buddy	I3	Buddy team do not communicate with each and coordinate descents.	Buddy team may become separated. Bubble check not carried out, dive may be conducted solo.	None	M	-	Training – emphasise the importance of bubble checks.
3.9.1 Press diluent manual inflator	A6	O2 manual inflator pressed rather than diluent inflator	PO_2 spike, remedy with diluent flush (unlikely to be problematic at 6 msw)	5.1	M	-	Training, Consider use of a CCR which has an ADV fitted.

6m Bubble Check							
4.1 Pause descent at 6 m	A4 / A8	Descent is not paused at 6 msw	Buddy pair may separate, bubble check not possible. Failing to complete the bubble check is not immediately critical however it may mean that leaks are not detected which may lead to critical issues later.	Signal buddy and attempt bubble check at greater depth	M	-	Training - practice bubble checks on every dive.
4.2 Perform 360 rotation to allow buddy bubble check	A9	Buddy does not do complete 360 rotation	Elements of buddy inspection may be missed, leaks may not be detected.	Signal buddy to perform 360 degree rotation	M	-	Training – practice bubble checks on every dive.
4.3.1 T-pieces inspected	C1/C2	T-pieces not inspected	Breathing Loop Leaks not picked up. Increased WOB, Water in scrubber, TLF. Bailout	Bailout	M	!	Training - divers should allow adequate preparation time with CCR assembly, and perform negative and positive loop tests for sufficient durations. Assume a TLF will occur on every dive, carry and bailout and practice bailout drills.
4.3.3 SPGs inspected	C1/C2	SPGs not checked	O2 supply system may be leaking, Diluent supply system may be leaking.	6.3, 6.4	M	!	Training - monitor SPGs every 5 minutes.
4.3.4 Top of canister inspected	C1/C2	Top of canister / shell not inspected	Water ingress into Scrubber, potential scrubber flood and caustic cocktail.	Bailout	M	!	A caustic cocktail may cause involuntary throat constriction and make bailout impossible. Listen for unusual noises in the loop, be alert to changes in WOB and taste of the gas in the breathing loop. Be prepared to immediately bailout.

4.5 OPRV not set appropriately	C1	OPRV is not opened sufficiently (unit specific)	Likely to manifest on first Diluent flush, gas not vented, buoyancy and increased WOB.	Open valve and in case of OTSCL, squeeze.	M	!	Training - build this check into every bubble check.
			If no diluent flush performed likely to manifest on ascent, gas from breathing loop not able to escape, rapid ascent. Potential gas expansion injuries (AGE etc.), omitted decompression leading to DCS.	Pre ascent checks	M	!	Emphasise importance of pre-ascent checks. Ensure training regime has opportunity to practice sufficient ascents. Ensure ascent control has been mastered prior to undertaking mandatory decompression stop diving.
4.6.3 Check PO_2 on handsets can read 1.6	C1	Cells reading over PO_2setpoint check not performed	O2 cell readings not checked to see if they can read over the high setpoint. Indicates cells reading lower than loop PO_2.Potential hyperoxia - CNS toxicity, Convulsion, Drowning, Death.	None	M	!	Training, Drills. Practice on every dive. If this occurs terminate dive and consult / follow manufacturer's guidance with respect to oxygen cell replacement. Note: This 6m check also acts as a reference flush in that PO_2 should read 1.6 when the loop is flushed with O2 at 6m.
4.6.4 Diluent flush	A8	Diluent flush omitted following high PO_2reference flush	Loop PO_2 is high, descent will increase PO_2 further leading to a high PO_2 alarm	5.1 Diluent flush or Bailout	M	!	Training – always check PO_2 prior to initiating main descent.
Main Descent							
5.1 Check PO_2	C1	Post bubble check (6 msw) PO_2 check omitted	PO_2 not precisely known prior to descent. Possible PO_2spike which if unmanaged may lead to CNS hit. Convulsion, Drowning, Death.	5.5 PO_2 high alarm	M	!	Training – ensure CCR divers can mentally calculate PO_2 on the bottom from PO_2 at bubble check (1.6 atm), so need for Diluent flush can be anticipated.
5.3 Change to high set point at 15-20m	A8	Change to high setpoint not performed	Planned decompression plan and actual decompression plan may be different. Non-optimal PO_2 leading to higher decompression obligations. Higher gas volumes required for decompression, potential DCS if not spotted and diver forced to surface by insufficient decompression gas quantities.	5.5	M	!	Consider automation of CCR such that setpoint changed automatically, or provide user with audible cue to perform this task.
5.4 Listen for solenoid operation	C1	Solenoid not listened for	Solenoid potentially not operative	5.5	M	!	Monitor PO_2 at all times.

5.5 Check PO_2 intermittently	C1	PO_2 on descent not checked	Potential hyperoxic spike not anticipated. CNS toxicity, Convulsion, Drowning, Death.	6.1	M	!	Training – ensure CCR divers can mentally calculate PO_2 on the bottom from PO_2 at bubble check (1.6 atm), so need for Diluent flush can be anticipated.
5.5	C1	PO_2 on descent not checked	O2 cell readings not checked to see if they can read high (over 1.0), leading to hyperoxia. CNS toxicity, Convulsion, Drowning, Death.	None	M	!	Ensure that O2 cell life is not exceeded. Mandatory service intervals for CCR units. Education campaign in the diving press. "New for Old" offers by manufacturers. Training.
5.5	C1	PO_2 on descent not checked	Slow O2 cells not checked	None	M	!	Include O2 cell function as core theory within CCR course.
5.6 Check buddy	C1	Buddy not checked on descent	Potential separation on descent.	None	M	-	Education - while a buddy should not be relied upon for assistance, lives have been saved due to timely and appropriate buddy intervention.

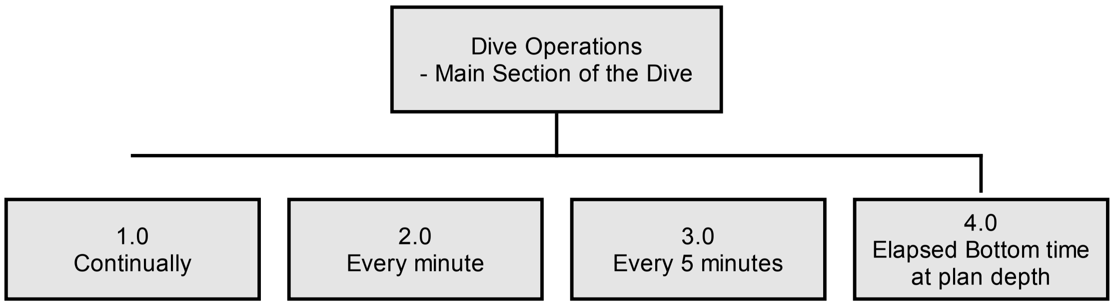
Arrival at Target Depth							
6.1 Check PO_2	C1	PO_2 at target depth not checked	Hyperoxic spike, CNS toxicity, Convulsion, Drowning, Death.	Open Loop Diluent Flush	H	!	Training – OLDF should be anticipated at arrival at target depth.
6.2.1 Check OPRV fully open	C1	OPRV not fully open	Diluent flush, gas not vented, buoyancy and increased WOB.	Exhale through nose, Open OPRV	M	-	Training, over-train this skill to ensure the CCR diver can locate OPRV instinctively.
6.2.3 Press manual diluent inflator button	A6	An inflator other than the manual diluent inflator is pressed (BCD inflate)	No diluent is added to loop, and positive buoyancy likely	Operate BCD deflation system	L	-	Ensure in training that a CCR diver can locate all relevant valves and inflators by touch alone.
6.2.3 Press manual diluent inflator button	A6	An inflator other than the manual diluent inflator is pressed (O2 inflator)	If O2 added then very high PO_2	Diluent flush, or bailout	M	!	Ensure in training that a CCR diver can locate all relevant valves and inflators by touch alone.
6.3 Check O2 SPG	C1	O2 SPG not checked	O2 supply system may be leaking.	Checks during dive. Buddy may spot leaks.	M	!	Training - monitor SPGs every 5 minutes

6.4 Check diluent SPG	C1	Diluent SPG not checked	Diluent supply system may be leaking.	Checks during dive. Buddy may spot leaks.	M	!	Training - monitor SPGs every 5 minutes
6.5 Check buddy arrived at plan depth and is OK	C1	Buddy check not performed	Buddy may have a problem you are unaware of.	None	M	-	Training - emphasise the advantages of diving as a team.

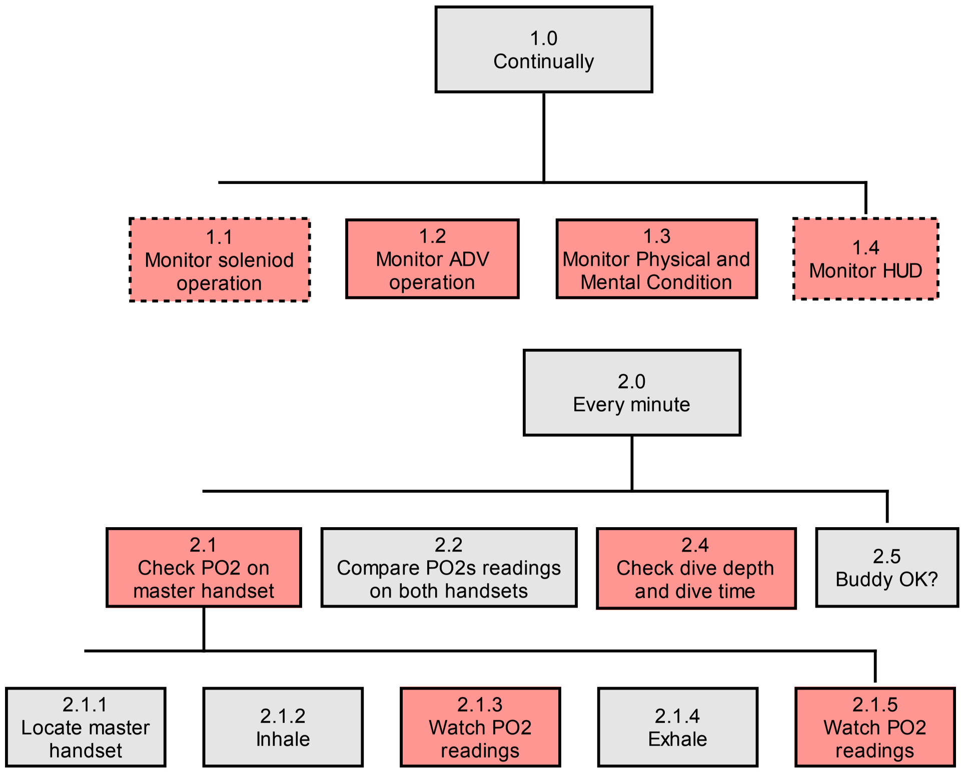
APPENDIX 7: HIERARCHICAL TASK ANALYSES FOR MAIN STAGE OF THE DIVE

Task Category Key:

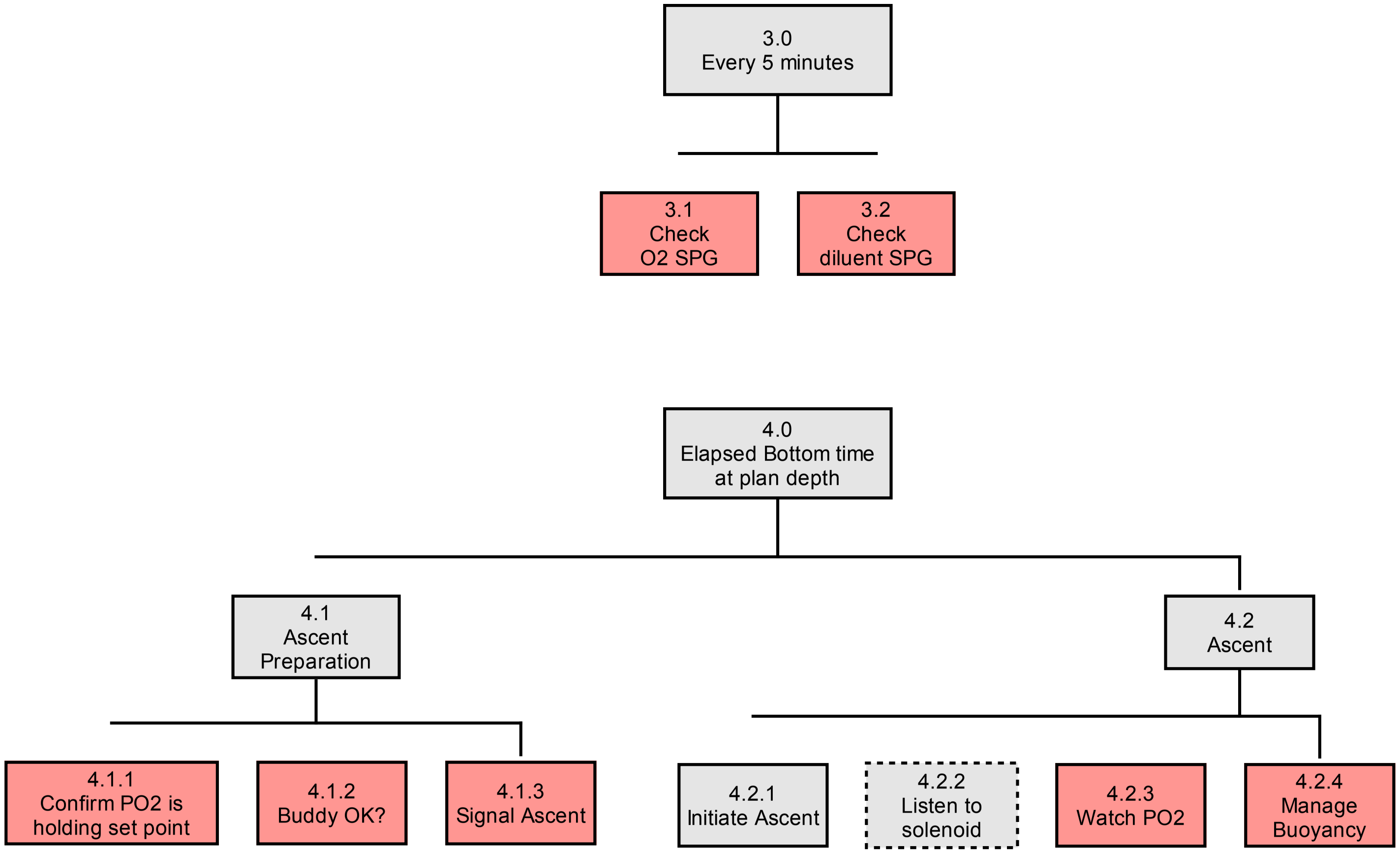
⬜ Task step with no error identified ⬚ Unit specific task step 🟥 Task step with viable error identified



MAIN DIVE HTA 0



MAIN DIVE HTA 1 & 2



MAIN DIVE HTA 3 & 4

APPENDIX 8: SHERPA ANALYSIS FOR THE MAIN STAGE OF THE DIVE

Main Dive Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
Monitor continually							
1.1 Monitor solenoid operation	C1	Solenoid operation not listened for	Solenoid may be non functional, or not injecting enough gas into the breathing loop.	PO_2 alarm	M	-	Design – ensure that solenoid action is audible.
1.2 Monitor ADV operation	C1	ADV operation not listened for	ADV may be adding diluent into the loop – suggesting there may be a leak	Diluent SPG check	M	-	
1.3 Monitor physical and mental condition	C2	Not being aware of deterioration of physical or mental condition	Unfortunately hypoxia, hyperoxia and hypercapnia may all cause diver disabling symptoms without warning; hypoxia causing unconsciousness, hyperoxia causing convulsions and hypercapnia causing irrationality, confusion, panic and unconsciousness making diver self-rescue impossible. Hypercapnia in high PO_2 environments may not present the diver with symptoms such as dyspnea, may cause convulsions (a symptom of Carbon Dioxide Narcosis) and may cause fatal secondary effects such as a CNS oxygen toxicity convulsion. If warning instrumentation fails or is absent, the passive failure modes involved in these conditions (especially hypercapnia and hypoxia) coupled with the insidious and incrementally compromising nature of physiological symptoms makes diver self-rescue extremely unlikely.	Buddy	M	*	Diving in a buddy team is a potential extra safety measure (especially in hypoxic and hypercapnic scenarios). In buddy diving situations, an additional HUD display that is visible to the buddy would provide a potential extra safety measure. Instrumentation to measure CO2 directly at the point downstream from the scrubber would potentially warn a CCR diver of rising CO2 levels indicative of breakthrough.
1.4 Monitor HUD	C1	HUD not monitored	Potential problems will be manifested through audible and tactile alarms	Audible alarm, tactile alarm	L	-	
Monitor every minute							
2.1	C1	PO_2 reading not checked on handsets	PO_2 levels may be diverging from the setpoint	Audible alarm, tactile alarm	M	!	Training – ensure that CCR divers are aware of the importance of knowing their PO2 at all times.

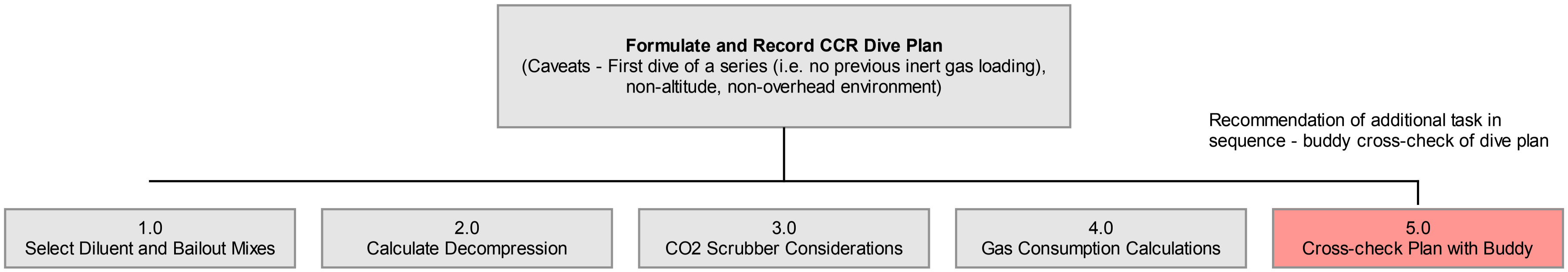
Main Dive Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
2.1.3 and 2.1.5 Monitor handsets during inhalation and exhalation	R3	PO_2 reading on handset not referenced during inhalation/ exhalation.	PO_2 readings on cells not seen to be moving, consequently cells that are slow to respond are not picked up.	None	M	-	Emphasis on procedure in training.
2.4 Check dive depth and time	C1	Dive depth and time not monitored	Diver may exceed dive depth and duration – consequently diving outside the plan.	None	M	-	Training – ensure that dive planning is emphasised in the training
Monitor every 5 minutes							
3.1 Check O2 SPG	R1/C1	O2 SPG not checked	O2 may be leaking	Low O2 alarm at O2 supply failure	M	!	Training
3.2 Check diluent SPG	R1/C1	Diluent SPG not checked	Diluent supply may be leaking (terminate dive) or ADV may be compensating for a leak in the breathing loop – and diver unaware (bailout to off-board supply)	None	M	!	Training
Ascent							
4.1.1 Confirm PO_2 is holding setpoint	C1	PO_2 versus setpoint check not performed prior to ascent	Potential O2 supply issue on ascent may cause hypoxia. O2 supply issue may result from jammed O2 solenoid valve or O2 supply failure.	Manual O2 inflator	M	!	Training
4.1.2 and 4.1.3 Confirm ascent with buddy	C1/A8	Ascent is not made with Buddy	Buddy unable to assist if CCR diver develops a problem on ascent, or during decompression	None	M	-	Training
4.2.3 Monitor PO_2	C1	PO2 not watched on ascent	Given that PO2 will be dropping on ascent, waiting for a low PO_2alarm may not give the CCR diver long enough to react, especially if ascent is rapid. Potential hypoxia, unconsciousness and death.	None	M	!	Training

Main Dive Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
4.2.4 Manage buoyancy	A8	Buoyancy not managed on ascent.	Potential rapid ascent, omitted decompression leading to DCI or AGE	None	M	!	Training – ensure that divers are taught a rapid ascent drill / how to deal with issues such as stuck inflators or ADV. Ensure that divers have enough practise of ascents during training course.

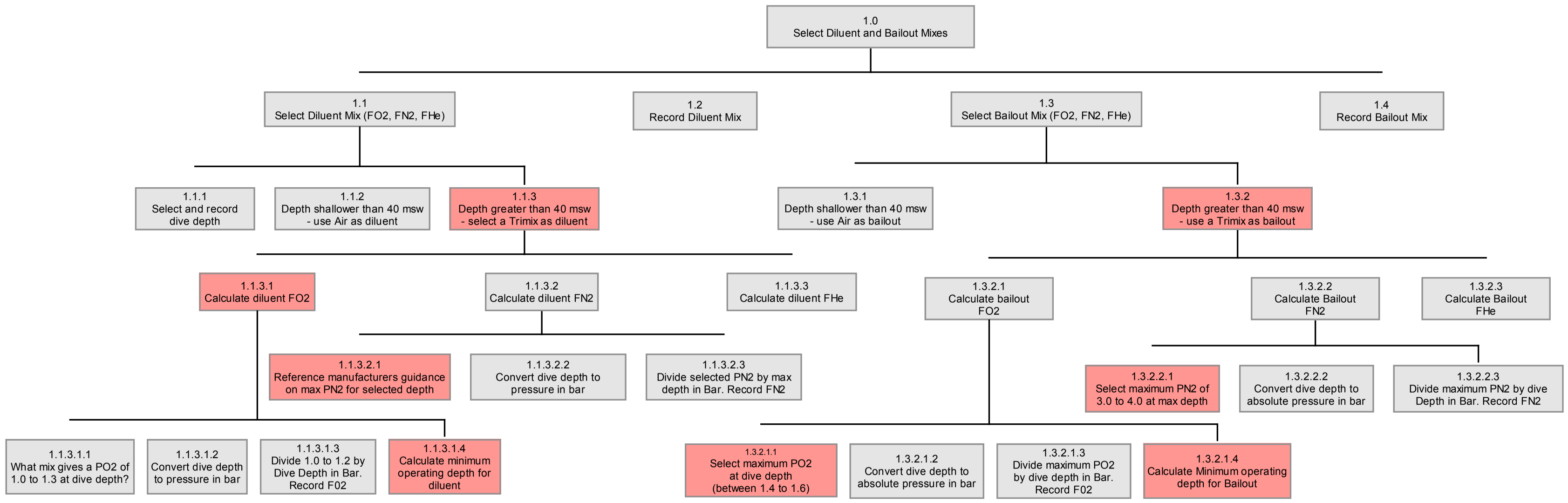
APPENDIX 9: HIERARCHICAL TASK ANALYSES FOR GENERIC CCR DIVE PLANNING (WITH NO PREVIOUS INERT GAS LOADING, NON-ALTITUDE, NON-OVERHEAD ENVIRONMENT DIVE)

Key:

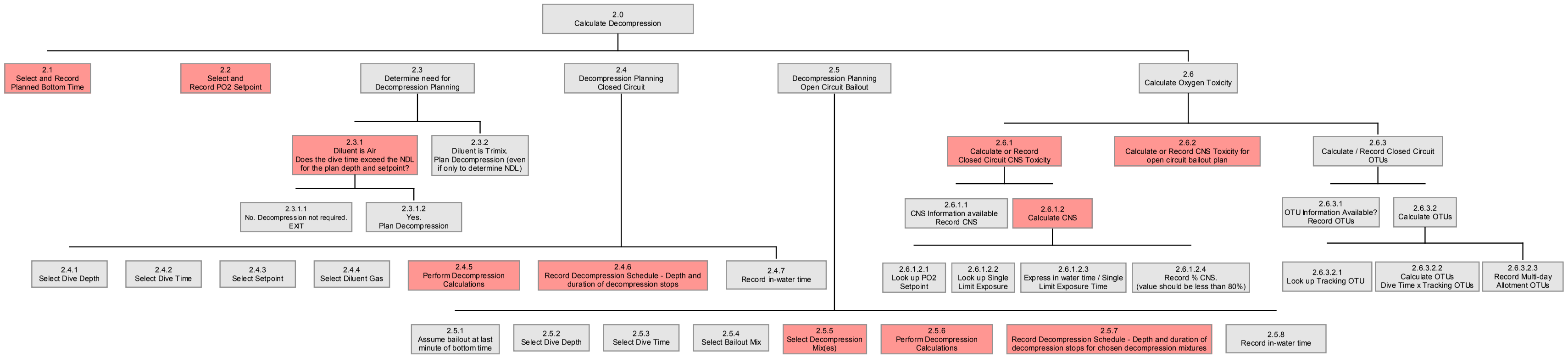
▨ Task step with no error identified ⬚ Unit specific task step 🟥 Task step with viable error identified



DIVE PLANNING HTA 0



DIVE PLANNING HTA 1



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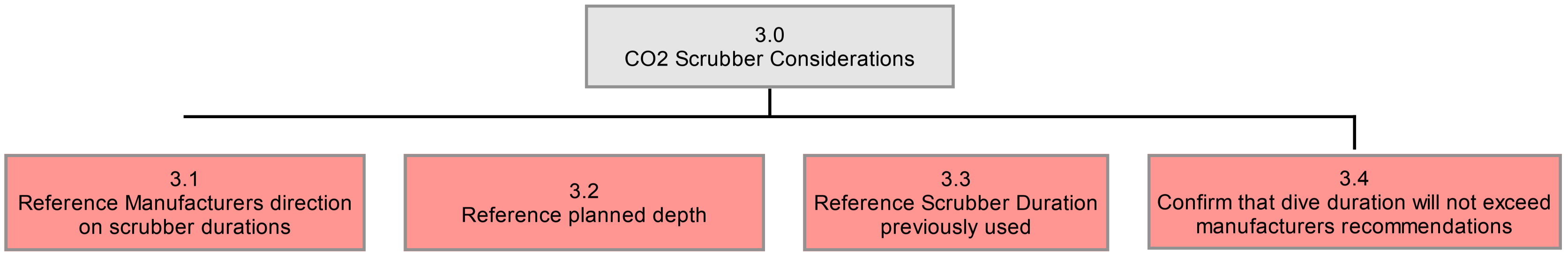

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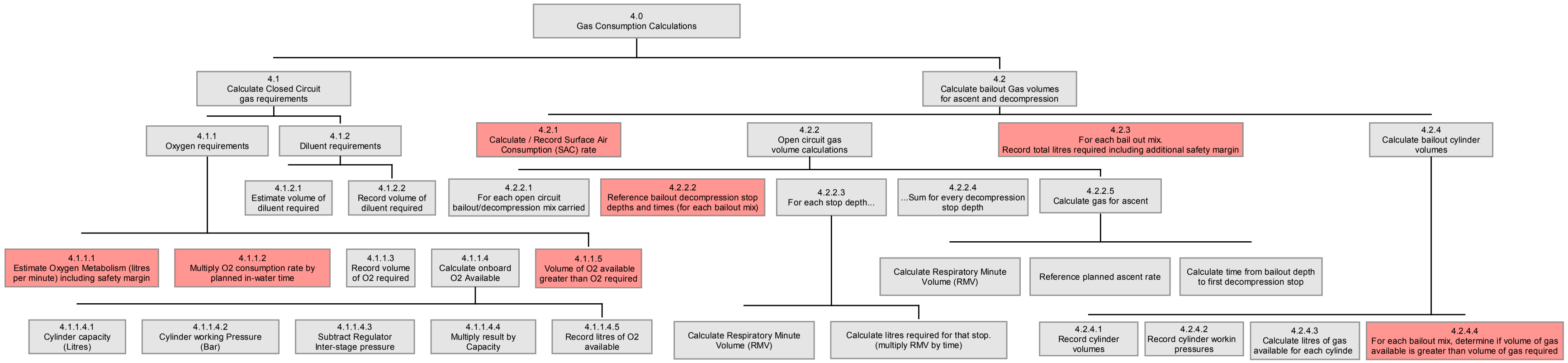
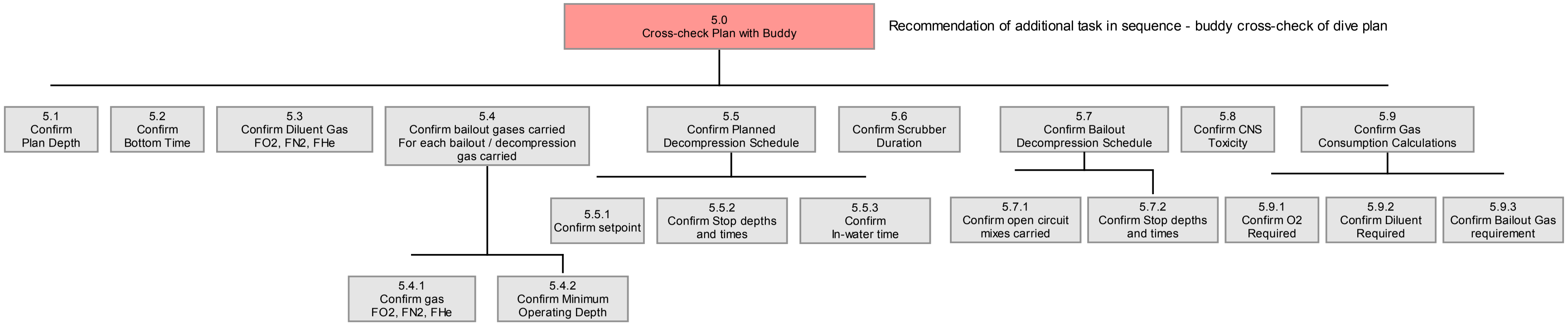


DIVE PLANNING HTA 4



Recommendation of additional task in sequence - buddy cross-check of dive plan

DIVE PLANNING HTA 5

APPENDIX 10: SHERPA ANALYSIS FOR GENERIC CCR DIVE PLANNING (WITH NO PREVIOUS INERT GAS LOADING, NON-ALTITUDE, NON-OVERHEAD ENVIRONMENT DIVE)

Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
Diluent Selection							
1.1.1 Select and record dive depth	R1	Dive depth not selected	Unable to make a dive plan.	5.1	L	-	Confirm dive depth with buddy.
1.1.3 Depth greater than 40 msw select a Trimix as diluent	R2	Trimix not selected for a dive greater than 40 msw	Nitrogen Narcosis, greater breathing resistance due to greater gas density.	5.3	M	!	Confirm diluent with buddy.
1.1.3.1 Calculate diluent FO2	R2	Diluent FO2 not calculated correctly	Diluent FO2 calculation incorrect. Either potential Hypoxia or Hyperoxia.	5.3	M	!!	Confirm diluent FO2 with buddy prior to dive. Use dive planning software.
1.1.3.1.4 Calculate minimum operating depth for diluent	R2	Minimum operating depth for diluent incorrectly calculated	Diver may breathe hypoxic diluent. Potential for instant unconsciousness, death.	5.3	M	!!	Confirm diluent FO2 with buddy prior to dive. Use dive planning software.
1.1.3.2.1 Calculate bailout FO2	R2	PN2 selected is too high Manufacturers maximum PN2 guidance ignored.	Loop gas density is above recommended limits. Increased CO2 retention, increased nitrogen narcosis, oxygen toxicity, potential DCS.	5.3.2	M	!	Reference manufacturer's maximum PN2 guidance. Confirm planned Diluent FN2 with buddy prior to dive.
Bailout Selection							
1.3.2 Depth greater than 40 msw - use a Trimix as bailout	R2	Trimix not selected as a bailout gas for use deeper than 40m	Excessive Narcosis, possible IBCD depending on gas loadings	5.4	M	B!	Confirm bailout FO2 with buddy prior to dive. Consider the use of dive planning software.

Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
1.3.2.1.1 Select maximum PO_2 at dive depth between (1.4 and 1.6)	S2	Maximum PO_2 selected for bailout incorrect	Either, Decompression not optimised (PO_2 too low) or risk of CNS toxicity.	5.4.1	M	B!	Confirm planned bailout PO_2 with buddy prior to dive. Consider the use of dive planning software.
1.3.2.1.3 Divide maximum PO_2 by dive depth in Bar. Record FO2	R2	Bailout FO2 not calculated correctly	Bailout FO2 calculation incorrect. Either potential Hypoxia or Hyperoxia if Bailout is used.	5.4.1	M	B!!	Confirm planned Bailout FO2 with buddy prior to dive. Consider the use of dive planning software.
1.3.2.1.4 Calculate Minimum operating depth for Bailout	R2	Minimum operating depth for bailout not calculated	Diver may breathe hypoxic bailout. Potential for instant unconsciousness, death.	5.4.2	M	B!!	Confirm bailout mixes FO2 and minimum operating depths with buddy prior to dive. Consider the use of dive planning software.
1.3.2.2. Calculate Bailout FN2	R2	Bailout FN2 is incorrectly calculated	Excessive nitrogen narcosis, possible IBCD on bailout depending on gas loadings	5.4.1	M	B!	Confirm planned Bailout FN2 with buddy prior to dive. Consider the use of dive planning software.
1.3.2.2.1 Select maximum PN2 of 3.0 to 4.0 at max depth	S2	An excessive maximum PN2 value is used for FN2 calculation	Excessive nitrogen narcosis, possible IBCD on bailout depending on gas loadings	5.4.1	M	B!	Confirm planned Bailout FN2 with buddy prior to dive. Consider the use of dive planning software.
Decompression Calculations – closed circuit							
2.1 Select and Record Planned Bottom Time	A8	Dive duration not planned	Decompression plan and gas volume consumption calculations cannot be performed. Potential to run out of gas or suffer DCI	5.2	L	-	Confirm dive duration with buddy.
2.2 Select and Record PO_2 Setpoint	A8	Planned dive setpoint not selected	Unable to complete decompression plan (and therefore gas consumption calculations	5.5.1	L	-	Confirm dive setpoint with buddy. Consider the use of dive planning software.
2.2 Select and Record PO_2 Setpoint	R2	Non-optimal setpoint determined	Either decompression is not optimised or risk of CNS toxicity	5.5.1	L	!	Confirm planned setpoint with buddy prior to dive. Consider the use of dive planning software.

Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
2.3.1 Diluent is Air Does the dive time exceed the NDL for the plan depth and setpoint?	R1	Requirement for Decompression planning not established	The dive planned is a decompression dive and this has not been established. Decompression planning not conducted; gas consumption requirements for decompression not determined. Potential DCI or drowning.	5.5	M	!	Confirm dive decompression plan with buddy. Consider the use of dive planning software.
2.4.5 Perform Decompression Calculations	R2	Diver undertakes decompression diving without calculating decompression stops	Diver relying on decompression dive computer to calculate decompression stops. Failure of equipment leads to diver not knowing what schedule to follow (Potential DCI). Gas requirements for decompression not established, potential to have insufficient quantities of O2 available (DCI or Hypoxia, Death).	5.5	M	!	Plan all decompression dives, have a written decompression schedule if dive fails. Consider redundant dive computers and/or instrumentation.
2.4.5 Perform Decompression Calculations	R2	Incorrect decompression schedule calculated	DCI.	5.5.2	M	!	Confirm decompression plan with buddy. Use decompression software (rather than decompression tables). Carry and monitor dive decompression computers.
2.4.6 Record Decompression Schedule - Depth and duration of decompression stops	R2	Incorrect decompression schedule recorded	DCI.	5.5.2	L	!	Consider the use of dive planning software directly printing and laminating decompression schedules to avoid copying errors. Cross-check decompression schedule with buddy.
Decompression Calculations – bailout							
2.5.1 Assume bailout at last minute of bottom time	R2	Diver does not assume bailout situation occurs at last minute of bottom time	Calculations are not "worst-case scenario", decompression requirement may exceed emergency decompression plan	5.7	M	B!	Confirm dive decompression plan with buddy. Consider the use of dive planning software.

Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
2.5.5 Select Decompression Mix(es)	R2	Bailout Decompression mixes selected are not optimal	Decompression takes longer than necessary.	5.7.1	M	-	Consider decompression software which recommends optimal decompression mixes for any planned dive.
2.5.6 Perform Decompression Calculations	R2	Incorrect bailout decompression schedule calculated	DCI.	5.7.2	M	B!	Confirm decompression plan with buddy. Use decompression software (rather than decompression tables).
2.5.7 Record Decompression Schedule - Depth and duration of decompression stops for chosen decompression mixtures	R2	Incorrect decompression schedule recorded	DCI.	5.7.2	L	!	Consider the use of dive planning software directly printing and laminating decompression schedules to avoid copying errors. Cross-check bailout decompression schedule with buddy.
Oxygen Toxicity Considerations							
2.6.1 Calculate or Record Closed Circuit CNS Toxicity	R1	CNS toxicity risk ignored	CNS Convulsion, Drowning, Death	5.8	M	!!	Confirm dive decompression plan with buddy. Consider the use of dive planning/decompression software.
2.6.1.2 Calculate CNS	R2	CNS toxicity incorrectly calculated	CNS Convulsion, Drowning, Death	5.8	M	!!	Confirm dive decompression plan with buddy. Consider the use of dive planning/decompression software.
2.6.2 Calculate or Record CNS Toxicity for open circuit bailout plan	R1	CNS toxicity for bailout plan incorrectly calculated	CNS Convulsion, Drowning, Death	5.8	M	!!	Confirm dive decompression plan with buddy. Consider the use of dive planning/decompression software.
2.6.3 Calculate / Record Closed Circuit OTUs	R1	OTUs not tracked	Pulmonary oxygen toxicity. Myopia.	None	M	!	Emphasise during training situations where Pulmonary oxygen toxicity should be considered.

Scrubber Endurance							
3.1 Reference Manufacturers direction on scrubber durations	R1	Diver does not reference manufacturers guidance on scrubber endurance	Scrubber endurance may be exceeded. CO2 Breakthrough, Hypercapnia. Death / Bailout	5.6	H	!!	Consider printing scrubber endurance information on the CCR unit, or publishing waterproof reference cards for essential unit information. Make divers aware that they can be incapacitated without any warning symptoms in high PCO2, high PO_2 environments (i.e. no opportunity to bailout). Incorporate the teaching of the dangers of carbon dioxide narcosis into CCR diving courses.
3.2 Reference planned depth	R2	Diver does not factor depth into scrubber endurance calculation	Scrubber endurance may be exceeded. CO2 Breakthrough, Hypercapnia. Bailout.	5.6	H	!!	Emphasis on point during training. Refer to and follow manufacturer’s guidance to the letter. Confirm scrubber duration with buddy. Make divers aware that they can be incapacitated without any warning symptoms in high PCO2, high PO_2 environments (i.e. no opportunity to bailout). Incorporate the teaching of the dangers of carbon dioxide narcosis into CCR diving courses.
3.2 Reference planned depth	R2	Diver exceeds manufacturers published scrubber duration because water is warm or low work rate assumption	Scrubber endurance may be exceeded. CO2 Breakthrough, Hypercapnia. Bailout.	5.6	H	!!	Training/education - always be conservative in calculating scrubber duration, always use fresh scrubber material for deep and/or cold water dives. Make divers aware that they can be incapacitated without any warning symptoms in high PCO2, high PO_2 environments (i.e. no opportunity to bailout). Incorporate the teaching of the dangers of carbon dioxide narcosis into CCR diving courses.
3.3 Reference Scrubber Duration previously used	R2	Use of scrubber on previous dive(s) is incorrectly factored into scrubber duration calculation	Scrubber endurance may be exceeded. CO2 Breakthrough, Hypercapnia. Bailout.	5.6	H	!!	Training/education - always be conservative in calculating scrubber duration, always use fresh scrubber material for deep and/or cold water dives. Make divers aware that they can be incapacitated without any warning symptoms in high PCO2 high PO_2 environments (i.e. no opportunity to bailout). Incorporate the teaching of the dangers of carbon dioxide narcosis into CCR diving courses.

3.4 Confirm that dive duration will not exceed Manufacturer’s recommendations	R1	Remaining scrubber endurance is estimated correctly; however this is not cross checked to in water time for the planned dive.	Scrubber endurance may be exceeded. CO2 Breakthrough, Hypercapnia. Bailout.	5.5.3 and 5.6	H	!!	Dive conservatively. Confirm with buddy. Make divers aware that they can be incapacitated without any warning symptoms in high PCO2, high PO_2 environments (i.e. no opportunity to bailout). Incorporate the teaching of carbon dioxide narcosis into CCR diving courses.
Gas Consumption – Closed Circuit							
4.1.1.1 Estimate Oxygen Metabolism (litres per minute) including safety margin	R2	Oxygen metabolic rate not estimated correctly with appropriate work rate in emergency situation.	Although insufficient on-board Oxygen to complete the dive is a very serious situation, a mistake on litres of O2 consumption per minute is unlikely to cause an error resulting in running out of O2 (due to so much excess O2 capacity carried)	5.9.1	L	!	Confirm O2 gas planning with buddy. Carry redundant supplies of O2 capable of being plugged into CCR breathing loop.
4.1.1.2 Multiply O2 consumption rate by planned in-water time	R1/R3	Oxygen volume requirement not calculated correctly (in water time not established or calculated correctly)	Insufficient on-board Oxygen to complete the dive. Bailout.	5.9.1	M	!	Critical factor on deep dives requiring extensive decompression. Confirm O2 gas planning with buddy. Ensure cylinders are filled adequately, monitor O2 SPG.
4.1.1.5 Volume of O2 available greater than O2 required	R1	Omitted check to establish that available volume of O2 is sufficient for the dive.	Insufficient on-board Oxygen to complete the dive. Bailout.	5.9.1	M	!	Confirm O2 gas planning with buddy. Ensure cylinders are filled adequately, monitor O2 SPG.
4.1.2.1 Estimate volume of diluent required	R1	Diluent requirement not referenced or calculated correctly	Implications for clearing loop floods, diluent flushes, buoyancy.	5.9.2	M	-	Refer to manufacturer’s guidelines and training agency recommendations.
Gas Consumption -Open Circuit Bailout							

4.2.1 Calculate / Record Surface Air Consumption (SAC) rate	R1	SAC rate calculated incorrectly (not conservative enough)	Open circuit bailout gas volume calculations inaccurate. DCI or Drowning.	5.9.3	M	B!!	Calculate SAC rate for trainee students / incorporate into training. Calculate conservatively. Consider the use of dive planning software with gas volume calculation functionality.
4.2.2.2 Reference bailout decompression stop depths and times (for each bailout mix)	R2/R3	Bailout decompression plan not calculated	Gas volume calculations cannot be performed. DCI or Drowning.	5.9.3	M	B!!	Confirm decompression plan with buddy. Use decompression software. Carry laminated tables for OC bailout. Use dive computers.
4.2.2.4 …Sum for every decompression stop depth	R1/2	Bailout gas quantity not correctly calculated	Open circuit bailout gas volume calculations inaccurate. DCI or Drowning.	5.9.3	M	B!!	Confirm Bailout gas planning with buddy. Calculate conservatively. Consider the use of dive planning software with gas volume calculation functionality.
4.2.3 For each bail out mix. Record total litres required including additional safety margin	R2	Adequate levels of conservatism not built into open circuit bailout calculations	Open circuit bailout gas volume is insufficient. DCI or drowning.	5.9.3	M	B!!	Confirm Bailout gas planning with buddy. Calculate conservatively. Consider the use of dive planning software with gas volume calculation functionality.
4.2.4.4 For each bailout mix, determine if volume of gas available is greater than volume of gas required	R1/2	Verify bailout cylinder capacities and fill pressures are sufficient for OC bailout	Open circuit bailout gas volumes carried not greater than planned gas volume requirements. Potential issue with rental stage bottles, unfamiliar capacity units etc. Open circuit bailout gas volume is insufficient. DCI or drowning.	5.9.3	L	B!!	Education – conversion of imperial and metric capacity units, information on reading of cylinder capacities on cylinders.

Cross-check of Dive Plan with Buddy ***(recommendation for additional task)***							
5.0 Cross-check Plan with buddy	C1	Dive plan is not checked with buddy prior to dive	There are a number of aspects of checking the plan with a dive buddy. Firstly is the plan as generated error free (i.e. no mistakes have been made in calculation of the plan). Secondly are the two dive plans in the buddy pair similar to the extent that they can be cross checked? Cross checking relies on dive planning calculations independently made and then referenced against each other. No opportunity to recover from any of the dive planning error consequences described above – such as insufficient on-board gas (hypoxia, death), insufficient bailout (drowning), incorrectly calculated decompression (DCI), incorrectly calculated CNS toxicity (hyperoxia, convulsions drowning), incorrectly calculated scrubber duration (hypercapnia, unconsciousness, drowning)	one	H	!	Encourage CCR divers to operate as a team prior to entering the water. Consider the use of dive planning and decompression software to plan dives and consider aligning plans so that buddy teams remain together throughout the dive. Consider teaching buddy planning as part of CCR diving courses.
5.3 Confirm Diluent Gas FO2, FN2, FHe	C1	A mistake in choice of diluent may have been made and the error not trapped	Nitrogen Narcosis, Hypoxia, Hyperoxia, increased breathing resistance, excessive Decompression requirements.	None	M	!!	Consider the use of dive planning software, or cross reference your dive plan with your buddy.
5.4.1 Confirm gas FO2, FN2, FHe	C1	A mistake in choice of bailout may have been made and the error not trapped	Nitrogen Narcosis, Hypoxia, Hyperoxia, excessive Decompression requirements.	None	M	!!	Consider the use of dive planning software, or cross reference your dive plan with your buddy.

5.4.2 Confirm Minimum Operating Depth	C1	A mistake in calculation of minimum operating depth of bailout gas may have been made and the error not trapped	Hypoxia, immediate unconsciousness.	None	M	!!	Consider the use of dive planning software, or cross reference your dive plan with your buddy.
5.5.1 Confirm setpoint	C1	Setpoint selection error not trapped	Decompression not optimal	None	L	-	Consider the use of dive planning software, or cross reference your dive plan with your buddy.
5.5.2 Confirm Stop depths and times	C1	Incorrect Decompression plan not trapped	Decompression plan incorrect for dive	None	M	!	Consider the use of dive planning software, or cross reference your dive plan with your buddy.
5.5.3 Confirm In-water time	C1	Total in-water time calculation error not trapped	In water time not correctly calculated (may impact on scrubber duration requirement)	None	M	-	Consider the use of dive planning software, or cross reference your dive plan with your buddy.
5.6 Confirm Scrubber Duration	C1	Scrubber duration overestimation error not trapped	Hypercapnia, confusion, unconsciousness.	None	M	!!	Consider the use of dive planning software, or cross reference your dive plan with your buddy.
5.7.2 Confirm Stop depths and times	C1	Bailout decompression schedule incorrect and the error not trapped	DCI if bailout used	None	M	!	Consider the use of dive planning software, or cross reference your dive plan with your buddy.
5.8 Confirm CNS Toxicity	C1	CNS toxicity underestimated and the error not trapped	CNS convulsion, drowning, death.	None	M	!!	Consider the use of dive planning software, or cross reference your dive plan with your buddy.
5.9.1 Confirm O2 Required	C1	O2 volume requirement underestimated and the error not trapped	Not enough O2 to complete dive	None	M	!!	Consider the use of dive planning software, or cross reference your dive plan with your buddy.
5.9.2 Confirm Diluent Required	C1	Diluent volume requirement underestimated and the error not trapped	Diluent flush not available, potential buoyancy issues	None	M	!	Consider the use of dive planning software, or cross reference your dive plan with your buddy.
5.9.3 Confirm Bailout Gas requirement	C1	Bailout volume requirement underestimated and the error not trapped	Not enough bailout to complete the dive.	None	M	B!!	Consider the use of dive planning software, or cross reference your dive plan with your buddy.

APPENDIX 11: EXAMPLES OF CCR UNIT LOCKDOWN PROTOCOLS

A. QINETEQ AND HSL GUIDANCE PROVIDED BY GAVIN ANTHONY

GUIDANCE IN THE EVENT OF HANDLING DIVING EQUIPMENT POST ACCIDENT

Personal Safety

If mishandled, diving equipment can be hazardous to health.

Do not place any person in a dangerous situation to recover any equipment.

Diving equipment may contain gas at high pressure.

Re-breathing equipment may contain hazardous chemicals.

Diving equipment may be heavy, ensure when lifting equipment that correct handling techniques are used.

General Procedure

DO NOT DISMANTLE THE EQUIPMENT

Record the following dive information:

- Date, time and location of incident.
- Dive time and maximum depth of dive for the diver and any companions.
- Dive plan, decompression schedules used and if completed correctly.

Try to handle the equipment as little as possible.

Note and record on recovery of equipment:

- If buoyancy device or dry suit hoses are connected on recovery.
- If equipment was damaged, prior to or during recovery.
- Information displayed on a dive computer at time of recovery.
- All pressure displays/gauges and record pressures.
- Any details displayed on other electronic instruments.

Gather together and isolate all equipment involved in the accident, including:

- Dive Slate/Logs covering previous 48 hours.
- If available at least one other gas cylinder charged from the same source.

Attempt (do not force) to close all cylinder and isolator valves, note and record number of turns required for each valve (1 turn = 360°).

Tape valves on cylinders and manifolds in the closed position.

Tape any controls or valves on regulators, buoyancy devices and dry suits (including swivel inflation connections) in the position found to prevent any inadvertent movement.

Specific for re-breathers

All re-breather mouthpieces to be closed.

The rebreather to be stored in an upright position.

Close any automatic overpressure exhaust valves (note number of clicks or turns needed to close valve).

Retain and keep with incident apparatus any samples of unused soda lime (from same batch) in the original container.

For storage and transportation

Allow any computer(s) to go into standby mode preferably by air-drying or switch computer off.

DO NOT

- Seal wet electronic equipment in plastic bag (a discharged battery can wipe any memory available).
- Leave valves open on cylinders.
- Vent the gas in a cylinder prior to transport.
- Move maximum depth recordings on analogue gauges.
- Change position on any regulator controls.

B. GUIDANCE PROVIDED BY MARTIN PARKER OF AP DIVING

EQUIPMENT INSPECTION FOLLOWING A DIVING INCIDENT.

A step by step guide:

Photography:

It is absolutely essential to photograph everything. Sometime later when you are working through scenarios, you will need to know what was connected to what, which side each cylinder was, how close to his body was it mounted, did he have dive reel etc – the possibilities of future questions are endless and the photos taken at this stage could prove invaluable. I would strongly advise that the photographer be a separate person to the equipment examiner and ensure the photographer is briefed on getting a shot of everything both prior and during dis-assembly.

Record Keeping:

Again, it is absolutely essential to record everything you do and find. E.g. If you are inspecting the diluent side and find no fault then write “No fault found” – you are going to need this data later.

The equipment inspection is a time for data collection – leave the analysis of the cause of the incident until afterwards, when you have all the data in and you have time to cross-reference with autopsy findings and statements.

Autopsy:

All too often a verdict of “death by drowning” is recorded.

A proper autopsy can reveal much: Contact Dr M. Calder – calderpath@hotmail.com. Telephone: 01223 277220 – a pathologist specialising in deaths in water.

Recovery:

On the bottom:

The divers need to be briefed on what to look for:

Does the diver have his mouthpiece in?

Mask On?

Is he heavy on the bottom or semi-floating?

Is there a beeping noise? If so –where is it coming from?

Are there any bubbles – if so where from?

Ensure they do not touch the cylinder valves.

Ensure they do not touch the handsets – If the diver is using a Classic Inspiration ask them to note whether the switches are towards the screen or towards the hose – on the diver’s left hand set and the diver’s right hand set – but don’t touch the switches.

(The reason for asking this is to test for continuity of evidence).

When they find the body, it’s likely to be a time of high stress for the rescue diver. Getting him to work to a checklist may help – but something to stress is that they are not to endanger themselves any more than a normal dive to that depth. **I don’t think it is reasonable to bring the diver slowly to the surface - Simply attach a lift bag to the top handle of the rebreather, ensuring the diver is still in the harness properly and send him up.**

Get statements from the divers as soon as possible after surfacing. The Police should be involved with this.

At the surface:

Once at the surface it is very common for the Police to take over. The best Police forces recover the body and equipment intact and follow a procedure similar to this, please communicate with them before the recovery if possible to ensure the continuity of evidence is assured. Try to get them to recover the body and equipment by holding the top handle and NOT the rear convoluted breathing hoses, the combined weight of the equipment and diver – they will pull the T piece fittings from the counterlungs!

It will help if the diver can be recovered to the shore with equipment still attached.

If the equipment can be kept on the diver when he is recovered lay him on his back and photo everything. Shots of the complete ensemble, shots of gauges, control valves, 1st stages, 2nd stages, rebreather front, back, side and top shots.

Equipment Inspection

Often the equipment inspector has no involvement until this stage. It is necessary to get some assurance from the Police that the equipment is received – as it was recovered from the water. If cylinder valves have been closed then it is necessary to get that information prior to your inspection.

Try and read witness statements prior to doing the equipment inspection – was the diver red faced on recovery or did he have cyanosis?

Try and glean some information regarding the incident:

Did the problem happen at the surface? – in which case High O2 is ruled out.

How soon into the dive did the problem occur? – Try and get a copy of the download from his dive computer.

Important Notes:

Classic Inspiration: *never switch on both handsets. Each handset has separate information which can be gleaned. Inspect one handset, switch off and then switch on the other handset.*

Vision Inspiration and Evolution: *the dive data must be downloaded before the unit is submerged again. If you switch the unit on and submerge the unit below 1.2m it will start to record over the top of the incident dive data ! The Vision stores in hard memory the dive info for nine hours of diving. It is stored in hard memory so even when the batteries die the information is retained. If the diver is submerged for some time, then it is the first nine hours that is retained in memory.*

The rebreather's job is to control CO_2, PO_2 and provide a breathing circuit – so those are the areas you need to concentrate on:

1) Is the loop intact?
2) Did the diver have a CO_2 hit? Mouthpiece valves?/ CO_2 bypassed the scrubber?/Scrubber material?
3) Was the machine switched on? Was it capable of controlling the PO_2?
4) From the circumstances - is it possible to determine whether high O_2 or low O_2 is most likely to be the problem and is there evidence from the equipment examination to support one line of thought rather than another?

At the end – you may be simply required to state what you think is the most likely cause of the incident – but you will need to state whether there was anything in the equipment inspection to support that. I strongly suggest an opinion isn't given until all the facts are gleaned.

The order of equipment test may vary with the state the equipment is in. If the mouthpiece is closed and the product is in good condition, it may be appropriate to place on a breathing simulator for a CO_2 challenge. Qinetiq at Alverstoke is the centre for such testing in the UK.

Work slowly and methodically:

a) Examine the loop for air tightness (positive pressure test)

- i) is the mouthpiece open or closed?
- ii) What is the pressure relief valve setting, fully open (counter-clockwise), half open or fully closed (clockwise)?
- iii) note if and where the loop is leaking

b) If a strip down is necessary, start with the gas cylinders, one by one:

- i) identify which gauge is with which cylinder
- ii) note the pressure and photograph the gauge
- iii) identify which cylinder is connected to the ADV and manual inflators)
- iv) check the cylinder valves – are they open or closed ? (some get confused with inverted cylinders – looking on the knob, clockwise is closed, anti-clockwise is open – sorry to state the obvious but this has been messed up on two separate equipment inspections that I know of – it seems the inverted cylinders may have caused confusion.)
- v) if gas leaks from a fitting – close the cylinder valve immediately – and identify where the gas is leaking from:
    - a. is the 1st stage attached to the cylinder valve properly?
    - b. Are all the hoses connected properly?
    - c. Are any hoses damaged?
    - d. Is the gas leaking from the 2nd stage?
    - e. Is the 2nd stage intact?
    - f. Basically identify and record what you find.
- vi) analyse the gas for oxygen content and if appropriate for helium content
- vii) consider checking gas for oil and Carbon monoxide contamination with relevant Draeger tubes
- viii) if the cylinder is empty – check for water – de-valve and empty into a measuring jug, note the volume of water.

c) Examine the loop for constrictions, components inserted in the loop such as mouthpiece with small orifice, VR3 4th cell holder – is the convoluted hose kinked?, are any of the convoluted hoses kinked?

d) Remove the mouthpiece and hoses at the T pieces,

- i. tip any liquids into a receptacle (extreme caution required – in the event of a pulmonary baratrauma (burst lung) there is potential for blood and body fluids to be in the exhale hose.)
- ii. The non-return valves need to be tested for back leaks – consider very carefully how this is to be achieved – ideally it needs to be done prior to cleaning so connectors may need to be employed.

e) Check the counterlungs for water and empty into a measuring jug.

f) Remove the canister from the loop by disconnecting at the T pieces.

- i) remove the lid
- ii) note if there is any liquid on top of the scrubber cartridge (if there is a volume of water then this would imply there has been no CO2 bypassing the Sofnolime. Tip the liquid out, measuring and noting the volume.
- iii) Check to see whether the scrubber spacer ring and O ring are in place and located correctly
- iv) Push down on the scrubber cartridge – does it travel up and down freely?
- v) Remove Spacer, O ring and Sofnolime cartridge

vi) Measure the position of the bottom "spider" – it should be only just inside the scrubber cartridge.
vii) Insert the complete scrubber cartridge in a strong polythene bag and seal it with a polythene bag sealer. (Even if soaked, it is possible to have the scrubber material analysed – contact Gavin Anthony – Qinetiq, Alverstoke: www.qinetiq.com .
viii) At this stage it is quite okay to remove the bottom spider and take a look at the material – what brand and grade is it? But, then simply screw the bottom spider back in place – under NO circumstances should the scrubber material be emptied.
ix) Try and impound the container with any unused scrubber material from the diver's home. (This will be required by QinetiQ (pronounced Kinetic)).
x) Try and glean some information from witnesses regarding the renewal of the Sofnolime.
xi) Tip the moisture from the scrubber base into a measuring jug and note the volume.

Lid and Handset examination:

It is difficult to give a step by step guide for the lid and handset because much will depend on the condition of the components in the lid. If the lid was flooded for some time, then the batteries and battery contacts may be destroyed. The oxygen cells may not be functioning properly or even be functioning at all. The difficult part is trying to determine what damage was there at the time of the incident and what is a result of what happened after the incident.

Just how much you re-build the power supply and oxygen cells depends on what you are trying to achieve. If the components need re-building by replacing components – are you really going to be able to prove anything ? e.g. on the Classic - if the handsets are badly flooded the electronic modules might be affected depended on how long they've been flooded – so you can rebuild the lid components to find the handsets don't work – but where has that got you?

With the Vision electronics – the priority is to power up the system so you can download the dive data. Using the LogViewer program a lot of information regarding the incident will be gleaned – so with the Vision it would be appropriate to re-build the entire power supply if necessary (if an external (6 volt DC power source is used it is essential to guarantee the correct polarity – incorrect polarity will damage the electronics.)

With the Classic there is very little data to be gleaned from the handsets. Slip the front covers off and inspect for water. If water is present it will have to be emptied and dried before any testing. The switch is unlikely to survive a flood. Are the handsets flooded due to a broken handset or has water passed down from the lid?

Oxygen cells might recover if allowed to dry. Simply measure the voltage of the cell by using a digital voltmeter across the outside two pins. On the Co-axial style connectors it is essential to use a spare connector – push it onto the cell and place the DVM probes on the connector. Under no circumstances should the DVM probes be inserted down the centre of the cell's co-xial connector – you will destroy the +ve contact.

Measure the voltage of the batteries - noting which battery comes from which slot (Controller One's battery is closest to the junction box on the Classic), Measure the voltage at rest and if live, under load – operating the solenoid. (I would use another solenoid for this test – simply bend the terminals on the solenoid out slightly so the terminals can bridge the battery contacts).

Classic Handset examination:

Note the position of the on/off switch on each handset.

Try switching on one handset (and ONE handset ONLY!!). Make a note whether it fires up or not. DO NOT calibrate! Make a note of what the handset says – at this stage it is simply going through a diagnostic check and will advise which oxygen cells are out of range. Make a note of the Elapsed on Time. Switch off. Do the same with the 2nd handset.

Assuming everything is in reasonable condition: Connect on some oxygen (from one of your cylinders) and see if the solenoid operates and adds oxygen, measure the O2 % - place the lid in a polythene bag, place an oxygen sensor inside the bag and feed out to your DVM.

C. GUIDANCE PROVIDED BY KEVIN GURR VR TECHNOLOGY

RB INCIDENT RECORDING

INTRODUCTION

The following is offered as a method of recording the state of any recovered equipment after a diving incident. In the event of a diving injury or fatality this form may be used to record other useful findings for the Authorities or training agency involved.

This document covers the two types of information needed;

1. Mandatory information (in Red). Mandatory information should be collected as soon as possible.
2. Additional information to be collected whenever possible (in black).

RECORDING OF DATA

Please complete this form as accurately as possible. Wherever possible the form should be backed up by photography or video. It is important to record the results without altering the state of the equipment (Other than those items noted). If an item of equipment has to be moved or an adjustment made (in the case of a free-flowing regulator), the pre adjustment/position state should be logged.

Remember any small piece of information may prove vital. Where ever possible take pictures or video as well.

This information may become evidence in a court of law. It must be kept private and confidential.

In the case of a recovery of a submerged diver, it may also be useful to record the 'as discovered state' of the person and equipment.

PRIMARY ASSESSMENT. INITIAL DATA COLLECTION.

UNDERWATER RECOVERY

If the equipment/diver is recovered underwater the following steps should be undertaken;

1. Ensure the RB mouthpiece is closed (this will help retain a gas sample within the loop for analysis)
2. Note the position of any cylinder valves and close ('clockwise closes') them to prevent further gas loss
3. Note the readings on any computer or analogue displays before ascending (do not turn off the electronics)
4. Ascend slowly with unit, maintaining positive buoyancy to prevent flooding and vent as required.
5. Photographs/video should be taken wherever possible.

SURFACE RECOVERY

If the equipment/diver is recovered on the surface the following steps should be taken;

1. Ensure the RB mouthpiece is closed (this will help retain a gas sample within the loop for analysis)
2. Note the position of any cylinder valves and close them to prevent further gas loss
3. Note the readings on any computer or analogue displays. Turn off the electronics to save battery power and prevent data loss, especially if the unit has download capability.
4. Photographs/video should be taken wherever possible.

AS SOON AS POSSIBLE A MANUFACTURERS REPRESENTATRIVE SHOULD BE CONTACTED AND ANY DIVE DATA DOWNLOADED, IF POSSIBLE.

Upon completion of this form the equipment should be placed in a secure container and not be tampered with again until collected by the recognised authority.

ON SURFACING RECORD FORM: RBI-01 DECEMBER 2006.

Note Copies of this document are confidential and may be used as evidence. Please supply a copy to the Police or Coast Guard upon request.

Recorders Name		**Date**	
Time of incident/recovery		**Location of incident/recovery**	
Victim/casualty name (s)			
Witness/Recovery personnel		**Contact phone (recorder)**	
Underwater Situation (note orientation of diver, any entanglements, equipment mis-placed etc.)			
Depth		**Method of recovery/rescue**	
LIST OF EQUIPMENT RECOVERED **(Include type of suit/BCD)**			
	Gas labels/identifying marks		

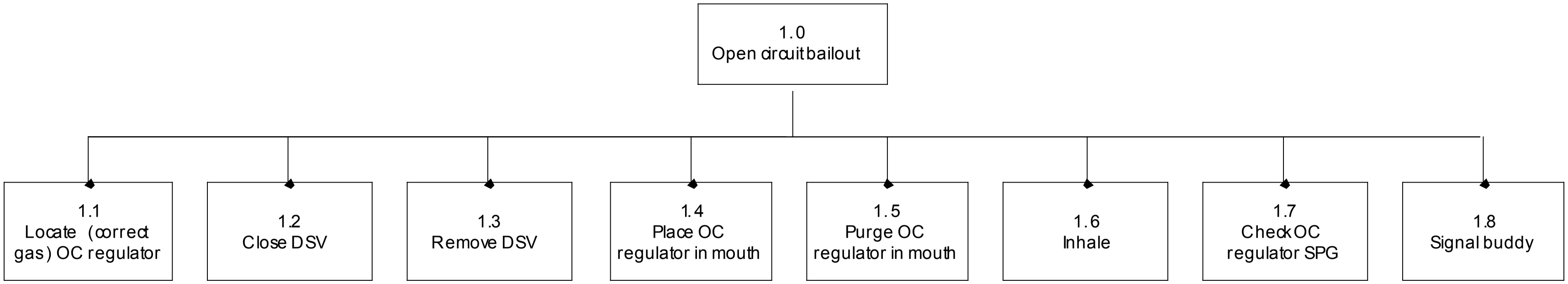
CYLINDERS If valves have to be closed, positions prior to closure must be noted. REMEMBER CLOCKWISE CLOSES!!	**Gas labels/identifying marks**			
	Valve position (close and use clock face reference as a guide)			
	Cylinder 1	**Cylinder 2**	**Cylinder 3**	**Cylinder 4**
	Pressures			
	Cylinder 1	**Cylinder 2**	**Cylinder 3**	**Cylinder 4**
Regulators. Note serial numbers if possible.	**Type of regulator**			
	Reg 1	**Reg 2**	**Reg 3**	**Reg 4**
	Location of regulator			
	Reg 1	**Reg 2**	**Reg 3**	**Reg 4**
In mouth. How stowed (neck tie, stowed on cylinder, deployed). Note location when found if possible. Describe which regulator to which cylinder.				

Mask (removed/dislodged/in place)		**Note position of additional inflation hoses (attached/detached etc.)**	
Rebeather type		**Note display readings.** **PO2. Depth. Time (as examples). Photograph if possible.**	
Electronics functioning? Y/N			
Mouthpiece open/closed			
Mouthpiece in mouth?			
Position of counterlung dump valve			
Position of any gas isolation valves	**O2** **ADV**		
Suit/BCD inflation (connected?)			
BCD/RB damage			

Note any other equipment damage/loss. Is there a weight belt?	
Condition of exposure suit. Note zip position in drysuits. **Note position of exhaust valve.**	

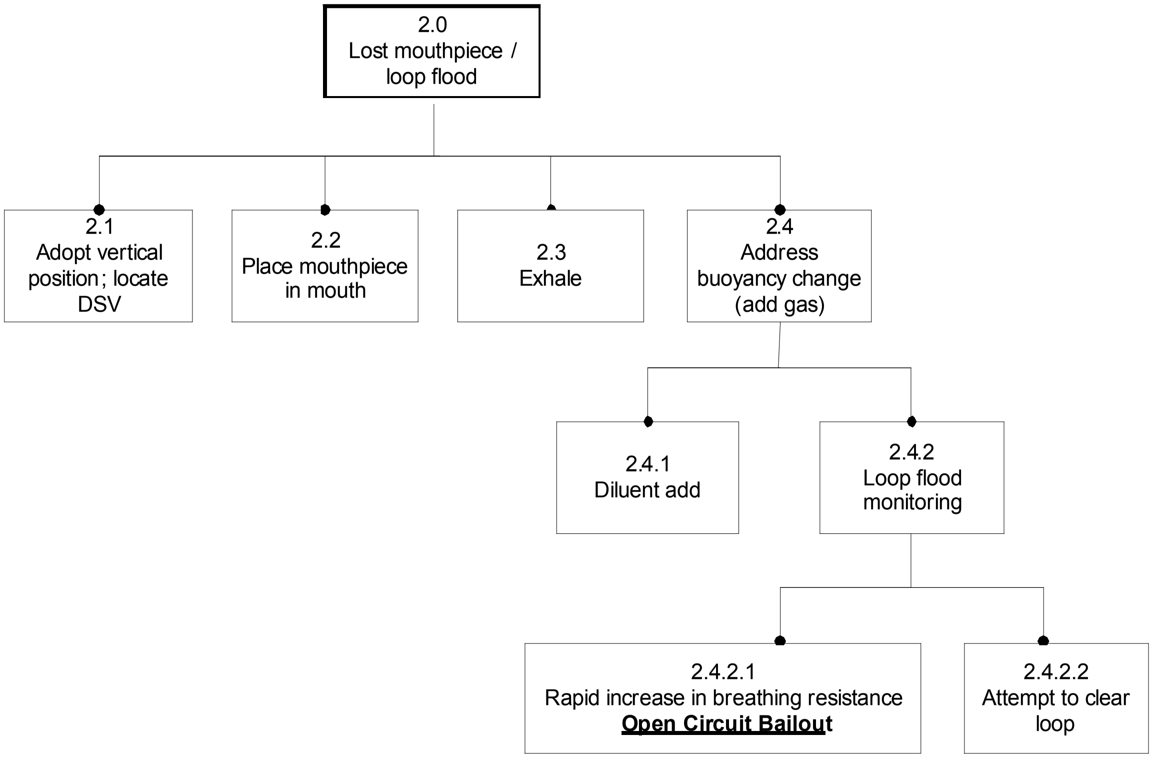
ADDITIONAL NOTES

APPENDIX 12: HIERARCHICAL TASK ANALYSES FOR NON-NORMAL OPERATIONS

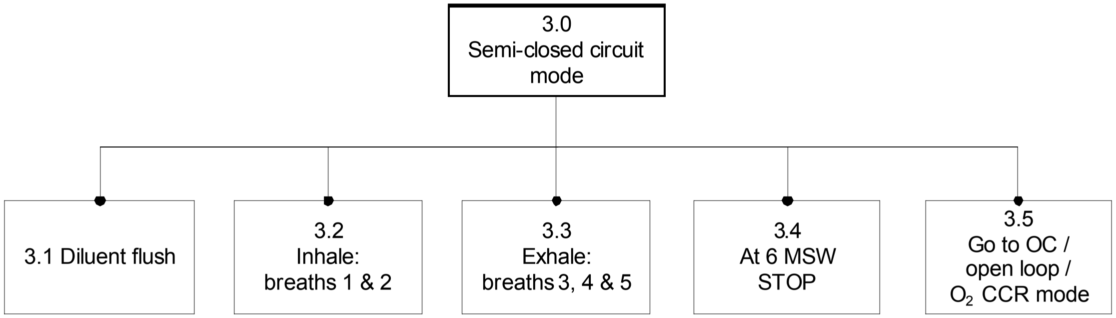


NB This is intended to represent a generic protocol and there may be variations according to CCR unit type design (one unit type, for example, would require a switch from BOV to OC which would eliminate steps 1.1 to 1.4).

EMERGENCIES HTA 1: OPEN CIRCUIT BAILOUT

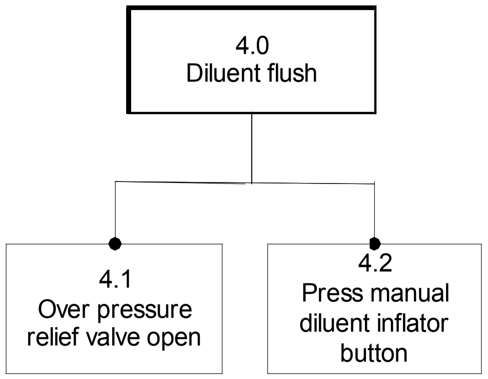


EMERGENCIES HTA 2: LOST MOUTHPIECE / LOOP FLOOD

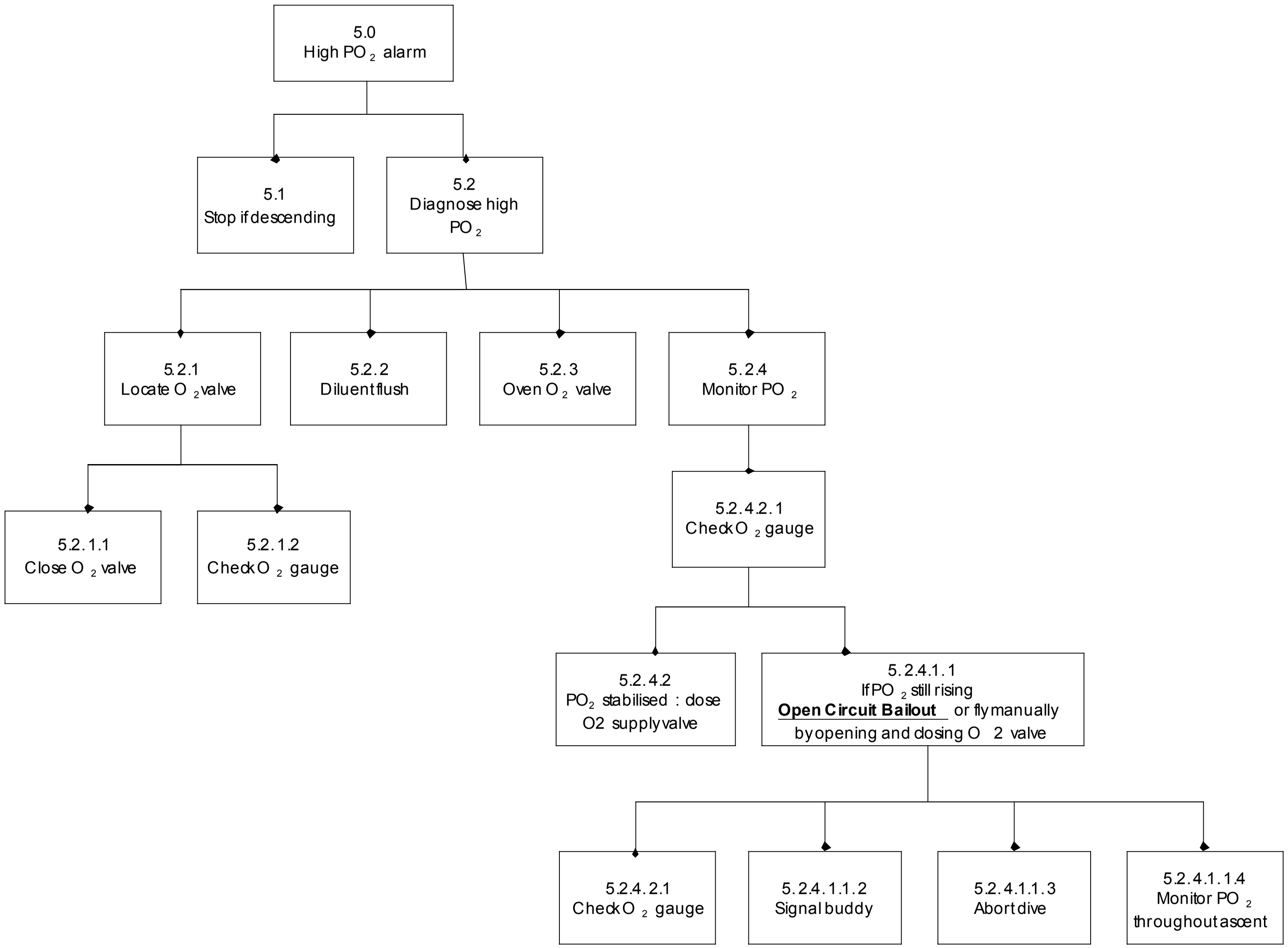


NB This procedure can only be performed with a functional PO_2 monitoring system

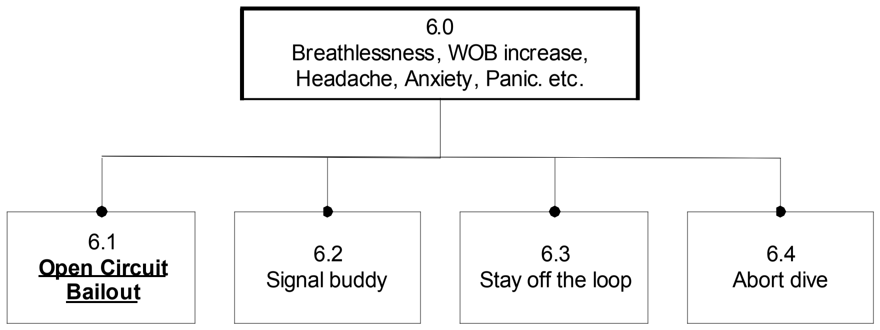
EMERGENCIES HTA 3: SEMI-CLOSED CIRCUIT MODE



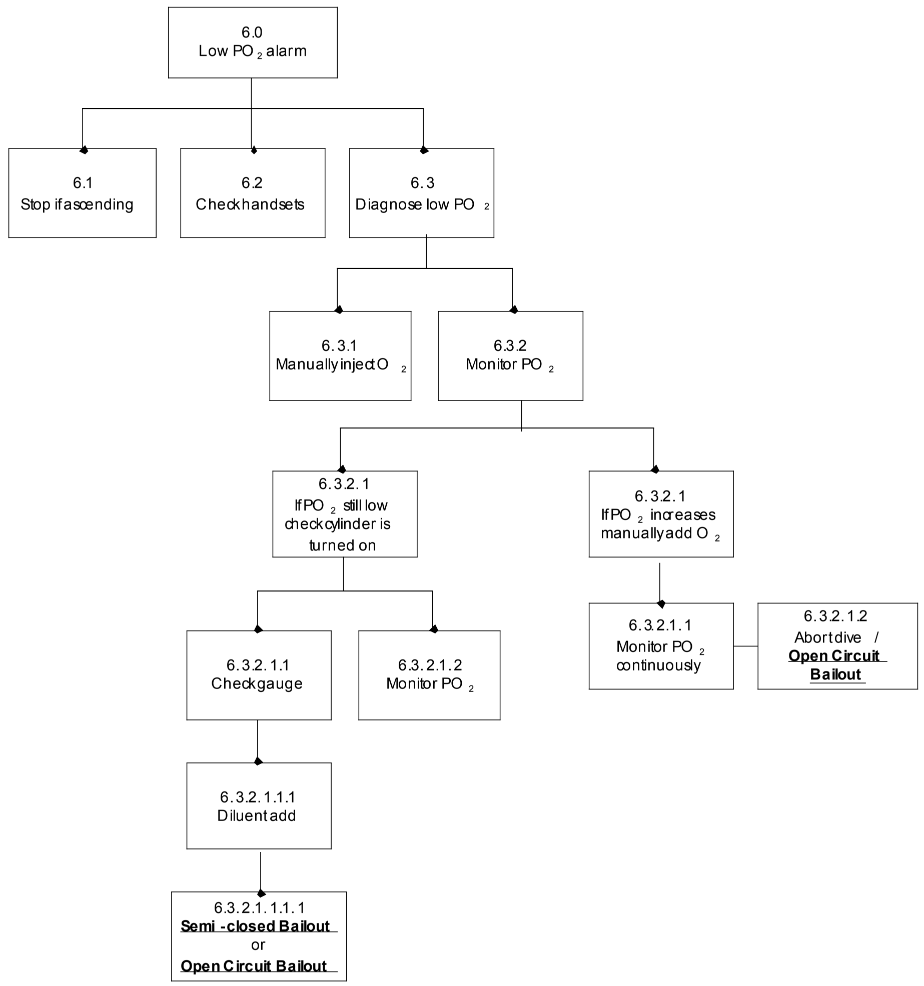
Emergencies HTA 4: Diluent Flush



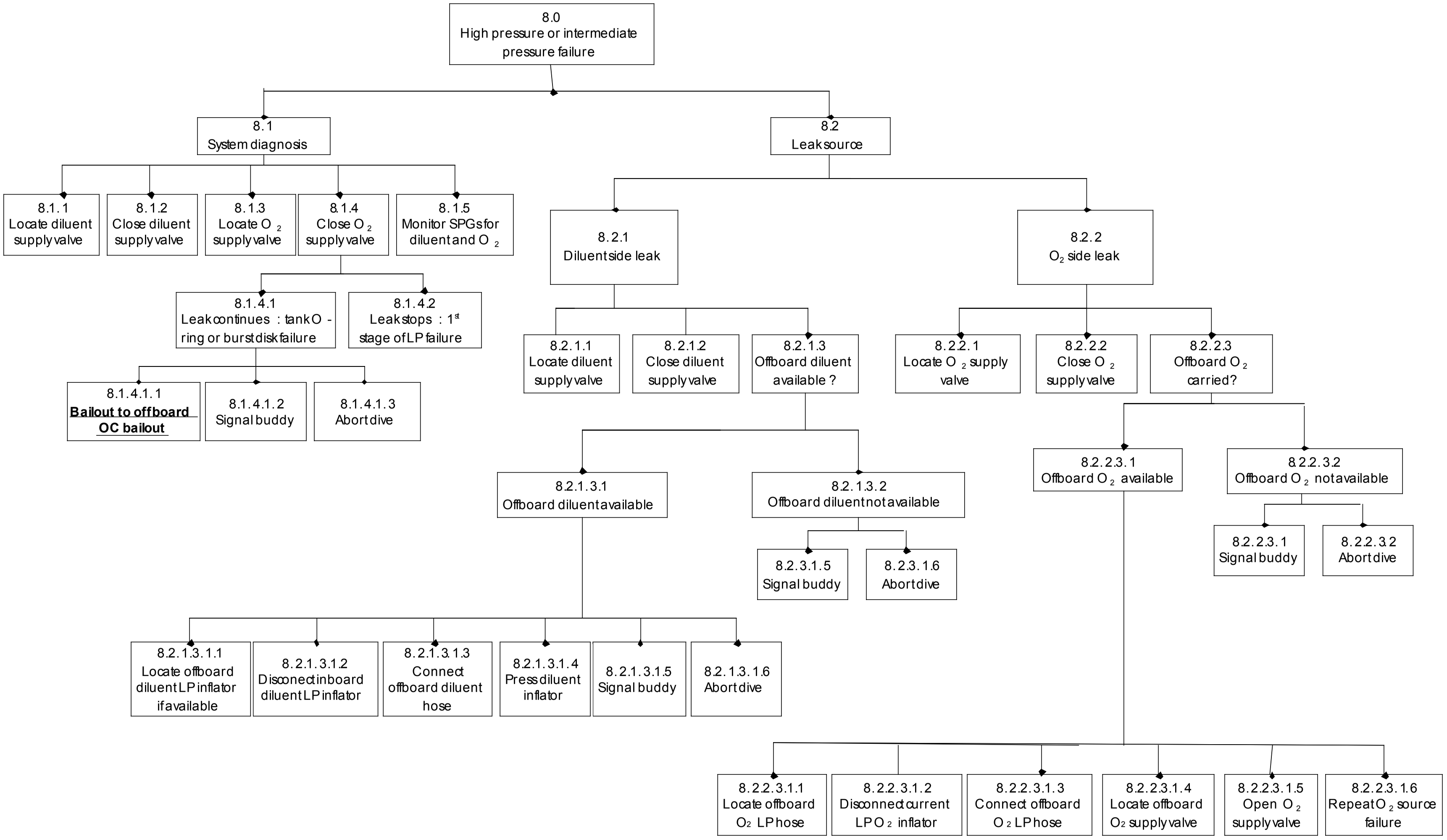
EMERGENCIES HTA 5: HIGH PO_2 ALARM



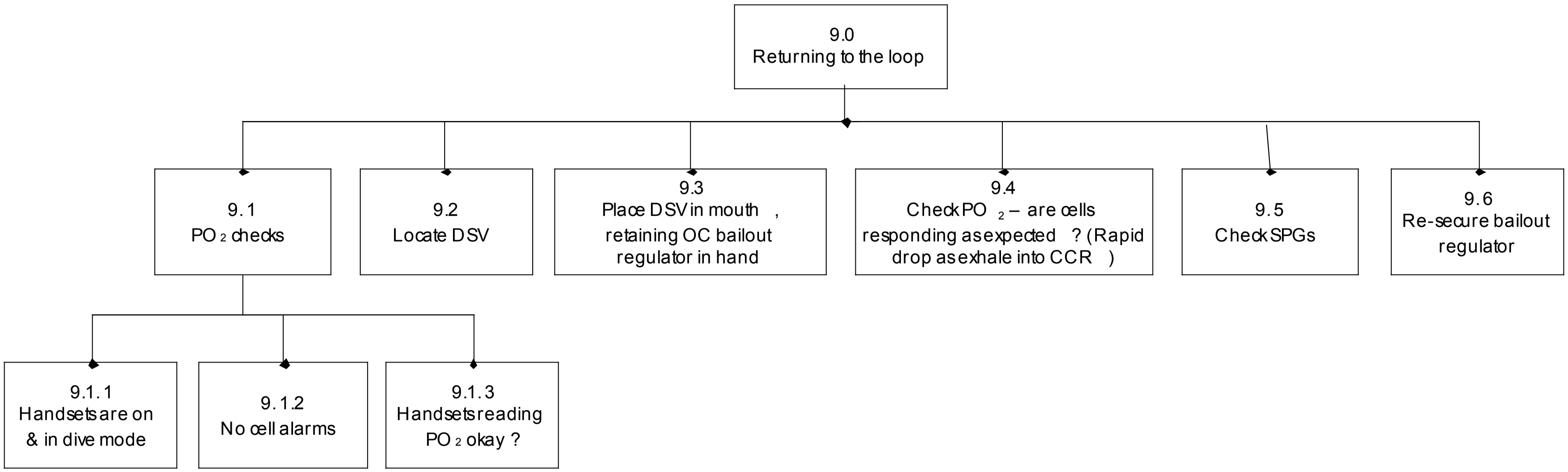
EMERGENCIES HTA 6: PHYSIOLOGICAL / AFFECTIVE DISORDER



EMERGENCIES HTA 7: LOW PO_2 ALARM



EMERGENCIES HTA 8: HIGH PRESSURE / INTERMEDIATE PRESSURE FAILURE



EMERGENCIES HTA 9: RETURNING TO THE LOOP

APPENDIX 13: SHERPA BASED ANALYSES FOR NON-NORMAL OPERATIONS

1. OPEN CIRCUIT BAILOUT

Open Circuit Bailout Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
1.1 Locate OC regulator	A6 A9	Incorrect selection; cannot find / deploy	Wrong gas for depth – Trimix Cannot bail out – Air Increased stress & choking	1.2 1.2	M L	! !	Stay on rebreather and diluent flush
1.2 Close DSV	A8	Diver forgets to close	Loss of buoyancy; rebreather floods	1.1		-	Leave it
1.3 Remove DSV	A2	Removed before OC regulator available	Diver inhales water		L	!	Better training Fit a bailout valve
1.4 Place OC regulator in mouth	A9	Poor kit configuration	Cannot breathe, etc		L	!!	Find a 2nd OC regulator / buddy or return to rebreather
1.5 Purge OC regulator in mouth	C1 A8	No gas or free flow; possible mouthpiece loss	Cannot breathe, etc Water on inhalation		L	!!	Find a 2nd OC regulator / buddy or return to rebreather
1.6 Inhale	C1	No gas	Cannot breathe, etc		L	!!	Find a 2nd OC regulator / buddy or return to rebreather
1.7 Check OC regulator SPG	C1	Failure to check	Possibly nil; possibly run out of gas unexpectedly		L	- !	Not a problem initially but may become a problem later; should be part of the OC bailout training
1.8 Signal buddy	A8	Omitting action			L		Ascend immediately

2. Lost Mouthpiece / Loop Flood

Lost Mouthpiece / Loop Flood Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
2.1. Locate DSV; look up / lean back – adopt vertical position	Action Error		Asphyxiation and drowning		L	!!	Find OC; Practice drills recommended
2.2 Place mouthpiece in mouth	A9		Asphyxiation and drowning		L	!!	Practice drills recommended
2.3 Exhale	A8	Omitting action	Water inhalation and choking; leading to asphyxiation and drowning		M	!	Keep breathing; Practice drills recommended
2.4 Attempt to clear loop	-						
2.4.1 Diluent add (automated or manual)	Auto – C1 Manual – A8	ADV switched off	No diluents addition, no breathable gas volume. Asphyxiation and drowning		L	!	Go open circuit; Practice drills recommended
2.4.2 Loop flood monitoring	C1	Natural course – just need to think about water quantity	Depends on water quantity		L	- !	Go open circuit; Practice drills recommended
2.4.2.1 Sudden change in buoyancy - address	A8	Omitting action	Sinking		L	!	Add gas to rebreather and buoyancy device in extreme case
2.4.2.2 Rapid increase in breathing resistance **Open circuit bailout**	A8	Diver fails to bailout	Increased work for breathing, increased CO2 retention. Asphyxiation and drowning		L	!	Find OC; Practice drills recommended

3. SEMI-CLOSED CIRCUIT MODE

Semi-closed circuit mode Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
3.1. Diluent flush	A8		Hypoxia potential HIGH		M	!!	Recommend the use of open circuit bailout instead
3.2 INHALE breaths 1 & 2							
3.3 EXHALE breaths 3,4,5 through nose							
3.4 At 6 MSW STOP							
3.5 Go to OC / open loop / O2 CCR mode							

NB Not to be practiced at air diluent – basic level

4. DILUENT FLUSH

Diluent flush Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
4.1. Over pressure relief valve (OPRV) open	A8		Gain buoyancy leading to rapid ascent		L		Exhale practice drills
4.3 Press manual diluent inflator button	S2	Press O2 valve by mistake	PO_2 rise leading to alarms and hyperoxia		M	-	Do correct diluents flush Practice drills Audible alarm and / or head up display (design recommendation)

5. HIGH PO_2 ALARM

High PO2 alarm Task Step	**Error Mode**	**Error Description**	**Consequence**	**Recovery**	**P**	**C**	**Remedial Strategy**
5.1. If descending – stop!	A8		PO_2 rises further; hyperoxia		L	!	
5.2 Diagnose high PO_2	R3		Hyperoxia		L	!!	
5.2.1 Locate O_2 valve							
5.2.1.1 Close O_2 valve							
5.2.1.2 Check O_2 gauge							
5.2.2 **Diluent flush**	A8		Hyperoxia		L	- !	
5.2.3 Open O_2 valve	Action Error		Low O_2 alarm eventually		L	!	
5.2.4 Monitor PO_2	R3, C1, C2, C5		Hypoxia; hyperoxia		L	!!	
5.2.4.1 Check O_2 SPG	Check error						
5.2.4.1.1 PO_2 stabilised: close O2 supply valve	A3, A8		Hyperoxia		L	!	
5.2.4.1.2 If PO_2 still rising: **Open circuit bailout** or fly unit manually by opening / closing O_2 valve	A3, A8 Action errors		Hyperoxia		L	!1	Practice drills
5.2.4.1.2.1 Check O_2 gauge	Check error						

5.2.4.1.2.2 Signal buddy							
5.2.4.1.2.3 Abort dive							
5.2.4.1.2.4 monitor PO_2 continually during ascent							

6. PHYSIOLOGICAL / AFFECTIVE DISORDER

Physiological / affective disorder Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
6.1. **<u>Open circuit bailout</u>**	Action errors		Deterioration; increasing symptoms		M	!	Education, practice drills
6.2 Signal buddy							
6.3 Stay off the loop					L	!	Education, practice drills
6.4 Abort dive	A2				L	!	Education, practice drills

7. LOW PO2 ALARM

Low PO2 alarm Task Step	**Error Mode**	**Error Description**	**Consequence**	**Recovery**	**P**	**C**	**Remedial Strategy**
7.1. If ascending: stop!	A8		Hypoxia		H	!!	Education
7.2 Check handsets		Checking errors					
7.3. Diagnose issue low PO2	R3		Hypoxia		L	!!	
7.3.1. Manually inject O2		Action and Selection errors			L	!!	
7.3.2 Monitor PO2		Checking errors	Hypoxia Hyperoxia		L	!!	
7.3.2.1 If PO2 still low check cylinder is turned on							
7.3.2.1.1 Check gauge		Checking errors			M	!!	
7.3.2.1.1.1 Diluent add		Action and Selection errors	Hypoxia		L	!!	
7.3.2.1.1.1.1 **Semi-closed bailout or Open-circuit bailout**							
7.3.2.1.2 Monitor PO2		Checking errors	Hypoxia Hyperoxia		L	!!	
7.3.2.2 If PO2 increases manually add O2		Action and Selection errors					
7.3.2.2.1 Monitor PO2 continuously		Checking errors	Hypoxia Hyperoxia		L	!!	
7.3.2.2.2 Abort dive / **Open-circuit bailout**							

8. HIGH PRESSURE / INTERMEDIATE PRESSURE FAILURE

High pressure / intermediate pressure failure Task Step	Error Mode	Error Description	Consequence	Recovery	P	C	Remedial Strategy
8.1 System diagnosis							
8.1.1 Locate diluents valve	S2		Leak continues		L	-	
8.1.2 Close diluents valve	A3		Leak continues		L	-	
8.1.3 Locate O2 valve	S2		Leak continues		L	-	
8.1.4 Close O2 valve	A3		Leak continues		L	-	
8.1.4.1 Leak continues							
8.1.4.1.1 **Bailout to offboard open-circuit bailout**					L	-	
8.1.4.1.2 Signal buddy	I1				L	-	
8.1.4.1.3 Abort dive					L	-	
8.1.4.2 Leak stops							
8.1.5 Monitor SPGs for diluents and O2							
8.2 Leak source							
8.2.1.1 Locate diluent valve	S2						

8.2.1.2 Close diluent valve	A3						
8.2.1.3 Offboard diluent available?							
8.2.1.3.1 Offboard diluents available							
8.2.1.3.1.1 Locate offboard diluent LP inflator if available	S2		Wrong gas injected into rebreather Alarms if hyperoxic / hypoxic		L	- !	Disconnect + connect to correct gas
8.2.1.3.1.2 Disconnect inboard diluent LP inflator	S2		None		L	-	
8.2.1.3.1.3 Connect offboard diluent hose	A9		None, providing diver is not descending; if descending there is potential for lung damage		L L	- !	Push disconnector on harder or ascend
8.2.1.3.1.4 Press diluents inflator	A9	Button pressed but no gas	None, providing diver is not descending; if descending there is potential for lung damage		L	-	Check hose connection + check if offboard cylinder valve is open
8.2.1.3.1.5 Signal buddy	I1				L	-	
8.2.1.3.1.6 Abort dive							
8.2.1.3.2 Offboard diluents not available							
8.2.1.3.2.1 Signal buddy							
8.2.1.3.2.2 Abort dive							
8.2.2 O2 Side leak							
8.2.2.1 Locate O2 supply valve	S2		Leak continues		L	-	
8.2.2.2 Close O2 supply valve	A3		Leak continues		L	-	

8.2.2.3 Offboard O2 carried?							
8.2.2.3.1 Offboard O2 available							
8.2.2.3.1.1 Locate offboard O2 LP hose	S2	Wrong hose selected	Wrong hose would have lower O2 content and lead to buoyancy problems Risk of hypoxic gas being added in shallows		L L	- !	Monitor PO2 displays; vent loop
8.2.2.3.1.2 Disconnect current O2 LP inflator	S2		none		L	-	
8.2.2.3.1.3 Connect offboard O2 LP hose	A9		None providing diver is not ascending; if diver ascending there is risk of hypoxia. If diver continues without checking PO2 there is risk of hypoxia		L	!	Monitor Po2 displays, checks
8.2.2.3.1.4 Locate offboard O2 supply valve	S2		Leak continues		L	-	
8.2.2.3.1.5 Open O2 supply valve	A3		No gas addition when inflator opens		L	-	Monitor PO2 displays, open O2 valve
8.2.2.3.1.6 Repeat O2 source failure							
8.2.2.3.2 Offboard O2 not available							
8.2.2.3.2.1 Signal buddy	I1				L	-	
8.2.2.3.2.2 Abort dive							

9. RETURNING TO THE LOOP

Returning to the loop Task Step	**Error Mode**	**Error Description**	**Consequence**	**Recovery**	**P**	**C**	**Remedial Strategy**
9.1 PO2 checks	C1	Diver fails to check PO2 display	PO2 could be at dangerous levels		L	!	Check display; diluents flush
9.1.1 Handsets are on and in dive mode							
9.1.2 No cell alarms							
9.1.3 Handsets reading PO2 okay?							
9.2 Locate DSV	A9		Potential for drowning		L	!	Return to open-circuit bailout and then relocate DSV
9.3 Place DSV in mouth, retaining OC	A1	Diver fumbles due to lack of practice	Potential for drowning		L	!	Return to open-circuit bailout
9.4 Check PO2 – are cells responding as expected? Rapid PO2 drop as exhale into CCR	A1	Diver fails to check PO2 display	PO2 could be at dangerous levels		L	!	
9.5 Check SPGs	C1	Diver fails to check SPGs	Potential for running out of gas		L	!	
9.6 Re-secure bailout regulator	A4	Unable to stow again	None		L	-	Ask for assistance from buddy

HSE
Health and Safety
Executive

Assessment of manual operations and emergency procedures for closed circuit rebreathers

Closed Circuit Re-breather (CCR) diving has become increasingly popular as more sophisticated units enable diving for longer and at greater depths. CCR diving is much more complex than traditional open circuit diving in many ways and there is an increased potential for problems and diver errors to emerge. However, formal research examining CCR safety has been rare. To address this, the UK Health and Safety Executive commissioned the Department of Systems Engineering and Human Factors at Cranfield University to conduct a scoping study into the human factors issues relevant to CCR diving apparatus. The scoping study was designed to explore five principal subject areas: accident / incident analysis, unit assembly / disassembly, normal / non-normal diving operations, training needs analysis, interface and display. This scoping study has approached this with a series of studies each addressing separate issues that are relevant to the principal subject areas. These studies can be seen as potentially stand alone, each with its own objectives, method and results. These studies comprise; Accident / Incident Analysis; Human Error Potential Analysis: Assembly and Disassembly; Human Error Potential Analysis of Diving Operations; Training Needs Analysis; Interface and Display Recommendations and Human Error Potential in Non-Normal Operations.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

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