Guidelines For Good Working Practice In High Pressure Compressed Air

ITA Working Group n°5
Health & Safety in Works
In Association with the British Tunnelling Society Compressed Air Working Group

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PREPARED JOINTLY

BY INTERNATIONAL TUNNELLING ASSOCIATION WG 5

"HEALTH & SAFETY IN WORKS"

IN ASSOCIATION WITH BRITISH TUNNELLING SOCIETY

COMPRESSED AIR WORKING GROUP

>> Table of contents

>> TABLE OF CONTENTS

>> Document history

At its meeting in Vancouver in 2010, International Tunnelling Association Working Group 5 identified the need for guidance on the use of high pressure compressed air. WG5 defined this as "work in compressed air at pressures above historical statutory limits, which in most countries are between 3 and 4 bar (gauge), and which involves the use of breathing mixtures other than compressed natural air and can involve the use of saturation techniques".

High pressure compressed air working was a topic of interest which had previously been addressed by the British Tunnelling Society Compressed Air Working Group and which BTS CAWG had identified as a significant development in the use of hyperbaric techniques on site for which no guidance existed.

Consequently, the ITA and BTS CAWG came together to jointly publish the first edition of these guidelines in 2012 for use by the international tunnelling community.

In 2013 a review and update of this document began, to take account of the relatively rapid development of this technique. Revised guidelines were published in 2015.

In 2016 a second and comprehensive revision of the guidelines was commenced to take account of recent experience and ongoing developments in the application of the techniques. The second revision of these guidelines was published in 2018.

Comment and feedback continue to be welcomed and should be made to the ITA Secretariat through the website www/ita-aites.org.

It is not the purpose of this document to give guidance on commercial matters. However, the nature of HPCA work is such that expensive equipment can be required at short notice or equally it can stand unused for long periods of time. Consequently, ITA WG5 recommends that the tunnelling industry should standardise shuttle dimensions, capacity and pressure capability so that equipment can be interchangeable and reusable between projects. Standardising dimensions to allow shuttles to be containerised for ease of transport is also suggested.

>> FOREWORD

This document sets out guidance on good practice in high pressure compressed air work. Guidance is given in the form of recommendations and consequently has a lower standing than regulation or standards. The guidance given aims to be goal setting in nature rather than prescriptive. However, because of the lack of alternative sources of published information or standards on HPCA work, some of the recommendations given are fairly detailed.

Often in hyperbaric work there are no absolute rights or wrongs. Users of this guidance are free to adopt their own solutions however these should not be less safe than the recommendations in this document. For many limits quoted, such as maximum gas exposure limits, the recommended values given have been arrived at over a period as the consensus of expert opinion within the hyperbaric community. Means of achieving set goals have been given in some cases, however other equally valid means of achieving the same goals can exist and it is down to the experience of the reader to select the (more) most appropriate. Likewise, not all hyperbaric situations have been covered and the reader should use discretion and experience in determining the appropriateness of applying or interpolating between recommendations given in the text.

Regulators should be wary of enforcing these guidelines in an overly prescriptive manner as this may stifle innovation and creativity, resulting in a less safe outcome overall. Often in hyperbaric work it is not possible to guarantee absolute safety and in these cases it is the relative safety of proposals which should be considered. Likewise, the inter and intra-individual variation in response to pressure exposure should be considered. Isolated or unexpected cases of decompression illness should always be considered a negative outcome but may be an indicator of personal susceptibility rather than of deficiencies in a decompression regime.

One major addition over revision 1 is the coverage of saturation techniques. To many people, saturation presents a psychological barrier beyond which they will not pass. We should perhaps remember that for most people, life is one long saturation exposure to air at atmospheric pressure. Why then should saturation at higher pressures present such an insurmountable mental obstacle? Saturation if done safely removes much of the health risk associated with the multiple decompressions required to achieve the same productive working time from non-saturation exposures even at low pressures. The use of heliox eliminates the narcotic risk from breathing high pressure nitrogen and significantly reduces the work of breathing. With helium reclaim, it is an environmentally sound option. Full advantage should be taken of favourable gas properties when devising exposure and decompression procedures.

>> Glossary of terms and abreviations

Appointed Doctor or Appointed Medical Practitioner
A doctor formally appointed by the national regulatory authorities to certify medical fitness in persons undertaking work in compressed air (not required in all jurisdictions). Ideally this duty should be undertaken by the Contract Medical Adviser.

Bailout bottle
A small gas cylinder used to contain an emergency air or breathing mixture supply in diving

Breathing mixture
A non-air respirable mixture, such as oxygen and nitrogen (nitrox); oxygen and helium (heliox) or oxygen, nitrogen and helium (trimix) capable of supporting human life under appropriate hyperbaric conditions. Various mixtures can be used during an exposure and some can be described by their function –

- Pressurisation mix – a breathing mixture used in the compression from atmospheric pressure to storage pressure to achieve the desired storage mix.
- Storage mix – a breathing mixture used during storage of MGSWs in the habitat.
- Working mix – a breathing mixture used during the working phase of the exposure.
- Emergency mix – a breathing mixture which can be used in emergencies e.g. fire.
- Treatment mix – a breathing mixture used during therapeutic treatment of DCI.

BTS "Guide"
The British Tunnelling Society's document "Guide to the Work in Compressed Air Regulations 1996".

Built in Breathing System (BIBS)
Closed circuit system for supplying gas to a mask and removal of exhaled gas from the mask to a dump location (normally outside of the pressurised environment).

Compressed air worker (CAW)
Person certified medically fit for working in compressed air. Used in this document to imply low and intermediate pressure exposures in which air is the breathing mixture.

Contract Medical Adviser (CMA)
A suitably qualified and experienced medical practitioner competent in occupational health and hyperbaric medicine who is permitted to practice in the location at which the HPCA work is being undertaken and who is responsible for all medical aspects of HPCA work.

Decompression illness (DCI)
All ill health conditions resulting from exposure to pressure and decompression.

Diver medic or diver medic technician (DMT)
The holder of an advanced hyperbaric first aid certificate endorsed by the International Marine Contractors Association (IMCA) or a national equivalent.

Excursion
A period in saturation away from the habitat during which work is undertaken at a pressure different to the storage pressure. Excursions can be at pressures greater than or less than storage pressure. The terms "upward" i.e. to a pressure less than storage pressure and "downward" i.e. to a pressure greater than storage pressure which are used in diving to describe excursions should not be used in tunnelling as they can lead to confusion.

Gas
Used in this document to mean either oxygen or a breathing mixture.

Gauge Pressure
Pressure above atmospheric pressure as in normal tunnel practice. Pressures given in this document are in gauge pressure.

Habitat
Pressurised living complex normally situated on the surface.

Health and Safety Executive (HSE)
The UK regulatory authority for occupational health and safety.

Heliox
An oxygen/helium breathing mixture.

High Pressure Compressed Air (HPCA) work
Work in compressed air at pressures above historical statutory limits, which in many countries are between 3 and 4 bar (gauge), and which involves the use of breathing mixtures other than compressed natural air and can involve the use of saturation techniques.
Note: In the past it was customary in some countries to describe exposure pressures from which stage decompression was not required as "low pressure" and to describe exposure pressures from which stage decompression was required as "high pressure". It is now proposed that the latter be referred to as "intermediate pressure" i.e. pressures between "low pressure" and the statutory limit.

HPCA Contractor
Contractor with overall responsibility for the HPCA work, normally but not exclusively the principal contractor.

Intervention
Time spent away from the habitat including transfer under pressure and at work. An intervention extends from time of lock off from the habitat to lock on to the habitat on the return to storage.

Isobaric counterdiffusion
A complex phenomenon arising from having different concentrations of different inert gases on either side of a "boundary", e.g. such as blood in a blood vessel within a tissue, as a result of which each gas will diffuse across the boundary down its own concentration gradient meaning that it is possible for the total inert gas partial pressure to exceed the surrounding pressure on either side of the boundary. Consequently, gas bubbles can form on either side of the boundary even though the surrounding pressure has not been changed by a decompression move.

Life Support Technician
A person competent to control life support functions associated with a Habitat and

holding the qualification of life support technician awarded by the International Marine Contractors Association.

Life Support Supervisor
A life support technician supervising habitat operations.

Mixed Gas Worker (MGW)
Person certified medically fit for working in high pressure compressed air in non-saturation mode.

Mixed Gas Saturation Worker (MGSW)
Person certified medically fit for working in high pressure compressed air in saturation mode. This would include psychological fitness also.

Nitrox
An oxygen/nitrogen breathing mixture normally other than air.

Non-saturation exposure ("non-sat" exposure)
A short duration exposure comprising a compression, a working period under pressure, immediately followed by a decompression. It does not involve any storage time in a habitat (equivalent to a "bounce dive" in diving).

Oxygen
Used in this document to mean oxygen of medical or diving grade.

Oxygen tolerance unit (OTU)
A measure of the cumulative oxygen exposure which takes account of partial pressure and time (also referred to in some documents as oxygen toxicity unit or unit of pulmonary toxicity dose).

Oxygen toxicity dose (OTD)
See Oxygen tolerance unit.

Partial pressure (of a gas)
The pressure of a gas in a gas mixture that the gas would have if it alone occupied the gas filled space (Dalton's Law). It is normally stated in bar and is the product of the absolute pressure of the mixture and the volume fraction of that gas in the mixture. In this document partial pressure of a gas (e.g. oxygen) is shown as PO_2.

Person in charge
A senior member of the staff of the principal contractor who is responsible for all aspects of HPCA work.

Pressure
Pressures in this document are stated in bar (gauge).

Pressure vessel for human occupancy (PVHO)
Manlocks and similar pressure vessels in which persons are exposed to pressure.

Principal contractor
Contractor primarily responsible for tunnel construction.

Quad
Transportable gas storage consisting of multiple cylinder configurations connected to a common manifold, within a protective frame.

Saturation exposure ("sat" exposure)
A long duration exposure during which the exposed person lives at a storage pressure and can make transfers under pressure to and from the working chamber.

Saturation run
The colloquial term for the period, often 28 days, from start of compression to end of decompression for a saturation exposure.

Shuttle
Mobile pressure vessel for human occupancy in which a transfer under pressure is undertaken.

Storage
Maintenance of persons at pressure in a habitat as part of a saturation exposure.

Storage pressure
The pressure to be maintained in the habitat when it is occupied.

Transfer under pressure (TUP)
The transfer of persons between a habitat and shuttle or manlock whilst maintaining those persons under pressure.

Trimix
An oxygen, nitrogen and helium breathing mixture. The convention in this guidance is that a trimix is described as oxygen/nitrogen/helium.

Tunnel Boring Machine (TBM)
A machine which in Europe would come within the scope of EN 16191 (formerly EN 12336).

Tunnelling
In this document tunnelling includes shaft sinking and caisson work.

Unit of pulmonary toxicity dose (UPTD)
See oxygen tolerance unit (OTU)).

Working period (non-saturation exposures) Time spent under pressure from leaving atmospheric pressure till start of decompression.

Working period (saturation exposures)
The time during an excursion or intervention from when a person leaves the shuttle following TUP from the habitat, to work in the cutterhead until that person arrives back in the shuttle for TUP back to the habitat.

1 >> Introduction

1.1. BACKGROUND

In recent years several tunnels have been built which required the application of high pressure compressed air (HPCA) for interventions in the head of the Tunnel Boring Machine (TBM). This is a significant development in hyperbaric activity in tunnelling and has required the transfer of hyperbaric technology and knowledge, from the diving industry to tunnelling.

Regulators should be wary of enforcing these guidelines in an overly prescriptive manner as this may stifle innovation and creativity, resulting in a less safe outcome overall. Often in hyperbaric work it is not possible to guarantee absolute safety and in these cases it is the relative safety of proposals which should be considered. However, these guidelines are considered to represent current good practice.

1.2. SCOPE

These guidelines are intended for use by all parties – including regulatory authorities, clients, designers, contractors, insurers, operators and others involved in HPCA work.

These guidelines apply to the use of HPCA in tunnelling. To date, such work has been mainly associated with TBM interventions for maintenance and repair. However, it is foreseeable that conventional (i.e. continuous) tunnelling operations may have to be undertaken in HPCA.

Whilst this guidance is intended to apply to HPCA work as defined above, the guidance is equally applicable to intermediate pressure exposures above 3.5 bar.

1.3. MINIMISING HYPERBARIC EXPOSURE

Before undertaking HPCA work in accordance with these guidelines it is implicit that all reasonably practicable measures should have been taken to minimise the number of persons exposed to pressure along with the pressure and duration of each exposure, commensurate with minimising the overall risk to the health and safety of those exposed.

Note : there are measures such as remote wear detection and the use of CCTV which can be used alone or in conjunction with other ground stabilisation techniques (see Cl 1.7) to further reduce the need for HPCA interventions.

1.4. PRESSURISING MEDIUM

In the HPCA work covered by these guidelines, the pressurising medium envisaged in the working chamber is compressed natural air except where stated otherwise. Non-air mixtures used for breathing are fed through a mask and umbilical. The pressurising medium envisaged in the habitat, shuttle and trunking can be air or breathing mixture as appropriate.

There should be the capability to flush and pressurise manlocks, along with trunking and shuttles where appropriate, with either air or breathing mixture.

1.5. CHOICE OF HYPERBARIC TECHNIQUE

Non-sat exposures permit only short working periods e.g. for planned routine inspection work, because of the relatively lengthy decompression required. Where a considerable amount of work is required under pressure, saturation exposures should be considered. See Cl 8.8 for further guidance. It is important that the Contract Medical Adviser and any specialist hyperbaric advisers are involved in taking the decision on choice of hyperbaric technique.

Note : saturation exposures have been undertaken at 3.5 bar and are technically feasible at lower pressures where long exposure periods are required.

1.6. EXISTING STATUTORY LIMITS ON PRESSURE

In many countries existing limits on exposure pressure do not appear to have changed since work in compressed air was first regulated. Although there may not be evidence to show how statutory limits were derived, there is ample evidence that they were adequate for the requirements of the tunnelling industry of the day as records show very few exposures to pressures close to the limit. The inference is therefore that they were based on a degree of empiricism which reflected both the state of knowledge and the practical working limits which could be achieved with air breathing in the early to mid-20th century when most countries with statutory limits set these limits. The pressures now being considered for HPCA work are well within the range of pressures routinely experienced in offshore commercial diving. Consequently, it is concluded that there is nothing inherently unsafe about exposure to higher pressures per se, provided appropriate safe systems of work are adopted.

1.7. GROUND STABILISATION TECHNIQUES OTHER THAN COMPRESSED AIR

Other ground stabilisation techniques which are utilised in tunnelling include grouting, ground treatment, ground freezing, and dewatering. These guidelines deliberately give no guidance on the often complex issues around selection of an appropriate ground stabilisation technique. The guidelines apply to the use of HPCA once the decision has been made to use it.

1.8. HPCA AS A CONTINGENCY MEASURE

On some projects high pressure compressed air interventions can be a contingency measure to be undertaken only in the event that certain foreseeable adverse conditions arise. In these circumstances consideration must still be given at the planning stages to the requirements for HPCA however only the minimum essential provisions need be made in terms of plant and equipment capability or provisions which cannot be retrofitted thus minimising the abortive costs should HPCA not be required. Clauses 4.1 and 8.8 are particularly relevant.

It is recommended that all necessary exemptions and approvals are identified and discussions held with the regulatory authorities to ascertain the time necessary to obtain them. The contractor in conjunction with the tunnel owner should considered whether to proceed with obtaining the exemptions and approvals to mitigate the risk of delay, or to assume they can be obtained within an acceptable timescale should the need for HPCA arise.

Consideration should also be given to the extent to which procedures are worked up and personnel are identified for key roles in the hyperbaric team.

As part of the design and manufacture of the TBM, the TBM manlocks should have sufficient penetrations to allow for the supply of mixed gas and oxygen to the manlocks and cutterhead along with space for the relevant gas storage, supply lines, control panels and working space.

Where a need for saturation exposures is foreseen, a shuttle path through the TBM should be identified and that space envelop protected. Either the manlocks should be fitted with mating flanges or should have the capability to be so fitted in the future. The lead time for the procurement of habitats and shuttles should be confirmed.

1.9. DEVELOPMENT OF THE HPCA TECHNIQUES

HPCA has developed rapidly in the past decade however it remains a developing technique in tunnelling. Hence during the currency of this guideline, techniques and applications for HPCA may arise which are not covered by this document. That does not mean they cannot be undertaken safely. In particular, as the commercial and safety benefits associated with the use of saturation are recognised its use is likely to develop. Also, greater awareness of gas properties will mean that the use of heliox for both routine breathing and decompression purposes is likely to occur.

This is a guideline only and total adherence to its requirements may not always be possible or desirable. It is not possible to guarantee absolute safety in decompression matters due to human variability in response to exposure to pressure.

2 >> Legislation, standards, guidance etc.

2.1 NATIONAL LEGISLATION, STANDARDS AND GUIDANCE

These Guidelines are intended to complement existing national legislation, standards and guidance as appropriate. As HPCA work is still a rarely used but developing technique, few countries are likely to have altered existing legislation and guidance to permit it. **These guidelines build on and should be read in conjunction with the current version of the guidance documents listed in 2.3 and 2.4 (and 2.5 where relevant).**

2.2 ILO CONVENTION C167

The International Labour Organisation convention C167 on Health and Safety in Construction has been ratified by 24 countries and requires through Article 21 "Work in compressed air" :

- Work in compressed air shall be carried out only in accordance with measures prescribed by national laws or regulations.
- Work in compressed air shall be carried out only by workers whose physical aptitude for such work has been established by a medical examination and when a competent person is present to supervise the conduct of the operations.

2.3 RELEVANT GUIDANCE SOURCES - TUNNELLING

Although no comprehensive guidance on HPCA has been identified, a number of organisations provide highly relevant background guidance and information on hyperbaric issues. These Guidelines depend extensively on the information which they provide.

2.3.1 ITA Report No 001

The International Tunnelling Association Report No 001 "Guidelines for good occupational health and safety practice in tunnel construction" was published in 2008 and has a section covering work in compressed air. The report was drafted to apply within national statutory limits and consequently does not have specific requirements for HPCA work.

2.3.2 EN 12110 – Tunnelling Machines – Air Locks – Safety Requirements

CEN/TC151/WG4 has confirmed that the current edition of EN 12110 applies only to work in compressed air within national statutory limits, assumed to be between 3 and 4 bar. However, WG4 has recognised that EN 12110 could be used to inform requirements for air locks for use in HPCA. Where reference is made to EN 12110, it is the current version of the standard which should be used (see Cl 6.3 for application of EN 14931:2006 "Pressure Vessels for Human Occupancy"). *Note: CEN/TC151/WG4 "Tunnelling Machinery" is a working group of the European Standard technical committee CEN/TC151 "Construction Machinery – Safety". WG4 is responsible for EN 16191 "Tunnelling machinery Safety requirements" and EN 12110 "Tunnelling machines — Air locks — Safety requirements". At the time of publishing revision 2 of this Report, CEN/TC151/WG4 is considering revising ENs 12110 and 16191 to take account of HPCA requirements.*

2.3.3 British Tunnelling Society "Guide to the Work in Compressed Air Regulations 1996".

The British Tunnelling Society (BTS) document "Guide to the Work in Compressed Air Regulations 1996" which was published in 2012, is a revised and updated version of the guidance which was formerly published by the Health and Safety Executive (HSE) as publication L96. The BTS Guide primarily covers work in compressed air within the existing UK statutory limit of 3.45 bar. However, the possibility of HPCA work had been foreseen when the Regulations were drafted in 1996. Consequently, the "Guide to the Work in Compressed Air Regulations 1996" recognises the use of HPCA and provides extensive guidance on good working practice in compressed air which is of fundamental relevance to HPCA work.

The BTS "Guide" should be taken as the default standard for the principles of good practice in compressed air work within statutory limits in the absence of more rigorous national requirements.

2.3.4 BS 6164:2011 – "CoP for health and safety in tunnelling in the construction industry"

This British Standard has a section giving guidance on work in compressed air. It complements the BTS "Guide" by addressing the design of the tunnel/ground interface, effects of compressed air on the ground and air loss. It also gives guidance on a range of emergency situations which could arise. The principles covered are relevant to HPCA work. The prevention of sudden air loss through the ground is a safety-critical part of HPCA work. A revision of the 2011 text is in progress.

2.3.5 EN 12021 – Breathing gas quality

Compressed air and all breathing gases supplied in connection with HPCA work should comply with EN 12021 : 2014 "Respiratory Equipment – Compressed Gases for Breathing Apparatus".

2.4 RELEVANT GUIDANCE SOURCES – DIVING

The hyperbaric techniques required for HPCA can be similar to those for diving at similar pressures but without immersion in water or the limitations imposed by working from a diving support vessel far from land. Consequently, whilst there is considerable relevant guidance from diving sources the significant differences between the working environments should be taken into account when applying it and the guidance applied with discretion.

Unlike offshore construction where the atmosphere in underwater work habitats can be a breathing mixture, in HPCA work the pressurising medium in working chambers is high pressure compressed air in which the PO_2 and/or PN_2 are likely to be above safe limits. (See Cl 8).

2.4.1 Classification Societies

"Classification societies" are the major international insurance companies which set detailed rules for the design, construction and testing of equipment for use in the marine environment. This includes the hyperbaric systems used in diving and other underwater hyperbaric activity. Care should be taken to ensure their application is appropriate, when transposing rules intended for the marine environment to the underground environment. The HPCA contractor should be aware that these rules will most likely be applied to plant and equipment used in HPCA work as a condition of the insurance of the works. Classification societies involved in HPCA projects should have good knowledge of tunnelling works. At least one classification society has already developed specific rules covering pressure vessels and equipment for use in the tunnelling environment. Reference is made to classification society rules in these guidelines.

2.4.2. Diving Medical Advisory Committee

The Diving Medical Advisory Committee (DMAC) (see www.dmac-diving.org) is a European organisation comprising diving and hyperbaric medical experts from civilian, military and clinical backgrounds which endorses guidance on a range of issues relating to the medical aspects of hyperbaric exposure in diving. Although this guidance is intended for hyperbaric exposure in the diving industry, much DMAC guidance is equally applicable to HPCA exposure.

2.4.3. European Diving Technology Committee

The European Diving Technology Committee (EDTC) has the fundamental aim to make commercial diving safer across Europe through providing an independent forum which makes recommendations relating to diving safety, technology and diving medicine.

2.4.4. International Marine Contractors Association

The International Marine Contractors Association (IMCA) formerly the Association of Offshore Diving Contractors (AODC) publishes extensive guidance on non-sat and sat diving issues. IMCA guidance on generic issues associated with saturation exposure can be equally applicable to HPCA work. Requirements in IMCA guidance on plant and equipment which are specific to diving support vessels, dynamic positioning or the marine environment should be ignored.

2.4.5. HSE diving guidance

HSE publishes extensive guidance on commercial diving, some of which is relevant to HPCA work.

2.5. ASME PVHO STANDARDS

The American Society of Mechanical Engineers produces standards for pressure vessels for human occupancy (PVHO). Although reference can be made to them as an alternative to EN 12110 or Classification Society rules as a source of guidance, any tunnelling specific requirements in EN 12110 should be adopted in addition to the ASME requirements.

2.6. OTHER PVHO STANDARDS

There are other standards covering pressure vessel design and construction including EN 13445. Although reference can be made to them as an alternative to EN 12110 or Classification Society rules as a source of guidance, any tunnelling specific requirements in EN 12110 should be adopted in addition to those of the standard adopted.

2.7. NATIONAL FIRE PROTECTION ASSOCIATION

The NFPA is an American organisation, widely recognised as a source of authoritative guidance on fire suppression in hyperbaric facilities.

2.8. GUIDANCE FROM OTHER COUNTRIES

2.8.1. Germany

For non-saturation exposures, the "Druckluftverordnung" (Technical regulation for compressed air application) applies. This should be referred to along with the RAB 25 ("Regeln zum Arbeitsschutz auf Baustellen" – Rules for occupational health and safety on construction sites).

2.8.2. Canada

Canadian Standard Z275.1-05 "Hyperbaric Facilities" provides comprehensive guidance on requirements for hyperbaric chambers including those for saturation systems. Canadian Standard Z275.3-09 provides guidance on work in compressed air.

2.8.3. Switzerland

For non-saturation exposures, a confederate regulation concerning work in hyperbaric environment applies, a revised version of which came into effect on 1st January 2016. In every case, planned works in high pressure compressed air, as described in this guideline, must be notified and discussed in advance with the responsible authority (Suva - contact via www.suva.ch/bau).

2.8.4. Norway

Norwegian Standards (NORSOK) document U100 "Manned underwater operations" 3rd edition 2009 is referenced in this guideline. The significant differences between the working environments in diving and HPCA work should be taken into account when referring to it and the guidance applied with discretion.

2.8.5. France

"Annexes de l'arrêté du 30 Octobre 2012 relatif aux travaux subaquatiques effectués en milieu hyperbare (mention A)", published in the Official Journal No 290 of 13th December 2012 and the Official Bulletin of the "Ministère du travail, de l'emploi, de la formation professionnelle et du dialogue social" no 2012-12 of 30th December 2012 is also a source of relevant guidance.

These regulations describe intervention procedures and provide air or air and oxygen tables specifically designed for tunnel interventions.

3 >> Notifications, exemptions and approvals

3.1 NOTIFICATION OF REGULATORY AUTHORITY

In some countries it is a statutory requirement to notify the regulatory authority for occupational health and safety or labour inspection of the intention to work in compressed air. Whether this is a requirement or not, it is strongly recommended that the relevant authority is notified and their advice sought.

The early engagement of the client, designer(s) and contractor(s) with the national regulatory authority is strongly recommended as the process for gaining regulatory approval can be a very long and arduous one.

3.2 EXEMPTIONS, VARIANCES AND APPROVALS

3.2.1. General principles

In countries where there are statutory limits on hyperbaric exposure, and/or prescribed decompression procedures, it is likely that HPCA work will require formal exemption from or a variation in statutory requirements probably accompanied by a formal approval of part or all of the exposure procedures proposed. Similarly, the use of non-air breathing mixtures may require exemption, variance or formal approval. As part of the application process a robust safety case should be prepared and submitted to the regulatory authorities setting out the technical reasons dictating the need for HPCA interventions and justification of the hyperbaric procedures being proposed.

Where exemption, variance etc from national legislation is granted, stringent requirements may be placed by the national regulatory authority on the duty holders.

In countries where there is no statutory power of exemption etc, the advice of the national regulatory authority on how to proceed, should be sought at an early stage in planning the project.

3.2.2. Prohibition on the use of oxygen and non-air breathing mixtures

Where national regulations prohibit or do not currently allow the use of oxygen and/or non-air breathing mixtures, additional exemptions, approvals or variances should be sought to cover their use. The principles for such applications, set out elsewhere in this clause, should be followed.

3.2.3. Technical justification

A full technical justification of the proposed use of HPCA should accompany any application for an exemption, approvals or variance. It should include information on likely ground and ground water conditions (see also Cl 5.2), proposed tunnel excavation and lining techniques along with information on the manlocks and other plant and equipment required for the hyperbaric interventions.

3.2.4. Exemptions

The supporting evidence for an application for an exemption from regulations should include:

- A description of the exemption sought.
- A robust technical and/or medical justification of why the exemption is considered necessary.
- Submissions from those providing specialist hyperbaric advice (see Cl 3.9), if any, supporting the exemption.
- Proposals for alternatives to the matter exempted.

3.2.5. Approval of hyperbaric procedures

The package of supporting evidence for approval of hyperbaric procedures or decompression regime should include a description of the compression and decompression procedures, exposure limits and breathing mixtures. The evidence should include:

- A description of the tables to be approved;
- Relevant theoretical derivations along with methodology to develop and validate the tables;
- Reports of any relevant mathematical modelling, statistical analyses, hyperbaric trials or trial runs of the tables;
- Details of relevant experience of the tables in tunnelling applications using recognised measures of DCI risk where available;
- A robust technical justification of the likely benefits of the proposals;
- Submissions from specialist advisers, if any, supporting the application;
- A scheme for monitoring the overall effectiveness of the hyperbaric procedures throughout their use on site. Such a scheme should allow for physiological monitoring during and following decompression at the level of individual exposed persons. Ideally the monitoring should be linked to any modelling or trials undertaken in advance.
- An assessment of the likely risks of decompression illness including dysbaric osteonecrosis using the proposed procedures and a comparison of these risks with those occurring from the use of the existing decompression tables currently used in tunnelling or diving in the country concerned. If there are no existing tables, the comparison should be made with internationally accepted good practice.
- Procedures for dealing with omitted decompression, exceptional exposure and emergency decompression e.g. on failure of the oxygen supply during decompression

Note : A list of additional topics which should be considered for inclusion in the submission is set out in Appendix 1.

3.2.6. Variances

In some countries, the regulatory authority grants variances. These are formal permissions to depart from or vary statutory requirements. Where there is no guidance on how to apply for and issue a variance, the regulatory authority should treat them as exemptions and/or approvals as appropriate.

3.3. DERIVATION OF THE TABLES TO BE USED

When relevant the submission should include details of the proposed compression and decompression regime along with information on how the decompression tables were derived and validated. This is not required for nationally recognised tables. However, the choice of such tables should be justified.

3.4. MATHEMATICAL MODELLING OF DECOMPRESSION TABLES

Physiological and probabilistic mathematical models of the human response to pressure exist primarily for diving research purposes but can be used as part of the process of demonstrating the effectiveness of decompression regimes. There can be limitations on their validity for tunnelling applications due to lack of data for verification purposes.

Some models can be used to predict gas in blood levels during the decompression and for some time following decompression. Relevant references include HSE Contract Research Report 201/1998 "Decompression risk factors in compressed air tunnelling: options for health risk reduction", Unimed Scientific Ltd, available from www.hse.gov.uk and "Physiology and Medicine of Diving" 5th Ed, Chapter 10, authors Bennett and Elliott (ISBN-10: 0702025712).

Any physiological mathematical model used to predict the outcome of a hyperbaric exposure should meet the following criteria:
- The model should be capable of analysing the full exposure from start of compression to end of decompression at regular closely spaced intervals.
- The model should be capable of predicting the outcome of the decompression in objective and scientifically robust terms. Such models give the results in terms of the amount of gas in the blood or the risk of DCI arising from the decompression procedures modelled.
- The model should be capable of identifying any hyperbaric abnormalities or potential issues of concern during the exposure.
- The model should previously have been verified against data from practical hyperbaric experience.
- The predictions from the model should be capable of being verified during any subsequent HPCA work using physiological monitoring on site and/or statistical analysis of site data.
- The choice of profiles to be modelled should take account of worst case conditions.
- Modelling should be undertaken to predict the safety of the procedures to be trialled and to identify least favourable conditions.

Note : If a number of different breathing mixtures are proposed, the most unfavourable profile(s) in terms of decompression outcome may not be those at highest pressure or longest exposure period.

3.5. STATISTICAL ANALYSIS.

A number of recognised parameters for reporting the results of statistical analysis of exposure data are available. Where sufficient data exists it is recommended that single exposure risk factors are calculated to quantify the incidence of decompression illness and that the standardised bends ratio is used for comparison between datasets for non-saturation exposures. Both measures are described by Lamont and Booth in "Acute decompression illness in UK tunnelling", Proc Inst of Civil Engineers, London, Paper 14384, Nov 2006. For saturation exposures it is difficult to undertake meaningful statistical comparisons.

3.6. HYPERBARIC TRIALS

It is recommended that hyperbaric trials should not routinely be undertaken to demonstrate the safety of an unproven technique. Careful consideration should be given before deciding to proceed with trials, to the value of the information which they would provide. For trial exposures to produce statistically meaningful results, a considerable number of exposures (with their associated costs) is required.

Trials are at their most representative when the work undertaken during the trials most closely reflects the work to be done in practice. Hence comprehensively monitoring working exposures can give more representative results than a trial with simulated work. In most cases therefore modelling along with enhanced monitoring during the first few working exposures on site, should be sufficient to demonstrate the safety of the proposed technique. There is also guidance and experience from diving along with a growing body of evidence from trimix use in tunnelling, against which comparisons can be made.

3.7. TRIAL RUN

Some regulators may consider that a trial run should be undertaken, in which a small number of exposures are carried out to demonstrate the intended procedures are not grossly unsafe. Whilst only a statistically valid trial can demonstrate safety, a trial run can show them not to be grossly unsafe.

Again however modelling along with enhanced monitoring during the first few working exposures on site, should be sufficient to demonstrate the safety of the proposed procedures without the need for a demonstration of procedures.

Should a demonstration of procedures be insisted on then the following is suggested :
- For non-saturation exposures, 4 exposures on each of 2 separate days for each worst case pressure/time combination should be undertaken.
- For saturation exposures, 4 persons should undergo a compression/storage/ decompression procedure. The period at storage should be long enough for saturation at the storage pressure to be established.
- In both cases the exposure protocol should include some form of work activity.

Physiological monitoring should be undertaken during and following all decompression during the trial run. For non-saturation exposures, monitoring at intervals of not more than 60 minutes should suffice unless abnormal responses are recorded in which case more frequent monitoring may be required. For saturation exposures monitoring should be undertaken at regular intervals not exceeding 12 hours.

On return to atmospheric pressure from any exposure, monitoring should continue at intervals not exceeding 60 minutes, until the parameter being monitored has been demonstrated to have been reduced to a pre-determined acceptable level.

3.8. PHYSIOLOGICAL MONITORING

Ultrasonic monitoring if undertaken, should be in accordance with the "Consensus Development Conference - Consensus guidelines for the use of ultrasound for diving research", published by Møllerløkken et al in "Diving and Hyperbaric Medicine" Vol 46, No 1, March 2016. Further information is set out in Appendix A1.

3.10. ACCEPTANCE CRITERIA FOR AN ACCEPTABLE LEVEL OF SAFETY

When modelling, hyperbaric trials/trial runs or post-decompression monitoring is undertaken it is necessary to have criteria against which the results can be assessed to determine if the procedures are acceptably safe.

Acceptance of exposure and decompression profiles as being safe, should be undertaken holistically. Both physiological outcomes and the absence of clinical signs of DCI or other ill-health effect are important. The regulatory authority may set its own criteria however in the absence of such criteria the following should be considered.

3.10.1. Assessment criteria – model predictions

Whilst it is not intended to be prescriptive over the model used, in practice there are very few physiological models available which are suitable for this application. Even fewer have been validated against hyperbaric tunnelling data. This is why ITA encourages contractors undertaking HPCA work to make their exposure data available to the industry for future research purposes. Any validated model is acceptable provided the output can be linked to a physiological monitoring technique for subsequent verification of results. The predicted results should be considered acceptably safe if they represent a DCI risk not greater than that set out below in terms of Doppler bubble score on the Kisman-Masurel scale.

- Not more than 20% of decompressions are predicted to have a Doppler bubble score of K-M Grade 3 or above.
- An insignificant occurrence of Grade 4 bubbling is predicted.

Note : one model, for which validation data are available along with correlations between predicted gas in blood and Doppler score on the Kisman Masurel scale, as well as between Doppler score and DCI risk is described in Flook, V. (1989) Application of an Advanced Physiological Model of Decompression in the Evaluation of Decompression Stress, Offshore Technology Report OTO 98 090, Sheffield, HSE Information Services and Flook, V. (2011) Predictions from a mathematical model of decompression compared to Doppler scores, UHM 38, 185 - 194.

As model predictions are often based on statistical distributions these can give rise to a very low probability of an extreme event - in this case Grade 4 bubbling. As predictions are frequently based on the "average person", it is also important to note that inter and intra-individual variability in response to decompression means that a DCI event can occur even in persons with very low levels of detectable bubbles. Hence it is prediction of DCI risk (not DCI events) on which the acceptance criteria should be based.

3.10.2. Statistical analyses

Traditionally these have been used in tunnelling and have been based on DCI incidence as a measure of the safety of decompression procedures. The large number of exposures required to give meaningful results and the unreliability of DCI as a scientifically robust measure make such techniques unlikely to be suitable for predictive work.

Where statistical analysis is undertaken, comparison should be made with the incidence of DCI in mixed gas non-saturation and saturation diving until sufficient tunnelling data becomes available for comparison purposes.

3.10.3. Assessment criteria – hyperbaric trials/trial run

One set of criteria which has been used previously in tunnelling, can be based on bubble grades on the Kisman Masurel scale arising from Doppler monitoring techniques. The profiles trialled are considered to be acceptably safe if

- Not more than 20% of decompressions result in a Doppler bubble score of Grade 3 or above;
- There is no more than an insignificant occurrence of Grade 4 bubbling (to take account of inter-individual and intra-individual variability in response to decompression).

Recommendations for Sonography in Decompression Management are set out in Appendix 1.

Note : DCI is a subjective measure and consequently is a poor indicator of decompression safety even if subsequently confirmed by the CMA. Whilst the occurrence of a DCI event during a trial or demonstration would raise concern over the safety of the procedure, the CMA should apply professional discretion in determining if that event could be considered sufficiently abnormal to be disregarded. Recompression therapy should always be given even if the CMA has reservations over the diagnosis of DCI.

Note : the reporting of DCI can be influenced by the culture within which the trials are undertaken. Those exposed should be encouraged to report symptoms and seek treatment even if this leads to an apparently high level of DCI.

3.11. Post-contract report

On completion of all HPCA work, the HPCA contractor should prepare a report on the effectiveness of the decompression regimes used on the project. This should be based on the statistical analysis of exposure data and post-decompression physiological monitoring of workers. If possible the report should be published in the tunnelling literature.

3.12. Hours of work

In some jurisdictions it may be necessary to seek exemption by the Regulator from statutory requirements in respect of maximum daily working hours and/or rest breaks as well as holiday provision.

4.1. INITIAL PLANNING FOR HPCA WORK

It is absolutely essential for the safe and successful delivery of the HPCA work that the implications of having to undertake such work are considered by the Tunnel owner, his advisers and contractors from a very early stage in the planning and design process and throughout the development of the project design. It is important at this time to consider in principle the exposure techniques to be undertaken. Thereafter the engineering requirements of the HPCA techniques selected as they affect the design of the tunnel and the TBM should be taken into account. It should be remembered that retro-fit may not be an option.

The need for coordination and communication between principal contractor, the Contract Medical Adviser, the specialist hyperbaric adviser, the HPCA contractor, the TBM supplier and the supplier of hyperbaric equipment should also be recognised from an early stage.

Where HPCA work is considered at the planning or design stage to be a contingency measure which may or may not be required, it is still necessary to make basic provisions particularly in the dimensioning of the tunnel cross-section and in the design and layout of the TBM for such work (see Cl 6). For non-saturation work there should be space for a sufficiently large manlock along with sufficient penetrations to allow for the supply of mixed gas and oxygen to the manlocks and cutterhead along with space for the relevant gas storage, supply lines, control panels and working space. For saturation work there should be sufficient space to allow for the passage of a TUP shuttle from its carrier vehicle to the manlock. With both techniques the provision of an intermediate chamber (see Cl 6.11) along with space provision for a hyperbaric control panel adjacent to the manlock along with gas storage and supply should be made. It is the responsibility of the tunnel owner, his advisers and contractors to make their requirements in this respect known to the TBM/manlock manufacturer.

4.2. CONTRACTOR RESPONSIBILITIES

The contractor with principal responsibility for the tunnelling project (Principal Contractor) should have overall management control of the HPCA work and should appoint a “person in charge” from amongst its senior personnel on site.

Because of the nature of HPCA work it is possible that a specialist sub-contractor will have to be engaged to undertake it – the HPCA contractor. As this engagement is likely to be done some time after many of the critical decisions about HPCA work have been taken, the late appointment may prevent the HPCA contractor from being able to optimise the hyperbaric techniques used. Otherwise the Principal Contractor will also be the HPCA Contractor.

Because of the rarity and specialised nature of HPCA work it is likely that the hyperbaric equipment, personnel and specialist advisers will be procured from a number of sources. For non-saturation work it is possible the HPCA Contractor would provide personnel to plan, manage and undertake the HPCA work. For saturation work the HPCA contractor could be a supplier of plant and equipment such as the habitat as well as providing personnel to plan, manage and undertake the HPCA work.

The HPCA contractor should be responsible for ensuring that all plant, equipment and materials necessary for HPCA work along with the personnel to operate and maintain that plant and equipment, are immediately available on site. Plant, equipment and materials should be robust enough to withstand the rigours of the tunnelling environment. The recommendations in the BTS “Guide”, on personnel required for and on the management of work in compressed air should be followed.

4.3. CONTRACT MEDICAL ADVISER

The HPCA contractor should appoint an occupational health doctor, the “Contract Medical Adviser” (CMA), to advise on all aspects of occupational health arising from the planning and delivery of HPCA work. That doctor should hold a recognised specialist professional qualification in occupational health and be familiar with the tunnel environment. The CMA should be competent in current good practice in hyperbaric medicine for the pressures anticipated along with the medical, social and psychological problems of saturation working where appropriate.

4.4. SPECIALIST HYPERBARIC ADVICE

The HPCA contractor should have access to specialist hyperbaric advice during the planning of the HPCA works. This can be from in-house sources or from independent specialists. Likely topics on which advice could be sought include international practice in hyperbaric exposure, plant and equipment, the availability and selection of appropriate decompression regimes, gas and breathing mixtures, saturation and TUP techniques if appropriate and human physiology relevant to hyperbaric exposure.

4.5. NOTIFICATION OF PUBLIC EMERGENCY SERVICES

It should be agreed which contractor should notify the public emergency services for the area of the works, of the HPCA work. In addition, any off-site facility operating a hyperbaric chamber to which HPCA workers might be taken in an emergency should be notified of the typical exposure regimes being operated on site, the decompression being undertaken along with the breathing mixtures and gases used. There should be discussions between the CMA along with the contractor’s hyperbaric experts and the hyperbaric facility over the maximum pressure capability of the facility and possible treatment regimes which that facility could/should provide, to reflect the exposures being undertaken on site. The facility should have contact details of a responsible person on site with whom contact can be made at any time.

4.6. EMERGENCY PLANNING

As the public emergency services are normally unwilling to enter the pressurised workings the Contractor should make provision for emergency response in the pressurised workings from within his own resources. Personnel trained and equipped to undertake rescue within the pressurised workings along with an ambulance capable of operating within the tunnel should normally be available on site.

Given the relative rarity of any compressed air tunnelling work, the local emergency services are unlikely to have had experience of dealing with hyperbaric emergencies. Nevertheless, the emergency services (fire, rescue, ambulance, paramedics etc.) can provide useful assistance in the tunnel as far as the manlock door (see Clause 10). The contractor should provide equipment and training facilities as necessary.

Where the emergency services are prepared to enter the pressurised workings, they should be offered assistance in planning their response to an on-site emergency. That assistance should again extend to the provision of equipment and training facilities as necessary.

4.7. ROLES TO BE DISCHARGED BY PERSONNEL IN THE DELIVERY OF HPCA WORK

It is essential for the execution of HPCA work in a healthy and safe manner that a number of personnel are appointed to take on various roles relating to the management or undertaking of the work. The HPCA Contractor through the person in charge should make the necessary appointments and make clear the respective roles and responsibilities of each appointee and the overall management structure. All those appointed should be competent and have had relevant previous experience however some site-specific training and familiarisation may be required.

The personnel and the roles set out in the BTS “Guide” are still required, however HPCA work and in particular the use of saturation techniques requires additional management roles to be filled and a more extensive and sophisticated management structure to be established.

4.7.1. Personnel required for saturation operations

For saturation work there are two specific roles to be filled in the management of the HPCA work. One role is the management of the surface operations and habitat whilst the other role is management of the hyperbaric and tunnelling aspects of the deployment of MGSWs from the habitat to the working chamber and back to the habitat. The titles, relative seniority and management responsibility given to these respective roles is a decision for the person in charge. It is unlikely that one person could discharge both roles.

4.7.1.1. Surface operations role

The person appointed to this role by the HPCA Contractor should be responsible for managing the safe operation of all surface aspects of the HPCA work including the habitat and life support for those in storage along with the gas supply including the procurement, storage, testing and use of gas and the relevant support personnel. The person undertaking this role should have experience of managing hyperbaric operations involving the use of surface habitats, non-air breathing mixtures along with saturation exposure techniques and should be fully familiar with the plant and equipment required, the support personnel needed as well as with gas management requirements, life support procedures, welfare and hygiene requirements, testing and inspection, record keeping and relevant emergency procedures etc. The person undertaking this role should work with the person in charge, the CMA, the person undertaking the deployment role and those providing specialist hyperbaric advice as necessary to deliver a safe system of work in which occupational health and safety risk is minimised and the welfare of those exposed is protected.

4.7.1.2. MGSW Deployment role

The person appointed to this role by the HPCA Contractor should be responsible for managing the safe deployment of MGSWs by TUP from the habitat to the working chamber, the safe completion of work in the working chamber and the return of the MGSWs by TUP to the habitat. The role will include managing the relevant support personnel, transport of the shuttle, gas supplies, manlock and mating procedures, interfacing with those in charge of the TBM over work to be done and face stability and relevant emergency procedures.

The person undertaking this role should have experience of hyperbaric operations involving saturation techniques along with experience of tunnelling operations including cutterhead maintenance and tunnel face stability procedures and should be fully familiar with the plant and equipment required along with the support personnel needed.

The person undertaking this role should work with the person in charge, the CMA, the person undertaking surface operations role and those providing specialist hyperbaric advice as necessary to deliver a safe system of work in which occupational health and safety risk is minimised and the welfare of those exposed is protected.

4.7.2. Personnel required for non-saturation operations

For non-saturation work it is probably sufficient to extend the role of the “hyperbaric supervisor” as described in the BTS “Guide” to cover the control and coordination of all hyperbaric and tunnelling aspects of non-saturation intervention. The person filling this demanding role should have had experience of HPCA work or of saturation diving along with experience of compressed air work in tunnelling.

The person undertaking this role should work with the person in charge, the CMA and those providing specialist hyperbaric advice as necessary to deliver a safe system of work in which occupational health and safety risk is minimised and the welfare of those exposed is protected.

4.7.3. Life support personnel - Habitat

Personnel responsible for operating the habitat and ensuring the safety of those in it should hold an IMCA qualification as a life support technician or equivalent and have had relevant experience. At all times when the habitat is occupied, there should be two life support personnel on duty at the habitat.

4.7.4. Gas attendant

There should be a person responsible for the organisation of gas supplies on site. Such a person should either have had previous experience as a gas attendant in HPCA work or have had experience of the management of gas supplies in saturation diving as well as an appreciation of the tunnel environment. The competence to manage stock, undertake gas testing, keep records and work within a quality control system is essential for this role.

The gas attendant should be responsible for receiving deliveries of gas on site and for ensuring cylinders or quads are clearly marked with their contents. The gas attendant should also ensure that all gas supplies are tested on delivery to site and that the cylinder contents reflect those marked on them. The gas attendant should retest all gas cylinders or quads immediately before dispatch to the manlocks.

The gas attendant should be responsible for organising the orderly storage of gas cylinders or quads within the dedicated gas storage compound on site and for ensuring there are adequate supplies of gas in storage to cover immediate use and also sufficient for contingency use including the orderly decompression of all those in saturation, should gas deliveries from the supplier be disrupted for any reason. Disruption includes plant breakdown, public holidays, industrial action affecting the supplier or adverse weather.

The gas attendant should organise the transfer of gas of the correct composition from storage to the area adjacent to the habitat where gas is drawn off for use in the habitat.

The gas attendant should ensure that sufficient gas of the correct composition is made available in the tunnel for routine and emergency daily use. Where TUP is being undertaken, the gas attendant should oversee the replenishment of the gas supplies which accompany the shuttle during TUP.

Appropriate measures should be taken by the gas attendant to prevent layering or separation of the constituent gases in cylinders in storage.

4.7.5. Shuttle supervisor

The shuttle supervisor should hold an IMCA qualification as a life support technician or equivalent and should be responsible for controlling the hyperbaric aspects of the TUP shuttle and its life support equipment use during transit between the habitat and TBM manlock. The shuttle supervisor should also be responsible for shuttle handling procedures along with lock on/off and shuttle docking procedures. There should be at least two shuttle supervisors with the shuttle at all times when it is occupied.

Additional personnel may be required to assist with the actual process of moving the shuttle between habitat and TBM.

4.7.6. Lock attendant

The lock attendants working in the tunnel should have had previous experience of lock keeping at similar pressures to those to be used on site. They should also have had experience of using exposure techniques and breathing mixtures similar to those to be used on site. This experience may have been gained in the diving industry; however, familiarity with the tunnelling environment is also necessary.

Whenever a lock is in use for HPCA work there should be two lock attendants present to operate it.

4.7.7. Umbilical tender

When using line fed masks, there can be a need for a person in the manlock or intermediate chamber (see Cl 6.11) to tend the umbilicals of those in the working chamber. One person should tend no more than two umbilicals simultaneously.

4.7.8. Worker selection

Mixed Gas workers (MGWs) should be medically fit. In addition, they should be instructed in and have sufficient knowledge of the risks of hyperbaric exposure to be able to work safely in a hyperbaric tunnelling environment using non-air breathing mixtures. They should preferably have had previous experience of working in hyperbaric environments in tunnelling. Inevitably however, because of the rarity of HPCA work, they may come from a commercial air diving background. If so they should demonstrate their ability to transfer their skills to HPCA in the tunnelling environment. There are likely to be benefits in HPCA work from building a team of workers made up from both diving and tunnelling backgrounds.

4.7.9. Saturation workers

Because of the nature of saturation working, its psychological and social impact requires special qualities in those doing the work. No-one should be considered for saturation working unless they can demonstrate having successfully undertaken such work previously in either the tunnelling or diving industry or have recently successfully completed specific training and been assessed as suitable. Mixed Gas Saturation workers (MGSWs) workers should hold an appropriate qualification such as the French Class 3 "Mention D" qualification (see www.INPP.org) or equivalent or an appropriate saturation diving qualification (HSE Part 2 or equivalent). Appropriate internationally recognised diving qualifications are listed on the HSE website at http://www.hse.gov.uk/diving/qualifications/approved-list.pdf.

4.8. COMMUNICATIONS AND LANGUAGE

In order to reduce the risk of communication errors, at the start of HPCA work, there should be an agreement over which language should be used for communications between those involved in the HPCA work. The MGWs/MGSWs and the persons ensuring their life support and supervising them should speak a common language. The default language should be English.

A protocol for emergency non-voice communication should also be established.

4.9. EMERGENCY EXERCISES

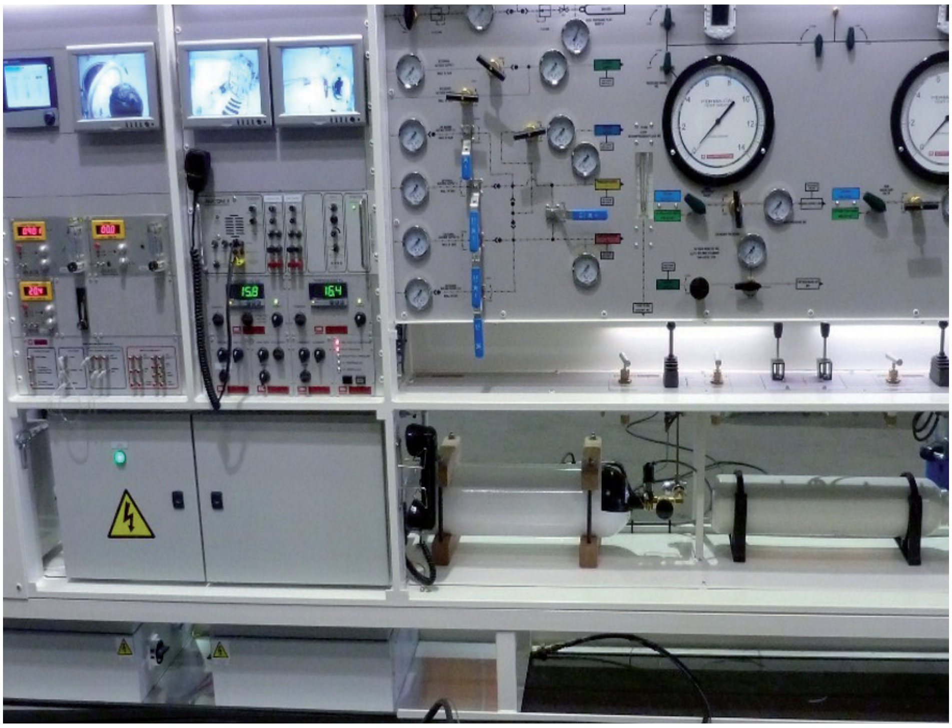
Emergency exercises should be undertaken by the HPCA contractor early in the works period and at intervals of not more than 12 months thereafter.

The Principal Contractor should work with the HPCA contractor and the emergency services where appropriate to allow the Emergency Services to undertake simulations and joint exercises to improve their ability to respond to emergencies.
As a minimum the scenarios which should be tested by emergency exercises should include

the interaction of CMA acting remotely with the on-site medical team and a casualty in the cutterhead, rescue of seriously injured casualty from the cutterhead, contamination/loss of the breathing mixture supply in the cutterhead and breathing mixture and/or power failure to the habitat.

4.10. INTERMITTENT WORKING

It may be necessary on some projects to undertake hyperbaric work intermittently or to restart operations following a period without hyperbaric activity. In both situations, where the hyperbaric plant and equipment has been maintained in an operable but unused condition and all relevant certification of plant and equipment along with calibration of instrumentation either remains current or has been brought up to date, a full functional check of all systems and procedures should be undertaken. Only once that check has been satisfactorily completed should hyperbaric activity be restarted and then only in accordance with previously agreed procedures. Where any modification of the plant and equipment has occurred. the complete hyperbaric system should be re-certified or recalibrated as appropriate. The hyperbaric system should be certified oxygen clean. Thereafter following successful functional testing in accordance with 6.51.2, hyperbaric activity in accordance with previously agreed procedures could restart.



5.1 SAFE SYSTEMS OF WORK

The requirements for safe systems of work set out in the BTS "Guide" are generally applicable to HPCA and should be adopted with modifications as necessary to reflect the higher pressures and differences in exposure techniques. No productive or maintenance work should be carried out on the TBM whilst work in HPCA is being undertaken on it. Additional requirements are set out in these guidelines.

5.2 STRUCTURAL INTEGRITY, FACE SUPPORT AND AIR LOSS

It is of fundamental importance to the safe execution of HPCA work that the stability of the ground is maintained along with the structural integrity of the tunnel lining including any bulkhead(s) in it. The interaction between the ground and the tunnel structure should also be considered. This is all the responsibility of the Principal Contractor. Calculations should be prepared by professional engineers with relevant structural and geotechnical experience, acting on behalf of the Principal Contractor to demonstrate that these requirements are being met. The client's designer(s) should formally confirm in writing on behalf of the client, their acceptance of the contractor's proposals for maintaining ground stability and the structural integrity of the tunnel.

Independent checking (Category 3) of all relevant calculations should be undertaken. The design input data should be updated as actual data on water table and geological strata become available from site (see also Cl 1.3). The calculations should be submitted as part of the technical justification required under Cl 3.2.1.

In addition, the Principal Contractor should ensure that the correct air pressure is maintained in the working chamber without excessive air loss. Excessive air loss can be defined in this case as exceeding twice the required ventilation flow in an intermediate pressure tunnel which is 0.3 m^3 per minute per person in HPCA at tunnel pressure, or more than 30 % of the compressed air supply capacity.

Unexpected increases or decreases in air loss can each be a sign of decreasing face stability.

Additional sources of air loss such as around the tailskin of the TBM should be considered and appropriate remedial action taken if required.

Because of the small size of TBM working chambers, a relatively large drop in pressure can result from a relatively small air loss and this should be taken into account when providing reserve compressed air capacity.

5.3. ACCESS AND WORKING SPACE ON TBM

In order to undertake HPCA work safely a considerable amount of space is required on the TBM. This is particularly so for saturation exposures and TUP operations. Due allowance should be made in the design of the TBM for an intermediate chamber and for a clear path to allow for the passage of a TUP shuttle from its transport vehicle through the TBM to the manlock. The TBM manufacturer must take these requirements into account when designing the TBM. A sufficient number of penetrations of adequate size should also be provided through the manlock shell and forward bulkheads, positioned close to the doors.

The working space requirements have a significant bearing on the minimum diameter and type of TBM on which HPCA work can be undertaken. There should be sufficient access and working space around the TBM manlocks to facilitate mating of the shuttle with the TBM lock, and to permit the lock attendants to have access to all control panels, gas quads, umbilical connection points, life support equipment, clamp controls, fire suppression systems etc.

For non-sat HPCA operations the TBM should be designed and constructed to provide adequate working space to access and operate the manlock safely. When HPCA operations are being undertaken a working platform should extend for at least 2 m on the free air side of the manlock door to provide working space and to facilitate the removal of a casualty from the manlocks. The working platform should also accommodate the workstation for the lock attendant and the air lock control panel. Appropriate connection points and pipework for gas supplies including gas for extended or emergency decompression, should also be available when required.

Note : if space on the TBM is limited, the working platform may be a temporary structure which is set up only for the duration of the HPCA work.

5.4. RESTRICTIONS ON HPCA DUE TO TUNNELLING CONSIDERATIONS

5.4.1. Geometrical constraints

Geometrical constraints make TUP and hence saturation exposures using the TBM manlock, impracticable on smaller sized machines normally because of conflict with the screw conveyor and/or erector.

Space constraints should be considered likely to arise in EPB machines designed for tunnels below 7 m internal diameter because of conflict with the screw conveyor and erector and on slurry TBMs below 5.5 m internal diameter because of conflict with the erector.

5.4.2. Smaller tunnels

In smaller tunnels where because of space constraints it is not possible to use a TBM manlock, it can be possible to install one or more bulkheads in the tunnel. Where fewer than three bulkheads are installed (i.e. a two compartment airlock system has not been formed), a two compartment manlock should be attached to the outbye bulkhead to provide normal emergency access for the working chamber.

As much of the TBM backup equipment as possible should be moved back prior to any interventions to allow the bulkhead(s) to be positioned close to the rear of the TBM shield to minimise the travel distance for workers using umbilicals or any system of overlapping umbilicals, for breathing mixture supply and to allow HPCA personnel to move along the TBM with the minimum of hindrance.

In particular, all flammable materials and their storage containers (such as hydraulic fluid tanks and grease) within the HPCA installation should be emptied and removed if possible.

Major electrical installations should be de-energised. It may be necessary to provide residual power to mechanically inch the cutterhead only, for maintenance purposes. Electronic and touchscreen equipment can malfunction in or be damaged by the pressurised environment.

5.5. FACE ENTRY PROCEDURES

Before any face entry takes place, the stability of the ground and the availability of suitable protective measures necessary to enhance stability should be confirmed. The extent of drawdown of excavated material or slurry required, should be carefully assessed to minimise the differential pressure across the face but should be sufficient to provide adequate working space along with space from which to rescue an injured person. Face entry procedures should take into account that work within the cutterhead is taking place above a liquid pool or soft soil mass. Face stability should be monitored throughout the time persons are in the cutterhead.

Before anyone enters the manlock to be compressed, the working chamber should have been pressurised and air pressure maintained for sufficient time without excessive air loss (see Cl 5.2) above to demonstrate the stability of the face. It is recommended that this period is for at least one hour. Shorter periods may be acceptable but only in applications where a quickly drying bentonite cake at the tunnel face limits the access times.

All valves and gauges should have been shown to be functionally operative before face entry procedures begin

5.5.1. Slurry TBM

On a slurry TBM, slurry in the excavation chamber should be allowed to seal the face to minimise air leakage, before any man-entry takes place. Ensuring that the bentonite slurry (or similarly effective skin forming slurry additive), used prior to or for refilling the excavation chamber during an intervention, has the correct material properties and is subject to strict quality control is an essential aspect of the overall safety of the HPCA work.

5.5.2. EPB TBM

In permeable ground the excavated material in the excavation chamber should be mixed with bentonite slurry (see 5.5.1) during the last advance cycle before entry to the excavation chamber takes place. In cohesive ground the conditioned muck in the excavation chamber can be lowered without prior injection of additional bentonite suspension.

Where very adverse ground conditions are anticipated, a bentonite (see 5.5.1) circuit should be provided on EPB TBMs to allow for a refill or refreshment of the filtercake during long interventions. Refilling with a muck – bentonite mixture would require further excavation which depending on the reason for the intervention might be not possible.

Note : Large EPB TBMs are normally fitted as standard with bentonite (see 5.5.1) injection facilities.

5.6. REFILLING HEAD WITH SLURRY WHILST DECOMPRESSION STILL GOING ON

5.6.1. Slurry TBM

On a slurry TBM, the cutterhead should be refilled with slurry to maintain face support as soon as possible after HPCA work has been completed and the HPCA workers are sealed in the manlock. This requirement may conflict slightly with requirements in documents such as the BTS " Guide " or EN 16191 regarding energising of equipment on the TBM during hyperbaric interventions, but it is an essential precaution for HPCA work.

5.6.2. EPB TBM

Restarting an EPB TBM in a controlled manner after an intervention is a highly critical activity especially for larger diameter machines. Depending on the face permeability two different procedures are possible. If the face is permeable, bentonite (see 5.5.1) suspension should be pumped into the excavation chamber before restarting the advance. In less permeable soils, it is assumed that the TBM will restart without the need to refill the excavation chamber with bentonite suspension.

Note : Filling the chamber with bentonite may produce a chamber fill that is too liquid to be discharged via the screw conveyor whilst maintaining full pressure control. The restarting procedure eliminates any information about volume loss or mass balance for a significant amount of time and needs very stable face conditions. In critical areas, this problem could be overcome by the injection of an artificial "conditioned soil mix" brought from outside such as a thick inert grout.

5.7. INCHING OF CUTTER HEAD

When designing a TBM for HPCA use, due account should be taken to ensure the requirements in EN 16191 relating to access to the cutter head or excavation chamber and rotation of the cutter head in jog mode can be complied with when access is by means of a manlock.

The control panel inside the chamber should be suitable for the maximum rated pressure including pressure changes (internal pressure compensation).

5.8. ACCESS IN CUTTER HEAD

The increased difficulty in moving around the cutter head and excavation chamber when wearing an umbilical fed mask should be recognised during machine design and construction so that appropriate access and fall prevention equipment along with provision for rescue can be provided.

5.9. WELDING, CUTTING AND OTHER HOT WORK

5.9.1. Minimising hot work risk on TBM

Where it is foreseeable at design stage that maintenance of the cutterhead will have to be done under HPCA, the tools on the cutterhead should be mounted and fixed in such a way that hot cutting or welding is not required when changing them. However hot work may still be required for repair works after accidental structural damage.

5.9.2. Undertaking hot work on TBM

Welding, burning and other hot work shall only be carried out in HPCA in accordance with a permit to work system. Before any work is undertaken, all flammable material in the vicinity of the hot work shall be removed or covered with a flameproof blanket. Those undertaking such work should normally wear outer garments made from a highly flame resistant material such as Nomex or equivalent. These garments should completely cover the head, neck, torso and legs as well as covering the shoes.

Hot work should only be undertaken in one place at a time. Due to the increased fire risk from such work, hot work should be continuously supervised by at least one person on fire watch duties. That person should be equipped with a fire hose so that in the case of a fire immediate action can be taken to extinguish it. The fire watch should be maintained for an hour after completion of the hot work or until the head intervention has been completed and all personnel withdrawn from the working chamber. Due account should be taken of the impact of shift changeover on this requirement.

5.9.3. Fuel gas

The use of any fuel gas under pressure incurs risk and particular care must be taken to prevent leakage of fuel gas. Acetylene should not be used as compressed acetylene can undergo spontaneous explosive decomposition. Carbon arc-air cutting or gouging techniques should be considered instead.

5.9.4. Welding fume

Occupational health risks from exposure to welding fume should be low, as all personnel should be wearing umbilical fed masks whilst in the cutterhead. Masks should be compatible with the hot work being undertaken. Nevertheless, it should be possible to flush the working chamber with air to maintain visibility and to flush the manlocks with breathing mixture to remove welding fume.

Note : It is important to ensure the correct dimensioning and installation of welding supply cables as there have been incidents in the past in which hot cables have been a source of ignition.

5.10. USE OF EXPLOSIVES

Explosives should not be used under HPCA. Non-explosive techniques for rock bursting should be used instead.

5.11. CLAMPING OF BULKHEAD DOORS

It should be possible to clamp shut the door between a manlock intermediate chamber and the working chamber as required by EN 12110:2014 Clause 5.3.5.

5.12. CCTV SURVEILLANCE

There should be CCTV surveillance of the plenum chamber so that face stability can be observed during drawdown of material in the cutterhead before any intervention takes place.

CCTV should also be used to observe and guide workers in the cutterhead when undertaking maintenance or inspections.

6.1. PLANT AND EQUIPMENT

6.1.1. General requirements

All plant and equipment for use in HPCA work environment should be suitable for the tunnelling hyperbaric environment and for the maximum foreseeable working pressure taking into account seasonal ground water variations or tidal variations as appropriate. In designing pressure vessels, the effects of pressure reversal on intermediate bulkheads should be taken into account.

In the absence of national requirements, the plant and equipment should meet the requirements of these guidelines along with relevant requirements in other guidance. "Other guidance" includes the BTS "Guide", EN 12110, Classification Society rules, NORSOK U100 and IMCA D 024 Diving Equipment Systems Inspection Guidance Note "DESIGN for Saturation (Bell) Diving Systems". The caveats in clause 2.4 on the relevance of diving guidance to HPCA work should be taken into account.

6.1.2. Information to be provided to TBM manufacturer

The TBM manufacturer should be provided with all necessary information regarding the space requirements for TUP shuttle transfer, the shuttle handling requirements, space requirements for control panels and gas storage, the number and size of penetrations for the manlocks and to the cutterhead. Mating flange dimensions should be agreed with the suppliers of the habitat and the shuttle.

6.1.3. Plant and equipment - non-saturation operations

For non-saturation exposures all hyperbaric operations associated with the intervention should be controlled from a panel at the TBM manlock. The panel should incorporate the valves and gauges necessary for the pressurisation and depressurisation of the manlock and working chamber. Additionally, there should be means to monitor and control the supply and analysis of breathing mixtures for the working phase of the intervention along with the supply of oxygen or other gas for decompression purposes. The control panel should also be inscribed with a mimic diagram of the pipework – content and direction of flow, valves – function and direction of operation, instrumentation etc.

6.1.4. Plant and equipment - saturation operations

For saturation exposures the plant and equipment should include a habitat on the surface for storage of personnel living under pressure, one or more shuttles for transfer under pressure along with any equipment required for transfer under pressure between the habitat and tunnel manlock. There should also be a self-contained chamber at the habitat which would be capable of housing the occupants of the largest of the living chambers in an emergency. The self-contained chamber should be equipped with washing and toilet facilities. It should also be capable of acting as a therapeutic recompression chamber and as a medical chamber. It should be possible to transfer under pressure into this chamber if TUP is being undertaken on site.

Guidance on dimensions, space requirements and minimum requirements for fixtures and fittings in diving habitats is given in NORSOK U100.

The habitat, TUP shuttle and all ancillary equipment required for the hyperbaric operations should be engineered to comply with Classification Society Rules such as the "Rules for Classification and Construction; VI Additional Rules and Guidelines; 11 Other Operations and Systems; 4 Chamber Systems for Tunnelling" published by Germanischer Lloyd or equivalent. As EN 12110 does not currently cover TBM manlocks for HPCA working, any TBM manlock used for HPCA operations should comply with both EN 12110 and Classification Society Rules. This will particularly affect the pipework, penetrations, valves and gauges.

Note : it is likely that EN 12110 will be revised to cover HPCA during the life of this guideline. All hyperbaric operations associated with interventions or excursions should be controlled from a panel at the TBM manlock. The panel should incorporate the valves and gauges necessary for the pressurisation and depressurisation of the manlock and working chamber. Additionally, there should be means to monitor and control the supply and analysis of breathing mixtures for the working phase of the intervention. The control panel should be inscribed with a mimic diagram of the pipework – content and direction of flow, valves – function and direction of operation, instrumentation etc.

6.2. USE OF ELECTRONIC CONTROL SYSTEMS

The control of compression and decompression procedures may be done by an electronic control system. The control system reliability and architecture should comply with a recognised national standard.

All remotely operated valves should have a manual override.

6.3. MINIMUM LOCK DIMENSIONS

The dimensions of the manlocks should not be less than those set out in EN 12110.

Note : EN 14931:2006 "Pressure Vessels for Human Occupancy" does not apply to plant in the tunnel or to TUP shuttles but does apply to surface chambers.

6.4. LIVING HABITAT FOR SATURATION

The habitat should normally be located on the surface in a purpose built structure and fully protected from adverse weather and temperature fluctuations. The structure should be lit and heated/cooled as necessary. The habitat and associated equipment in the structure including the hyperbaric control panel should be protected by a water spray or high pressure water mist fire extinguishing system. There should be a workstation for the life support personnel. Accommodation for food preparation, laundry and staff welfare should also be provided.

It is recommended that there is a minimum vertical clearance of 2 metres above the floor of the living chamber and a minimum volume of at least 4 cubic metres per occupant in the habitat complex. Some classification societies set additional requirements for living chambers covering bed size and washing/toilet facilities.

6.5. TUP SHUTTLE

Each shuttle should be designed and constructed in accordance with relevant standards e.g. classification society rules and relevant principles for manlocks. Its size should reflect the guidance on minimum dimensions in EN 12110. The TUP shuttle should be of double chamber construction as for manlocks. Entrance/exit doors are recommended at both ends of the shuttle to provide greater flexibility in use.

The shuttle should be fitted within a protective frame to facilitate lifting and minimise the risk of impact damage. Lifting of the shuttle should be done by means of lifting points on the protective frame and not on the pressure vessel. Lifting points should be designed for personnel lifting (or "man-riding") operations. Lifting points on the shell of the pressure vessel used during fabrication of the shuttle should be rendered inoperable by the manufacturer as part of factory testing of the shuttle.

The shuttle in its frame can be wheel mounted or transported on a tunnel vehicle such as a flat car or multi service vehicle. Where the shuttle in its protective frame is transported on a tunnel vehicle, the protective frame should be secured to the vehicle during travel.

Persons in the shuttle require life support. Normally this comprises a control panel, main gas supply and emergency gas supply, a heating/cooling system, fire suppression system, essential power supply. These can either be fitted integrally with the shuttle within the protective frame or transported separately and connected to the shuttle by umbilical. If separate, appropriate steps should be taken to transport the life support equipment with the shuttle and should always prevent any strain on or damage to the umbilicals and their connections. Umbilical connections should be designed to facilitate quick connection and disconnection, be self-sealing but also designed to minimise the risk of cross connection. The shuttle should be covered with thermal insulation where appropriate to minimise heat transfer.

There should be a BIBS in the shuttle for the supply of breathing mixture capable of supplying the intended number of shuttle occupants plus one spare. There should also be a separate BIBS in the shuttle dedicated to high oxygen content mixtures used for decompression purposes and which need to be discharged outside the shuttle.

Communications including CCTV and voice communications are considered to be part of the life support provisions.

6.6. PAINT SYSTEMS

Care should be taken in the selection of paints and coatings for internal chamber surfaces. A fire retardant surface which emits minimal harmful vapour is required. Although polyamide epoxy coatings are used by chamber manufacturers and have been found to emit only low level of hydrocarbon solvents at atmospheric pressure, they have been found to emit significant levels of aromatic hydrocarbons under pressure. All PVHOs coated with such materials should be fitted with appropriate scrubbers to reduce contamination to within the limits calculated in accordance with HSE publication EH75/2 "Occupational exposure limits for hyperbaric conditions" (http://www.hse.gov.uk/pubns/priced/eh75-2.pdf).

6.7. ESSENTIAL SERVICES

Electrical power to essential services in the working chamber should be supplied from appropriate uninterruptible low voltage sources situated outside the working chamber.

The area around the manlocks and control panels should be adequately lit.

The layout of the living chambers and system of work (team size, shift patterns, etc) should allow occupants to have the required periods of undisturbed rest.

6.8. INSPECTION MAINTENANCE AND TESTING

The HPCA contractor should ensure there are formal planned inspection, maintenance and testing procedures along with appropriate records, for the plant and equipment, taking account of the maximum foreseeable working pressure. This should also take account of national requirements for the inspection and testing of pressure systems. The procedures should take account of the principles for such systems set out in IMCA D 018 Rev 1, the BTS "Guide", EN 12110 and relevant classification society rules along with the requirements of the insurers of the HPCA contractor. Full records should be kept of all inspection, maintenance and testing.

6.9. SELECTION OF FACE PIECE

The most suitable face pieces be they masks or helmets should be used, taking account of user comfort, the need to provide security of fit and to minimise inward and outward leakage. Full face masks or helmets should be used in the working chamber and during decompression with oxygen. The breathing resistance for all masks or helmets should meet diving industry standards. There should be voice communication capability built into the masks or helmets.

Masks for oxygen breathing during decompression should have dual hose capability for overboard dump of exhaled gas. Otherwise masks may be single hose type unless helium reclaim is being undertaken.

Requirements for masks for welding are set out in Cl 5.8.3.

6.10. SPARE MASKS ETC

There should be a spare mask or helmet in the working chamber, kept bagged when not in use, and attached to both the main breathing mixture supply and the emergency supply. In addition, there should be a separate mask also kept bagged when not in use and attached to a cylinder containing at least a 10-minute supply of breathing mixture of similar composition to that being supplied by umbilical. Spare masks should be routinely transferred into normal service use and replaced as spares by others.

6.11. UMBILICALS

Each person in the working chamber should have a single multipurpose umbilical supplying breathing mixture, emergency breathing mixture supply through a separate core of the umbilical and communications including a body-mounted camera output (see Cl 6.12) to that person. The umbilical casing should protect the lines from damage. To permit rapid evacuation of the working chamber in an emergency, all umbilicals should originate in a place of relative safety outside the working chamber. This can be in the manlock or in an intermediate chamber which can be securely isolated from the working chamber. This intermediate chamber (motor chamber in Fig 1 below) can be considered as the first point of escape or safe area but should not be considered as a manlock chamber for compression or decompression purposes. There should then be provision for transfer to the manlock chamber whilst still breathing the appropriate breathing mixture.

Note : there can be more than one intermediate chamber on very large TBMs

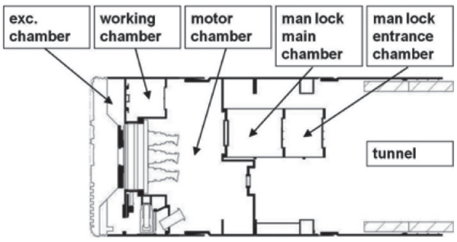


Figure 1: Example of typical intermediate chamber arrangement on slurry TBM.

6.12. COMMUNICATIONS

All masks or helmets for use in the working chamber should be fitted with an appropriate two-way communications system linked to the control panel in use at that time.

Body mounted cameras are a useful safety aid and are recommended for use in HPCA work. If fitted, they should feed the signal back to the relevant control panel.

6.13. ALIGNMENT FOR MATING

In order to affect a pressure tight seal when mating the shuttle with a manlock or living habitat it is essential that the shuttle and manlock or habitat are accurately aligned. This can be achieved by using some form of guides or docking frame on to which the shuttle can been placed. The manufacturer's tolerances on alignment for mating should be observed.

There should be no transfer of self-weight between vessels by means of the mating clamp. The sole purpose of the mating clamp is to prevent separation of PVHOs and maintain the pressure seal.

Note : if necessary there can be the capability when mating, to lift, move and/or rotate the shuttle to achieve good alignment. Good alignment can also be achieved by controlled movement within the suspension system of the shuttle transport vehicle.

6.14. MATING

Shuttles are normally mated directly to manlocks on the TBM or in the tunnel. However, for HPCA applications where only saturation exposures are undertaken, a simplified single compartment PVHO acting as an intermediate chamber can be substituted for the TBM or tunnel manlock. In this situation the shuttle acts as the manlock.

Direct mating of the shuttle to the excavation chamber bulkhead or tunnel bulkhead is considered unsafe and should not be undertaken.

On the surface, mating to a habitat is often done via trunking which can be pressurised. The trunking should be pressurised with habitat breathing mixture to avoid unnecessary contamination of the habitat.

6.15. MATING FLANGE

In the absence of a CEN standard for mating flanges it is recommended that the tunnelling industry adopts an industry standard flange. Details for such a flange are set out in Clause 12 of this document. The dimensions in Clause 12 have been agreed for operating pressures up to 17 bar between leading TBM and PVHO manufacturers in Europe.

Flanges should be kept clean and spare sealing rings for the mating flanges if fitted, should be held on site.

6.16. MATING CLAMP

It is imperative that it should not be possible to release the mating clamp when the trunking between the doors linking the shuttle to the manlock is under pressure or the trunking between the shuttle and the living habitat is under pressure. The mating clamp should be equipped with a robust mechanical interlock, activated by pressure in the trunking, for this purpose. Where the mating clamp is power operated there should be a manual means of operating the clamp in the event of power failure.

There is a preference for having the clamp mounted on the vessel to which the shuttle is to be mated to reduce the risk of mechanical damage to the mating flange and any subsequent delays.

There should be a clearly defined procedure for incrementally increasing or decreasing trunking pressure as part of clamping procedures.

Note : Particular attention should be paid to chamber mating systems. Requirements for interlocking doors on food and medical locks are set out in BTS "Guide" and EN 12110.

6.17. CONNECTIVE TRUNKING

Connective trunkings should be considered as pressure vessels in their own right and as such they should have an independent means of pressurization (not just equalisation) with relevant pressure controls, gas analysis and gauges. They should also include all the relevant safety features for Transfer Under Pressure as appropriate including interlock systems. When not in hyperbaric use, trunkings should be treated as confined spaces with all the relevant controls on access. There should be a means to flush them with air and a procedure for free air entry should be established. MGSWs should not enter a trunking unless other personnel are aware of that entry and monitoring it. A specific hazard is the presence of mixed gas pockets with low oxygen content which can remain for a long time after hyperbaric use, particularly if the trunk remains closed or under slight pressure.

Emergency or rescue procedures should to take into account access through trunkings as appropriate.

6.18. MOVEMENT OF TUP SHUTTLE TO/FROM AND AROUND THE TBM

When the TUP shuttle is being transported in the tunnel, transport should be by a dedicated train or other vehicles. The risk assessment for the emergency procedures should include the scenario in which the shuttle transport vehicle breaks down. There should be a standby locomotive or vehicle available in the tunnel to move the shuttle in the event of breakdown along with appropriate mechanical handling equipment to facilitate the transfer of the shuttle between vehicles. Where transport is by train, re-railing equipment should be available in the tunnel.

There should be a ready means of access to the shuttle controls and gas/power connections for use in the event of a vehicle breakdown.

All vehicles involved in TUP transport should have a fixed, automatic or manually operated, on-board fire protection system covering motor compartments, cabs, fuel tanks, switchgear, transmission systems, wheels and tyres as relevant. A “double shot” system may be required to cover the tyres of rubber tyred vehicles to counter re-ignition of the tyres.

Movement of the shuttle should preferably be by sliding, jacking or hydraulic lifting platform. The shuttle should be maintained in a horizontal position at all times. The movement path should be designed to avoid the need to lift the shuttle by crane whenever possible. Hydraulic lifting equipment should be fitted with industry standard check valves for personnel lifting. When in the elevated position the platform should be retained in position by mechanical devices and not depend on its hydraulic mechanism. Where lifting by crane cannot be avoided, that crane should be suitable for personnel lifting and be dedicated to shuttle lifting duties only during HPCA operations.

All mechanised equipment for shuttle handling should be considered to be an essential service and meet the relevant requirements for continuity of power supply in EN 16191.

Seat belts or similar restraints should be provided in the shuttle for use during movement of the shuttle

6.19. MOVEMENT OF TUP SHUTTLE IN SHAFTS

Where craneage for TUP handling is required, such as in shafts, the crane must fully meet recognised standards for the lifting of personnel. In the absence of national requirements at the place of use, only cranes with power lowering should be used. There should be a factor of safety of 10 on all hoist ropes and below hook lifting accessories. Lifting of the shuttle in the shaft should be done with the shuttle restrained to prevent rotation and umbilical entanglement if relevant.

Equipment for shuttle handling should be considered to be an essential service and have continuity of power supply (see 6.22).

6.20. LIFE SUPPORT FOR SHUTTLE DURING LIFTING IN SHAFT

Whilst lifting the shuttle in a shaft, the shuttle should be self-sufficient for life support or supplied by umbilical. The risk assessment for the emergency procedures should include the scenario in which the shuttle becomes stranded in the shaft. There should be the capability to provide extended life support in an emergency (see 6.35.3).

Where life support is provided by an umbilical from the surface, arrangements should be made for supporting and handling the umbilical. In this case the life support system for the shuttle should remain under the direct control of a lock attendant.

The fire suppression system in the shuttle must remain immediately operational at all times.

During the lift, the shuttle should be constrained from swinging or rotating.

6.21. TRANSFER FROM MANLOCK TO DEDICATED VEHICLE

There should be sufficient redundancy and/ or diversity in the handling system, that a failure of one part of the system does not prevent transfer of the TUP shuttle to the dedicated vehicle. The risk assessment for the emergency procedures should include the scenario in which the handling system breaks down.

6.22. EMERGENCY POWER CONTINUITY

All necessary steps should be taken to ensure continuity of power to safety critical equipment associated with the hyperbaric operations for at least the time taken to perform decompression or to remove those under pressure from the tunnel to the living habitat. Such equipment includes lighting, heating/cooling system, fire-fighting system, communications systems and emergency air supply for the lock attendant’s station. The risk assessment for the emergency procedures should include the scenario in which the primary power supply fails.

As a minimum a grid connection along with standby generators should be provided. Sufficient fuel to run the generators for the time required to perform a full decompression + 24 hours should always be available on site.

6.23. EXTERNAL THREATS

The ability to continue to supply power, compressed air, breathing mixtures and other essential services to the habitat or tunnel should not be disrupted by external threats such as public holidays, labour disputes, loss of grid power supplies, flooding or adverse weather events. The risk assessment for the emergency procedures should include the foreseeable range of external threats.

6.24. IDENTIFICATION AND MARKING

6.24.1. Marking of valves, lines

All valves should be labelled with their function and if manually operated, with their direction of operation.

All lines carrying gas should be marked at regular intervals with their function, contents and direction of flow. Rigid lines should have colour coded markers to indicate their contents. In addition to colour coded markers there should be a consistency in the colour of the outer sheath of flexible lines to reflect their contents – air, oxygen, mixed gas.

Heating and cooling water lines should also be marked with function, contents and direction of flow. Flexible lines should be coloured red for hot water and blue for cold.

The pipework and valves of the firefighting installation should be clearly and immediately distinguishable by colour.

6.24.2. Colour coding of gas cylinders and pipework

Colour coding along with marking the direction of flow in pipework can contribute to safety by facilitating the identification of functions and thus reducing the risk of human error.

Quads and gas cylinders should be colour coded in accordance with national standards in the country of use or where no such standards exist, in accordance with an internationally recognised colour coding scheme such as EN 1089-3: 2011 "Transportable gas cylinders - Gas cylinder identification (excluding LPG); Colour coding" using the colours set out for "gases used in diving". An alternative standard is ISO 32:1977 "Gas cylinders for medical use – marking for identification of content".

6.25. HYPERBARIC OPERATIONS CONTROL PANEL

6.25.1. Requirements for hyperbaric control panel

The control of the HPCA work is a safety-critical operation. There should be at or adjacent to each habitat, chamber, shuttle or manlock, a control panel from which all hyperbaric operations in that habitat, chamber, shuttle or manlock along with its associated working chamber can be controlled. Each panel should be of good ergonomic design.

During HPCA work, this panel, the chamber, manlock, associated working chamber and all services necessary for their safe operation should be considered "essential services" (term as used in EN 16191), if located on the TBM.

Where there is a centralised control panel for the complete habitat there should be a section of that panel devoted to each PVHO. In addition, the main gauges and controls should be duplicated on a local panel immediately adjacent to each PVHO.

The control panel should incorporate the following :

- All necessary pressure gauges and valves.
- Digital clock with both real time and stopwatch facilities. The display should be clearly visible from a distance of 2m under the prevailing lighting conditions.
- Mimic diagram showing the layout, direction of operation and function of all valves and gauges.
- Results of analysis of gas and breathing mixtures.
- Pressure of gas in each supply.
- Computing facilities for recording and storing exposure and decompression data.
- Essential communication links including helium voice unscrambler.
- CCTV display of the inside of each compartment controlled from that panel;
- Temperature gauge for each compartment controlled from that panel.
- BIBS feedback pressure lines.
- Water traps.

The control panel design should be such as to :

- Prevent damage to one worker's umbilical interfering with the supply of breathing gas to other workers' umbilicals. The panel design should not require manual intervention by the panel operator to achieve this.
- Ensure that any failure of one gas supply line will not bring about the loss of any of the other gas supplies to the panel.
- Allow immediate switching to a secondary supply in the event of failure of a worker's primary supply. This should not deprive another worker of his primary supply.
- Prevent the unintended crossover of air, gas or oxygen supplies

6.25.2. Miscellaneous requirements for control panel

The control panel should be provided with an un-interruptible power supply.

Seating for the panel operators should be provided.

The area should be lit to a minimum standard of 100 lux at working surface level. Emergency lighting with a minimum duration of 12 hours should be provided.

The control panel should be fitted with sufficient air-line fed full face masks to provide a supply of respirable air to enable the panel operator (s) on duty, to continue to operate the panel even when the tunnel atmosphere is irrespirable. The air supply should have a minimum duration of 3 hours. In addition, there should be a self-rescuer for each operator on duty.

When not in use, the control panels on shuttles or in the tunnel should be capable of being protected from leaks of pressurised fluids, dirt and grout ingress as well as from damage. This can be achieved either by a lockable cover or by removing the panel. If the panel is removable all services to the panel should be capable of being securely capped.

6.26. PROVISION OF GAUGES

The control panel should provide sufficient gauges, each of sufficient size, to enable the lock attendant to accurately monitor the pressures of each supply into the panel and the supply to the workers. Each gauge should be preceded upstream by a protective shut off valve. The gauge scale should indicate the pressure in bar. The gauge for indicating storage or working pressure should have a full scale reading such that it normally operates in the upper third of its scale. On many chambers the working or storage pressure required for

HPCA will be much less than the capacity of the chamber. There should be a separate valve and gauge for controlling the final 2 bar of decompression to ensure accuracy in pressure control. It should be possible to read that gauge to the nearest 0.05 bar.

Digital gauges should be used if they remove susceptibility to vibration.

It is recommended that gauges should be calibrated every 6 months or more frequently if recommended by the manufacturer.

6.26.1. Pressure control

A regulator should be provided to reduce the supply pressure to the workers' umbilicals. A relief device should be included to prevent breathing mixture being delivered at excessive pressure to the worker if the regulator fails.

6.27. VOICE SCRAMBLING DUE TO USE OF HELIUM

Voice distortion will occur from helium based breathing mixtures and appropriate equipment should be provided to compensate for that distortion where required.

6.28. TEMPERATURE AND HUMIDITY

6.28.1. General thermal control

The temperature and humidity in the habitat and shuttle should be controlled to ensure the safety and welfare of those occupying them.

6.28.2. Temperature in TBM

Immediately after the TBM has stopped the temperature in the excavation chamber is usually too high to allow safe entry without giving rise to excessive risk of heat stress. The tolerable maximum temperature for entry to the cutterhead is around 36 – 40 o C depending on humidity and worker acclimatisation. The CMA should advise on maximum permissible temperature. The excavation chamber temperature should be displayed on the hyperbaric control panel.

Note 1: A water spray cooling system for the cutterhead can reduce waiting time.

Note 2 : chiller systems for the compressed air supply can also be used.

6.29. BREATHING MIXTURE SUPPLY

There should be two independent supplies of breathing mixture piped to a control panel. In addition, there should be an independent emergency breathing mixture supply to the control panel which feeds a separate core of the umbilicals leading from that panel. (see clause 6.11). The minimum quantity of breathing mixture available in the emergency supply is set out in clause 6.35 The emergency supply should come from a different delivery of gas to site from that used for primary or secondary supply.

6.30. OXYGEN AND HELIUM COMPATIBILITY

There are well publicised procedures for the ensuring safety in the design, construction and operation of pipework systems containing oxygen. These are set out in the BTS "Guide" and other references and should be strictly adhered to. The use of hyperbaric industry standard specialist materials such as aluminium-nickel-silicon-brass alloys for pipework on control panels and in manlocks, shuttles etc is recommended.

Helium is a highly mobile gas due to its chemical structure and can diffuse through apparently solid materials such as hose linings. Appropriate helium compatible hoses, fittings and valves etc should be used.

6.31. Oxygen cleanliness

Because of the risk of combustion, all pipework, fittings, valves and other equipment which might be exposed to oxygen or an oxygen enriched atmosphere (> 23% oxygen by volume) should be kept thoroughly clean. Guidance on cleaning for use with oxygen is set out in IMCA D 031.

6.32. MAXIMUM OXYGEN CONCENTRATION – FIRE SAFETY

The maximum volume concentration of oxygen in the chamber atmosphere should not exceed 23% for fire safety reasons. Where the combination of breathing mixture composition and chamber pressure results in this limit being exceeded in the inspired gas the breathing mixture should be supplied through a BIBS with overboard dump of the exhaled gas.

6.33. OXYGEN MAKE-UP

Oxygen make up should be provided for each chamber and shuttle. This can be done through a pressure reducing valve from a cylinder on the control panel. It should inject into or near the fan of the scrubber. Provisions are to be made to prevent over-injecting of oxygen into the atmosphere.

6.34. REMOVAL OF CARBON DIOXIDE

Where carbon dioxide is removed from any chamber or shuttle atmosphere by chemical scrubbing, two independent scrubbers each with an independent power supply and a reserve supply of chemical absorbent should be provided. A single scrubber should be able to maintain the carbon dioxide level in the atmosphere below the maximum acceptable level.

The manlocks can also be fitted with scrubbers to minimise the amount of gas required for flushing purposes.

6.35. MINIMUM GAS AND BREATHING MIXTURE QUANTITIES

6.35.1. Gas quantities - non-saturation exposures

There should be a primary, secondary and emergency gas supply to the manlock. For the primary supply the quantity of breathing mixture required should be sufficient for the full working exposure for all MGWs exposed, along with any gas required for their decompression. In addition, there should be sufficient gas to compress the manlock twice from 0 bar(g) to working pressure if done with breathing mixture as part of the site procedures, along with an allowance for leakage, wastage, flushing, contingencies and emergency medical intervention or intervention by a rescue team.

The secondary mixed gas supply should consist of at least 33% of the primary gas supply for the working phase of the exposure along with the gas required for decompression of the MGWs and sufficient to compress the manlock once from 0 bar(g) to working pressure if done with breathing mixture as part of the site procedures.

The emergency gas supply should be equivalent in volume to the secondary supply. The spare gas line in the umbilicals should be connected to the emergency gas supply.

Furthermore, sufficient oxygen, nitrox and/or heliox as required for decompression purposes should be provided in the tunnel along with a contingency allowance of 100%.

There should be a similar primary, secondary and emergency supply for the emergency recompression chamber. The primary supply should be sufficient for a compression of the chamber from atmospheric pressure to maximum treatment pressure along with sufficient gas for 24 hours of daily use at chamber capacity followed by a full decompression to atmospheric pressure. The secondary and emergency supplies should be sufficient for a compression of the chamber from atmospheric pressure to maximum treatment pressure along with sufficient gas for 8 hours of normal use at chamber capacity followed by a full decompression to atmospheric pressure.

Where compression of the manlock or emergency recompression chamber is by air, there should be two independent sources of respirable quality compressed air. The sources can be compressors powered by independent power sources, a single compressor along with a supply from cylinders or two separate banks of cylinders.

6.35.2. Gas quantities - Saturation exposures

There should be a primary, secondary and emergency supply to the manlock and working chamber. A number of different gas mixtures may be required depending on the exposure profile being used. Some may be breathed through masks; some may form the pressurising medium in the manlocks.

For the primary supply the quantity of each gas mixture required at the manlock and working chamber should be sufficient for the full working exposure for all MGSWs exposed. In addition, there should be sufficient gas mixture to compress any manlocks twice from 0 bar(g) to working pressure if not done on air, along with an allowance for leakage, wastage, flushing and contingencies and emergency medical intervention or intervention by a rescue team.

The secondary gas supply should consist of at least 33% of the primary gas supply for the working phase of the exposure. In addition, the secondary supply should contain sufficient gas to permit the full decompression to atmospheric pressure of all MGSWs at work on the TBM.

The emergency gas supply should be equivalent in volume to the secondary supply. The spare gas line in the umbilicals should be connected to the emergency gas supply.

Furthermore, sufficient oxygen, nitrox and/or heliox as required for decompression purposes should be provided in the tunnel along with a contingency allowance of 100%.

Where compression of the manlock is by air, there should be two independent sources of respirable quality compressed air. The sources can be compressors powered by independent power sources, a single compressor along with a supply from cylinders or two separate banks of cylinders.

6.35.3. Shuttle gas supply

As a minimum when transporting the shuttle in the tunnel it should be accompanied by an appropriate quantity of compressed air and breathing mixture to maintain pressure in and life support to the shuttle for at least 12 hours longer than the predicted journey time with an additional allowance for make-up resulting from the locking in/out of food etc. The quantities should be based on maximum occupancy.

An additional quantity of breathing mixture sufficient to pressurise the shuttle to working pressure twice, from atmospheric pressure along with 12 hours of normal occupancy should be provided. There should be external non-return valved fittings on to which additional breathing mixture supplies and respirable compressed air supplies can be connected in an emergency.

Similarly, sufficient chemical absorbent to last for the predicted journey time plus 12 hours should be provided in the shuttle.

There should be sufficient oxygen for metabolic make-up for full occupancy of the shuttle for 24 hours. In addition, there should be sufficient breathing mixture to pressurise the shuttle once from 0 bar (g) to storage pressure.

There should be two standby gas lines in the tunnel to connect the shuttle to the primary and secondary tunnel gas supplies whilst the shuttle is within the back-up equipment of the TBM.

6.35.4. Surface gas supply

There should be a primary, secondary and emergency supply to each chamber of the habitat. A number of different gas mixtures may be required depending on the storage pressure and the breathing mixture used for storage.

The daily allowance for gas consumption should allow for the normal 24-hour work/rest cycle in the habitat. It should include flushing the chamber atmosphere, typically 15% of chamber volume every 24 hours along with sufficient gas to pressurise all shuttles normally mated to that chamber from 0 bar(g) to storage pressure. Additional gas to allow for routine medical intervention should be included.

The primary gas supply should have sufficient gas for 2 x 24-hour work/rest cycles at normal consumption rates in addition to that for the current work/rest cycle. In addition, there should be sufficient gas for a full compression of the habitat from atmospheric pressure along with the quantity required for decompression to 0 bar (g) for all MGSWs in storage. If the gas supplier cannot routinely replenish the normal supply within 24 hours, then additional gas to reflect the capability of the supplier to replenish supplies should be stored.

In addition to storage mixture, there should be sufficient oxygen for metabolic oxygen make up along with oxygen, nitrox and/or heliox as required for decompression of all MGSWs in the chamber all with a contingency allowance of 100%.

The standby supply to each chamber should provide sufficient gas for 1 x 24-hour work/ rest cycle. Additionally, there should be sufficient gas for a full decompression to 0 bar (g) for all MGSWs in storage. In addition to storage mixture, there should be sufficient oxygen for metabolic oxygen make up along with oxygen, nitrox and/or heliox as required for decompression of all MGSWs in the chamber all with a contingency allowance of 50%.

The emergency supply to each chamber should contain the same quantity of gas as the secondary supply but taken from a different batch of gas from the supplier.

There should be a similar primary, secondary and emergency supply for the emergency chamber. The primary supply should be sufficient for a full compression from atmospheric pressure, 48 hours of daily use at chamber capacity followed by a full decompression to atmospheric pressure. The secondary and emergency supply can be reduced by 24 hours of daily use provided the gas supplier can routinely replenish the normal supply within 24 hours otherwise additional gas to reflect the capability of the supplier to replenish supplies should be stored provided reliable.

Where compressed air is required as part of the hyperbaric procedures, there should be two independent sources of respirable quality compressed air. The sources can be compressors powered by independent power sources, a single compressor along with a supply from cylinders or two separate banks of cylinders.

The quantities of gas required for the surface gas supply are also applicable when there is a mixing plant located on site.

6.36. SEPARATION OF OXYGEN SUPPLY FROM BREATHING MIXTURE SUPPLY

There should be separate supply lines to chambers and manlocks for oxygen and breathing mixtures along with separate umbilicals and connection manifolds. The masks for oxygen breathing should be of a twin hose design and have an overboard dump facility. The pressure of oxygen in the supply lines, or of oxygen rich gases (i.e. higher than 23% oxygen by volume), should be reduced directly at the quad or cylinder to a maximum of 40 bar.

6.37. BREATHING RATES ETC.

When calculating gas supply volumes, a breathing rate at work of 45 l/min per person should be used along with a breathing rate at rest of 20 l/min per person.

Metabolic consumption of oxygen should be taken as 0.5 l/min per person. Mask leakage should be taken as 10%. Cylinders should be considered empty with 20 bar pressure remaining in them.

6.38. GAS OR BREATHING MIXTURE SOURCING

Gas and breathing mixtures should be sourced from a reputable supplier normally supplying the medical or diving sectors. The supplier should be able to demonstrate that control of gas purity and blending of breathing mixtures conforms to a quality assurance scheme complying with an internationally recognised standard such as ISO 9001.

Gas purity should comply with national standards in the country of use or where there are none, with a recognised standard such as the current version of EN 12021 “Respiratory protective devices. Compressed air for breathing apparatus”.

The proportions of individual gases in a mixture should meet the tolerances set out in the current version of EN 12021.

It is essential that all gas including that used to form breathing mixtures, should be of medical or diving quality. For routine HPCA operations only pre-mixed breathing mixtures should be used.

All gas supplied should be accompanied by a certificate of composition.

6.39. SAMPLING AND TESTING

The HPCA contractor through the hyperbaric supervisor and gas attendant should ensure all gas or breathing mixtures are sampled on delivery to site and again immediately prior to use to confirm their composition is as intended. The HPCA contractor should ensure that on delivery to site, all gas or breathing mixture cylinders are properly colour coded. Where more than one gas or breathing mixture is used on site, the HPCA contractor should ensure that proper arrangements are in place for the separate identification, marking, storage and handling of each to prevent accidental misuse.

6.40. GAS STORAGE FACILITY

There should be a dedicated gas storage facility on site where all gas cylinders and quads can be stored in an orderly fashion for use in HPCA work. It is likely the facility will be located close to the habitat. The gas cylinders and quads in storage in the facility should be protected from adverse weather but do not necessarily require a fully enclosed structure. When designing the facility, due account should be taken of the need to have sufficient space to allow a forklift truck to operate safety within the storage area.

There should also be an area within the facility where cylinders or quads currently in use for supplying the habitat are located. This includes the cylinders or quads for the primary, secondary and emergency supply to the habitat. All gas lines from this area to the habitat building should be protected from damage and adverse weather.

Empty cylinders or quads should be clearly marked as such and should be stored separately from full ones.

6.41. SECURITY

The gas storage facility and the building housing the habitat and its essential services should be located within a secure compound to which only authorised personnel have access.

6.42. HELIUM RECLAIM

The reclaim and reuse of helium should be considered for reasons of sustainability however this is recognised to be a commercial matter. Helium reclaim can be undertaken from exhaled breathing mixture, chamber flushing and/or gas exhausted during decompression of the shuttle, manlock or habitat. The reclaim system should not present additional risk to or place any additional burden on the MGSWs or the hyperbaric operations.

Should helium reclaim be undertaken, exhaled or exhausted gas should be piped to a purpose-built gas reclaim system for purification and storage. Reclaimed helium can be reused either by the off-site gas supplier or in an on-site mixing plant.

6.43. GAS MIXING

For saturation exposures, a gas mixing plant may be set up on site at the compressed air contractor's discretion. The gas mixing operation should be set up as a stand-alone facility separate from any HPCA activity and preferably run by a reputable gas supplier. The plant should operate in accordance with a quality assurance scheme certified as conforming to ISO 9001.

Cylinders of gas to replenish the stocks for gas mixing should have their purity confirmed on arrival at the gas mixing plant.

Before leaving the mixing plant for re-use in HPCA work, every cylinder should be tested to check its composition and purity are within specification for the gas mixture marked on the cylinder.

All gas or breathing mixture supplied from the plant should be treated as being from an off-site supplier and subject to the equivalent sampling and testing regime. The person testing the gas or breathing mixture on delivery to the HPCA work should not be the same person as tested that cylinder prior to dispatch from the mixing plant.

The HPCA contractor should not permit the piecemeal mixing of small quantities of breathing mixture on an ad-hoc basis for use in HPCA exposures.

6.44. ON-LINE GAS ANALYSIS

There should be direct sampling of the supply to the masks immediately downstream of the control panel to permit continuous on-line analysis of the oxygen content of the breathing mixture. Analysis should be to an accuracy of +/- 0.1% by volume. An audible and visual alarm should be triggered when the oxygen concentration deviates by more than +/- 1% by volume from the required oxygen content.

There should also be the capability for on-line analysis of helium. The on-line analysis of nitrogen is optional.

6.45. CALIBRATION OF INSTRUMENTATION

Instrument calibration etc should be undertaken in accordance with manufacturer's instructions and recognising the guidance in IMCA D 018 Rev 1 " Code of practice on the initial and periodic examination, testing and certification of diving plant and equipment ".

6.46. PROVISION OF GAS IN THE TUNNEL

The Hyperbaric Supervisor should confirm that the volume of breathing mixture required for each supply is available in the tunnel and on the TUP shuttle, if being used, before HPCA work begins. Immediately before use he should satisfy himself that the composition of each quad of breathing mixture is correct. He should do the same for any oxygen required for decompression purposes.

6.47. LOSS OF FLOW

Fracture or disconnection of any gas supply line should not lead to the uncontrolled loss of gas from other parts of the hyperbaric system.

Where more than one person is being supplied by umbilical from a single panel, severance or disconnection of one umbilical should not result in loss or deprivation of supply to the others being fed from that panel.

6.48. CLEANING AND DISINFECTION OF MASKS

The cleaning and routine disinfection of masks is important to prevent the growth of micro-organisms including fungi, yeasts, bacteria and viruses. Fungi are one of the most likely contaminants and these can produce large quantities of spores. Inhalation of these spores can cause an allergic reaction in the lungs, producing potentially life-threatening conditions, particularly in those individuals who may be predisposed to allergy. The recommendations of HSE Diving Information Sheet Nº 12 "Cleaning of diving equipment" should be followed.

6.49. STORAGE OF MASKS

After cleaning, masks and helmets should be bagged and stored in a clean, dry environment. Masks, helmets and all demand valves should be checked for function and cleanliness before every use.

6.50. CHAMBER HYGIENE

Personal hygiene and the general standard of cleanliness and hygiene of the surface habitat should be in accordance with DMAC 26.

6.51. CERTIFICATION AND TESTING (SEE ALSO 6.9)

The habitat, shuttles and manlocks should undergo to a comprehensive programme of inspection, certification and testing before being put into service.

6.51.1. Factory acceptance testing

The PVHOs which make up the habitat along with the shuttles and manlocks should each be subject to factory acceptance testing. This should include basic inspection and pressure testing along with the certification of the vessels as well as testing of all gauges, valves, lighting, communications, control systems, a live test of the firefighting equipment, washing or sanitary equipment, gas analysis, environmental control equipment etc in or on the PVHOs. A written record of the tests should be kept as part of the planned maintenance system which should follow the principles set out in IMCA D 018.

6.51.2. Commissioning on site

On completion of installation on site, a comprehensive commissioning programme should be undertaken. Commissioning should include a formal audit of all plant and equipment to ensure that no item of plant and equipment is missing and that all plant and equipment is as specified.

Commissioning should conclude with a formal functional test of all systems in or on the habitat, shuttles and manlocks. or systems which are part of life support for those in the habitat, shuttles and manlocks. A written record of the tests should be kept as part of the planned maintenance system which should follow the principles set out in IMCA D 018.

The functional testing programme should include all emergency power and other safety critical backup systems which are essential for life support systems.

Once the TBM has progressed sufficiently far into the ground to withstand the pressure, compressed air should be applied in the excavation chamber and the TBM bulkhead checked for airtightness.

Commissioning should conclude with a full exercise of emergency procedures to demonstrate their adequacy.

In some countries inspection and testing of the pressure vessels on site before use, by a locally recognised competent person can be required to meet statutory requirements.

6.51.3. Oxygen cleanliness

A certificate confirming the oxygen cleanliness of all pipes and vessels containing gas with > 23% oxygen by volume should be lodged in the planned maintenance system before any pressurised tests of the system are undertaken. Further certificates should be obtained and lodged following any intrusive maintenance of these pipes or vessels.

6.51.4. TUP trials

A series of trials of the TUP procedure should be undertaken starting with an unmanned and unpressurised trial and progressing through an unmanned but pressurised trial and a manned but unpressurised trial and culminating in a manned and pressurised trial. The trials should demonstrate the capability to undertake TUP safely within the timescales proposed by the contractor.

Trials of the emergency procedures associated with TUP should also be undertaken.

7.1. DELIVERY OF OCCUPATIONAL HEALTH CARE

The CMA should be the professional leader for delivery of the medical and occupational health aspects of the HPCA work throughout its duration. The CMA should be fit and willing to enter the hyperbaric environment in response to a medical emergency. The CMA should liaise regularly with the rest of the project team. The CMA needs to be on call whenever an HPCA operation is in progress and be capable of providing professional oversight of the medical response to any medical incident which could occur. Where the CMA is routinely unable to attend site within 60 minutes of being summoned, the emergency procedures should reflect this and may include the appointment of a suitably qualified local practitioner (depending on local statutory requirements) acting under his control, to assist. The pre-arranged use of a police escort or ambulance to facilitate transport of the CMA or local deputy to site in an emergency should be considered in heavily trafficked urban areas.

7.2. HEALTH ASSESSMENT

All those undergoing HPCA work should be subject to a health assessment regime appropriate to the pressures being experienced. Where appropriate national requirements do not exist, the regime should take the form of a stringent annual medical exanimation to establish fitness for HPCA work coupled with periodic health checks throughout its duration, to ensure continuing fitness for such work. The CMA should advise on the form and content of the examination and health check. The CMA should undertake the examinations and periodic checks unless national requirements dictate otherwise. Reference can be made to the BTS “ Guide ”. The results of both examinations and checks should be recorded. Clinical records should be retained by the CMA in his archive in a secure fashion complying with recognised professional standards.

Anyone intending to enter saturation conditions should have a medical check within the 24 hours before entering saturation, to confirm their fitness. This check can be performed by the CMA or by the senior diver medic using an appropriate clinical protocol prepared by the CMA.

In the event of the CMA changing, or being on holiday, clinical records should be made accessible to or transferred in copy form to the new CMA or locum as part of a professional handover.

7.3. HEAT STRESS IN THE HYPERBARIC ENVIRONMENT

Those undertaking heavy physical work in the hyperbaric environment are at risk from heat stress. Wearing the full face masks required for efficient breathing purposes can further increase the risk as can the wearing of protective clothing when tunnelling through contaminated ground. The risk arises from the reduction in body cooling from sweat evaporation, due to the pressurised atmosphere. The normal indices by which heat stress risk is assessed, such as wet bulb globe temperature are for normobaric conditions only (including exposure to sunlight) and should not be applied to hyperbaric exposure without first seeking expert advice.

Entry into the cutterhead should not be undertaken until its temperature has dropped to around 36°C. Even then high humidity in the cutterhead chamber can make entry conditions unbearable. The CMA should advise on appropriate conditions for entry. Artificial cooling may be required to control the temperature in the cutterhead.

The effects of breathing gas mixtures containing helium and of living in a helium-rich atmosphere should be considered when assessing the thermal comfort of MGSWs.

7.4. GENERAL HEALTH CARE FOR THOSE LIVING IN SATURATION

In addition to normal occupational health provision, for saturation working the HPCA contractor has to make provision for the general physical and mental healthcare and dental healthcare of those living in saturation. The CMA should be able to advise on these matters also.

7.5. FIRST AID AND EMERGENCY MEDICAL RESPONSE

7.5.1. General requirements

The HPCA contractor should ensure there is adequate availability of emergency medical and first aid facilities for those under pressure. This should cover the working chamber, manlocks, any TUP facilities and the habitat if in saturation.

Procedures should be in place for treating and decompressing casualties from general injury incidents occurring in the working chamber or the PVHOs.

A protocol should be in place for dealing with major injury during saturation exposures. Periodic exercise of the protocol should be undertaken with a debrief afterwards. Any lessons learned should be incorporated into the protocol. Experience has shown that any TUP of the casualty to an off-site hyperbaric facility is fraught with problems.

Consequently, part of the on-site hyperbaric facility should be capable of being turned into an emergency medical facility. The CMA should oversee the development and exercise of the protocol and be able to provide medical advice and assistance during an injury incident. Consideration should also be given to how specialist medical or surgical support could be provided to the casualty if needed.

Whilst the protocols and procedures above are expected to include the involvement of persons with DMT qualifications, in some countries there are restrictions on the extent to which non-medically qualified personnel can give treatment except in an emergency.

7.5.2. Non-sat exposures

All persons undergoing non-sat exposures should have an appropriate up-to-date first-aid qualification as well as an understanding of the physiological matters relevant to working under pressure. As a minimum, two of those under pressure should have a DMT qualification. At least one person in the team, other than those under pressure should be qualified as a DMT or similar. This person should be in addition to the hyperbaric supervisor because of his need to be in direct control of the operation at all times.

7.5.3. Sat exposures

All workers making saturation interventions should have an appropriate up-to-date first-aid qualification as well as an understanding of the physiological matters relevant to working under pressure. As a minimum, two of those under pressure should have a DMT qualification. At least one person in the team, other than those under pressure should be qualified as a DMT or similar. This person should be in addition to the hyperbaric supervisor because of his need to be in direct control of the operation at all times. There are situations where additional members of the team should be qualified to DMT standard, including situations where the worker requiring first aid is under pressure and emergency medical assistance cannot be provided by normal emergency medical services. The HPCA contractor in his risk assessment, should consider the numbers required to be qualified to this standard.

7.6. BIOLOGICAL INFECTIONS

Bacterial and fungal infections can readily occur in saturation living. The guidance from the DMAC should be observed. No one suffering from such infections of the ear, nose or throat which are normally a bar to entry into compressed air should undertake saturation exposures. Skin infections are an additional bar to saturation work.

7.7. PHYSIOLOGICAL MONITORING

7.7.1. Use of physiological monitoring – effectiveness of decompression

It is recommended that physiological monitoring of tunnel workers during and post-decompression, should be adopted for assessing the effectiveness of decompression regimes in real time particularly when using tables with no history of satisfactory use. There are recognised techniques within the wider hyperbaric community and monitoring should be undertaken by recognised specialists using standard protocols – see Appendix 1. Techniques available include Doppler monitoring and ultrasonic scanning but other equally effective procedures can be used. Research is ongoing to improve the interpretation of the results in the context of tunnelling exposure. The Contract Medical Adviser should be competent to advise on the use of monitoring techniques and other indicators of clinical decompression stress.

7.7.2. Monitoring frequency

All persons exposed should be subject to physiological monitoring in accordance with established protocols for the technique selected. The frequency of monitoring should reflect its purpose – initially establishing the effectiveness of the decompression regime followed by routine confirmation of ongoing effectiveness. The effectiveness of the decompression regime should be demonstrated against the acceptance criteria in clause 3.10, to a confidence level of at least 95%. Once the effectiveness of the decompression regime has been established its continuing effectiveness should be demonstrated through ongoing monitoring at an appropriate frequency to reflect the statistical variation in the results obtained when establishing acceptance.

For non-sat exposures, monitoring should be undertaken after each exposure, until the effectiveness of the tables has been established.

For saturation exposures, the effectiveness of decompressions associated with excursions and the final decompression following the end of each period in sat should be established. The need for more frequent monitoring such as during the final decompression should be identified by the CMA as necessary.

The monitoring procedure should ensure that each person exposed is subject to monitoring at some point in their exposure history on a contract.

7.7.3. Doppler monitoring

Relationships exist between bubble score and what is considered an unacceptably high risk of DCI. Because of inter and intra-individual variation, no indication of the absolute risk to the individual can be inferred from personal Doppler scores. Based on the Kisman Masurel scale, it is recommended that continued use of a particular decompression schedule be assessed if more than 20% of individuals monitored routinely have Doppler scores of grade III or above. Whilst any grade IV score is considered an unacceptably high risk of DCI, it is not per se a reason to give that person a prophylactic recompression treatment.

Doppler monitoring should be undertaken by a competent technician within the framework of a recognised quality assurance scheme.

7.7.4. Other monitoring

The physiological monitoring should include where appropriate consideration of heat stress and weight loss from dehydration. Sometimes symptoms of physical stress may mimic symptomatic decompression stress. For sat exposures, regular monitoring of MGSWs for heat stress and weight loss through dehydration may be needed. The CMA should advise on an appropriate monitoring regime and should review the results regularly. The CMA should ensure all necessary preventative and treatment measures are in place.

The symptoms of physical stress can mimic symptomatic decompression stress.

7.8. MEDICAL CAPABILITY

7.8.1. Medical facilities

Guidance on the provision of medical facilities for saturation work is given in DMAC 28 Rev 1 “The Provision of Emergency Medical Care for Divers in Saturation”.

7.8.2. Medical equipment to be held at the site

It should always be possible to undertake emergency recompression on site with suitable supporting medical equipment available. In addition, it should be possible to monitor blood pressure, pulse rate along with the mood and state of confusion of a casualty. Blood pressure, pulse rate and the ECG can easily be monitored automatically.

Where saturation exposures are being undertaken, the medical equipment and supplies set out in the current edition of "Medical Equipment to be Held at the Site of an Offshore Diving Operation" DMAC 15 and DMAC 28 should be available on site. Monitoring equipment should be shown to be functional in hyperbaric environments.

7.9. DECOMPRESSION INCIDENTS

The CMA should ensure there are appropriate procedures in place for the diagnosis and treatment of actual and suspected decompression illness arising from the HPCA work. There should also be procedures for dealing with omitted decompression, exceptional exposures and emergency decompression such as required after failure of the oxygen supply during routine decompression.

The Contract Medical Advisor should advise on the tables to be used as part of the development of emergency procedures. Whilst the CMA should provide professional oversight of DCI treatment, recompression should not be delayed pending his agreement to treat. The medical lock attendant should proceed with treatment whilst trying to contact the CMA by phone.

7.9.1. Decompression illness and saturation exposures

There are three circumstances when DCI is foreseeable in saturation exposures – following the initial decompression and during the working phase of an excursion to pressure lower than storage pressure, following decompression at the end of an excursion to pressure greater than storage pressure and during or following the final decompression to atmospheric pressure. For DCI occurring during an excursion to pressure lower than storage pressure, the casualty should be compressed back to storage pressure as soon as possible.

In the absence of project specific procedures, a person in saturation reporting DCI should in the first instance be put on oxygen enriched therapeutic breathing mixture at the storage pressure. The storage PO_2 is typically 350 - 450 millibars and the casualty should breathe a PO_2 of 2.0 bar +/- 0.5 bar in 20 – 30 minute cycles through BIBS as recommended in DMAC 23. Consideration should also be given to increasing the storage pressure to the maximum working pressure experienced by the casualty to get the benefit of both increased pressure and PO_2. If required, the CMA may advise further pressure increases following protocols depending on the response of the casualty. A consideration in making any decision to raise storage pressure is whether it is possible to split the chamber occupants to avoid unnecessary exposure risks to the remaining occupants or transfer the casualty under pressure to the emergency chamber for treatment.

O_2 breathing at enhanced PO_2 should continue in cycles until symptoms are completely relieved. This should normally be followed by a dwell of 12 - 24 hours at the increased storage pressure after which a decompression should be performed to bring the casualty (and entire crew if relevant) back to the original storage pressure.

If DCI occurs following the last scheduled excursion of a saturation campaign, the decompression could start from the maximum pressure of treatment.

The best determinant of the treatment will be the choice of saturation tables being used by the contractor since they should be accompanied by treatment schedules and tables stating how to return to the surface following a DCI incident.

Any DCI in saturation that does not resolve rapidly on enhanced O_2 will add problems of deployment and overall saturation duration.

It is useful to remember that DCI in saturation divers after in-water dives is uncommon, and that DCS with limb pain only in tunnellers has always been more frequent in the lower limbs allegedly because of the physical strain. In that respect methods of access and maintenance of position while working are important.

7.10. ASSESSING FITNESS TO RETURN TO HPCA WORK AFTER DECOMPRESSION ILLNESS

In non-saturation exposures, following a DCI event no one should be exposed to HPCA until declared fit by the CMA. Following a DCI event in saturation the casualty should not be exposed to pressure above storage pressure until declared fit by the CMA.

Note : Given the infrequent occurrence of DCI in saturation, a CMA lacking experience of dealing with this situation may wish to seek advice from more experienced colleagues, an experienced hyperbaric supervisor or diver medics on the project.

8.1. GAS PROPERTIES AND EXPOSURE LIMITS

Limits of exposure vary depending on whether non-sat or sat exposures are being undertaken. The following properties of gases and exposure limits should be taken into account when designing a breathing mixture.

8.2. OXYGEN

8.2.1. Minimisation of hyperbaric oxygen dose

Hyperbaric oxygen dose should be kept as low as possible consistent with good hyperbaric practice.

8.2.2. Limits on exposure

Oxygen is essential for sustaining life but breathing oxygen is harmful at high partial pressures and for long durations.

Any breathing mixture in routine use should always provide the user with oxygen at a minimum partial pressure of 0.2 bar. An upper limit on partial pressure of 1.4 bar should be adhered to.

For saturation exposures typical PO_2 in storage is between 0.3 and 0,4 bar. During decompression in storage higher PO_2 limits can temporarily apply. PO_2 can be increased to 0.6 – 0.8 bar during interventions and excursions, provided due care is taken to maintain the cumulative dose within the limits below.

Excessive long-term exposure to hyperbaric oxygen is harmful to health. Such exposure is measured in oxygen tolerance units (OTU) (also referred to as units of pulmonary toxicity dose (UPTD) or oxygen toxicity dose (OTD), or oxygen toxicity unit (OTU)). There is a threshold for the PO_2 below which intolerance to oxygen does not occur; this is generally agreed to be 0.5 bar. A PO_2 of 0.6 bar can cause pulmonary symptoms in less than 24 h of continuous exposure in humans. Above a PO_2 of 0.5 bar OTUs are accumulated on a non-linear basis.

In order to allow for the cumulative effects of multi-day exposures with some recovery between exposures each day, a recommended maximum limit for routine exposure of 400 OTUs daily and 1800 OTUs over any period of seven consecutive days of exposure should be adhered to.

It should be noted that additional oxygen exposure will be incurred if therapeutic recompression becomes necessary. Higher PO_2 of up to 2.8 bar is used under appropriately controlled conditions in recompression therapy for DCI in accordance with recognised treatment tables. The generally accepted upper limit for oxygen exposure for a patient suffering from serious decompression illness has been taken as 1425 OTUs. Exceptionally a limit of 1700 OTUs can be applied for a single severe exposure.

The risk of harm from short or long term exposure to oxygen should be reviewed regularly by the Contract Medical Advisor.

Oxygen volume concentration in any habitat, chamber, shuttle or manlock should be kept below 23% for fire safety reasons (see Cl 6.31).

8.2.3. Symptoms of oxygen toxicity

Oxygen is toxic to both the neurological system and the lungs. A subject's response to high PO_2 is neither predictable nor constant. In this respect it mimics the unpredictability of DCI after even provocative hyperbaric exposures and contrasts with the apparent linearity of symptoms in Nitrogen narcosis. Testing for neurological oxygen susceptibility is not recommended as part of fitness assessments. There are no tests for pulmonary oxygen toxicity susceptibility.

Neurological symptoms are usually acute in onset, and include seizures, facial muscular twitching, nausea, pins and needles, dizziness, loss in coordination, euphoria, fatigue and visual disturbance. These usually resolve quickly when the PO_2 is reduced, i.e. the source of high PO_2 is removed. Neurological symptoms have not been reported where the PO_2 is 1.4 bar or less.

Pulmonary symptoms are more dose-related and cumulative over a period of hours or days. Typical symptoms at onset are of tracheitis and bronchitis with irritable throat and coughing. Eventually these become intense with painful inspiration and uncontrollable cough. Pulmonary symptoms resolve within two or three days after exposure has ceased, depending on severity of exposure and injury. Symptoms similar to those in neurological toxicity may also occur. Prolonged and repeated high doses may lead to refractory or permanent lung damage. A more detailed description of symptoms and the nature of oxygen damage can be found in most standard hyperbaric medical texts e.g. "Physiology and Medicine of Diving" 5th Ed, Chapter 10, authors Bennett and Elliott (ISBN-10: 0702025712).

Retinal damage can also occur as a result of excessive exposure.

8.3. NITROGEN

Nitrogen is a narcotic gas at high partial pressures. It also has a high gas density which makes the work of breathing more strenuous as pressure is increased.

Although exposure to compressed natural air at up to 5 bar is generally accepted in diving practice, the narcotic effect of nitrogen at such pressures should not be underestimated and is considered to create an unsafe and inefficient working situation. Workers suffering from an equivalent level of narcosis due to the effects of alcohol or drugs would not be permitted to enter HPCA.

Compressed air or any breathing mixture containing nitrogen and in routine use for non-saturation exposures, should provide the user with a partial pressure of nitrogen (PN_2) not exceeding 3.6 bar. This limit is equivalent to breathing air at 3.5 bar (gauge).

Prolonged exposure under saturation conditions at a PN_2 of 3.6 bar can lead to symptoms of narcosis and excessive fatigue from the work of breathing, hence it is recommended that the limit for saturation exposures is a (PN_2) of 2 bar.

The narcotic effects of nitrogen exposure whilst breathing a compressed air atmosphere are summarised in Table 1. Physical exercise can exacerbate the narcotic effects.

8.4. HELIUM

Helium is a relatively rare and hence expensive gas. Helium is a light and inert gas. It is less soluble than nitrogen and it on-gases and off-gases more rapidly. It has a low gas density which facilitates breathing in HPCA at high work rates. It also has high thermal conductivity which can be beneficial in countering the effects of heat stress. Some voice distortion can be expected from helium based mixtures. Exposure to helium at high pressure can lead to high pressure nervous syndrome. The threshold at which this occurs is not clearly defined but can be around 15 bar or higher.

8.4.1. Heliox

Oxygen helium (heliox) mixtures are the normal breathing mixtures used in commercial diving for saturation exposures. The absence of nitrogen from the breathing mixture significantly reduces the work of breathing and eliminates the risk of nitrogen narcosis. Because of the greater thermal conductivity of helium, temperature control of the living and working environment can be more complex. Some degree of voice distortion will also be encountered but can be overcome by the use of signal processing equipment if needed.

There is extensive experience of the use of heliox from the offshore diving industry. This should make the sourcing and approval of appropriate decompression tables easier.

Heliox can be used in the treatment of DCI.

8.5. Trimix

Trimix – an oxygen, nitrogen, helium mixture - trimix has been used on a number of HPCA contracts in tunnelling as the breathing mixture for exposures at pressures above 3.5 bar in tunnelling. The helium content reduces the work of breathing gas density and the narcotic effects of nitrogen but as it requires less helium than heliox is cheaper than heliox. Currently there is only limited experience of trimix exposures below 10 bar as it is not a gas used extensively in diving at these pressures.

AIR PRESSURE (GAUGE)	SYMPTOMS OF NARCOSIS
< 1 bar	No noticeable symptoms.
1 - 3 bar	Performance of unfamiliar tasks and reasoning slightly impaired. Slight euphoria possible.
3 - 5 bar	Delayed response to visual and auditory stimuli. Reasoning and immediate memory affected more than coordination of limbs. Calculation errors and wrong choices. Idea fixation. Over-confidence and sense of well-being. Euphoria more pronounced to the point of laughter on loss of self-control. Noticeably talkative.
5 - 7 bar	Sleepiness, impaired judgment, confusion, hallucination, dizziness. Severe delay in response to signals, instructions and other stimuli. Pronounced euphoria including uncontrolled laughter or hysteria. Terror in some.
7 - 9 bar	Increasing mental confusion, hallucination leading to stupefaction accompanied by some decrease in dexterity and judgment as pressure increases. Memory loss and increased excitability
> 9 bar	Euphoria, manic or depressive states, loss of awareness of surroundings and time. Incapacitation Unconsciousness. Death.

8.6. NITROX

Oxygen nitrogen (Nitrox) mixtures can be of use for exposures around the interface between the intermediate and high pressure exposure range but is of little use in normal HPCA work because of the relatively limited range of pressures over which it can safely be used.

Nitrox can be used in the treatment of DCI.

8.7. OXYGEN CONTENT IN CYLINDERS AND CHAMBERS

It is good safety practice for all inert gas cylinders delivered to site to contain at least a sufficient concentration of oxygen to support life, normally taken as a PO_2 of 0.12 bar, were they to be connected directly to an umbilical in error. Helium cylinders normally contain a minimum of 2% oxygen by volume in diving practice for use at 5 bar and over. However, a 2% heliox is not sufficient to support life if used in error at 3.5 bar (g) at which pressure 3% oxygen would be required. However, in situations where helium is used as a compression gas to bring an air pressurised chamber to a required trimix formulation, the use of a 3% heliox for pressurisation can result in excessive PO_2 in the chamber which can be slow to reduce through the normal metabolic process. Nitrogen in cylinders is not normally used in HPCA work. Where pure inert gas is required the procedures in IMCA document AODC 038 should be followed.

Particular care is also needed where trimix is used as this can have an oxygen concentration of less than 12%. Mixed gas breathing during compression should only commence once the PO_2 at the point of delivery exceeds 0.2 bar.

All mixtures with an oxygen content greater than 23% oxygen by volume should be treated as pure oxygen.

8.8. CHOICE OF ROUTINE EXPOSURE TECHNIQUE

The choice of exposure technique depends on the amount of work to be done and the space available on the TBM as well as on the working pressure and the breathing mixture to be used.

Non-saturation exposures at high pressure typically allow for relatively short working periods (typically 45 minutes at 6 bar (g)). Such exposures permit inspection and limited maintenance only to be undertaken.

Saturation techniques remove much of the health risk associated with the multiple decompressions required to achieve the same productive working time from non-saturation exposures even at intermediate pressures (< 3.5 bar).

For safety reasons, exposures at pressures of 7 bar and over should normally be undertaken using saturation techniques.

8.9. BREATHING MIXTURE SELECTION - BASIC PRINCIPLES

There is some flexibility when selecting the proportions of each gas in the mixture depending on the exposure technique and the exposure pressures being used. Commercial considerations around the cost of helium and whether it is vented to the atmosphere or reclaimed are also relevant. The advice of specialist advisors and contract medical adviser should be sought on the hyperbaric safety issues associated with the decision making process.

The breathing mixture at working pressure may be trimix or heliox. However, the work of breathing and the risk of nitrogen narcosis should be minimised. This can best be achieved by using heliox as the breathing mixture.

Where trimix is used for saturation exposures the partial pressure of nitrogen should be kept as near constant as possible between the various breathing mixtures used in the habitat, TUP shuttle, manlock and the working chamber.

8.10. BREATHING MIXTURES FOR NON-SATURATION EXPOSURES

Although a single trimix formulation can service the full range of pressures between atmospheric pressure and 6 bar (g), it may not be the most effective option for maximising working time. The use of breathing mixtures with a higher helium content would reduce the work of breathing along with narcotic risk and could allow for shorter decompression times. To reduce PO_2 and cumulative oxygen dose, MGWs could be switched to breathing mixtures with less than 20% oxygen once compressed to an appropriate pressure breathing air.

8.11. EXPOSURE LIMITS NON-SATURATION EXPOSURES

For many non-sat exposures the MGWs will enter the manlock, don masks and the manlock will be compressed to working pressure using air. The MGWs still breathing from masks will transfer to the working chamber pressurised with air. At the end of the working period the MGWs will transfer to the manlock and be decompressed. At some point during the decompression the MGWs will change to masks with overboard dump capability for the oxygen breathing phase of the decompression. Mask-off breaks should be factored into the exposure profile as necessary.

For reasons of worker comfort and control of hyperbaric exposure the following limits should be observed:

For manlocks less than 1.8 m internal diameter:
- A single exposure in 24 hours such as to require a decompression time in the manlock of not more than 2 hours or the exposure period and decompression time combined should not exceed 3 hours.
- Not more than five consecutive exposures should be worked without a break of at least 48 hours at atmospheric pressure.

Such exposures typically permit inspection and limited maintenance only to be undertaken.

For a manlock of at least 1.8 m internal diameter with an internal volume of at least 1.5 m^3 per occupant:-
- A single exposure period of not more than 2 ½ hours and such that the exposure period and decompression time combined do not exceed 8 hours. This is to be followed by a minimum of 24 hours at atmospheric pressure.
- There should be a mask-off break of at least 30 minutes between finishing work and starting oxygen breathing for decompression.
- Not more than four consecutive exposures should be worked without a break of at least 48 hours at atmospheric pressure

Such exposures should only be undertaken with the agreement of the CMA. The decompression criteria set out in clause 3 and the oxygen limits in clause 8 of this document apply. Seats should be staggered or on one side of the lock only to permit gentle leg movements during decompression., During decompression the MGWs should have access to food and drink along with basic welfare facilities.

8.12. NON-SATURATION EXPOSURES IN TUNNELS TOO SMALL FOR TUP

In tunnels where there is insufficient space to undertake TUP the contractor should have the option of undertaking non-saturation exposures to 8 bar pressure. The limits in clause 8.11 apply. No one should undertake more than 14 exposures in a 35-day period.

8.13. SATURATION EXPOSURES

The MGSWs will typically enter the habitat and be compressed to storage pressure followed by a period in the habitat to attain saturation. On a daily basis the MGSWs will transfer under pressure to the TBM manlock and hence to the working chamber where they will breathe the working mix through masks. A mid-shift mask off break will be taken on working mix probably in the manlock. At the end of the working period the MGSWs will return via the manlock to the shuttle for transfer under pressure back to the habitat. A final decompression to atmospheric pressure will be undertaken in the habitat at the end of the saturation run which would normally be up to 28 days long.

Saturation typically gives productive working periods of around 5 hours with a typical intervention. Hence where significant working time is required for major maintenance, saturation working should be undertaken. Although saturation techniques are often associated with high pressures, they can and have been undertaken from pressures as low as around 2 bar to limit the decompression risk.

Saturation exposures are much more complex in the gas mixtures required. A number of different breathing mixtures are likely to be required in the course of a saturation run. When the saturation run is on trimix, compression from atmospheric pressure will be by trimix or a combination of air followed by helium. Storage and working mixes can be different. In many tunnels it is likely that the working pressure will increase and/or decrease as the tunnel drive progresses. Consequently, storage pressure may have to be varied regularly to reflect the working pressure.

When run on heliox, compression will be by heliox.

The changeover between different mixes has also to be considered. The use of small readily portable cylinders of breathing mixture rather than mask-off transfers in air should be adopted to minimise the risk to the MGSWs. Contamination of the manlock by air when transferring between working chamber and manlock should be minimised.

The habitat mix and the working mix can be different in composition and pressure of use. An increased oxygen content can be required for the working mix and a different pressure may be involved.

The partial pressure and cumulative dose limits in clause 8 above should be adhered to and the basic principles in this clause taken into account. Otherwise the contract medical adviser and specialist hyperbaric advisers as necessary should seek to optimise the various trimix formulations involved to minimise the risk and discomfort to the MGSWs.
This is likely to result in trimix formulations with an oxygen concentration below 20%. Care must therefore be taken to ensure that at all times the MGSWs receive the minimum partial pressure of oxygen to sustain normal life.

8.14. LIVING IN SATURATION CONDITIONS

For saturation working, the HPCA contractor has to extend the safe systems of work to cover the occupational health, welfare and general well-being of those in the habitat between interventions. This includes the provision of food and drink, the maintenance of a safe and clean living environment in the habitat with a reasonable degree of comfort and amenity, the provision of washing and toilet facilities, laundry facilities, first aid and medical provision. The standards of the saturation diving industry should be followed.

8.15. STORAGE PRESSURE

Storage pressure should be as near as possible to the working pressure but should not normally exceed it.

A preliminary schedule of storage pressure should be determined in advance by the HPCA contractor in consultation with the engineers responsible for TBM operation, ground stability and maintenance. This should be updated as tunnel construction proceeds. The schedule should be used for determining the number of MGWs or MGSWs required to do the work as well as for planning the hyperbaric operations, ordering gas supplies and saturation procedures. The person responsible for the deployment of MGSWs together with the CMA and specialist hyperbaric advisers where necessary, should determine the hyperbaric procedures required to deliver the required number of personnel at the planned working pressure and duration.

Storage pressure may be increased during a saturation run. When MGSWs are in the habitat the rate of compression should be in accordance with routine compression procedures. Alternatively, compression of the habitat can be undertaken when the habitat is unoccupied.

Note : on many sub-fluvial tunnels the vertical alignment will be such that working pressure will increase from the launch shaft towards mid channel and then decrease as the tunnel heads towards the reception shaft. This can result in a need for an increasing storage pressure followed by a decreasing storage pressure. It is good hyperbaric practice to regularly increase the storage pressure to reflect increases in working pressure.

Reductions in storage pressure should normally be undertaken between saturation runs. A reducing working pressure profile can be achieved by undertaking a series of progressively smaller excursions to pressure greater than storage. Exceptionally, when a reduction in storage pressure has to be undertaken during a saturation run, it should be done using the relevant portion of the final decompression table and reducing the storage pressure in small decrements of say 0.2 bar. There should be at least 5 days between reductions in storage pressure. The reduction in storage pressure should not follow within 12 hours of an excursion to pressure greater than storage pressure.

8.16. DAILY SHIFT PATTERNS IN SATURATION

In order to ensure safe and efficient operations, MGSWs should work within a time routine which allows them to develop a regular work and sleep pattern which should where possible coincide with a normal daytime/night time regime. The minimum rest period in the living complex should be 12 hours (i.e. not working or carrying out pre or post-work checks). Therefore, when operations are carried out on a 24/7 basis only one work period per 24-hour period is recommended and that work period should occur within the same time period each day relative to the start time of the site working day with a maximum excursion or intervention of 8 hours.
Where more than one team of MGSWs is occupying the same habitat, each team should occupy its own living chamber. Wet pods can be shared but the daily living patterns of the respective teams should be phased to even out demand for showers etc.

8.17. DURATION OF SATURATION EXPOSURES AND SURFACE INTERVALS

Where relevant national requirements do not exist, it is recommended that experienced saturation workers should not experience a saturation exposure exceeding 28 days under pressure. Otherwise the exposure should not exceed 14 days.

Note : The imposition of a 14-day limit on experienced saturation workers does not enhance safety as it unnecessarily increases the number of workers required to complete a set amount of work. This increases the number of decompressions, the training/learning/familiarisation requirements and can significantly increase the proportion of time not spent under pressure but spent travelling between home and worksite if international travel is involved.

Thereafter that person should not undergo any further saturation exposure until at least an equal interval of time at atmospheric pressure has elapsed. However, after 48 hours at atmospheric pressure that person can again become involved in hyperbaric works but only for non-sat excursions.
A person's cumulative saturation exposure should not exceed 13 weeks in any 26-week period.

8.18. INTERVENTION DURATION

The intervention duration in saturation should be calculated from initial lock-off the habitat until the final lock-on to the habitat and personnel are ready to transfer back into the habitat The maximum intervention duration should normally be 8 hours in any 24- hour period. No more than one intervention per day is recommended. Exceptionally the intervention can be increased with the agreement of the CMA, to a maximum of 10 hours where TUP times exceed 1 hour each way.

8.19. WORK/REST PERIODS DURING INTERVENTIONS

As personnel are involved in strenuous physical work during interventions, they should have at least one mid-intervention rest and refreshment period. This should be undertaken with masks off.
The work period during any intervention should not exceed 6 hours from start to finish and there should be a rest period of at least 30 minutes around the middle of the work period. The rest period should preferably be taken in the TUP shuttle or manlock. The work period duration may need to be reduced for very heavy work.

8.20. TBMS AT DIFFERENT WORKING PRESSURES

Two TBMs at different working pressures can be serviced from a single habitat by setting storage pressure to the working pressure of one TBM and using excursions to a working pressure greater than storage pressure for the other.

Exceptionally when the pressure differential between the TBMs exceeds the maximum permissible excursion pressure above storage, excursions to pressures above and below storage can be used to achieved the required differential pressure. Alternatively, a split habitat catering for two storage pressures or two separate habitats at different storage pressures can be used.

8.21. EXCURSIONS

Excursions can be undertaken to pressures greater than or less than storage pressure. However, of the two, excursions to a pressure greater than storage pressure are always to be preferred.

Excursions to pressures less than storage pressure should be avoided when possible as it is physiologically undesirable to undertake heavy physical activity following a decompression due to the unpredictable bubble formation which can occur particularly in muscle tissue. The decompression involved in such excursions should normally be undertaken at the start of the intervention. The safety of excursions to pressures less than storage pressure, can be dependent not only on the storage pressure but on any excursions to pressures greater than storage pressure in the previous 24 hours.

Where possible when planning excursions MGSWs should consistently excurt to pressures lower than storage or the pressures greater than storage during a saturation run but should preferable not undertake both. Where, MGSWs have to undertake both they should excurt to pressures lower than storage before undertaking excursions to pressure greater than storage. MGSWs should not normally excurt to pressures both lower and greater than storage within a single intervention.

Limits on pressure differential during excursions are given in references such as NORSOK Standard U-100 Table 8 or Table 4 of the French “Annexes de l’arrêté du 30 Octobre 2012”. These limits are based on heliox breathing, immersion in water and work rates which can be significantly lower than in tunnelling and hence should be used with caution in tunnelling. Excursions when breathing trimix in tunnelling will need to be developed and verified for the specific trimix formulations being used on site.

The maximum rate of pressure change for excursions should be 0.5 bar per minute. Pressure or gas mix changes required for excursions should be undertaken with the shuttle at the habitat or TBM manlock but not in transit.

Work/rest periods for excursions should be the same as for interventions.

8.22. FINAL DECOMPRESSION

Starting the final decompression whilst bubbles are present is a significant factor in initiating DCI. To ensure that any bubbles formed during excursions have totally resolved, there should be a period of rest at storage pressure before starting final decompression.

8.23. AIR BREATHING DURING EXPOSURES

8.23.1. Period without use of masks in non-sat exposures

Decompression tables which include one or more stages where masks are not required to be worn, may be advantageous as they permit communication, rehydration, and comfort breaks for the workers as well as facilitating medical monitoring.

8.23.2. Air breaks during oxygen decompression in non-sat exposures

Appropriate air breaks should be incorporated in the oxygen stages of any decompression regime used. The ratio should be around 20 to 30 minutes of oxygen breathing interspersed with 5 minutes breathing on air or as required by the decompression schedule being used.

8.23.3. Loss or removal of masks

Loss or removal of masks should be included in the risk assessment for emergency procedures.

Appropriate steps to prevent unintentional loss or removal of masks should be taken and those wearing masks should be warned against deliberately removing them except on the instructions of the lock attendant.

There are pressures at which the unintentional loss or removal of masks is dangerous and the immediate onset of narcotic symptoms or loss of consciousness can be expected to occur (see Table 1). At these pressures the compressed air environment in the working chamber is toxic and irrespirable. Risks leading to unintentional loss or removal of masks should be identified and mitigated appropriately as far as possible such as by the use of helmets rather than masks.

Those working in saturation should be specifically instructed on the risks associated with loss or unauthorised removal of masks. The use of CCTV and effective supervision from outside the working chamber will reduce risks further. However, there is no accounting for panic responses. There should be good communications and a suitable contingency plan to deal with a «lost» mask situation.

During compression and decompression, it may be necessary to remove the mask briefly to give access to the nose as part of the procedure for equalising pressure in the ears.

8.23.4. Air breathing as part of the exposure profile.

In the living habitat the pressurising medium is normally trimix or heliox and it is relatively straight forward to prevent contamination of the habitat atmosphere by air. However, during man-transfer between shuttle and manlock and manlock to the working chamber it becomes increasingly difficult to prevent contamination of the atmosphere by air. It can therefore be expedient for persons to transfer through the trunking between PVHOs without having to wear masks or having to maintain a mixed gas atmosphere in the manlock, shuttle or trunking. Likewise, it can be expedient for those who are away from the habitat to breathe air to facilitate comfort breaks, rehydration etc as part of the decompression for return to the habitat. However, such an approach should be avoided as it introduces unnecessary exposure to high pressure nitrogen. If a mixed gas atmosphere cannot be maintained in the vessels or trunking either by flushing with gas or the use of flexible curtains to limit mixing between vessels, bailout bottles or additional BIBS connections should be used to provide a temporary supply of mixed gas until the proper atmospheric mix has been re-established.

Should air breathing be deemed an essential part of hyperbaric operation, the upper pressure for such activities should be 5 bar or other such pressure as determined by the CMA in conjunction with any specialist hyperbaric advisers retained by the contractor taking due account of the breathing mixtures being used, the narcotic effects of nitrogen, narcotic shock, gas diffusion and the toxic effects of oxygen. Where air breathing is part of the exposure procedure, mask removal should be done one worker at a time.

8.24. DECOMPRESSION TABLES

The HPCA contractor should with the advice of the CMA and specialist hyperbaric advisers if necessary, select the decompression tables to be used taking account of the gas mixes being used.

Tables with a proven history of effectiveness are to be preferred. Un-proven tables should be subject to a stringent verification process before they are put into routine site use. Post decompression physiological monitoring should be undertaken to demonstrate the effectiveness of any unproven tables being used.

8.25. TREATMENT TABLES, OMITTED DECOMPRESSION TABLES, OVER RUNNING PERMITTED EXPOSURE PERIOD

As part of the safe system of work, the HPCA contractor, with the advice of the CMA and specialist hyperbaric advisers, should identify appropriate treatment tables for use in treating DCI.

Similarly, the HPCA contractor should with the advice of the CMA and specialist hyperbaric advisers if necessary, identify procedures for dealing with omitted decompression and extended exposure periods. Extended exposure periods should not be allowed unless the extension is short. Extended exposure periods should not be used to compensate for insufficient numbers of suitable workers or inadequate work planning.

Additionally, procedures for dealing with the use of incorrect breathing mixtures during exposure if relevant should be drawn up.

8.26. LOSS OF OXYGEN SUPPLY DURING DECOMPRESSION

There should be procedures in place including an appropriate air-only decompression table for use in the event the oxygen supply fails.

8.27. REMAINING ON SITE AFTER DECOMPRESSION

All persons exposed should remain on site for at least 2 hours after decompression with MGSWs remaining on site or in the immediate vicinity of site for 24 hours following decompression. This will allow time for physiological monitoring to be undertaken.

8.28. ASCENT TO ALTITUDE

Personnel undergoing HPCA exposures should not fly or otherwise ascend to altitude in excess of 150 metres or 500 feet e.g. mountaineering or driving over hilly terrain, for 24 hours after decompression. Where geographical or logistical conditions render this requirement un-acceptably restrictive, the CMA should produce local rules for travel should it involve ascent above this height.

8.29. FIRE RISK IN SATURATION

The risk of ignition and fire in a pressure vessel is dependent on the pressure of the vessel atmosphere and the volume concentration of oxygen. Increasing one or other parameter will increase the risk however the risk is more sensitive to an increase in volume concentration than to an increase in pressure. The converse applies to reductions in volume concentration of oxygen.

Life support is dependent on partial pressure of oxygen and not total pressure in the vessel, hence life can be sustained at high pressure with a low volume concentration of oxygen. Accordingly, there is a “zone of reduced combustion” in which respiration is safe but fire risk is reduced. Where the option exists to reduce the oxygen volume concentration and still maintain a safe respirable atmosphere in a PVHO, the benefits in terms of reduced fire risk by making such a change should be considered. Whilst there is also a “zone of no combustion” the oxygen volume concentrations within that zone can be too low to give a partial pressure of oxygen which will support life.

9.1. RECORD KEEPING

Exposure records should be made in the agreed language of communication for the HPCA work is being undertaken. Records should be held in electronic format using one of the internationally available office software packages. Record keeping should generally be as described in the BTS "Guide" along with any additional requirements of the national regulatory authority. In addition, a full record of the composition of all breathing mixtures and gases used along with the times and pressures at which they were used should be kept for each working exposure and subsequent decompression. Gas purity records should also be kept.

9.2. RECORDS OF SATURATION WORKING

9.2.1. Individual recording

For saturation exposures, a full record for each person exposed should be kept starting at the point of initial compression until the end of the final decompression, including details of each intervention and any excursions associated with it. On termination of employment, each person exposed should be given a full record of his exposures on the project including details of breathing mixtures used, exposures, interventions and excursions undertaken, details of training received, results of medical surveillance, along with details of any decompression illness events experienced and their treatment.

9.2.2. Exposure log

There should be a full record kept of the saturation exposure including details of supervisory personnel, all changes of pressure, gas mixture, incidents, lock outs and lock ins, illness or injury, DCI treatments, decisions of a safety critical nature and other relevant issues. It should be retained until the end of the contract period. It should be signed off at the end of the period by the senior representative of the HPCA contractor.

9.2.3. Individual log books

For sat exposures, all lock attendants and life support personnel should keep logbooks recording their role in the operations. It should be signed off at the end of the period by the senior representative of the HPCA contractor.

9.3. DISTRIBUTION OF RECORDS

On completion of the work, in addition to copies of the records given to individuals and their employers, a copy of all records, in its official language, should be offered to the national regulatory authority for occupational health and safety in the country where the work was undertaken.

9.4. RETENTION OF RECORDS

The HPCA contractor should retain the records in the company archives for a period of 40 years from the end of HPCA work.

9.5. HEALTH AND MEDICAL RECORDS

Access to health and medical records should generally be as described in the BTS "Guide" along with any additional requirements of the national regulatory authority.

10.1. EMERGENCY PROCEDURES AND CASUALTY EVACUATION

The HPCA contractor should draw up a comprehensive set of emergency procedures covering reasonably foreseeable emergencies including those which require the evacuation of personnel and casualties to a place of safety on the surface. The HPCA contractor should ensure that all necessary equipment and personnel identified in the procedures is immediately available for deployment and that a comprehensive test of the evacuation procedures is undertaken and recorded before any HPCA work begins. Procedures should be revised as necessary during the course of the works and further tests carried out.

Typical emergencies include but are not limited to :

- Medical emergency or injury to a person in the working chamber/manlock/TUP shuttle.
- Fire in working chamber, man lock or other PVHO
- Fire on TBM
- Fire elsewhere in tunnel
- Fire on TUP shuttle transport vehicle
- Breakdown of transport vehicle
- Fire affecting saturation living complex
- Umbilical damage
- Excessive air loss through tunnel face
- Blow out
- Ground collapse
- Lifting equipment failure
- Lock attendant taken suddenly ill or otherwise no longer available
- Loss of air pressurisation supply
- Inability to dock TUP shuttle
- Loss of communications systems
- Loss of electrical power
- Loss of gas supply to any PVHO
- Oxygen toxicity incident in PVHO
- Mask malfunction or accidental removal
- Exceptionally adverse weather
- Disruption to gas supplier's business

10.2. ACCELERATED EMERGENCY DECOMPRESSION FROM SATURATION

An accelerated emergency decompression (AED) protocol should be developed so that in the event of life threatening injuries or illness and only when the CMA deems the risk to the patient from decompression illness to be less than the risk from the illness or injuries, an accelerated decompression can be undertaken. This should be in accordance with the guidance in DMAC 31. AED should only be done under the direct supervision of the CMA.

10.3. FIRE PROTECTION WITHIN AND AROUND THE TBM LOCK, SHUTTLE, HABITAT ETC

The requirements of the BTS "Guide" and EN 12110 in respect of fire prevention and suppression apply and should be supplemented by the outcome of a project-specific fire risk assessment of the HPCA work being undertaken and all relevant site conditions. No productive work or maintenance work should be undertaken elsewhere on the TBM whilst HPCA work is underway.

10.4. FIRE RISK MITIGATION

Because the pressurising medium in the shuttle, manlocks and working chamber is normally compressed air, the fire risk in HPCA work will be very high due to the greatly elevated PO_2. All practicable steps through design, construction and systems of work should be taken to eliminate sources of ignition and fuel sources from the shuttle, manlocks and working chamber. Whenever practicable but avoiding any problems due to isobaric counter diffusion or to absorption or de-absorption of inert gas through the skin, the shuttle atmosphere should be pressurised with breathing mixture rather than with compressed air to reduce the fire risk.

The choice of breathing mixture for storage in the habitat should take account of the reduction in ignition and fire risk which can be achieved by reducing the oxygen volume concentration in the breathing mixture used.

The normal ban on materials for smoking should be extended to include electronic cigarettes.

10.5. FIRE PROTECTION IN SHUTTLE, MANLOCKS AND HABITATS

Every shuttle, manlock or habitat should have a self-contained pressurised water fire suppression system. The system for each compartment should comprise a reservoir tank of water constantly pressurised by high pressure inert gas and feeding fixed discharge nozzles in the compartment to which it is connected. It should not be possible for the inert gas to break through into the compartment. Activation, operation and duration of the suppression system should be in accordance with the requirements of Section 14.2.5.2 of NFPA 99 "Health Care Facilities Code" published in 2015. Activation of the system should be possible from both the inside and outside of the chamber and activation should automatically trigger a fire alarm warning at the chamber control panel.

Spray or mist systems can be used however their performance in soaking and cooling the interior of the compartment to extinguish a fire and prevent re-ignition should be shown to be as effective as a deluge system. The spray or mist should not result in an irrespirable atmosphere being formed in the compartment.

10.6. FIRE PROTECTION SHUTTLE TRANSPORT VEHICLE

Any vehicle involved in transporting the shuttle on the surface or in the tunnel should have an on-board fire suppression system covering the engine compartment, fuel tanks, tyres and cab as a minimum.
Vehicles used in the tunnel for shuttle transport should comply with EN 1889 or equivalent.

10.7. FIRE PROTECTION FOR SURFACE FACILITIES

These buildings should be constructed from incombustible materials whenever possible. The buildings housing the saturation living complex should be fitted with a comprehensive spray or mist system. Sufficient mass of water should be discharged to soak and cool the structure sufficiently to prevent re-ignition. Hose reels or portable fire extinguishers should also be available for fire-fighting purposes.

The control panel should be equipped with at least one independent compressed air respirator for the lock attendant.

In addition, there should be an emergency air supply or sufficient oxygen self-rescuers at the control panel for everyone normally working there.

10.8. FIRE PROTECTION FOR GAS CYLINDERS ON SURFACE

Gas cylinders on the surface should be stored in a well ventilated and secure enclosure. It should be physically separated from other buildings or protected by a suitable fire wall.

Cylinders in use for the habitat should be protected by a water sprinkler system.

10.9. HYPERBARIC SELF-RESCUERS IN THE WORKING CHAMBER

A compressed gas self-rescuer for use in hyperbaric environments was shown to be feasible by HSE in the 1990s but its manufacturers never put it into mass production. The concept has been shown to be technically feasible. There is no restriction by HSE, on others to develop the concept further.

10.10. EMERGENCY ASSISTANCE IN HYPERBARIC ENVIRONMENT

10.10.1. Emergency assistance

The contractor should ensure there is appropriate external rescue and medical capability to provide assistance in the cutterhead or manlock in an emergency.

10.10.2. Gas supply

An additional quantity of gas should be stored underground for use by the external rescue personnel. Only a primary and emergency supply is required. When non-saturation exposures are being undertaken on site, the external rescue personnel will probably follow an exposure profile similar to that being undertaken by the MGWs.

When saturation exposures are being undertaken on site, emergency planning needs to take account of how the external emergency personnel could be deployed. Where the TBM is large enough to have two manlocks, one can be used for mating the shuttle whilst the other provides access for the emergency personnel. Where there is only one manlock then the shuttle should be designed to act as a two compartment manlock in an emergency. The external rescue personnel should follow a non-saturation profile if possible. Relays of emergency personnel may be required in some circumstances. However, it is foreseeable that because of the pressure or duration of their exposure, external rescue personnel may end up becoming saturated.

10.10.3. Emergency medical assistance

Should prolonged medical intervention under pressure be required, a DMT, the CMA or other medical specialist could end up becoming saturated and have to be decompressed in accordance with the normal saturation procedures. This outcome should be allowed for in emergency planning and in planning habitat and in-tunnel logistics.

11.1. INFORMATION, INSTRUCTION, TRAINING

All those undergoing HPCA exposures should be given appropriate training in the risks from such work and how these risks should be mitigated along with the tasks to be undertaken.

An appropriate qualification for HPCA sat workers is the French Class 3 “Mention D” qualification or equivalent, or an appropriate sat diving qualification. Reference should be made to the INPP website and BTS “Guide” for a comprehensive list of topics. The training should take full account of site procedures.

The theoretical training modules of internationally recognised diver training qualifications give an indication of the level of hyperbaric knowledge required for non-sat and sat HPCA workers.

Most of the HPCA interventions to date have been undertaken by personnel with diving experience. However, it is foreseeable that conventional tunnelling operations may have to be undertaken in HPCA. Personnel for such work would require experience as miners in conventional tunnelling techniques. The additional training required to make such persons competent to work under HPCA would be extensive and should reflect the risks associated with the work to be done.

11.2. TRAINING FOR MOVING SHUTTLE

Trials in moving the shuttle between the surface habitat and the TBM or tunnel manlock should be undertaken before the shuttle is used for TUP. Unless the shuttle is regularly moved between surface habitat and the tunnel manlock, periodic exercises should be undertaken to maintain the expertise in TUP procedures.

Shuttle mating with the TBM should be part of the TBM factory acceptance test likewise mating of the shuttle with the habitat should be part of testing the living habitat.

In the absence of a CEN or ISO standard for mating flanges for use in HPCA applications it is recommended that for pressures below 17 bar the flange dimensions specified below are adopted as a tunnelling industry standard. The dimensions illustrated have already been used on a number HPCA contracts.

The mating flange shall be formed on the end of a length of trunking 800 mm internal diameter and 30 mm wall thickness. The flange shall be formed as an upstand around the end of the trunking. The upstand shall be 30 mm high by 30 mm wide giving an overall external diameter across the flange of 920 mm. The flange upstand shall be shaped as shown in *Figure 2*.

It remains the responsibility of the user to ensure the manufacturer selects appropriate materials and undertakes all necessary design calculations, fabrication checks and pressure tests to ensure the flanges are safe for use in their particular application and meet the statutory requirements of the country of use and the requirements of the user's insurers.

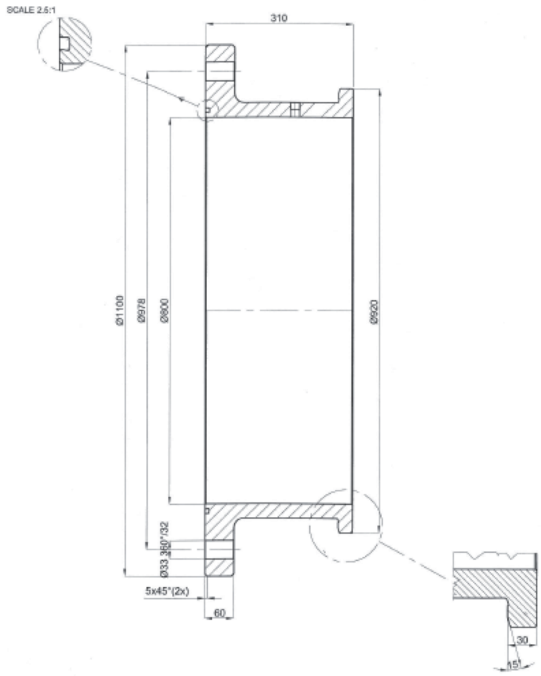


Figure 2 : Standard mating flange details.

13 >> Acknowledgements

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APPENDIX 1 - THE USE OF SONOGRAPHY IN DECOMPRESSION MANAGEMENT

Some of the bubbles which form in the body as a consequence of decompression can be detected by ultrasonic methods. Although technology is evolving, the most common technique is the detection of intravascular bubbles using either a Doppler flow transducer to give an audio signal, or by two-dimensional echocardiography to give an image. The detection of bubbles in any individual will not diagnose decompression sickness (DCS). However, the number of bubbles detected in a group of people exposed to pressure is considered to be correlated with the observed incidence of DCS [1,2]. Therefore, Doppler monitoring of bubbles can be a useful outcome measure of decompression safety.

The ability of Doppler measurements to assess any decompression procedures should be considered carefully. If the studies are to be meaningful, they must be carefully designed and conducted to produce useful results that can be compared to other decompression procedures. A wide variety of Doppler monitoring protocols and data analysis can be found in the literature. Ideally, well established protocols should be employed and investigators who are new to Doppler monitoring should seek assistance from experienced technicians to develop effective protocols. Obtaining clear bubble signals requires practice and accurately scoring the bubble count takes many hours of learning alongside an experienced technician.

The equipment most commonly used is either a small, portable audio only Doppler monitoring system (e.g. Techno Scientific Doppler Bubble Monitor) or a more sophisticated two-dimensional echocardiography imaging machine, of which there are many suitable models. If the technicians are experienced in ultrasonography, then the imaging equipment is probably preferable. However inexperienced technicians will find it easier and quicker to learn audio only techniques. Whichever equipment is employed, it should be kept in a clean environment and inspected for damage prior to each use. Audio only equipment may be used in an increased pressure environment, however it is unlikely that imaging equipment would be suitable for use under pressure. Clinical ultrasound is generally well tolerated by subjects/patients but the potential impact should be considered when directing ultrasound energy into any person [3]. The intensity of sound energy used during ultrasonic monitoring should be kept as low as reasonably achievable. Mechanical and thermal indices should be considered and scan duration should be as short as possible.

Guidelines [4] have been drawn up by an international group of experts to promote best practice and standardization of protocols across the diving/tunneling/compressed air community and these have been summarized here :

Recommendation 1 :

Doppler technician training and/or level of experience should be described in all reports. If technicians do not have a published record, then independent review of the raw Doppler data should be carried out before any conclusions are made on the safety of a decompression procedure

Recommendation 2 :

Doppler signal grading should employ either the Spencer or Kisman-Masurel (KM) scales [5-8].

Recommendation 3 :

The precordial site should be used as the standard for audio Doppler monitoring. The standard for two-dimensional echocardiography is the apical long-axis view. These sites allow assessment of bubbles in the entire systemic venous return. A control measurement should be taken before a pressure exposure. Subclavian monitoring may be useful in providing additional information.

Recommendation 4 :

Resting measurements should always be made. The minimum period of rest prior to the measurement should be standardized and reported. When measurements following provocation (e.g. deep knee bend) are collected, the provocation should be standardized and clearly described.

Recommendation 5 :

Measurements should be conducted for a minimum of two hours from the completion of decompression as a standard rule. Consideration should be given to extending monitoring periods if bubbles persist at the end of the planned monitoring period.

Recommendation 6 :

The first measurements should be made within 15 minutes following decompression. During the first two hours following decompression, measurement intervals should be no greater than 20 minutes. Sampling frequency may be reduced after two hours following decompression.

Recommendation 7 :

Standard parameters to report include time to onset of non-zero grades, time to maximum grade reached, and maximum grade for individual subjects. In addition, median grade, grade range, and mode can be reported; all measured zero grades should be included. Where possible, raw data should be reported. Bubble grade data are most appropriately analyzed non-parametrically

Recommendation 8 :

Measurements should be recorded and preserved for future review. This includes audio and visual files, as appropriate for the technology employed.

Conclusion

In a commercial arena it is appreciated that time and resources are finite and compressed air workers may not feel motivated to make themselves available for monitoring after a work shift has ended. However, when new decompression procedures are being used, Doppler monitoring of a population can give a good indication of the decompression stress being imposed on the tunnellers, and hence on the safety of the decompression procedure. The Doppler monitoring of compressed air workers on the Belfast sewer project funded by HSE [9] illustrates that this type of work is achievable and worthwhile.

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APPENDIX 2 - CONTENTS OF SUBMISSION

The formal submission for exemption, approval or variance should act as a method statement, health and safety plan and risk assessment for the hyperbaric works. For saturation exposures it is particularly likely to be a lengthy document. It should cover as a minimum :

- Project description
- Ground conditions
- Description of TBM and its operation etc
- Work activity to be undertaken in hyperbaric environment
- Relevant guidance etc
- Justification of methodology chosen
- Detailed methodology for non-saturation exposures – gas mixes, exposure limits, compression/decompression regimes, operational procedures, environmental control
- Detailed methodology saturation exposures – gas mixes, exposure limits, TUP, shift patterns, compression/decompression regimes, operational procedures, environmental control
- Hyperbaric plant and equipment – airlocks, TUP shuttles, habitat, umbilicals, masks etc
- Management and coordination arrangements for tunnelling and hyperbaric work
- Gas management
- Working procedures
- Inspection and maintenance procedures
- Record keeping
- Health and safety procedures
- Fire safety
- Provision of life support under normal and emergency conditions
- Chamber hygiene
- Organisation
- Personnel – CVs and duties
- Training
- Medical provisions – health surveillance and preventative measures
- Medical provisions – illness and injury
- Emergency procedures

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