Guidelines for good working practice in high pressure compressed air

ITA Working Group N°5
Health & Safety in Works

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ITA Working Group N°5
Health & Safety in Works

PREPARED JOINTLY BY

INTERNATIONAL TUNNELLING ASSOCIATION
WORKING GROUP N°5 - “HEALTH & SAFETY IN WORKS”

AND

BRITISH TUNNELLING SOCIETY
COMPRESSED AIR WORKING GROUP

ITA AITES

British Tunnelling Society

>> Foreword

At its meeting in Vancouver in 2010, International Tunnelling Association Working Group N°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 two organisations have come together to jointly produce the first edition of these guidelines for use by the international tunnelling community.

This document will be reviewed and revised as necessary in the light of practical experience of HPCA work on site. Comment and feedback is welcomed and should be made to the ITA Secretariat through the website www/ita-aites.org.

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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, from the diving industry to tunnelling.

1.2 SCOPE

These guidelines apply to the use of HPCA in tunnelling (including shaft sinking).
To date, such work has been mainly associated with TBM interventions for maintenance and repair. However it is foreseeable that conventional tunnelling operations may have to be undertaken in HPCA.
The guidelines are intended for use by regulatory authorities, clients, designers, contractors, insurers and others involved in HPCA work.
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

It is implicit when undertaking HPCA work in accordance with these guidelines, that all reasonably practicable measures should be taken to minimise the number of persons exposed 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 BALANCING 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 unbilical.

1.5 CHOICE OF HYPERBARIC TECHNIQUE

High pressure, non-sat exposures only permit short working periods because of the relatively lengthy decompression requirements required from such pressures. Hence for exposures at pressures in excess of 5 bar, saturation working should be considered. See Cl 8.1 for further guidance.

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 OTHER GROUND STABILISATION TECHNIQUES

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.

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 accomodate it.

These guidelines 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. These Guidelines build extensively on the information which they provide.

2.3.1 ITA Report N°001

The International Tunnelling Association Report N°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 EN 12110 would apply only to work in compressed air within national statutory limits, assumed to be between 3 and 4 bar. However WG4 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.

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 12336 "Tunnelling machines - Shield machines, thrust boring machines, auger boring machines, lining erection equipment – Safety requirements" and EN 12110 "Tunnelling machines — Air locks — Safety requirements". EN 12336 is currently being revised and will be harmonised as EN 16191" Tunnelling machinery - Safety 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 information of fundamental relevance to HPCA work.

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.

2.4 RELEVANT GUIDANCE SOURCES – DIVING

The hyperbaric techniques required for HPCA are very similar to those for diving at similar pressures but without being immersed in water. From the 1970s onwards, diving technology and hyperbaric safety advanced greatly with the exploitation of oil in the relatively deep waters of the North Sea. Consequently there is much relevant guidance to be had from diving sources.

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. At least one classification society has already developed specific rules for the tunnelling environment. Care should be taken to ensure their application is appropriate, when transposing rules intended for the marine environment to the underground environment. The Contractor in Charge 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. 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 provides guidance on a range of issues relating to the medical aspects of hyperbaric exposure in diving. Even though the much of its guidance is not relevant to the environments in which the hyperbaric exposure occurs, some DMAC guidance is equally applicable to HPCA exposure.

2.4.3 HSE diving guidance

HSE publishes extensive guidance on commercial diving, some of which is equally 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 GUIDANCE FROM OTHER COUNTRIES

2.6.1 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).

2.6.2 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.

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.

3.2 EXEMPTIONS, VARIANCES AND APPROVALS

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.

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.

3.2.1 Technical justification

A full technical justification of the proposed use of HPCA should be made including information on likely ground and ground water conditions (see also Cl 5.2). It should include information on proposed tunnel excavation and lining techniques along with information on the airlocks and other plant and equipment required for the hyperbaric interventions

3.2.2 Exemption

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 expert advisers, if any, supporting the exemption.
- Proposals for alternatives to the matter exempted

3.2.3 Approval of alternative hyperbaric procedures

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

- A description of the tables to be approved;
- Relevant theoretical derivations;
- Reports of any relevant laboratory evaluation or hyperbaric trials of the tables;
- Details of relevant experience of long-term use using recognised measures of DCI incidence where available;
- A robust technical justification of the likely benefits of the proposals;
- Submissions from expert 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 post-decompression physiological monitoring at the level of individual exposed persons.
- An assessment of the likely risks of decompression illness and 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 the country concerned.

3.2.4 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 DEMONSTRATION OF EFFECTIVENESS OF DECOMPRESSION REGIMES

On completion of all HPCA work, the Contractor in Charge 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.

3.3.1 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.

3.3.2 Mathematical modelling of decompression tables

Physiological mathematical models of the human response to pressure exist and can be used as part of the process of demonstrating the effectiveness of decompression regimes. The models can be used to predict gas in blood levels and as part of the retrospective analysis of exposure data. A relevant reference is 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.

3.3.3 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 used to calculate the incidence of decompression illness and the standardised bends ratio is used for comparison between datasets. 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.

3.3.4 Details of personnel, expert advisers etc
The submission should include details of the qualifications and expertise of the main personnel to be used in overseeing HPCA work along with similar details for expert advisers to the project

3.4 PROHIBITION ON THE USE OF OXYGEN AND NON-AIR BREATHING MIXTURES

Where national regulations do not 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.

4.1 CONTRACTOR IN CHARGE

Experience has shown that there should be a contractor with overall responsibility for the HPCA work – the Contractor in Charge. The Contractor in Charge should be able to provide the senior personnel to manage the HPCA work from his own resources. The Contractor in Charge should be responsible for ensuring that all plant and equipment necessary for HPCA work along with the personnel to operate and maintain that plant and equipment, are immediately available on site. The recommendations in the BTS "Guide", on personnel required and management of work in compressed air, should be followed.

4.2 NOTIFICATION OF PUBLIC EMERGENCY SERVICES

The Contractor in Charge 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.

4.3 EMERGENCY PLANNING

Given the relative rarity of any compressed air tunnelling work, the local emergency services may have had no experience of dealing with hyperbaric emergencies. Therefore the Contractor in Charge should assist the services in planning their response to an on-site emergency. That assistance should extend to the provision of equipment and training facilities as necessary. Where the emergency services are unable to respond, and this is likely to be the norm, the Contractor in Charge should make provision for emergency response from within his own resources.

4.4 EMERGENCY EXERCISES

The Contractor in Charge should work with the emergency services to allow them to undertake simulations and joint exercises to improve their ability to respond to emergencies. Such exercises should be undertaken early in the works period and at intervals of not more than 12 months thereafter.

4.5 EXPERT HYPERBARIC ADVICE

The Contractor in Charge should have access to expert hyperbaric advice. Likely topics with which the hyperbaric expert(s) should be familiar 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.

4.6 ROLES TO BE DISCHARGED BY PERSONNEL

It is essential for the execution of HPCA work in a healthy and safe manner that a number of personnel are nominated by the Contractor in Charge to take on various roles relating to the management or undertaking of the work. All those nominated should be competent and have had relevant previous experience as appropriate, of managing, overseeing or undertaking work in compressed air or other high pressure hyperbaric exposure along with knowledge of the tunnel environment. Given the rarity of HPCA work, it is likely (and could be desirable) that for those managing or overseeing the work, part of that experience would have been gained from a diving support role in the offshore saturation diving industry. Those managing or overseeing HPCA work do not need to hold diving qualifications but should hold relevant hyperbaric support qualifications (see the BTS «guide»).
It is recommended that the personnel and the roles set out in the BTS «guide» are adopted for HPCA work but with the changes noted below.

4.6.1 Hyperbaric supervisor
For HPCA work the role of the hyperbaric supervisor as described in the BTS «guide» should be extended to overall control and coordination of both the hyperbaric and tunnelling aspects of each intervention. The hyperbaric supervisor would effectively be a deputy to the "person in charge". The person filling this demanding role should have had experience of HPCA work and also extensive experience of the tunnelling environment.

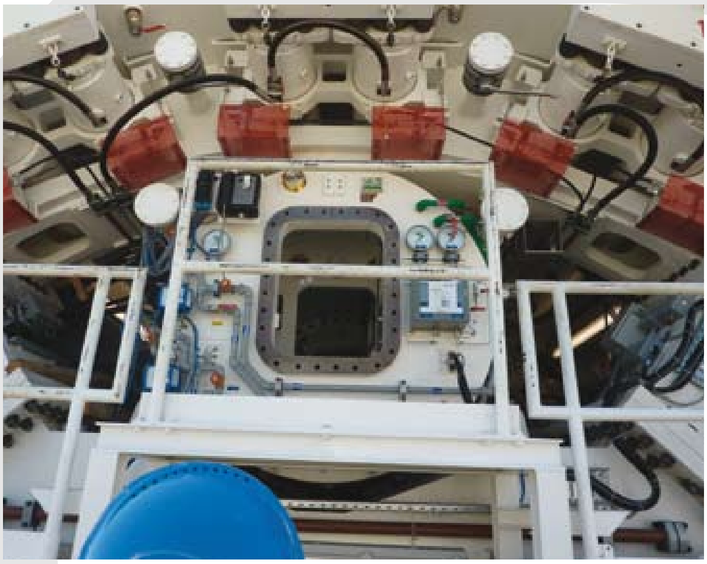
4.6.2 Gas attendant
When deemed necessary by the hyperbaric supervisor, there should be a person responsible for the organisation of gas supplies on site. Such a person should have had experience of the management of gas supplies in saturation diving as well as an appreciation of the tunnel environment.

4.6.3 Lock attendant
The lock attendants 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. Lock attendants should also control the hyperbaric aspects of TUP shuttle use.

4.6.4 Umbilical tender
When using line fed masks, there should be a person in the manlock or intermediate chamber (see Cl 6.9) to tend the umbilicals of those in the working chamber. One person can tend no more than two umbilicals simultaneously.

4.6.5 HPCA worker selection
Those being exposed to HPCA 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 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.

4.6.6 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 diving or tunnelling industry or have undergone specific training and been assessed as suitable. HPCA workers should ideally hold an offshore commercial diving qualification in saturation techniques. Appropriate internationally recognised qualifications are listed on the HSE website at http://www.hse.gov.uk/diving/qualifications/approved-list.pdf.



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. No work should be carried out on the TBM which could endanger those undergoing HPCA exposures whilst work in HPCA is being undertaken. Additional requirements are set out in these guidelines.

5.2 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. Calculations should be prepared to demonstrate that these requirements are being met. Independent checking (Category 3) of the calculations should be undertaken. In addition, it is important to ensure that the correct air pressure is maintained in the working chamber without excessive air loss. The design input data should be updated as actual data on water table and the 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.
Additional sources of air loss such as around the tailskin of the TBM should be considered and appropriate remedial action taken if required.

5.3 DUTY LOCK ATTENDANTS

There should be two lock attendants on duty at a hyperbaric control panel whenever the health and safety of anyone in saturation or undergoing HPCA exposure is dependent on that panel.

5.4 FACE INTERVENTION PROCEDURES

Before any face intervention takes place, the stability of the ground and the availability of suitable protective measures necessary to enhance stability should be confirmed.
Before anyone enters the manlock to be compressed, the working chamber should have been pressurised and air pressure maintained for at least one hour. All valves should have been shown to be functionally operative.

5.4.1 Slurry TBM

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

5.4.2 EPB TBM

In permeable ground the excavated material in the excavation chamber should be mixed with bentonite slurry 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.

5.5 REFILLING HEAD WITH SLURRY WHILST DECOMPRESSION STILL GOING ON

5.5.1 Slurry TBM

On a slurry TBM, the cutterhead should be refilled with slurry as soon as possible after HPCA work has been completed and the HPCA workers are sealed in the manlock, to maintain face support. This requirement may conflict slightly with requirements in documents such as the BTS "Guide" or EN 12336 regarding energising of equipment on the TBM during hyperbaric interventions, but it is an essential precaution for HPCA work.

5.5.2 EPB TBM

Restarting an EPB 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 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 its 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.

5.6 INCHING OF CUTTER HEAD

When designing a TBM for HPCA use, due account should be taken to ensure the requirements in EN 12336 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.

5.7 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 can be provided.

5.8 WELDING, CUTTING AND OTHER HOT WORK

Welding, burning and other hot work shall only be carried out in HPCA in accordance with a permit to work system. 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 and torso as well as covering the shoes.

Notes: There should be a person immediately available and capable of responding to an outbreak of fire during hot work.

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.

5.9 USE OF EXPLOSIVES

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

5.10 CLAMPING OF BULKHEAD DOORS

It should be possible to clamp shut the door between a manlock chamber and the working chamber.

6.1 PLANT AND EQUIPMENT

6.1.1 All HPCA work

The Contractor in Charge should ensure suitable and sufficient plant and equipment is available on site, whenever needed, to undertake safely and without risk to health, both the HPCA work, and any action which may be necessary in the event of a reasonably foreseeable emergency connected with the HPCA work.

In the absence of national requirements, the plant and equipment shall meet the requirements of these guidelines along with the requirements in the BTS “Guide”, EN 12110 and relevant classification society rules.

Assisting the Contractor in Charge in complying with this requirement is an important part of the hyperbaric supervisor’s duties.

6.1.2 Saturation operations

In addition to the requirements above, for saturation exposures a transfer under pressure shuttle, a saturation living complex on the surface for storage of personnel under pressure and handling equipment for the TUP shuttle shall be provided.

6.2 RESTRICTIONS ON HPCA DUE TO TUNNELLING CONSIDERATIONS

In order to undertake HPCA work safely a considerable amount of space is required on the TBM. This is particularly relevant to TUP operations and hence saturation exposure. The geometrical constraints this presents have a significant bearing on the minimum diameter and type of TBM on which HPCA work can be undertaken.

It is suggested that geometrical constraints make TUP using the TBM airlock, and hence saturation working, impractical on EPB machines below 6 m in diameter because of conflict with the screw conveyor and erector and on slurry TBMs below 5 m in diameter because of conflict with the erector.

In smaller tunnels where it may not be possible to use a TBM airlock, it will be necessary to install one or more bulkheads in the tunnel. As much of the TBM backup equipment as possible should be moved back to allow the bulkhead(s) to be positioned close to the rear of the TBM shield. In particular all hydraulic fluid tanks and grease injection stations should be removed. Major electrical installations should be de-energised.

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

6.3 ACCESS AND WORKING SPACE ON TBM

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 2m 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.

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.

Likewise there should be a clear path to permit the passage of the TUP shuttle from its transport vehicle to the manlock. This area should be adequately lit.

6.4 MINIMUM LOCK DIMENSIONS

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

6.5 LOCATION OF LIVING HABITAT

The saturation living habitat should be located on the surface in a purpose built structure and fully protected from adverse weather and temperature fluctuations. There should be a workstation for the lock attendants and the hyperbaric control panel.

The structure should be lit and heated/cooled as necessary. The structure should be protected by a water spray or high pressure water mist fire extinguishing system.

6.6 SUITABILITY OF PLANT AND EQUIPMENT

All plant and equipment should be suitable for the maximum foreseeable working pressure taking into account seasonal ground water variations or tidal variations as appropriate.

6.7 INSPECTION MAINTENANCE AND TESTING

The Contractor in Charge should ensure there are formal inspection maintenance and testing procedures 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. They should take account of the requirements of the BTS “Guide”, EN 12110, relevant classification society rules or the requirements of the insurers of the Contractor in Charge should be adopted. Full records should be kept of all inspection, maintenance and testing.

6.8 EMERGENCY BREATHING SUPPLY

Where the working pressure is above 5 bar, there should be the immediate capability to supply an emergency breathing mixture to each person under pressure in the working chamber. It should comprise a suitable mask or helmet and independent source of breathing mixture. The quantity of emergency breathing mixture available shall be at least sufficient to allow all persons under pressure to return to the manlock and to remain on the emergency supply until breathing from the masks in the manlock or from the manlock atmosphere itself, can be established with a reserve of at least 10 minutes (see Cl 6.24).

6.9 UMBILICALS

Each person in the working chamber should have a single multiline umbilical supplying breathing mixture and communication lines to that person. The umbilical casing should protect the lines from damage. Where there is a need for an emergency supply of breathing mixture, a second breathing mixture supply line should be provided in the umbilical. 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 the illustration below) can be considered as first point of escape or safe area but should not be considered as 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.

There should also be an on-board system to supply breathing mixtures to those in the TUP shuttle. It should be set up in a way which will not impair the operation of the access door(s) between the man lock and the transfer shuttle.

6.10 COMMUNICATIONS

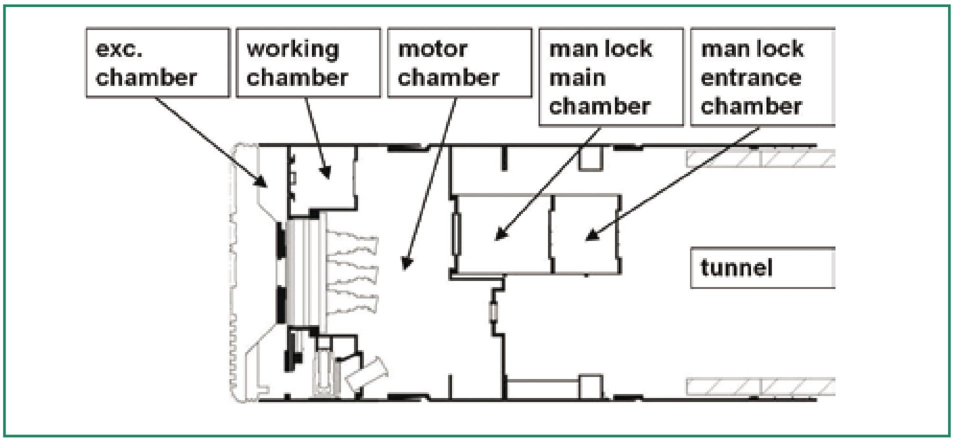
All masks or helmets for use in the working chamber should be fitted with an appropriate two way communications system. For non-sat exposures, an integral communications system is required whenever the mask or helmet has the potential to interfere with normal verbal communication.

6.11 TUP SHUTTLE

The transfer under pressure shuttle should be designed and constructed in accordance with relevant standards e.g. classification society rules and relevant principles for airlocks. Its size should reflect the guidance on minimum dimensions in EN 12110. The TUP shuttle should be of double chamber construction as for manlocks. The shuttle should be fitted with all necessary life support systems including appropriate backup capacity.

6.12 COUPLING

Pressurised systems should be fitted with safety interlocks where necessary, to prevent any unintentional pressurisation or de-pressurisation, or uncontrolled loss of pressure. Particular attention should be paid to chamber mating systems, and food



Example of typical intermediate chamber arrangement on slurry TBM

and equipment locks. The requirements in the BTS "Guide" and EN 12110 regarding the opening of doors should be observed.

It should be possible to pressurise the trunking with either air or breathing mixture.

It is imperative that it should be impossible to open the mating clamp when the trunking between the TUP shuttle and the PVHO with which it is being mated, remains under pressure. The clamping mechanism should be equipped with an interlock which makes it impossible to release a clamping mechanism in the event that an undesirable drop in pressure would then take place.

Appropriate performance criteria for coupling systems including mating flanges can be found in classification society rules. Germanischer Lloyd has a set of rules specifically covering HPCA work.
Note: the term "NATO flange" seems to be used to denote a flange to STANAG 1079. There is no European or international standard for mating flanges and clamps.

The person operating the clamping mechanism must make sure that opening it will not cause an undesirable drop in pressure. There should be a clearly defined method for incrementally increasing or decreasing trunking pressure as part of clamping procedures.

6.13 MOVEMENT OF TUP SHUTTLE TO/FROM AND AROUND THE TBM

Transport of the TUP shuttle in the tunnel should be by a dedicated vehicle. There should also be a standby vehicle available in the tunnel to move the shuttle in the event of breakdown. There should be appropriate mechanical handling equipment to facilitate the transfer of the shuttle between vehicles.

All vehicles involved in TUP transport should have a fixed, manually operated, on-board fire protection system covering motor compartments, 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 or jacking. The movement path should be designed avoid the need to lift the shuttle by crane whenever possible. Where craneage for TUP handling, is required, the crane must fully meet recognised standards for personnel lifting. In the absence of national requirements at the place of use, a factor of safety of 10 should be applied to the hoist ropes.

All mechanized equipment for TUP handling should be considered to be an essential service and meet the relevant requirements for continuity of power supply in EN 12336.

During all these movements, the life support system for the shuttle should remain under the direct control of a lock attendant . This can temporarily be the team leader inside the capsule provided he is competent to do so and the internal equipment of the capsule is properly designed to allow control to be exercised from inside the capsule. At any time, a lock attendant outside the shuttle should be able to take over full control of the life support system.

6.14 EMERGENCY TRANSFER FROM LOCK 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.

Tunnel workers involved in the shuttle transfer should have ready access to self rescuers.

6.15 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. Such equipment includes lighting and communications systems for the lock attendant's station.

6.16 AIR AND GAS SUPPLY TO TUP SHUTTLE

The TUP shuttle should be mounted on a support frame. The frame should have the capability to carry 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. The quantity of compressed air should as a minimum be sufficient to pressurise the shuttle to working pressure twice, from atmospheric pressure. There should be additional non-return valved fittings on to which additional air and/or breathing mixture supplies can be connected in an emergency.

6.17 SHUTTLE DOORS

Internal communicating doors in the TUP shuttle should be shut, and a seal should be obtained when mating or unmating to a manlock or the transfer of personnel or equipment is taking place. These doors should not be opened again until the internal door between the transfer chamber and the connecting tunnel has been shut.

6.18 COLOUR CODING OF GAS CYLINDERS AND PIPEWORK

Gas cylinders and pipework 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: 1997 "Transportable gas cylinders . Gas cylinder identification (excluding LPG). Colour coding" using the colours for set out for "gases used in diving". An alternative standard is ISO 32:1977 "gas cylinders for medical use – marking for identification of content" .

6.19 MAN LOCK CONTROL PANEL

The TBM should be designed to incorporate a panel from which all hyperbaric operations on the TBM can be controlled. It should be remembered that unlike in intermediate pressure compressed air working, it may not be safe to breath the high pressure compressed air used as the pressurising medium because of the risk from nitrogen narcosis or oxygen toxicity. Accordingly, control of the HPCA work is a safety-critical operation.

During HPCA work, this panel, the manlocks and all services necessary for their safe operation should be considered “essential services” (term as used in EN 12336), on the TBM . It should be located close to the manlocks on the TBM. The panel should be laid out according to good ergonomic principles and should incorporate the following:

- All necessary pressure gauges and valves;
- A digital clock with both real time and stopwatch facilities;
- A 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 the supply cylinders;
- Computing facilities for recording and storing exposure and decompression data;
- Essential communication links;
- CCTV display of the inside of each manlock compartment;
- Temperature gauge for each compartment and the working chamber ;

The control panel should be provided with an un-interruptible power supply. Seating for the lock attendant at the panel 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 hyperbaric control panel should be fitted with sufficient air-line fed full face masks to provide a supply of respirable air to enable the lock attendant(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 rescuers for each attendant on duty.

When not in use, the panel should be protected from dirt ingress and damage either by a lockable cover or by removing the panel. If the panel is removed all services to the panel should be securely capped.

6.20 FACE PIECES - MASKS OR HELMETS

The most suitable mask for purpose, should be used, taking account of the need to provide security of fit and to minimise inward leakage. Full face masks or helmets should be used in the working chamber for sat exposures where the pressurising gas is different to the breathing mixture. The breathing resistance should meet diving industry standards.

6.21 VOICE SCRAMBLING DUE TO USE OF HELIUM

Some voice distortion can be expected from helium based breathing mixtures and appropriate equipment should be provided to compensate for that distortion.

6.22 EXCAVATION CHAMBER TEMPERATURE

Steps should be taken to ensure that no one should enter the excavation chamber when the TBM has just stopped and the temperature in it exceeds 28°C. The excavation chamber temperature should be displayed on the hyperbaric control panel.
Note: a water spray cooling system for the cutterhead can reduce waiting time.

6.23 OXYGEN SAFETY

This is extensively covered in the BTS “Guide”.

6.24 GAS OR BREATHING MIXTURE QUANTITY

6.24.1. Primary gas supply
The quantity of each breathing mixture required in the tunnel for the HPCA work including decompression, along with an allowance for leakage, wastage and contingencies should be calculated.

6.24.2. Secondary gas supply
A secondary gas supply of at least the gas volume required for decompression plus 1/3 the primary gas supply for the working phase of the exposure should be provided in the tunnel.

6.24.3. Emergency gas supply
For HPCA work at pressures above 5 bar, an emergency gas supply equivalent in volume to the secondary supply should also be provided in the tunnel. The emergency gas supply should be connected to the spare gas line in the umbilical.

6.25 SEPARATION OF OXYGEN SUPPLY FROM BREATHING MIXTURE SUPPLY

There should be separate supply lines for oxygen and breathing mixtures along with separate masks, umbilicals and connection manifolds.

6.26 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 BS 8478 “Breathing gases for diving and hyperbaric applications” or EN 12021 “Respiratory protective devices. Compressed air for breathing apparatus”.

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.

6.27 SAMPLING AND TESTING

The Contractor in Charge 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 Contractor in Charge 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 Contractor in Charge should ensure that proper arrangements are in place for the separate identification, marking, storage and handling of each to prevent accidental misuse.

6.28 GAS MIXING

For sat exposures, it may be preferable to have a gas mixing and reclaim plant on site when the quantity being processed is sufficiently large to make it reasonable to do so. The gas mixing and reclaim operation should be set up as a stand-alone operation 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 with ISO 9001.

Cylinders of gas to replenish the stocks on site should have their purity confirmed on arrival at the gaz mixing and reclaim plant.

Before leaving the plant for re-use in HPCA work, every cylinder should be tested to check its composition and purity meet the data 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 sampling and testing in Cl 6.25. 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 Contractor in Charge should not permit the piecemeal mixing of small quantities of breathing mixture on an ad-hoc basis for use in HPCA exposures.

6.29 OXYGEN SAMPLING

For all exposures where the breathing mixture is supplied from cylinders, there should be direct sampling of the supply to the masks immediately downstream of the control panel to permit analysis of the oxygen content. Analysis should be to an accuracy of +/- 0.1% by volume. An audible alarm should sound when the oxygen concentration deviates by more than +/- 1% by volume from the required oxygen content.

6.30 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 cylinder of breathing mixture is correct. He should do the same for any oxygen required for decompression purposes.

6.31 LOSS OF FLOW

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.

6.32 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 N° 12 “Cleaning of diving equipment” should be followed.

6.33 STORAGE OF MASKS

After cleaning, masks and helmets should be bagged and stored in a clean environment.

7.1 PROVISION OF OCCUPATIONAL HEALTH ADVICE

The Contractor in Charge should appoint an occupational health doctor, the "Contract Medical Adviser" (CMA), to advise on all aspects of occupational health arising from the HPCA work. That doctor should hold a recognised specialist professional qualification in occupational health and be familiar with the tunnel environment and 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. The doctor should act as the professional leader for the medical aspects of the HPCA work throughout its duration. The CMA needs to be on call whenever an HPCA operation is in progress.

7.2 HEALTH ASSESSMENT

All those undergoing HPCA work should be subject to a health assessment regime appropriate to the pressures being used. Where appropriate national requirements do not exist, the regime should take the form of a stringent annual medical examination 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 should undertake the examinations unless national requirements dictate otherwise. Reference can be made to the BTS « guide «. The results of the examinations 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.

7.3 HEAT STRAIN IN THE HYPERBARIC ENVIRONMENT

Those undertaking heavy physical work in the hyperbaric environment are at risk from heat strain. Wearing the full face masks required for efficient breathing purposes can further increase the risk. The risk arises from the reduction in body cooling from sweat evaporation, due to the pressurised atmosphere. The normal indices by which heat strain 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.

7.4 GENERAL HEALTH CARE FOR THOSE LIVING IN SATURATION

In addition to normal occupational health provision, for saturation working the Contractor in Charge 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 this matter also.

7.5 FIRST AID

7.5.1 General requirements

The Contractor in Charge should ensure there is adequate availability of emergency medical and first aid facilities for those under pressure. This should cover the working chamber, airlocks, any TUP facilities and the living accommodation if in saturation.

7.5.2 Non-sat exposures

All persons undergoing non-sat exposures should have had basic first aid training.

7.5.3 Sat exposures

All personnel undergoing saturation exposure should have had basic hyperbaric first aid training. This training should cover the use of common items of first aid equipment including oxygen administration systems. In the absence of an appropriate hyperbaric first aid qualification, a diving first aid qualification is an acceptable substitute.
A minimum of two trained diver medics should be at pressure in the chamber system. Fewer than two could result in the situation where the only trained diver medic is the casualty.

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 or the ear, nose or throat infections which are normally a bar to entry into compressed air should undertake saturation exposures.

7.7 PHYSIOLOGICAL MONITORING

7.7.1 Use of physiological monitoring

It is recommended that physiological monitoring of tunnel workers post-decompression, should be adopted as a technique for assessing the effectiveness of decompression regimes in real time. The monitoring should be undertaken by recognised specialists using standard protocols. Techniques available include Doppler monitoring and ultrasonic scanning. 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 these techniques and other indicators of clinical decompression stress.

7.7.2 Monitoring frequency

For tables with no history of satisfactory use, all persons exposed should be subject to physiological monitoring after each exposure, until the effectiveness of the tables has been established. Thereafter a representative sample of exposures should be checked to confirm the ongoing effectiveness of the tables

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.

7.8 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 and pulse rate can easily be monitored automatically.

Where sat exposures are being undertaken in a location without ready access to public emergency medical services, 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 should be available on site.

7.9 ASSESSING FITNESS TO RETURN TO HPCA WORK AFTER DECOMPRESSION ILLNESS

No one should be exposed to HPCA following a decompression illness event until declared fit by the CMA.

8.1 CHOICE OF ROUTINE EXPOSURE TECHNIQUE

Routine non-sat exposures at high pressure allow for only short working periods (typically 45 minutes at 6 bar (g)). Such exposures permit inspection and limited maintenance only to be undertaken. Where significant working periods are required for major maintenance, saturation working should be undertaken. When the exposure pressure exceeds 6 bar the useful working period available with non-sat exposures but still adhering to the 2 hour decompression limit (see Cl 8.8) becomes impracticably short and saturation exposure should be considered. For safety reasons, saturation exposure should always be undertaken at pressures of 7 bar and over.

8.2 MINIMUM OXYGEN CONTENT IN CYLINDERS

All gas cylinders delivered to site should contain at least a sufficient concentration of oxygen to support life were they to be used in error. Helium cylinders should contain a minimum of 2% oxygen by volume. Nitrogen cylinders should contain a minimum of 16% oxygen by volume.

8.3 GAS PROPERTIES AND LIMITS OF EXPOSURE

The following properties of gases and exposure limits should be taken into account when designing a breathing mixture

8.3.1 Oxygen

Oxygen is toxic at high partial pressures. Consequently any breathing mixture in routine use should provide the user with oxygen at a partial pressure of between 0.2 and 1.6 bar.

Excessive chronic or repeated exposure to hyperbaric oxygen is harmful to health. Such exposure can be measured in units of pulmonary toxicity dose (UPTD) (sometimes referred to as oxygen toxicity dose (OTD) or oxygen toxicity unit (OTU)). Limits should be placed on maximum daily and weekly UPTD arising from hyperbaric exposure. Hyperbaric oxygen dose should be kept as low as possible consistent with good hyperbaric practice. Recommended maximum limits for routine exposure are 400 UPTD daily and 2000 UPTD over any period of seven consecutive days. It should be noted that additional oxygen exposure will be incurred if therapeutic recompression becomes necessary. The ongoing risk of oxygen toxicity should be reviewed regularly by the contract medical advisor.

8.3.2 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. Exposure to compressed natural air at up to 5 bar is accepted in some diving legislation. However the narcotic effect of nitrogen at such pressures is considered to create an unsafe and inefficient working situation.

Compressed air or any breathing mixture in routine use containing nitrogen, 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). Due to the narcotic effects of nitrogen, caution should be exercised in breathing air giving a partial pressure of nitrogen (PN_2) of 3 bar and over.

8.3.3 Helium

Helium is a relatively rare and hence expensive gas. It has a low gas density which facilitates breathing in HPCA at high work rates. It also has a high thermal conductivity which can be beneficial in countering the effects of heat strain. 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.

Heliox is an alternative to trimix or nitrox for saturation exposure.

8.4 TRIMIX

Trimix may be considered as an alternative to heliox or nitrox for saturation exposures. Trimix is probably the breathing mixture of choice for non-sat exposures at pressures above 3.5 bar because it reduces gas density and the narcotic effects of nitrogen.

8.5 NITROX

Nitrox may be 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 be used

8.6 BASIC PRINCIPLES IN SELECTING BREATHING MIXTURES

There is considerable flexibility when selecting the proportions of each gas in the mix but the following principles should be adhered to:

- The oxygen content of the mix for non-sat exposures should never be less than 16% and the PO_2 in the mix should never exceed 1.6 bar in use. For sat exposures the PO_2 in storage should be between 0.35 and 0.45 bar.
- The nitrogen content should not give a PN_2 of more then 3.6 bar in use.
- It is preferable to select a breathing mixture which reduces the gas density.
- It is preferable to select a single mixture which satisfies the above.

8.7 AIR BREATHING DURING NON-SAT DECOMPRESSION

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

8.7.2 Period without use of masks.
Tables which include periods where a mask is 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.

8.8 EXPOSURE LIMITS - NON-SAT EXPOSURE

For reasons of worker comfort and control of hyperbaric exposure the more conservative of the following criteria should be adhered to:
- The exposure period should be such as to require a decompression time in the manlock of not more than 2 hours. If longer decompression is required it should take place in a saturation habitat.
- The total of exposure period and decompression time should not exceed 3 hours

8.9 SHIFT PATTERNS – NON-SAT EXPOSURES

For non-sat exposures a shift pattern of five days on, two days off should be adopted.

8.10 DECOMPRESSION TABLES

The Contractor in Charge should select the decompression tables to be used taking account of the advice of his expert hyperbaric advisers and the Contract Medical Adviser.

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.

8.11 TREATMENT TABLES, OMITTED DECOMPRESSION TABLES, OVER RUNNING PERMITTED EXPOSURE PERIOD

As part of the safe system of work, the Contractor in Charge should with the advice of the CMA, identify appropriate treatment tables for use in treating DCI. Similarly, the Contractor in Charge should with the advice of the CMA identify procedures for dealing with omitted decompression and extended exposure periods.

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

8.12 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.

8.13 LIVING HABITAT FOR SATURATION

In general the chambers in which workers live whilst in storage should satisfy the relevant requirements of one of the classification societies. They should normally be sited on the surface.

8.14 LIVING HABITAT

The living habitat should meet the requirements of this document.

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. Some classification societies set additional requirements for living chambers covering bed size and washing/toilet facilities.

The layout of the living chambers and system of work (team size, shift patterns, etc) should allow occupants to have the required periods of rest and not be woken up by other occupants going to/from the TUP shuttle.

8.15 LIVING IN SATURATION CONDITIONS

For saturation working, the Contractor in Charge has to extend the safe systems of work to cover the welfare and well-being of those in the living chambers between excursions. This includes the provision of food and drink, the maintenance of a comfortable living environment, the provision of washing and toilet facilities, first aid and medical provision. The normal standards of the saturation diving industry should be followed.

8.16 SATURATION SHIFT PATTERNS

In order to ensure safe and efficient operations, HPCA personnel should work within a time routine which allows them to develop a regular work and sleep pattern. 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.

8.17 DURATION OF SATURATION EXPOSURES AND SURFACE INTERVALS

Where relevant national requirements do not exist, it is recommended that no one who is an experienced saturation worker should experience a saturation exposure exceeding 28 days under pressure. Otherwise the exposure should not exceed 14 days.

Thereafter that person should not undergo any further exposure to HPCA until at least an equal interval of time at atmospheric pressure has elapsed.
A person's cumulative saturation exposure should not exceed 13 weeks in any 26 week period.

Prior to decompression a person should have a 12 hour pressure stabilisation period in the living complex. An excursion at the pressure of the living complex can be part of this 12 hour period.

8.18 WORKING PERIOD

The maximum working period is calculated from initial lock-off until the final lock-on to the living complex and personnel are ready to transfer. No more than one working period per day is recommended. The maximum working period away from the living complex shall be 8 hours in a 24 hour period. The working periods set out in these guidelines may need to be reduced for very heavy work.

As personnel are involved in tiring physical work, the hyperbaric supervisor should appreciate that it may be appropriate for them to return to the manlock periodically for a short rest and to take refreshment before finishing their task. In any case, the hyperbaric supervisor should ensure that the personnel have a refreshment break of at least 15 minutes, between 3 and 4 hours into the working period.

8.19 HYPERBARIC OPERATIONS

During the transfer from shutle to chamber or living complex and back again every effort should be made to avoid changes in temperature, in the composition of the mixture being breathed and physiological effects including isobaric counterdiffusion.

For tunnelling, it is normally desirable to set the storage pressure to the working pressure and thus avoid the need for different breathing mixtures for excursions. Where it is likely that excursions will be required for operational reasons, storage pressure should be selected to minimise pressure changes during excursions. The excursion procedure should be selected to minimise undesireable physiological effects in those undertaking the excursion.

Final decompression to atmospheric pressure should not be started with an excursion to a lower pressure in the working chamber. There should be a 12 hour stop in the habitat before final decompression begins unless there has been no excursion involving a working pressure different to storage pressure in the preceding 12 hours

8.20 REMAINING ON SITE AFTER DECOMPRESSION

Personnel undergoing HPCA exposures should remain on site or its immediate vicinity, for 2 hours after decompression from non-sat exposures and for 24 hours following sat exposures. This will allow time for physiological monitoring to be undertaken.

8.21 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-acceptable restrictive, Contract Medical Advisers should produce local rules for travel involving ascent above this height.

9 >> Record keeping

9.1 RECORD KEEPING

Exposure records should be made in the language of the jobsite on which 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

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 excursion from the storage habitat.

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

9.5 INDIVIDUAL RECORDS

On termination of employment, each person exposed should be given a full record of his exposures on the project, details of training received, results of medical surveillance, along with details of any decompression illness events experienced and their treatment

10.1 EMERGENCY PROCEDURES AND CASUALTY EVACUATION

The Contractor in Charge 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 Contractor in Charge 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, manlock of other PVHO
- Fire on TBM
- Fire elsewhere in tunnel
- Fire on TUP shuttle transport vehicle
- Breakdown of 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

10.2 FIRE PROTECTION WITHIN AND AROUND THE TBM LOCK

The requirements of the BTS “Guide” and EN 12110 in respect of fire precautions 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.

10.3 FIRE PROTECTION FOR SURFACE FACILITIES

The buildings housing the saturation living complex should be fitted with a comprehensive sprinkler system. These buildings should be constructed from incombustible materials whenever possible.

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

In addition, there should be sufficient oxygen self rescuers at the control panel for everyone normally working there

10.4 HYPERBARIC SELF RESCUERS IN THE WORKING CHAMBER

A compressed oxygen 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.

10.5 FIRE PROTECTION FOR GAS CYLINDERS

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 should be protected by a sprinkler system.

11.1 INFORMATION, INSTRUCTION AND TRAINING

All those undergoing HPCA exposures should be given appropriate training in the risks from such work and how these risks should be mitigated. Reference should be made to the 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.

12 >> ACKNOWLEDGEMENTS

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>> Glossary of terms and abbreviations

Breathing mixture
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.

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

Compressed air worker
Person working in compressed air.

Contract Medical Adviser (CMA)
Medical practitioner qualified in occupational health 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.

Contractor in Charge
Contractor with overall responsibility for the HPCA work, and not necessarily the main tunnel conractor.

Decompression illness (DCI)
A ill health conditions resulting from decompression following exposure to pressure.

Diver medic
An advanced hyperbaric first aid qualification endorsed by the International Marine Contractors Association (IMCA) or national equivalent.

Excursion
A period in saturation away from the living complex, spent in the working chamber normally at a different pressure to the storage pressure.

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

Gauge Pressure
Pressure above atmospheric pressure as in normal tunnel practice.

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. pressure between "low pressure" and the statutory limit.

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

Isobaric counterdiffusion
The diffusion of gases in different directions without decompression and without changes in the environmental pressure which leads to the formation of bubbles.

Non-saturation exposure ("non-sat" exposure)
A short duration exposure comprising a compression, a working period under pressure, followed by a decompression. It does not involve any storage time in a hyperbaric living complex.

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

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.

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.

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 person exposed lives under pressure and may make transfers into the working chamber.

Storage
Maintenance of persons at pressure in a hyperbaric living complex.

Transfer under pressure (TUP)
The transfer of persons between pressurised habitats whilst maintaining those persons under pressure.

Tunnel Boring Machine (TBM)
A machine which in Europe would come within the scope of EN 12336 (references to EN 12336 in this document to become references to EN 16191 on harmonisation of EN 16191).

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

Working period (sat exposures)
The elapsed time from when a person leaves the living complex for the working chamber until that person arrives back in the living complex.

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ITA Secretariat c/o EPFL - Bât. GC - Station 18 - CH - 1015 Lausanne - Tel. : + 41 21 693 23 10 - Fax : + 41 21 693 41 53
Email : secretariat@ita-aites.org - Web : www.ita-aites.org