# Guidelines For Good Working Practice In High Pressure Compressed Air

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

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# >> Document History & Disclaimer

**DOCUMENT HISTORY**

At its meeting in Vancouver in 2010, International Tunnelling Association Working Group 5 (ITA WG5) identified the need for guidance on the use of high pressure compressed air (HPCA). ITA 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".

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

Consequently, ITA WG5 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 and 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.

In 2022 work started on a third revision to reflect growing experience of the technique along with current thinking on good practice and taking account of recent revisions of standards and guidance relevant to HPCA work.

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

**DISCLAIMER**

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

Work in compressed air and diving both involve exposure to hyperbaric environments. However when at work in compressed air, immersion is in a gas whereas when at work in diving, immersion is in a liquid. Humans have evolved to breathe gas but require the use of breathing apparatus when underwater. Those working in compressed air lack the buoyancy of divers. These and other factors give rise to a number of significant differences in the human physiological response to pressure exposure depending on whether it is work in compressed air or diving which is being undertaken. The gas/liquid issue also gives rise to different pressure profiles affecting those exposed. It is important that the differences between the two activities are recognised and due account taken of them. However for the period spent living in a surface habitat during saturation exposures, there are no physiological differences between work in compressed air and diving. Whilst there is considerable guidance on mixed gas breathing and saturation exposure techniques in diving, to date there is very little similar guidance specifically aimed at tunnelling.

Report 10 is 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 its use.

These Guidelines set out good practice in high pressure compressed air work in the form of recommendations. Although guidance generally has a lower standing than regulation or standards, that standing can be raised to the equivalent of a standard where the guidance forms a normative reference in a standard or is adopted by a regulatory authority as the basis for its enforcement activity. The guidance given in this Report aims to be goal setting in nature rather than prescriptive. However, because of the lack of alternative sources of published information or standards on high pressure compressed air (HPCA) work, some of the recommendations given are fairly detailed.

Users of this guidance are free to adopt their own solutions but these should not be less safe than the recommendations in this document. For limits quoted, such as maximum gas exposure limits, the recommended values or range of values given have been arrived at over a period as the consensus of expert opinion normally within the diving or hyperbaric medical community. As experience of HPCA work increases, it is now becoming possible to modify some limits for tunnelling applications. 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 professional discretion and experience in determining the appropriateness of applying or interpolating between recommendations given in the text. As high pressure compressed air work differs in a number of fundamental respects from diving such as transfer under pressure techniques and the consequences of immersion in a gas rather than a liquid are different, rigid adherence to diving practice and guidance can often be inappropriate.

All concerned should be aware HPCA is still a developing technique, and these Guidelines represent current good practice. Innovation and creativity should still be encouraged provided it does not result in a less safe outcome. 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 human response to pressure exposure should be considered. Isolated or unexpected cases of decompression illness should always be considered a negative outcome but can be an indicator of personal susceptibility rather than of deficiencies in a decompression regime.

To many people, saturation presents a psychological barrier beyond which they will not pass, although it should be remembered that, for most people, life is one long saturation exposure to air at atmospheric pressure. Saturation 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 intermediate pressures.

The use of a helium-rich breathing mixture reduces or eliminates the narcotic effect from breathing gas with a high partial pressure of nitrogen and also significantly reduces the work of breathing. With helium reclaim, it can be an environmentally sound option. Full advantage should be taken of favourable gas properties when devising exposure and decompression procedures along with mixed gas formulations.

## >> Glossary Of Terms & Abbreviations

**Absolute pressure**
The total pressure in bar including atmospheric pressure and denoted in this document as bar(a). Bar(a) = bar(g) +1 bar.

**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.**

**Air**
Naturally occurring respirable mixture of oxygen, nitrogen and trace gases.

**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, helium and nitrogen **(trimix)** capable of supporting human life under appropriate hyperbaric conditions. (EN 12021:2014 specifies the order oxygen, helium, nitrogen).

*Note: Various mixtures can be used during an exposure and sometimes are described by their function.*

- *Pressurisation mix – a gas mixture – not necessarily respirable on its own - used in the compression 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 Guidance**
The British Tunnelling Society Compressed Air Working Group's document "Guidance on good practice for Work in Compressed Air" published most recently in July 2021.

**Built in Breathing System (BIBS)**
System for supplying gas to a mask in a personnel lock.

**Compressed air worker (CAW)**
Person certified medically fit and competent who works in compressed **air**. Used in this document to imply work at low and intermediate pressures in which air is the **breathing mixture** normally with **oxygen** assisted decompression.

**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. **DCI** includes the acute conditions of **decompression sickness**, arterial gas embolism barotrauma and pneumothorax along with the chronic condition of dysbaric osteonecrosis.

**Decompression sickness (DCS)**
A subset of **DCI** covering acute ill health conditions resulting from decompression from pressure often categorised in tunnelling as Type 1 or "pain only" **DCS** and Type 2 or "serious" **DCS**.

**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.

**Excavation chamber**
The section of the **working chamber** in the front part of a shield between the ground face and shield bulkhead, into which the ground is excavated (EN 16191 cl 3.14).

**Excursion**
Time spent away from the **habitat** including **transfer under pressure** and work at a pressure different to the **storage pressure. Excursions** can be at pressures greater than or less than **storage pressure.** An **excursion** extends from time of lock off from the **habitat** to lock on to the **habitat** on the return to **storage**.

*Note: 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 refer to **oxygen** or a **breathing mixture** but excluding air.

**Gauge Pressure**
Pressure above atmospheric pressure as measured by a pressure gauge in normal tunnel practice and denoted in this document as bar (g) .

**Habitat**
Pressurised living complex associated with **saturation** exposures and 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**
Defined in this report as "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 within statutory limits 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.**

**Intermediate Chamber**
A part of the **working chamber** situated between the personnel lock and the **excavation chamber** housing hyperbaric facilities for entry to the **excavation chamber** (cl 6.1.5).

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

*Note: tunnellers often refer to any entry into the excavation chamber whether in free air conditions or in compressed air as an "intervention". In this report **"intervention"** is used strictly in the context of the above definition.*

**Isobaric counterdiffusion**
A complex phenomenon arising from having different concentrations of different inert gases on either side of a "boundary", 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 and competent who works in **high pressure compressed air** in **non-saturation mode.**

**Mixed Gas Saturation Worker (MGSW)**
Person certified medically fit and competent who works 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 all within a single shift. Not all tissues become fully saturated before decompression commences. It does not involve any storage time in a **habitat** (sometimes incorrectly referred to as a bounce dive).

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

**Oxygen BIBS**
Closed circuit system for supplying **oxygen** to a mask for decompression purposes and removal of exhaled **oxygen** to a dump location outside of the pressurised environment.

**Oxygen tolerance unit (OTU)**
The currently preferred term for a measure of cumulative oxygen exposure which takes account of **partial pressure** and time (also referred to in some documents as **oxygen toxicity unit, oxygen toxicity dose** or u**nit 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 (g).

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

**Principal Contractor**
Contractor primarily responsible for all aspects of tunnel construction.

**Quad**
Transportable gas storage consisting of multiple cylinders in various configurations connected to a common manifold, within a protective frame.

**Saturation (exposure) ("sat" exposure)**
A long duration exposure during which the exposed person becomes saturated, living at a **storage pressure** and making **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 ("pressurised transfer shuttle" in EN 12110-2).

**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.

**Surface Equivalent Value**
Correlation of a gas inspired at pressure to its equivalent physiological effect if the same concentration were breathed at atmospheric pressure.

*Note: Used as a measure of contamination, e.g. carbon dioxide, in the **breathing mixture.***

**Transfer under pressure (TUP)**
The transfer of persons between a **habitat** and personnel lock whilst maintaining those persons under pressure in a **shuttle.**

**Trimix**
An oxygen, helium and nitrogen **breathing mixture.**

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

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

**Unit of pulmonary toxicity dose (UPTD)**
The original term for a measure of cumulative oxygen exposure reflecting its adverse effects on the pulmonary system, which takes account of partial pressure and time of exposure. See **oxygen tolerance unit** (OTU)).

**Working chamber**
Collective term for the air pressurised chambers on a TBM in which work is undertaken in compressed air including the intermediate chamber and the excavation chamber.

**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 **working chamber** 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 constructed which required the application of high pressure compressed air (HPCA) to provide ground support and control ground water ingress during inspection and maintenance operations in the excavation chamber of the Tunnel Boring Machine (TBM). This is a significant but still relatively uncommon development in hyperbaric activity in tunnelling and has required the transfer of hyperbaric technology and knowledge from the diving industry to tunnelling. Not only does HPCA work present technical challenges for the industry, but it presents regulatory challenges also.

Much of the guidance on mixed gas use is orientated towards diving applications. The significant hyperbaric differences between tunnelling and diving such as from the lack of immersion in water, lack of buoyancy and differences in body orientation, in tunnelling, should always be considered. There are no differences when at rest in a habitat.

## 1.2. SCOPE

Report 10 is intended to inform all parties - including, clients, designers, contractors, regulatory authorities, insurers, operators and others - involved in HPCA work on what is currently considered to represent good practice.

Report 10 applies to the use of HPCA in tunnelling. To date, such work has been mainly associated with the inspection, maintenance and repair of the TBM cutterhead. However, it is foreseeable that conventional tunnelling operations could be undertaken in HPCA.

Whilst Report 10 is intended to apply to HPCA work as defined above, its recommendations can be applied to the use of mixed gas and saturation techniques at pressures in the intermediate pressure range.

## 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 work in the excavation chamber under HPCA conditions.*

## 1.4. PRESSURISING MEDIUM

To minimise the amount of mixed gas required for the HPCA work covered by these guidelines, the pressurising medium envisaged in the working chamber is compressed natural air which at high pressure is irrespirable hence the need for non-air breathing mixtures which are supplied by mask and umbilical. The pressurising medium envisaged in the habitat, shuttle and trunking is breathing mixture.

There should be the capability to flush and pressurise personnel locks, 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 8.13 et seq 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 are technically feasible at pressures of less than 3.5 bar(g) – the lower pressure limit in European commercial diving guidance varies between 1 and 1.5 bar(g) depending on the guidance used. Although saturation techniques may be used it is a commercial decision for the contractor whether to use such techniques at these pressures.*

## 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 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 towards the lower end of the range of pressures routinely experienced in offshore commercial diving. Consequently, it is concluded that there is nothing inherently unsafe about exposure to high pressure compressed air *per se*, provided appropriate safe systems of work are adopted.

Although there are few if any statutory limits on saturation, some commercial diving practice categorises “saturation” as being to 18 bar(g), “deep saturation” to 30 bar(g) and “extreme saturation” to 35 bar(g).

## 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 to use it has been made.

### 1.8. HPCA AS A CONTINGENCY MEASURE

On some projects the use of high pressure compressed air 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 covering the aspects of HPCA plant and equipment provision which cannot be retrofitted thus minimising the abortive costs should HPCA not be required. Clauses 4.1 and 8.1 are particularly relevant as is ITA/BTS CAWG Report 20.

It is recommended that all necessary exemptions, approvals and variances are identified, and discussions held with the regulatory authorities to ascertain the time necessary to obtain them. Even before a contractor has been appointed the tunnel owner should consider whether to proceed with obtaining the exemptions and approvals etc to mitigate the risk of delay, or to assume they can be obtained by the contractor within an acceptable timescale should the need for HPCA arise.

Consideration should also be given to the extent to which safe operating 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, personnel locks should have sufficient penetrations to allow for the supply of mixed gas and oxygen to the personnel locks and intermediate chamber along with space for the relevant gas storage, supply lines, control panels and working space (see EN 12110-2).

Where the possible need for saturation exposures is foreseen, a shuttle path (see EN 16191 cl 3.41) through the TBM should be identified and that space envelope protected because retrospective provision of a shuttle path can be impossible. Vertical movement of the shuttle should be in accordance with EN 16191 cl 4.2.8.3. Either the personnel locks should be fitted with docking flanges or should have the capability to be so fitted in the future.

When docked, no vertical load should be transferred to the trunking or docking clamp of the shuttle (see EN 16191 cl 4.2.8.4). 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. All parties should recognise that HPCA work continues to develop and should allow new or alternative hyperbaric techniques to be proposed for operational implementation provided adequate risk assessment and validation procedures have been completed which provide evidence that the new or alternative techniques fully meet or exceed the health and safety standards or limits represented by these guidelines. However numerical limits set out in Report 10 should be considered fixed and without scope for relaxation.

As the commercial and safety benefits associated with the use of saturation techniques are recognised, its use is likely to develop further. Greater awareness of gas properties along with commercial considerations will dictate the choice of breathing mixture. Helium reclaim may be adopted by the tunnelling industry which could also influence the choice of breathing mixture.

Unless adopted by a regulator as the basis of enforcement, Report 10 is a set of recommendations only and departure from them can be acceptable provided equal or higher standards of risk mitigation can be demonstrated. Human variability in response to exposure to pressure should always be taken into account.

### 2.1. NATIONAL LEGISLATION, STANDARDS AND GUIDANCE

These Guidelines are intended to complement existing national legislation, standards and guidance as appropriate or to provide guidance if national legislation, standards or guidance do not exist. As HPCA work is still a rarely used but developing technique, few countries are likely to have altered existing legislation and guidance to permit its use.

**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).**

*Note 1: references in this report to EN 12110-1. EN 12110-2 and EN 16191 are references to the harmonised versions of these standards expected to be published by 2025 but currently available in provisional form as prEN 12110-1, prEN 12110-2 and prEN 16191 published in 2023.*

### 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

#### 2.3.1. ITA/BTS CAWG Report 10

This report is not a standalone document but along with EN 12110-1/2, EN 16191 and the BTS "Guidance on good practice for work in compressed air" forms a coordinated package of guidance on the topic of HPCA work. This report builds on and extends to mixed gas use, the general guidance on compressed air work in the BTS Guidance. EN 12110 is in two parts. EN 12110-1 standardises the essential safety requirements appertaining to the design and manufacture of air locks for use in tunnelling at low and intermediate pressures of ~3.5 to 4 bar (g) with air as the pressurising and breathing medium along with requirements for equipment associated with oxygen decompression. EN 12110-2 standardises the essential safety requirements appertaining to the additional equipment required for mixed gas breathing in non-saturation and saturation exposures up to 20 bar (g) along with the essential safety requirements for pressurised transfer shuttles. EN 16191 sets out the requirements appertaining to tunnelling machinery which are necessary to allow HPCA work to be undertaken and which come within the scope of that standard.

*Note 1: compliance with ENs 12110-1/2 and 16191 is effectively mandatory within Europe, additionally many countries outwith Europe choose to adopt or adhere to them also.*

*Note 2: the British Tunnelling Society (BTS) Compressed Air Working Group (CAWG) published revised guidance titled "Guidance on good practice for work in compressed air" in 2021. It can be downloaded for free at https://britishtunnelling.com/pages/work-in-compressed-air .*

*Note 3: there are no EN standards which cover surface habitats however recommendations on their construction, layout and operation is set out in the BTS Guidance.*

#### 2.3.2. 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.

#### 2.3.3. CEN Standards for safety of air locks and TBMs.

Relevant European (CEN) standards include EN 12110-1 "Tunnel boring machines - Air locks - Part 1: requirements for air locks utilising compressed air as the pressurising or breathing medium along with requirements for oxygen breathing systems for decompression purposes"; EN 12110-2 "Tunnel boring machines - Air locks - Part 2: Safety requirements for the use of non-air breathing mixtures and saturation techniques in personnel locks and for pressurised transfer shuttles" and EN 16191 and EN 16191 "Tunnel boring machines - Safety requirements" – see Note 1 to clause 2.1.

#### 2.3.4. BS 6164:2019 – "Health and safety in tunnelling in the construction industry – Code of practice"

This British Standard is widely adopted as a fundamental reference on health and safety practice in all tunnelling activity. It has a section covering work in compressed air which complements the BTS Guidance 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. There is a normative reference in BS 6164:2019 to ITA/BTS CAWG Report 10.

#### 2.3.5. EN 12021 – Breathing gas quality

Compressed air and all breathing gases supplied in connection with HPCA work should comply with the current version of EN 12021 "Respiratory Equipment – Compressed Gases for Breathing Apparatus" – (2014 edition at time of publication of this guideline). Guidance on acceptable levels of nitrogen contamination in heliox is given in NORSOK U100 section 13 "Saturation bell diving – heliox".

### 2.4. RELEVANT GUIDANCE SOURCES – DIVING

There are similarities between some of the hyperbaric practices used in HPCA work and those for diving at similar pressures such as the operation of surface habitats. However, there are also significant physiological differences between compressed air work and diving particularly as a result of diving involving immersion in water. 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 diving guidance should be applied with appropriate professional discretion.

Unlike offshore construction where the atmosphere in underwater work habitats can be a breathing mixture, for commercial reasons associated with the cost and availability of helium, with HPCA work the pressurising medium in working chambers in tunnelling is almost certain to be high pressure compressed air in which the $PO_2$ and/or $PN_2$ are likely to be above safe limits. (See Cl 8.3 et seq).

#### 2.4.1. Classification Societies

"Classification societies" are major international companies which set detailed rules for the design, construction and testing of equipment for use in the marine environment. This includes hyperbaric systems used in diving and other underwater hyperbaric activity. Care should be taken when transposing rules intended for the marine environment to the underground environment to ensure their application is appropriate. The HPCA contractor should be aware that these rules can be applied to plant and equipment used in HPCA work as a condition of the insurance of the works. However they are not an alternative to ENs 12110-1/2 and EN 16191 in Europe.

Classification societies involved in HPCA projects should have good knowledge of tunnelling works. For example DNVGL (https://www.dnv.com/) has published "Rules" for the construction of air locks, shuttles and hyperbaric treatment chambers including associated systems which are necessary for operation which will be certified by DNVGL. These rules can be used for chamber systems in tunnelling especially with a working pressure higher than 5 bar(g), caissons and other applications: "VI-Rules for Classification and Construction, Additional Rules and Guidelines Part 11 - Other operations and Systems Chapter 4 - Chamber Systems for Tunnelling – 2011 Edition.

#### 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 applicable to hyperbaric activity in general and thus 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. EDTC now has a growing awareness of tunnelling hyperbaric work and is actively seeking to align its tunnelling and diving guidance.

#### 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-saturation and saturation diving issues. IMCA guidance on generic issues associated with hyperbaric plant and equipment for 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. US Association of Diving Contractors International (ADCI)

The Association of Diving Contractors International (ADCI) publishes extensive guidance on commercial diving, some of which is relevant to HPCA work. The US Association of Diving Contractors International (ADCI) has links to IMCA.

#### 2.4.6. HSE diving guidance

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

#### 2.4.7. US Navy Diving Manual

The US Navy publishes online and in hard copy, a very comprehensive manual dealing with non-saturation and saturation diving using self-contained and umbilical fed breathing apparatus within the context of military operations. The manual extends to historical material, gas physics and physiology and adverse effects of pressure exposure.

#### 2.4.8. Norway

Norwegian Standards (NORSOK) document U100 "Manned underwater operations" currently in its 5th edition is referenced in this guideline. This standard is focussed on deep commercial diving operations particularly in the offshore oil and gas sector.

#### 2.4.9. France

"Bulleti Officiel No 1 -– 30th Janvier 2013" is a comprehensive collection of French legislation, decompression tables and guidance on hyperbaric operations in commercial diving (Mention A), scientific diving (Mention B), hyperbaric oxygen treatment (Mention C) and tunnelling (Mention D). It also contains a guidance section on saturation diving operations. More recent Arrêtés have been published relating to diving e.g. "Arrêté du 14.5.2019 relative aux travaux hyperbares effectués en milieu subaquatique (Mention A) along with an Annexe which contains revised diving decompression tables. The Annexe was published in the Journal Officiel de la Republique Française – Édition des Documents Administratifs – Ministere du Travail as "Regeles Relatives aux Travaux Hyperbares effectuées en Milieu Subaquatique". Annexes à l'arrêté du "4 mai 2019 (Journal Officiel du 24 Mai 2019).

#### 2.4.10. Brazil

Deep saturation diving has been undertaken in the development of offshore oil reserves. A national classification system has been developed – saturation to 20 bar, deep saturation to 30 bar and extreme saturation to 35 bar. Guidance on appropriate techniques has been published by the Brazilian Navy Directorate of Ports and Coasts in chapter 11 of "Maritime authority norms for subaquatic activities" as NORMAM-15 saturation diving procedures. Although deep diving guidance, many of the principles in it can be used to inform HPCA work albeit at much lower pressures.

### 2.5. EUROPEAN PVHO STANDARDS RELEVANT TO TUNNELLING

EN 12110-1/2 are the primary standards for the design and fabrication of air locks for use in tunnelling in Europe. In turn EN 12110 makes normative reference to EN 13445 parts 1 – 5 which is the generic CEN standard for the design, fabrication and testing of unfired pressure vessels. There are no restrictions on its use internationally if desired. Outside Europe, reference can be made to Classification Society rules as a source of guidance on PVHO. However any tunnelling-specific requirements in EN 12110 should be adopted in addition to those of the PVHO standard adopted.

EN 14931:2006 is applicable to the "performance and safety requirements and their associated test methods for multi-place pressure chambers designed for pressures in excess of ambient atmospheric pressure and employed in medical installations for therapeutic purposes, in the following referred to as pressure chambers". As it was drafted for chambers in a hospital setting it should be considered as relevant to, but not a mandatory standard applicable to a medical lock on site. In some jurisdictions a chamber used for recompression treatment can be considered a medical device, even if used as a medical lock as part of a tunnelling operation. In Europe medical devices are subject to EU Regulation EU/2017/745. EU Regulations lack some of the flexibility of implementation compared with an EU Directive. According to its scope there is therefore some uncertainty as to the status and applicability of EN 14931 in EU member states.

### 2.6. 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 13445 or Classification Society rules as a source of guidance for use outside Europe, any tunnelling-specific requirements in EN 12110 should be adopted in addition to the ASME requirements.

### 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).

### 3.1. NOTIFICATION OF REGULATORY AUTHORITY

In many 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 statutory requirement or not, it is strongly recommended that the relevant authority is notified, and their advice and co-operation 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 long and arduous.

### 3.2. EXEMPTIONS, APPROVALS AND VARIANCES

#### 3.2.1. General principles

In countries where there are statutory limits on hyperbaric exposure, and/or prescribed procedures for undertaking compressed air work, it is likely that HPCA work will require formal exemption from or a variation in statutory requirements possibly 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 the application of HPCA during excavation chamber entry, justification of the hyperbaric procedures being proposed, details of the working practices to be undertaken and proposals on the provisions in place to respond to emergency situations.

Where an application for exemption, variance etc from national legislation is granted, stringent requirements can be placed by the national regulatory authority on the applicant.

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, approval or variance. It should include information on likely ground and ground water conditions, proposed tunnel excavation and lining techniques along with information on the personnel locks and other plant and equipment required for excavation chamber entry under hyperbaric conditions.

#### 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, if any, supporting the exemption;
- Method statements, risk assessments and other supporting documentation covering the work to be done;
- Proposals for alternatives to the matter exempted.

#### 3.2.5. Experience of HPCA work to date

There is now a small collection of data on the successful use of HPCA techniques over the past decade or so, but unfortunately some of it considered commercially confidential. The results of literature research into the availability of such data should form part of any application for exemptions etc. ITA and BTS CAWG appeal to clients and contractors to publish as much information on HPCA use as possible for the greater benefit of the tunnelling industry as a whole.

#### 3.2.6. Approval of hyperbaric procedures

The limited history of its use to date should be enough to demonstrate in principle that HPCA work can be undertaken in a safe and healthy manner provided appropriate standards and guidelines are adhered to.

The package of supporting evidence for approval of hyperbaric procedures or a decompression regime should include a description of the compression and decompression procedures, exposure limits and breathing mixtures. The evidence required should be confirmed with the regulator in all cases and would be expected to include the following:

- 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 aborted compression, omitted decompression, exceptional exposure and non-routine decompression in situations such as a failure of the oxygen supply during decompression.
- Justification of the breathing mixtures proposed for use.

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

#### 3.2.7. 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

The submission should include details of the proposed compression and decompression regime. For decompression tables without any history of satisfactory use, information on how the tables were derived and validated should be provided. This is not required for currently-recognised national tables or for tables with a published history of successful use in HPCA applications. However, the choice of these 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 this approach for tunnelling applications due to lack of tunnelling data for calibration and 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 "Bennett and Elliott's Physiology and Medicine of Diving", 5th edition. Alf O Brubakk MD and Tom S Neuman MD, editors. London: Elsevier Science. 2003. (ISBN 9780702025716).

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 tunnelling 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 due to the very low incidence of DCI arising from such techniques.

### 3.6. HYPERBARIC TRIALS

It is recommended that hyperbaric trials should not routinely be undertaken to demonstrate the safety of an unproven technique now that some data to allow comparisons with successful techniques is available. Before deciding to proceed with trials, careful consideration should be given to the value of the information that they would provide. For trials to produce statistically meaningful results, a large number of exposures (with their associated costs) is required.

Trials are at their most representative when the work undertaken during the trials 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 or comparisons with existing techniques along with enhanced monitoring during the first few working exposures on site, should be sufficient to demonstrate the safety of the proposed technique.

### 3.7. TRIAL RUN

Some regulators may consider that a trial run of procedures should be undertaken, in which a small number of exposures is 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, comparisons with data from recent practical experience along with enhanced monitoring to the satisfaction of the national regulator during the first few working exposures on site, should be sufficient to demonstrate the safety of the proposed procedures without the need for a trial run.

Should a trial run 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 in storage should be at least 48 hours longer than the time for saturation at the storage pressure to be fully established.
- The exposure protocol should include some form of relevant work activity.

Physiological monitoring should be undertaken during and following all decompressions during the trial run. For a decompression to atmospheric pressure following any exposure, monitoring should continue at intervals not exceeding 60 minutes for non-saturation exposures and intervals of 3 hours for saturation exposures or other such frequency if instructed by the Contract Medical Adviser, until the parameter being monitored has been demonstrated to have been reduced to a pre-determined acceptable level. If abnormal responses are recorded more frequent monitoring should be undertaken if instructed by the Contract Medical Adviser.

### 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.

### 3.9. DETAILS OF PERSONNEL, SPECIALIST ADVISERS ETC.

The submission should include details of the qualifications, experience and skills of the main personnel to be used in overseeing HPCA work along with similar details for those providing specialist hyperbaric advice.

### 3.10. ACCEPTANCE CRITERIA FOR AN ACCEPTABLE LEVEL OF SAFETY

#### 3.10.1. Routine post-exposure monitoring

All monitoring of the effectiveness of the decompression procedures should be undertaken in accordance with clause 11.8 of the BTS Guidance.

Assessment of the acceptability of exposures and decompression profiles as being acceptably safe, should be undertaken holistically. Both physiological monitoring results and the absence of clinical signs of DCI or other ill-health effects should be considered.

The regulatory authority may set its own criteria however in the absence of such criteria the criteria in clause 11.8 of the BTS guidance should be adopted.

#### 3.10.2. 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 the reason ITA and BTS CAWG strongly encourage contractors undertaking HPCA work to make their exposure data available to the wider industry for 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 one or other of the criteria 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 in excess of K-M Grade 2 and an insignificant occurrence of Grade 4 bubbling is predicted.
- Or for the first 120 minutes of monitoring following decompression, a Kisman Integrated Severity Score (KISS) should be determined and should not exceed 50.

*Note: Decompressions arising from excursions or final decompression following saturation exposures can result in near zero bubble scores.*

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 low levels of detectable bubbles. Hence it is prediction of DCI risk (not DCI events) on which the acceptance criteria should be based.

#### 3.10.3. Statistical analyses

Traditionally these have been used in tunnelling to retrospectively monitor the effectiveness of decompression regimes for non-saturation low and intermediate pressure exposures. They have been based on DCI incidence as a measure of the effectiveness of decompression procedures. The large number of exposures required to give meaningful results and the unreliability of DCI as a scientifically robust indicator make such techniques unlikely to be suitable for predictive work.

Given the very low incidence of DCI arising from saturation exposures and the lack of relevant tunnelling data, statistical analysis is unlikely to be of value in assessing the effectiveness of decompression in saturation techniques in tunnelling.

### 3.10.4. Assessment criteria – hyperbaric trials/trial run

The profiles trialled 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 result in a Doppler bubble score in excess of K-M Grade 2 and an insignificant occurrence of Grade 4 bubbling is recorded (to take account of inter-individual and intra-individual variability in response to decompression).
- Or for the first 120 minutes of monitoring following decompression, a Kisman Integrated Severity Score (KISS) should be determined and should not exceed 50.

*Note 1: DCI is an ill-defined subjective measure and consequently is a poor indicator of decompression effectiveness even if DCI is 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 2: 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

As a contractual requirement, the Tunnel Owner should require that on completion of HPCA work, the contractor should prepare a report, to be shared with the regulator, on the effectiveness of the decompression regimes used on the project. The report should summarise the exposure data, the decompression regime used, and post-decompression physiological monitoring of workers. Any abnormal events such as DCI should be recorded. An additional requirement should be the publication of a suitably anonymised version of the report 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, especially in regard to saturation exposures.

#### 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 should be taken into account as they can affect the design of the tunnel and the TBM. It should be remembered that it can be impossible to make the necessary provisions retrospectively.

Tunnel Owners, designers and contractors lacking expertise in HPCA work should refer to ITA/BTS CAWG Report 20 "Guide to ITA/BTS CAWG Report 10 for Clients and others not familiar with high pressure compressed air work" before proceeding further. It is recommended that specialist hyperbaric advisers be appointed and consulted at this stage.

The need for coordination and communication between Principal Contractor, the Contract Medical Adviser, the specialist hyperbaric adviser, the HPCA contractor, the TBM supplier and any 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 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 EN 12110-2 cl 4.3.2.1). For non-saturation work there should be space for a sufficiently large personnel lock along with sufficient penetrations through the air lock shell and the TBM bulkhead to allow for the supply of mixed gas and oxygen to the personnel locks and working chamber along with space for the relevant gas storage, supply lines and control panels. In particular there should be adequate allowance for working space for panel operators and the requirements of EN 894 (Pts 1 to 4) "Safety of machinery. Ergonomics requirements for the design of displays and control actuators." should be met. For saturation work there should be sufficient space to allow for the passage of a TUP shuttle from its carrier vehicle to the personnel lock. With both techniques, space provision for a hyperbaric control panel adjacent to the personnel lock 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/personnel lock manufacturer (see EN 12110-2 and EN 16191).

#### 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 their senior personnel on site.

The Principal Contractor will usually also be the HPCA Contractor, but if the Principal Contractor has no experience of the specialised technical nature of HPCA work it is likely that a specialist sub-contractor will be engaged as the HPCA contractor. If this engagement is 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.

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 when HPCA work is being undertaken. Plant, equipment and materials should be robust enough to withstand the rigours of the tunnelling environment. The recommendations in the BTS Guidance on the management of work in compressed air and on personnel required for it should be followed in addition to the recommendations in this report.

#### 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 tunnelling hyperbaric advice during the planning and execution of the HPCA works. This can be from in-house sources or from independent specialists. Topics on which advice could be sought include international practice in hyperbaric exposure in tunnelling, 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

The Principal Contractor should ensure that the public emergency services covering the area in which the project is located are notified of the HPCA work. Notification should include sufficient detail of the nature of HPCA work for the emergency services to be able to plan their response, if any.

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 off-site 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 – possibly the duty medical lock attendant – 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 expect to have to make provision for emergency response in the pressurised workings from within their own resources along with the provision of all related equipment and trained personnel. This should extend to the treatment in-situ of any related trauma along with the extrication of a casualty into the personnel lock, any subsequent first aid treatment under pressure, decompression of a casualty and finally evacuation of a casualty from the tunnel to the surface. 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 and certainly not emergencies at high pressure. Nevertheless, the emergency services (fire, rescue, ambulance, paramedics etc.) can normally provide useful assistance in the tunnel as far as the personnel lock door (see Cl 10). The contractor should provide the emergency services with equipment, training and medical examination 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 also extend to the provision of equipment and training facilities as necessary. Irrespective of the source of the emergency response team, due allowance must be made for their needs when calculating gas supplies.

## 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, responsibilities and limits of authority of each appointee and the overall management structure. All those appointed should be competent and have relevant previous experience, however some site-specific training and familiarisation may be required.

The personnel and the roles set out in the BTS Guidance 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.

In addition to the roles highlighted below, support staff to assist those undertaking these roles will be required along with tunnel operatives to provide manual assistance.

### 4.7.1. Personnel required for saturation operations

For saturation work in addition to the Person in Charge (Cl 4.2), 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 Mixed Gas Saturation Workers (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 should include managing the relevant support personnel, transport of the shuttle, gas supplies, personnel lock and docking procedures, interfacing with those in charge of the TBM over work to be done, face support pressures and stability along with 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 assessment 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 Guidance to cover the control and coordination of all hyperbaric and tunnelling aspects of non-saturation exposures. The person filling this demanding role should have experience of HPCA work or saturation diving along with experience of working in the underground environment and the management of compressed air tunnelling work.

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 qualification from a recognised accreditation body such as the Australian Diver Accreditation Scheme (ADAS) and have relevant experience. At all times when the habitat is occupied, there should be at least 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, maintain minimum reserves of gas on site, 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. There should be clear procedures for isolating non-compliant cylinders or quads to ensure they are not put into use but are removed from site as quickly as possible and the supplier’s quality assurance personnel should be informed.

The gas attendant should retest all gas cylinders or quads immediately before dispatch to the personnel locks or habitat.

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 could include 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 including used by the emergency services where relevant. Where TUP is being undertaken, the gas attendant should oversee the replenishment of the gas supplies which accompany the shuttle during TUP.

Appropriate stock rotation 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 qualification and have had relevant practical experience. The supervisor should be responsible for controlling the hyperbaric aspects of the TUP shuttle and its life support equipment used during transit between the habitat and TBM personnel lock. The shuttle supervisor should also be responsible for shuttle handling procedures along with lock on/off and shuttle docking procedures. The shuttle supervisor should be assisted by a life support technician at all times when the shuttle is occupied and in transit.

Additional personnel are likely to be required to assist with the physical process of moving the shuttle between habitat and TBM under the control of a supervisor.

#### 4.7.6. Lock attendant

The lock attendants working in the tunnel should have had previous experience of lock attendance 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 or in a hyperbaric medical facility and 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 personnel lock or intermediate chamber to tend the umbilicals of those in the working chamber. One person should be required to tend no more than two umbilicals simultaneously. Tenders work in a pressurised environment and should be medically fit for such work.

#### 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. But because of the rarity of HPCA work, they can come from a commercial diving background and if so they should hold a mixed gas commercial diving certificate, demonstrate their ability to transfer their skills to HPCA and be trained to work 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 Closed bell (formerly Part 2) or internationally recognised equivalent). Appropriate internationally recognised diving qualifications are listed on the HSE website at http://www.hse.gov.uk/diving/qualifications/approved-list.pdf under the category "for closed bell diving or saturation diving techniques". The Association of Diving Contractors International (ADCI) bell/saturation diver qualification can be accepted with the proviso that the qualifications and experience, including training records of the diver should be documented, along with the certificate.

### 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. Where no one language predominates, 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 before productive work in HPCA commences 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 excavation chamber, rescue of a seriously injured casualty from the excavation chamber, contamination/loss of the breathing mixture supply to the excavation chamber 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. The hyperbaric system should be certified oxygen clean. Only once these checks have been satisfactorily completed should hyperbaric activity be restarted and then only in accordance with previously agreed procedures. Where any lack of maintenance or modification of the plant and equipment has occurred. The complete hyperbaric system should be re-certified or recalibrated as appropriate. Thereafter following successful functional testing in accordance with Cl 6.46.2, hyperbaric activity in accordance with previously agreed procedures can restart.

### 5.1. SAFE SYSTEMS OF WORK

The requirement to have safe systems of work is applicable to all compressed air work. The guidance on safe systems of work set out in the BTS Guidance is generally applicable to HPCA and should be adopted but with modifications as necessary to reflect the higher pressures and differences in exposure techniques.

No productive work, maintenance work or hot work should be carried out on the TBM or in the tunnel whilst work in HPCA is being undertaken. Additional requirements are set out in these guidelines.

### 5.2. PLANNING THE WORK UNDER PRESSURE

Because of the complexities of HPCA work, a high level of planning is required. Plant and equipment must be brought together with all testing and calibration in date, supplies of gas mixtures and other consumables must be set up, MGWs and especially MGSWs must be brought together with appropriate training and medical checks undertaken.

Prior to work under pressure commencing, a theoretical maximum pressure profile along with a predicted working pressure profile should be prepared and used to plan the pressures and exposure techniques to be used along with the gas mixtures and quantities required. This should be updated regularly with actual exposure data as tunnelling progresses.

In addition, before each saturation run a detailed plan for storage and working pressures along with excursion details should be prepared. This plan should set out the predicted storage pressure(s) for the run and the adjustments to storage pressure required. Excursions should also be planned to match likely working pressures. The object of the plan should be to ensure that only increases in storage pressure are undertaken, interventions are undertaken in preference to excursions and excursions when undertaken are to a pressure greater than storage in preference to excursions to a pressure less than storage. This is particularly important when the tunnel alignment is inclined upwards and working pressures in the excavation chamber can be expected to reduce as tunnelling progresses. Reductions in storage pressure should be avoided but if necessary, should be undertaken as segments of the final decompression profile.

### 5.3. 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.

Bulkheads and any tunnel lining forming a working chamber or air lock along with the pressurisation air supply should all be considered temporary works. As temporary works they should be managed and checked independently (Category 3) in accordance with the requirements on tunnelling temporary works management of BS 6164.

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.

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 should be defined as exceeding a percentage of the compressed air supply capacity agreed in advance between the Principal Contractor, compressed air contractor and their specialist advisers and reviewed in the light of changing ground conditions and experience. Work in the excavation chamber should be abandoned if air loss becomes excessive.

Unexpected changes in air loss can 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. A drop in pressure will lead to a drop in $PO_2$ for those working in the chamber and this should be taken into account when breathing mixtures are being chosen.

### 5.4. 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 TUP operations associated with saturation exposures. Due allowance should be made in the design of the TBM for a clear path to allow for the passage of a TUP shuttle from its transport vehicle through the TBM to the personnel lock. The TBM manufacturer must take these requirements into account when designing the TBM. ENs 12110-2 and 16191 set out requirements for shuttle paths and working space.

The working space requirements can 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 personnel locks to facilitate docking 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.

Requirements for air and breathing mixture supply to and in the locks, intermediate chamber, excavation chamber and trunking are set out in EN 12110.

For non-sat HPCA operations the TBM should be designed and constructed to provide adequate working space to access and operate the personnel lock(s) safely. When HPCA operations are being undertaken a working platform meeting the requirements of EN 16191 Cl 4.2.7.2 should be provided. The working platform should also accommodate the workstation for the lock attendants and the lock control panel(s). Appropriate connection points and pipework for gas supplies including gas for extended or emergency decompression, should be available. The number and function of the connection points for mixed gas use is set out in EN 12110-2. Oxygen for decompression purposes can also be 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.*

## 5.5. RESTRICTIONS ON HPCA DUE TO TUNNELLING CONSIDERATIONS

### 5.5.1. Geometrical constraints

Geometrical constraints make TUP and hence saturation exposures using the TBM personnel lock, impracticable on smaller sized machines. 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. On slurry TBMs below 5.5 m internal diameter space constraints should be considered likely because of conflict with the erector.

### 5.5.2. Smaller tunnels

In smaller tunnels space constraints can mean that it is not possible to use a TBM personnel lock, so it can be necessary to install one or more bulkheads in the tunnel. Where fewer than three bulkheads are installed (i.e. a two compartment air lock system has not been formed), a two compartment personnel lock 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 HPCA work 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. The use of a reliable self-contained supply from cylinders may also be considered.

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. Purging and filling with an inert fluid should be undertaken if removal is not possible.

Major electrical installations should be de-energised however 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.

## 5.6. FACE ENTRY PROCEDURE

### 5.6.1. General requirements

Face entry procedures should be drawn up as part of planning for HPCA work (see Cl 5.2).

Before any face entry takes place, the stability of the ground along with the availability and effectiveness of suitable protective measures 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 excavation chamber is taking place above a liquid pool or soft soil mass. Air loss and face stability should be continuously monitored throughout the time persons are in the excavation chamber.

Before anyone enters the personnel lock to be compressed, the working chamber should have been pressurised and air pressure maintained for sufficient time without excessive air loss (cl 5.3 above) to demonstrate the stability of the face. This period should be determined by those responsible for face stability and could vary from 10 – 30 minutes depending on ground conditions, speed of drying out of the ground and the vulnerability of structures above the tunnel.

All valves, gauges and other control devices should have been shown to be functionally operative before face entry procedures begin.

### 5.6.2. 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 work in the excavation chamber, has the correct material properties and is subject to strict quality control is an essential aspect of the overall safety of the HPCA work.

### 5.6.3. 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 often be lowered without prior injection of additional material.

Where very adverse ground conditions are anticipated, a bentonite circuit should be provided on EPB TBMs to allow for periodic refreshment of the filtercake during long periods of work in the excavation chamber. Refilling with a muck – bentonite mixture would require further excavation which depending on the reason for the excavation chamber entry might be not possible.

*Note: See clause 5.5.1 for information on TBM diameters for HPCA work.*

### 5.7. REFILLING HEAD WITH SLURRY WHILST DECOMPRESSION STILL GOING ON

#### 5.7.1. Slurry TBM

On a slurry TBM, the excavation chamber 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 personnel lock. This requirement may conflict slightly with guidance regarding re-energising of equipment on the TBM during hyperbaric interventions, but is an essential precaution for HPCA work.

#### 5.7.2. EPB TBM

Restarting an EPB TBM in a controlled manner after a face entry procedure is a highly critical activity especially for larger diameter machines. Depending on the face permeability two different procedures can be considered. 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 is too liquid to be discharged via the screw conveyor whilst maintaining full pressure control. The restarting procedure can disrupt the collection of information about volume loss or mass balance for a significant amount of time and needs very stable face conditions. In critical areas, this problem can be overcome by the injection of an artificial "conditioned soil mix" brought from outside such as a thick inert grout.*

### 5.8. INCHING OF CUTTER HEAD

When designing a TBM for HPCA use, due account should be taken to ensure the requirements in EN 16191 (e.g. cls 4.2.3 and 4.4.4), 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 personnel lock.

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

### 5.9. ACCESS IN EXCAVATION CHAMBER

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 (EN 16191 cl 4.4.4).

### 5.10. WELDING, CUTTING AND OTHER HOT WORK

#### 5.10.1. 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.

#### 5.10.2. 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. Although hypoxic breathing mixtures can be in use, the pressurising medium in the excavation chamber remains air and hence the fire risk remains high because of the increased concentration of oxygen in the compressed air. 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 cover the head, neck, torso and legs as well as covering the shoes. Flame resistant hand/arm protection should also be provided. Consideration can be given to reducing the volume concentration of oxygen in the excavation chamber by the injection of nitrogen. Discharge of nitrogen rich gas should be done carefully to avoid causing hypoxic conditions on the TBM or in the tunnel.

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 work in the excavation chamber 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. The fire watcher should not be left alone in the excavation chamber after completion of the hot work.

#### 5.10.3. 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, plasma cutting or gouging techniques should be considered instead of naked flame techniques.

#### 5.10.4. 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 excavation chamber.

Masks should be compatible with the hot work being undertaken. Nevertheless fume should be vented to a safe and adequately ventilated discharge point in the tunnel. If necessary, the working chamber should be flushed with air to maintain visibility; similarly the personnel locks should be flushed 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.*

### 5.11. USE OF EXPLOSIVES

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

### 5.12. CLAMPING OF BULKHEAD DOORS

It should be possible to clamp shut any door between a personnel lock chamber and the working or intermediate chamber as required by EN 16191 cl 4.2.9.2.

### 5.13. CCTV SURVEILLANCE

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

CCTV should also be used to observe and guide workers in the excavation chamber (and intermediate chamber if present) when undertaking maintenance or inspections.

# 6 >> Plant, Equipment & Gas Supply

## 6.1. PLANT AND EQUIPMENT

### 6.1.1. General requirements

All plant and equipment for use in the HPCA work 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 EN 12110-1 and -2, the BTS Guidance and these guidelines, supplemented if necessary by other relevant guidance from sources given in Section 2 above.

IMCA D 024 Diving Equipment Systems Inspection Guidance Note “DESIGN for Saturation (Bell) Diving Systems” provides useful guidance on the calibration and inspection of instrumentation in saturation applications. 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 (see EN 16191 Cl 4.3.2.1), the shuttle handling requirements, space requirements for control panels and gas storage, capacity of personnel locks, the number and size of penetrations for the personnel locks and the working chamber. Docking flange dimensions should be in accordance with EN 12110-2 Cl 4.6.2.

### 6.1.3. Plant and equipment - non-saturation operations

For non-saturation exposures all hyperbaric operations should be controlled from a panel at the TBM personnel lock. The panel should allow the ergonomic operation and provide the control functionally and information set out in EN 12110-2 including requirements for communications and CCTV.

EN 12110-2 sets out the requirements for valves, gauges etc necessary for the pressurisation and depressurisation of the personnel lock, intermediate chamber if fitted and working chamber along with the means to monitor and control the supply and analysis of breathing mixtures for those working in the working chamber. EN 12110-2 also specifies that 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. The supply of oxygen or other gases for decompression purposes is covered by EN 12110-1.

### 6.1.4. Plant and equipment - saturation operations

For saturation exposures the plant and equipment should include a habitat on the surface for personnel living under pressure, one or more shuttles for transfer under pressure along with ancillary equipment required as part of the transfer under pressure between the habitat and tunnel personnel lock. Transfer under pressure shuttles should meet the requirements of EN 12110-2.

Dimensions, space distribution requirements and minimum requirements for fixtures and fittings for surface habitats along with control functionality is set out in clause 6.48. It is based on a combination of diving industry guidance (NORSOK U100) and the requirements set out in EN 12110-2 for mixed gas exposures.

There should also be a self-contained chamber separate from the habitat which would be capable of housing the occupants of the habitat in an emergency (See cl 6.47. of the BTS guidance). The self-contained chamber should be equipped with washing and toilet facilities. It can also act as a therapeutic recompression chamber and as a medical chamber. The self-contained chamber should be a stand-alone PVHO, and it should be possible to transfer under pressure into this chamber when TUP is being undertaken on site.

All hyperbaric operations around the TBM and associated with excavation chamber entry should be controlled from a panel at the TBM personnel lock meeting the requirements of EN 12110-2.

### 6.1.5. Intermediate chamber

Where a shielded tunnel boring machine is intended for the use of non-air breathing mixtures and saturation techniques the machine should be designed to incorporate an intermediate chamber between the personnel lock and excavation chamber as set out in clause 4.2.9.2 of EN 16191. The intermediate chamber is a “dirty” air pressurised part of the working chamber from which entry into the excavation chamber is gained. Umbilicals for use in the excavation chamber should originate from the gas supply manifolds in it. MGWs/MGSWs should clean themselves and change into clean clothing in it before entering the personnel lock. It also forms a place of relative safety into which MGWs/MGSWs can escape in the event it becomes necessary to perform an urgent evacuation of the excavation chamber.

### 6.1.6. Minimum lock dimensions

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

*Note: EN 14931:2006 “Pressure Vessels for Human Occupancy - Multi-place pressure chamber systems for hyperbaric therapy” does not apply to plant in the tunnel or to TUP shuttles but can be applied to surface recompression chambers.*

### 6.1.7. 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 for such life-safety critical systems.

All remotely operated valves should have a manual override at the valve.

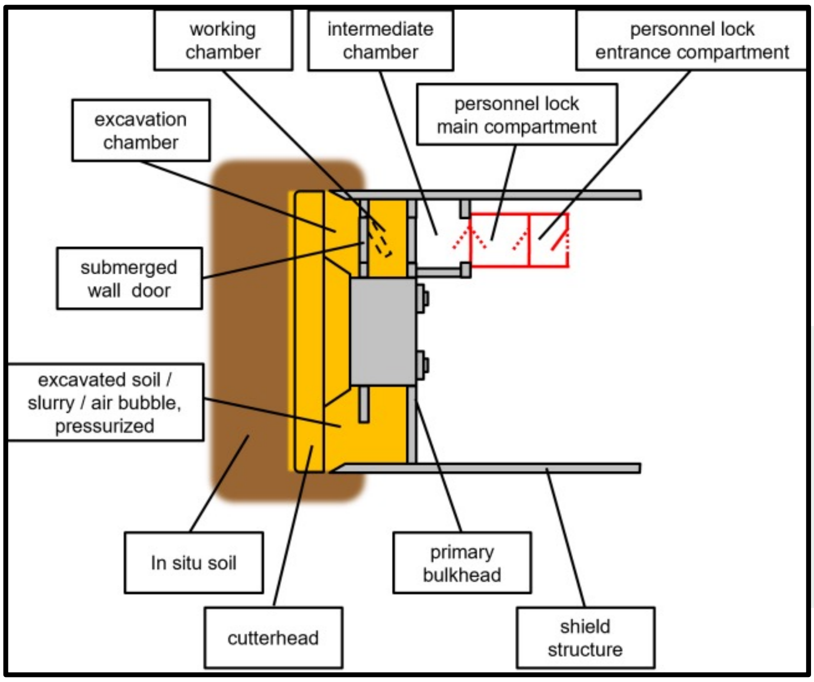


*Figure 1: Indicative location of intermediate chamber on EPB TBM (source – Herrenknecht GMBH)*

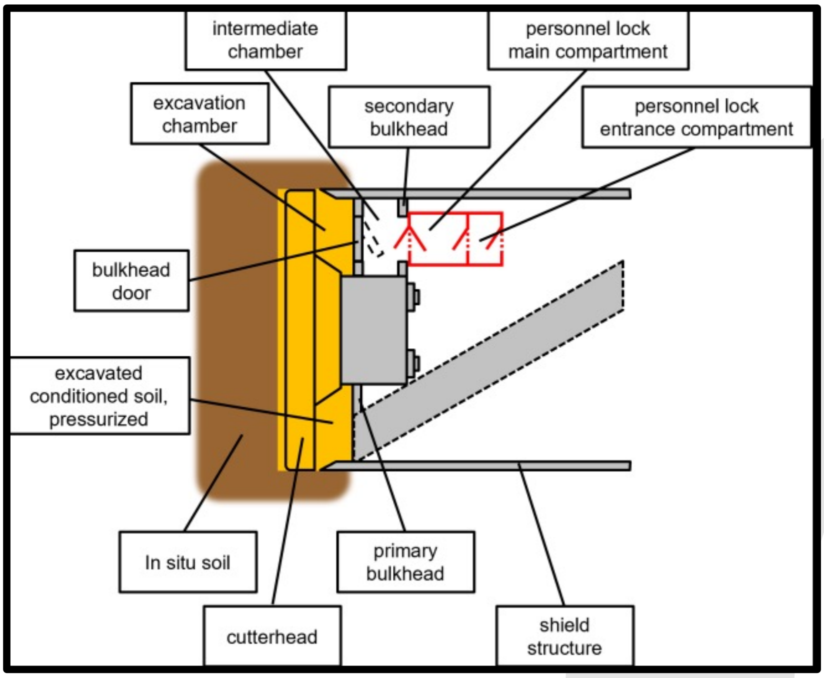


*Figure 2: Indicative location of intermediate chamber on Slurry TBM (source – Herrenknecht GMBH)*

### 6.2. TUP SHUTTLE

Each shuttle should be designed and constructed in accordance with EN 12110-2. Depending on the regulatory regime in the country of use, the TUP shuttle should be of one or two compartment construction. Two compartment construction is to be preferred. 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 as required by EN 12110-2. 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.

*Note:- a CEN standard on MSVs is in preparation.*

It is necessary to lift and transport the shuttle within its protective frame (including the onboard fire suppression system) as part of the TUP procedure. During TUP the shuttle will also need a power supply and a supply of mixed gas. This can be provided by mounting the shuttle in its protective frame, a generator or other power supply suitably protected, gas quads, an environmental control unit and a suitably enclosed workstation for the supervisors within a transportation structure. That structure should be designed for lifting persons and should be inspected, thoroughly examined and tested in accordance with requirements for personnel lifting equipment. Any lifting operation involving lifting of persons should be undertaken in accordance with national regulations.

Persons in the shuttle require life support including environmental control. Life support normally requires a control panel, main gas supply and emergency gas supply, a heating/cooling system, fire suppression system, essential power supply.

These should be provided from the transportation structure for travel between the habitat and TBM. Once the shuttle is on the TBM, life support and environmental control should be provided from the TBM. Care should always be taken to prevent any strain on or damage to pipes, cables, umbilicals and their connections. Connections should be designed to facilitate quick connection and disconnection, be self-sealing as appropriate and designed to minimise the risk of cross connection. The shuttle should be covered with non-flammable thermal insulation where appropriate to minimise heat transfer.

Breathing mixture supply to and in the shuttle should be in accordance with EN 12110-2. Communications including CCTV and voice communications are considered to be part of the life support provisions.

### 6.3. 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 levels of volatile organic compounds (VOCs) at atmospheric pressure, they have been found to emit significant levels of VOCs under pressure. All PVHOs coated with such materials or other VOC emitters 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).

### 6.4. ESSENTIAL SERVICES

The shuttle when on the TBM, the personnel locks, the intermediate chamber and the excavation chamber when occupied should all be treated as essential services in terms of the TBM power supply to them (see EN 16101 cl 4.2.7.8). The area around the personnel locks and control panels should be adequately lit.

### 6.5. INSPECTION, MAINTENANCE AND TESTING

The HPCA contractor should ensure there are formal planned inspection, maintenance and testing procedures along with appropriate record keeping 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. The procedures should take account of the principles for such systems set out in IMCA D 018 Rev 1, the BTS Guidance, EN 12110 and relevant classification society rules along with manufacturers’ instructions and the requirements of the insurers of the HPCA contractor. Full records should be kept of all inspections, maintenance and testing.

### 6.6. SELECTION OF FACEPIECE

The most suitable facepieces be they masks or helmets should be used, taking account of user comfort, the need to provide security of fit, to minimise inward and outward leakage, provide head protection and allow built in voice communication. Full face masks or helmets should be used in the working chamber.

There are no CEN standards specifically for umbilical-fed facepieces for use with air, heliox or trimix at pressure whilst immersed in air. The most appropriate diving standard for tunnelling applications is considered to be EN 15333-1:2008 “Respiratory Equipment – Open-Circuit Umbilical Supplied Compressed Gas Diving Apparatus – Part 1: Demand Apparatus.”. The requirements of that standard should be met in respect of general construction and performance, relevant breathing performance aspects including work of breathing, respiratory pressures and inspired carbon dioxide levels.

There should be voice communication functionality built into the masks or helmets meeting the requirements of EN 15333-1:2008 clause 5.19. Ideally there should be on mask/helmet video communication capability also.

Additional requirements for masks for oxygen breathing during decompression are set out in clause 8.28 of the BTS Guidance and guidance on oxygen discharge can be found in clause 8.30 of the BTS Guidance. Additional requirements for masks for mixed gas supply are set out in clause 8.29 of the BTS Guidance. Masks used during welding should be protected against contact with hot particles.

### 6.7. 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 other masks or helmets.

### 6.8. UMBILICALS

#### 6.8.1. Umbilical properties

Each person in the working chamber should have a single multicore umbilical supplying breathing mixture, emergency breathing mixture supplied through a separate core of the umbilical to the main supply and communications including a body-mounted camera output (see Cl 6.9). The umbilical casing should protect the lines from damage.

Gas carrying cores of umbilicals should have a burst pressure of 4 times design working pressure and be subjected to an annual pressure test to 1.5 times the design working pressure whilst subject to a tensile load of 100 kg on the core including fittings. The test pressure should be maintained for 10 minutes without loss of pressure.

Umbilicals should be marked with a unique identification mark and be subjected to a planned maintenance programme.

The umbilical and its terminal fittings ("D" rings or similar attachment devices) should be capable of withstanding a tensile load of 500 kg. There may be a separate tensile load resisting core in the umbilical if necessary.

#### 6.8.2. Umbilical connection point

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 should normally be in an intermediate chamber (where fitted) which can be securely isolated from the working chamber but otherwise in the personnel lock. The intermediate chamber (see EN 16191 Cl 4.2.9.2) can be considered as the first point of escape or safe area but should not be considered as a personnel lock chamber for compression or decompression purposes. There should then be provision for transfer to the personnel lock chamber whilst still breathing the appropriate breathing mixture. Note:- there can be more than one intermediate chamber on very large TBMs

### 6.9. 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.

### 6.10. REQUIREMENTS FOR DOCKING

#### 6.10.1. Alignment for docking

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

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

*Note: if necessary there can be the capability when docking, 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.*

#### 6.10.2. Docking

Shuttles are normally docked to personnel locks 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 personnel lock. In this situation the shuttle acts as the personnel lock and should be of two compartment construction.

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

EN 12110-2 specifies there should be a length of trunking between the pressure vessel and the docking flange. The trunking should be flushed and pressurised with habitat breathing mixture before doors on the pressure vessels are opened to avoid unnecessary contamination of the habitat with nitrogen.

#### 6.10.3. Docking flange

Dimensions for docking flanges and trunking are set out in EN 12110-2. Flanges should be kept clean and spare sealing rings for the docking flanges, if fitted, should be held on site. An illustration of a typical docking flange is given in Figure 3.

#### 6.10.4. Docking clamp

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

EN 12110-2 requires the docking clamp to be attached to the shuttle. The clamp should be protected from mechanical damage during TUP operations.

There should be a clearly defined procedure for incrementally increasing trunking pressure to ensure clamping has been effective and a seal achieved.

*Note 1: Particular attention should be paid to chamber docking systems.*

*Note 2: Requirements for interlocking doors on food and medical locks are set out in BTS Guidance and EN 12110-1.*

### 6.11. CONNECTIVE TRUNKING

Connective trunking should be considered part of the pressure vessel to which it is attached. Trunking should have independent means of pressurisation with air or mixed gas (not just by equalisation), with relevant pressure controls, gas analysis and gauges. Trunking should be flushed with air or mixed gas as appropriate, before and after use, if not open to the atmosphere. Apart from in an emergency MGSWs should only enter trunking between docked vessels on the instructions of the shuttle supervisor or lock attendant. A specific hazard is the presence of mixed gas with low oxygen content which can remain in the trunking after use, particularly if the trunk remains closed or under slight pressure. When not required for regular operation the open end of trunking should be covered.

Emergency or rescue procedures should take into account access through trunking where relevant.

### 6.12. 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 multi-service vehicle. The risk assessment for the emergency procedures should include the scenario in which the shuttle transport vehicle breaks down. To overcome vehicle breakdown, there should be a standby locomotive or vehicle available in the tunnel to move the broken down vehicle or to recover the shuttle separately. Appropriate towing and/or mechanical handling equipment to facilitate the transfer of the shuttle between vehicles should also be available. 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 suppression system covering motor compartments, cabs, fuel tanks, switchgear, transmission systems, wheels and tyres as relevant. A “kill and quench” approach should be taken by the fire suppression system provided. The fire suppression system should be integrated into the vehicle during construction and not be an add-on.

Movement of the shuttle should be in accordance with EN 16191 Cl 4.2.8. It 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 comply with requirements 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. Emergency procedures should include recovery of the shuttle following operational failure of any mechanical lifting equipment.

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 Cl 4.10.8.

### 6.13. 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.

A procedure for rescuing a shuttle stranded off the ground due to crane failure should be in place and should have been rehearsed prior to manned TUP operations beginning.

Equipment for shuttle handling should be considered to be an essential service and have continuity of power supply (see 6.21).

### 6.14. 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 and has to be rescued. There should be the capability to provide extended life support to the shuttle in an emergency.

There should be a secure working area with harness anchorage points for the shuttle supervisor and life support technician accompanying the shuttle. All life safety critical control functions relating to the shuttle should be accessible from that working area.

Where life support is provided by an umbilical from the surface, a mechanical umbilical handling system should be provided to handle the services to the external service connection panel of the shuttle. 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.

### 6.15. TRANSFER FROM PERSONNEL 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. The risk assessment for the emergency procedures should include the scenario in which the handling system breaks down.

### 6.16. EMERGENCY POWER CONTINUITY

All necessary steps should be taken to ensure continuity of power to essential services and 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 surface 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.

For the habitat, a minimum of 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.

### 6.17. 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.

## 6.18. IDENTIFICATION AND MARKING

### 6.18.1. General requirements

Labelling, marking direction of operation, colour coding and marking the direction of flow can contribute to safety by facilitating the identification of functions and thus reducing the risk of human error.

### 6.18.2. Marking of valves, pipework etc

All valves which are components of permanently installed pipework for gas distribution or directly attached to pressure vessels should be labelled with their function and if manually operated, with their direction of operation. It should be clear to which valve the label refers. Text on labels should be sufficiently prominent to be capable of being read at a distance of 1 m from the valve.

All permanently installed pipework carrying gas should be marked at regular intervals with its function, contents and direction of flow. Rigid pipework should have colour coded markers to indicate its contents. In addition to colour coded markers of flexible pipework there should be a consistency in the colour of the outer sheath to reflect the 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 from other services.

### 6.18.3. Colour coding of gas cylinders and pipework

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”.

The normal convention is white for oxygen, brown for helium, and black for nitrogen with mixtures marked according to constituents. Constituent percentages should also be indicated.

## 6.19. PROVISION OF GAUGES

All gauges which are components of permanently installed pipework for gas distribution should be labelled with their function.

Requirements for control and indicating gauges are set out in EN 12110 (both parts). A control gauge should have a full scale reading such that it normally operates in the upper third of its scale. There should be a dedicated control gauge with isolating valve 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. Calibration should take account of the altitude of the site at which they are used.

## 6.20. HYPERBARIC OPERATIONS CONTROL PANEL

### 6.20.1. Requirements for hyperbaric control panel

There should be at or adjacent to each habitat, chamber, shuttle or personnel lock etc, a control panel from which all hyperbaric operations in that habitat, chamber, shuttle or personnel lock etc can be controlled. Each panel should be of good ergonomic design complying with EN 894 (all parts).

Control functions in HPCA work are safety-critical. EN 12110-2 sets out the control functionality required for personnel locks, shuttles and the working chamber including intermediate chamber if fitted. Similar levels of control functionality should be provided for habitats. During HPCA work, the panel, the chamber, personnel lock, associated working chamber etc 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 a multi-chamber habitat there should be a section of that panel devoted to each chamber of the habitat. In addition, all necessary gauges and control functions should be duplicated on a local panel immediately adjacent to each PVHO.

The habitat 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:

- Ensure that a 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 primary supply.
- Prevent the unintended cross-connection of air, gas or oxygen supplies.
- Ensure uncontrolled back flow through a rupture in a line is prevented.

#### 6.20.2. 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 atmosphere around the panel is irrespirable. The air supply should have a minimum duration of 24 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.

### 6.21. PRESSURE REGULATION

Requirements for pressure regulation of gas supplies are set out in EN 12110 (both parts). High pressure supplies should be regulated down to under 40 bar at a point close to the high pressure source. Two categories of valve are used on air locks – slow acting valves often in the form of multi-turn valves or linear motion valves and fast acting valves often in the form of quarter-turn or rotary valves. Slow acting valves controlling the supply of oxygen or mixed gas downstream of a control panel to umbilicals or manifolds are also required to have a flow regulating capability.

The pressure of air or mixed gas for compression purposes, downstream of a control panel will reflect the pressure in the chamber or compartment being supplied. However, the pressure of oxygen or mixed gas supplied to manifolds and umbilicals can be higher, reflecting the pressure required on the inlet side of the lung demand valve.

These requirements should be applied to surface habitats also.

### 6.22. 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.

### 6.23. TEMPERATURE AND HUMIDITY

#### 6.23.1. 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. Helium is much more thermally conductive than nitrogen therefore the target temperature of a chamber or compartment depends on the helium content of the pressurising medium. Relative humidity in the habitat should be kept at 50% +/- 25%. Ultimately, occupant comfort should be the controlling criterion.

#### 6.23.2. Temperature in TBM

Immediately after the TBM has stopped the temperature in the excavation chamber can be too high to allow safe entry without giving rise to excessive risk of heat stress.

*Note 1: A water spray cooling system in the excavation chamber can reduce waiting time.*

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

### 6.24. BREATHING MIXTURE SUPPLY

There should be a primary and secondary supply of breathing mixture to a control panel. In addition, there should be a separate emergency supply to the control panel which should feed a separate core of the umbilicals supplied from that panel. The minimum quantity of breathing mixture available in the emergency supply is set out in clause 6.30. The emergency supply should come from a different delivery of gas to site from that used for primary or secondary supply.

### 6.25. OXYGEN AND HELIUM COMPATIBILITY

There are well publicised procedures for ensuring the safety in the design, construction and operation of pipework systems containing oxygen. These are set out in EN 12110-1 and the BTS Guidance and should be strictly adhered to. EN 12110 (both parts) set requirements for pipework materials and for oxygen and helium compatibility of hoses, valves, gauges etc. Hoses to ISO 21969:2009 can be considered suitable for oxygen use up to 250 bar(g).

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. Corrugated metal hoses to EN 14585 or EN ISO 10380:2012 can be used.

### 6.26. OXYGEN CLEANLINESS GUIDANCE

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. The principles of oxygen cleanliness are set out in IEC 60877:1999 and IMCA D 031. EN 12110 (both parts) sets requirements for oxygen cleanliness of personnel locks.

### 6.27. MAXIMUM OXYGEN CONCENTRATION – FIRE SAFETY

The maximum volume concentration of oxygen in the chamber atmosphere should not exceed 23% for fire safety reasons. This normally arises during the latter stages of saturation decompression such as when the target $PO_2$ is 0.5 bar. 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.

### 6.28. Oxygen make-up

Metabolic oxygen make-up should be provided for each compartment of locks, shuttles and habitats. The flow should be controlled from the control panel and the discharge should be into a ventilation stream in a compartment to disperse it. Make-up oxygen should be discharged in predetermined quantities.

The supply should be from an externally mounted source normally located at the chamber. That source shall be separate to the oxygen source for decompression purposes.

### 6.29. Removal of oxides of carbon

Where carbon dioxide or carbon monoxide 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 for each gas to be removed. A single scrubber should be able to maintain the contamination level in the atmosphere below the maximum acceptable level. The chemical absorbent cartridges for each gas should be easily distinguishable by colour coding and not interchangeable in use.

The personnel locks may also be fitted with scrubbers to minimise the amount of gas required for flushing purposes.

### 6.30. MINIMUM GAS AND BREATHING MIXTURE QUANTITIES

#### 6.30.1. Gas quantities - non-saturation exposures

There should be a primary, secondary and emergency gas supply to the personnel lock control panel. 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 personnel lock 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 as well as allowing access for emergency medical personnel or 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 personnel lock once 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 as well as allowing access for emergency medical personnel or a rescue team.

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. The emergency supply should be from a separate delivery of gas to site.

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 personnel lock 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 receivers, or two separate banks of cylinders or receivers.

#### 6.30.2. Gas quantities - Saturation exposures

There should be a primary, secondary and emergency supply to the personnel lock control panel. Distribution of gas from the panel should be in accordance with the requirements of EN 121110-2. 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 personnel locks.

For the primary supply the quantity of each gas mixture required at the personnel lock and working chamber should be sufficient for the full working exposure for all MGSWs exposed. In addition, there should be sufficient gas to compress any personnel locks twice from 0 bar(g) to working pressure if not done on air, along with an allowance for leakage, wastage, flushing and contingencies as well as allowing access for emergency medical personnel or a rescue team A regenerative system may be used to reduce the quantity of gas required.

The secondary gas supply should consist of at least 33% of the primary gas supply for the working phase of the exposure with no allowance made for a regenerative system. 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 along with an allowance for leakage, wastage, flushing and contingencies as well as allowing access for emergency medical personnel or a rescue team.

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. The emergency supply should be from a separate delivery of gas to site.

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 personnel lock 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 receivers, or two separate banks of cylinders or receivers.

**6.30.3. 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. In addition, there should be sufficient breathing mixture to pressurise the shuttle once from 0 bar(g) to storage pressure. A regenerative system may be used to reduce gas quantities required.

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.

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

**6.30.4. Surface gas supply**

There should be a primary, secondary and emergency supply of the breathing mixture in use to each chamber of the habitat.

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 docked to that chamber from 0 bar(g) to storage pressure. Additional gas to allow for routine access by medical personnel to the excavation chamber should be included.

The primary gas supply should have sufficient capacity immediately available 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.

A regenerative system may be used. Where such a system is in use the quantity of make-up gas and chemicals for scrubbing contaminants immediately available should be sufficient to ensure the system can provide the same capability as with a supply from cylinders.

In addition , 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%. A regenerative system should not be used as the standby supply.

A number of different breathing mixture formulations can be required over the course of a saturation run.

The emergency supply to each chamber should contain the same quantity of gas as the secondary supply but be taken from a separate delivery of gas to site.

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. A regenerative system may be used as the primary supply only, provided its capability meets the above requirements.

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 or receivers.

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

### 6.31. SEPARATION OF OXYGEN SUPPLY FROM BREATHING MIXTURE SUPPLY

As a general safety measure for all chambers etc, oxygen and breathing mixture supply lines along with their respective control functionality and manifolds should be kept separate as set out in EN 12110 (both parts). Cross connection of supply and of inhalation/exhalation connections for masks should be prevented by design of the connections. 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.

### 6.32. BREATHING RATES ETC

When calculating gas supply volumes, a breathing rate at work of 60 l/min per person at chamber pressure 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 above chamber pressure remaining in them.

### 6.33. 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.

All gas including that used to form breathing mixtures, should be of medical or diving quality. Only pre-mixed breathing mixtures should be used except where regenerative systems are in use.

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

### 6.34. SAMPLING AND TESTING

The HPCA contractor should set up a gas ordering, sampling, testing and site handling procedure. It should set out responsibilities for all persons in the gas chain from ordering of supplies and receipt on site to return of empty cylinders to the supplier and be applicable on the surface and underground. It should include a full schedule of sampling, testing, recording requirements along with arrangements for quarantining non-compliant gas. The procedures should be in accordance with a recognised quality assurance procedure though not necessarily certified as compliant if short term.

All gas or breathing mixtures should be 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 identification, marking, handling and separate storage of each to prevent accidental misuse.

### 6.35. 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 storage facility should be located within a secure compound to which only authorised personnel have access. The compound should be drained and surfaced with access and parking for essential vehicles. When designing the facility, due account should be taken of the need to have sufficient space to allow delivery vehicles and a forklift truck to operate safety within the storage area. The secure compound should be lit at night and be under CCTV surveillance. 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.

There should be a water sprinkler system providing fire suppression covering the gas storage facility. Any vehicles used regularly for the handling of gas cylinders in the storage compound should meet the requirement of cl 24 of BS 6164:2019 and be fitted with an on-board fixed fire suppression system with “kill and quench” capability as required by BS 6164:2019 cl 13.3.3.

There should be a storage area for full cylinders or quads as well as a separate 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.

### 6.36. 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, personnel lock or habitat. The reclaim system should not present additional risk to or place any additional burden on the MGWs/MGSWs. Additional personnel can be required to operate the reclaim system.

Helium reclaim can be undertaken using a regenerative or re-circulatory system feeding directly back into the gas supply or via a reclaimed gas storage system for later re-use. When a regenerative or re-circulatory system is utilised, exhaled gas should be scrubbed, analysed, have the oxygen content and humidity adjusted and the final mixture reanalysed before being injected into the breathing mixture circuit upstream of the personnel lock control panel on the TBM. Analysis should include $O_2$, CO, $CO_2$, He/$N_2$ content with the results available at the control panel.

Where helium reclaim is being practised, the gas attendant should manage the surface component of the helium reclaim cycle while the lock attendants should manage the underground component of the helium reclaim cycle.

### 6.37. 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 rather than by the HPCA contractor. 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 into storage at the HPCA worksite and the instrumentation used should not be the same as for testing cylinders prior to removal from storage before being put into use on site.

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.

### 6.38. ON-LINE GAS ANALYSIS

Requirements for gas analysis capability are set out in EN 12110 – both parts. Gas analysis procedures for the supply to surface habitats should be similar to that for personnel locks. Continuous analysis of all supply lines to a control panel is not necessary and intermittent checks should suffice as long as the immediate source of the gas supplying the panel remains unchanged. Hence one instrument can service more than one gas supply to the panel. Downstream of the panel continuous monitoring of the gas to umbilicals should be undertaken. There should always be separate instruments used for monitoring upstream and downstream of the control panel.

### 6.39. TOLERANCES ON MIXTURE COMPOSITION

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 demonstrate that the oxygen content of heliox or trimix conforms to the formulation intended by the HPCA contractor for the work in progress and is within the tolerances set out in EN 12021. An audible and visual alarm should be triggered when the oxygen concentration deviates from the tolerance levels given.

When trimix is being used there should be a similar capability for on-line analysis of helium. Analysis should demonstrate the helium content of trimix conforms to the formulation intended by the HPCA contractor for the work in progress and is within the tolerances set out in EN 12021.

Monitoring of the partial pressure of nitrogen should be considered to ensure it is kept within the limits set out in clause 8.6.

EN 12110-2 also requires the capability to monitor for carbon dioxide and carbon monoxide in each personnel lock or shuttle compartment with the information displayed at the relevant control panel. This requirement holds for living and sleeping compartments of surface habitats also.

### 6.40. 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".

### 6.41. PROVISION OF GAS IN THE TUNNEL

The Hyperbaric Supervisor or the person in the MGSW Deployment role should confirm that the volume of breathing mixture required for the planned HPCA operation 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 or group of cylinders of breathing mixture corresponds with the formulation intended by the HPCA contractor. He should do the same for any oxygen required for decompression purposes. If regenerative supply technology is being used the correct functioning of the supply equipment should be confirmed.

### 6.42. 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.

**6.43. 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 when cleaning masks.

**6.44. 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.

**6.45. CHAMBER HYGIENE**

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

**6.46. CERTIFICATION AND TESTING**

The habitat, shuttles and personnel locks should undergo to a comprehensive programme of inspection, certification and testing before being put into service and at regular intervals thereafter depending on the duration of the HPCA work.

**6.46.1. Factory acceptance testing**

The PVHOs which make up the habitat along with the shuttles and personnel locks should be subject to factory acceptance testing. PVHOs should be tested individually and then as a complete assembly. 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 but cold test of the firefighting equipment, washing or sanitary equipment, gas analysis, environmental control equipment etc in or on the PVHOs. The default standard for design, fabrication and testing should be EN 13445 (Parts 1- 5). 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.

**6.46.2. 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 including being in test and calibration.

Commissioning should conclude with a formal functional test of all systems in or on the habitat, shuttles and personnel locks or systems which are provided for life support. 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 use of 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.

**6.46.3. Oxygen cleanliness certification**

A certificate confirming the oxygen cleanliness of all pipes and vessels etc containing gas with over 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.

**6.46.4. TUP trials**

A series of formal trials of the TUP procedure should be undertaken starting with an unmanned and unpressurised trial and progressing through an unmanned but pressurised trial, 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.

**6.47. Surface habitats**

The habitat should normally be located on the surface in a purpose built structure within a secure compound with access restricted to personnel connected with the HPCA work. The compound should be drained and surfaced with access and parking for essential vehicles. The structure should protect the habitat from adverse weather and temperature fluctuations. Internally, the structure should be lit and heated/cooled as necessary. The structure floor should be constructed from an easy-clean solid material. The structure should be fabricated from low flammability materials. The structure housing the habitat should have a fire suppression system such as a high pressure water mist or sprinkler system protecting all internal spaces and any enclosed roof space. The secure compound should be lit at night and be under CCTV surveillance.

There should be access to the compound from the main site access and this should be by an all-weather roadway with signage as necessary. The contractor should assess the need for access control, bearing in mind the need to ensure rapid access for emergency vehicles.

The compound should be protected against flooding.

As an alternative, one or more ISO containers can be used but only if adequate space all around the chamber can be provided.

### 6.47.1. Surface habitat – general requirements

At present there are no European standards covering habitats for use in diving or in conjunction with HPCA work in tunnelling. Nevertheless, many of the requirements of EN 12110 will be relevant to surface habitats in tunnelling. One diving industry standard to which reference can be made, is Norwegian Standard NORSOK U100 "Manned Underwater Operations" (currently in edition 5, corrected version 2016-05-09). Until a relevant tunnelling industry standard is published, the guidance below should be followed.

The engineering design principles, fabrication, construction, fitting out and equipping of the habitat and emergency chamber should follow the requirements for personnel locks intended for use with mixed gas EN 12110-2.

The habitat should be located on the surface close to the access to the tunnel. It should comprise one or more PVHOs housed in a weatherproof structure(s) which together act as a hyperbaric living facility. In addition, the habitat requires to be supported by facilities for life support and the provision of hotel and medical services for those in the habitat. The habitat and its ancillary services should be set within a secure compound.

The habitat should provide living accommodation, sleeping accommodation and hyperbaric toilet/washing/showering facilities for those in saturation. The number of chambers making up the habitat along with their size, layout and number of compartments will depend on the complexity of the saturation operations being undertaken and thus the number of occupants to be accommodated.

The habitat should preferably have a headroom of 2.2 m above the deckplate or chamber invert however the minimum headroom should be 2 m. If no deckplates are used, the chamber invert should be covered in a non-slip material bonded to the shell.

Each chamber should have a capacity of at least 4 persons. The habitat should provide at last 4 $m^3$ of useable volume per person. The volume should be divided sensibly between the living and sleeping accommodation which should be separated by a non-flammable ventilated privacy partition. Where seats are arranged along both sides of a compartment, they should be staggered to allow greater leg room for occupants.

Living quarters should contain seats and a folding table. Sleeping quarters should contain bunks at least 2.0 m x 0.7 m. It should be possible to accommodate horizontally, a person on a stretcher of 2 m minimum length within the living or sleeping quarters.

There should be a supply lock for transferring food, medical supplies and consumables etc into each compartment and the wet pod. It should be big enough to allow passage of consumables for the $CO/CO_2$ scrubbers. It should conform to the requirements of EN 12110 – 2.

The habitat compartments should be designed for easy cleaning. Surfaces should be coated in an appropriate material which is fire retardant and a low emitter of VOCs. The colour(s) should be chosen to optimise illumination but with user acceptance in mind.

At least one of the compartments of the habitat should form an entry compartment as in EN 12110-1 unless entry can always be achieved though the wet pod. There should be a means of docking a TUP shuttle to at least one compartment.

When saturation exposures are being undertaken concurrently on more than one TBM, separate chambers should be provided for the MGSWs on each TBM. Multiple chambers may be interconnected via a wet pod.

### 6.47.2. Surface habitat - wet pod

The main hyperbaric toilet/washing/showering facilities should be in a separate chamber or compartment (wet pod) to the living/sleeping accommodation. The wet pod should also be capable of providing emergency life support to the occupants of any living/sleeping chamber connected to it until they can be evacuated under pressure to the emergency chamber. It should be possible to isolate the wet pod by a pressure resisting door from any other chamber connected to it. The wet pod should have a separate supply lock for transferring food, consumables etc.

The wet pod should provide the same headroom as a living chamber. Previous experience has shown that a minimum useable volume of around 6 $m^3$ is sufficient. Docking flanges should conform with EN 12110 - 2.

There should be the capability to dock at least one TUP shuttle to the wet pod. All docking flanges should conform to the requirements of EN 12110 – 2.

### 6.47.3. Surface habitat - control panel

There should be a single control panel from which the pressure, temperature, humidity, of all living/sleeping compartment(s) and wet pod(s) (if fitted) can be monitored and controlled. The supply of air, breathing mixture or oxygen to any chamber or manifold should be monitored and controlled from there also. The functionality of the control panel should be at least as extensive as set out in EN 12110-2. One set of controls for the fire suppression system should be readily accessible at the panel.

It should be possible in an emergency to control and monitor each chamber from controls and instrumentation on the chamber.

There should be two compressed air outlets at each panel for masks for the operators for use in an emergency.

There should be voice communications with compartment occupants along with the capability to observe living compartments and medical treatment areas from the panel. There should also be telephone communication capability with the national network.

The chambers should be designed so that any valves or gauges on them can be operated or viewed from floor level - see “zones within field of vision and actuation areas – standing” in EN 894-4. Where valves or gauges cannot be operated or viewed from floor level, raised platforms should be provided. Raised platforms should be designed to prevent falls from them.

**6.47.4. Surface habitat - environment control**

The heat exchange medium should be water based. There should be at least two environmental control units supplying the hot and cold water. Each unit should be capable of supplying the entire habitat on its own.

Each compartment should have at least two heating/cooling devices. It should be possible to maintain the environment in any compartment at a temperature which is considered comfortable by the occupants. Typically this can be in the range 22 to 33 $^{0}$C and between 40% and 60% RH or as agreed between the MGSWs and the CMA. The environmental control system should be capable of controlling the temperature in the habitat between 15 $^{0}$C and 45 $^{0}$C and the relative humidity at 50% +/- 25%.

Noise in a chamber should be kept to a minimum with the noise in the sleeping quarters not exceeding 60 dB(A) with the partition door shut.

**6.47.5. Surface habitat - water supply**

Water supplied to the habitat compound should be sourced directly from the public potable mains water supply. As an additional precaution against bacteriological infection, water should be passed through a UV steriliser before being used.

**6.47.6. Surface habitat - facilities.**

The structure should provide office and welfare accommodation for the life support and medical teams supporting the habitat along with associated washing/showering/toilet facilities. In addition, the environmental control equipment, potable water filtration plant and waste disposal facilities for the habitat should be located in the compound. Food preparation and laundry facilities for the habitat will be required and can be co-located in the compound. The structure should be sufficiently large to allow free movement around the habitat and access including access for operation, shuttle movement, maintenance and casualty removal. The structure should be designed to be easy to keep clean.

**6.47.7. Surface habitat - gas distribution panel**

A gas distribution panel should be securely mounted in the habitat building. The panel should be supplied with gas from the primary, secondary and emergency gas supplies in the gas storage facility. From the gas distribution panel, gas should be supplied to the control panel(s) for supply to each compartment of the habitat. Gas leaving the distribution panel should be regulated to a maximum pressure of 40 bar(g). Any risk of common mode failure in the construction or operation of the distribution panel should be assessed and mitigated.

It should be possible to shut off each incoming gas supply line at the panel. Separately it should be possible to shut off an individual gas supply to an individual chamber, as well as each outgoing supply line to a compartment.

**6.47.8. Surface habitat – power supply**

There should be a power supply and back-up power supply to the habitat compound which should feed all electrically powered equipment in the compound. Additionally, safety critical equipment associated with the habitat or emergency chamber should have a dedicated uninterruptible power supply capable of operating the equipment for at least 24 hours in the event of total power loss.

**6.47.9. Surface habitat - protection against fire**

The requirements of EN 12110-1 in respect of fire suppression in chambers should be complied with in respect of the habitat, wet pod. Additionally, an appropriately sized, hyperbaric fire extinguisher should be provided in each compartment.

The project fire risk assessment should extend to the habitat building along with the gas storage area.

**6.47.10. Surface habitat - chamber atmosphere monitoring**

The atmosphere in each compartment should be monitored as required by EN 12110-2 for lock compartments. A respirable atmosphere should be maintained through removing contaminants by chemical scrubbing with recirculation and oxygen make up as required. The scrubbing system should also provide ventilation circulation flow in each compartment.

Levels of atmospheric contamination in a compartment should not exceed those applicable in saturation diving. Guidance can be found in the current edition of Norwegian Standard U 100 “Manned underwater operations” or HSE publication EH75/2 (https://www.hse.gov.uk/pubns/books/eh75-2.htm).

Where scrubbers are fitted there should be at least two scrubber units per gas scrubbed, in any compartment. Each scrubber should be capable of servicing the compartment on its own. At least one spare scrubber cartridge should be kept in a compartment for each type of scrubber. Scrubbers for CO and $CO_2$ may be a combined unit or separate units for each gas.

A scrubbing system to remove VOCs should be available in each chamber. An odour scrubbing system should also be provided.

**6.47.11. Habitat - communications**

There should be voice communications between the control panel and each compartment. In addition, there should be the capability for CCTV monitoring of each compartment however privacy in sleeping areas etc should be respected. There should be Wi-Fi connectivity via a router mounted outside the habitat. Tablets, phones or any other rechargeable device should not be charged inside the habitat.

**6.47.12. Maintenance and certification**

The contractor should set up and maintain a planned preventative inspection, certification and maintenance system (PPICM) for all hyperbaric equipment on the contract. Extensive relevant guidance on the frequency of inspection and the competence required to undertake such inspection of hyperbaric plant and equipment is set out in the IMCA publication D 018 "Code of Practice for The Initial and Periodic Examination, Testing and Certification of Diving Plant and Equipment Rev. 1 – June 2014" and IMCA publication D 053 "DESIGN for the Hyperbaric Reception Facility (HRF) forming part of a Hyperbaric Evacuation System (HESS)" Rev. 0.1 – October 2018.

All maintenance work carried out on the habitat and emergency chamber should be recorded in the system.

All PVHOs making up the habitat should be tested in accordance with the requirements of EN 13445 and copies of the test certificates lodged in the PPICM system.

All pipework (and hoses) carrying gas or fluids to/from the habitat or emergency chamber should be functionally tested after assembly to 1.5 times their normal working pressure and be shown to be leak tight. Test certificates should be lodged in the PPICM system.

All pipework carrying oxygen or a gas mixture with more than 23% oxygen by volume should be oxygen cleaned to IEC 60877:1999. Certificates of cleanliness should be lodged in the PPICM system.

Calibration certificates for all gauges and gas analysis equipment should be lodged in the PPICM system.

A commissioning/compliance audit of the hyperbaric system to confirm that all necessary pipework, valves, gauges, controls/control functions, ancillary systems etc have been installed and are known to be tested and functional should be undertaken on site before the habitat is occupied for the first time and the results lodged in the PPICM system.

A functional test of all habitat systems at maximum pressure/maximum flow should be undertaken on site before the habitat is occupied for the first time. Test certificates should be lodged in the PPICM system.

**6.47.13. Surface habitat - emergency chamber**

The compressed air contractor should make provision for the transfer under pressure of all those in saturation to an alternative fully functioning emergency pressurised chamber in the event that occupation of the habitat becomes untenable. The chamber should be located so that fire, flood or other emergency situation affecting the habitat should not impinge upon the access to and operation of the emergency chamber.

The chamber should be a standalone facility meeting the requirements of clause 6.47. The capability to provide the full range of life, welfare and medical support to those in the emergency chamber should not be compromised by the event which rendered occupation of the main habitat untenable. The emergency chamber should be treated in all respects as if it were a substitute habitat.

**6.47.14. Provision of emergency medical care for persons in saturation**

It should be possible to provide emergency medical care for persons in saturation to a standard equivalent to that in DMAC 28 as recommended in this guideline.

There should be a chamber compartment meeting the requirements of section 6 of DMAC 28. This may either be in the emergency chamber or be a compartment of the living habitat however selecting the latter option can compromise the operational availability of the habitat.

The advice of the contract medical adviser on this matter should be followed.

### 7.1. DELIVERY OF OCCUPATIONAL HEALTH CARE

The CMA should be the professional leader for delivery of all aspects of the medical and occupational health care for those undertaking 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 should include the appointment of one or more suitably qualified local practitioner(s) (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 examination to establish fitness for HPCA work coupled with periodic health checks throughout its duration, to ensure continuing fitness for such work. Where not already set out in national requirements, the CMA should advise on the form, content and frequency, as relevant, of the examination and health check. The CMA should undertake the examinations and periodic checks unless national requirements dictate otherwise. Reference should be made to the BTS Guidance for a typical assessment regime. 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. Clause 10 of the BTS Guidance provides extensive guidance on health assessment and medical surveillance which is relevant at all pressures.

For many years it was standard practice to include long bone x-rays to screen for dysbaric osteonecrosis as part of the medical examination protocol. Current thinking is that the risk from x-ray *per se* is greater than the risk from osteonecrosis. The CMA should consider if screening for necrosis is necessary based on a person's previous exposure history to compressed air and if screening is considered necessary consider the use of MRI as an alternative to x-ray (see cl 10.10 et seq of the BTS Guidance).

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 full face masks can further increase the risk, as can wearing protective clothing such as when tunnelling through contaminated ground. The risk arises from the inability of the body to cool due to the reduction in sweat evaporation, as a consequence of the pressurised atmosphere.

As a result of the work of excavation, the temperature in the excavation chamber can exceed that to allow safe entry without giving rise to excessive risk of heat stress. The tolerable maximum temperature for entry to the excavation chamber is 36 °C allowing for humidity and worker acclimatisation. In some jurisdictions the maximum permissible temperature is 28 °C. The CMA should advise on maximum permissible temperature. The excavation chamber temperature should be displayed on the hyperbaric control panel.

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. No thermal indices specifically for hyperbaric work in tunnelling currently exist.

Although data exist correlating dry bulb temperature with wet bulb temperature for persons wearing breathing apparatus to give recommended exposure periods in hot and humid mining environments these are for normal atmospheric pressure (0 bar(g)). They should be applied with caution as wet bulb temperature is pressure sensitive.

Entry into the excavation chamber should not be undertaken until its temperature has dropped to below 36 °C. Even then, high humidity in the excavation 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 excavation chamber.

The effects of breathing gas mixtures containing helium which has a high thermal conductivity 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 should 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, intermediate chamber, personnel locks, TUP facilities along with the habitat and the emergency chamber 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 what is deemed to be medical treatment, even in an emergency.

#### 7.5.2. First aid – non-saturation exposures

All persons undergoing non-sat exposures should have an appropriate current first-aid qualification and an oxygen administration qualification as well as an understanding of the physiological matters relevant to working under pressure. At least one person present at the control panel other than those required to operate the lock, should be qualified as a DMT or similar. This person should be in addition to the hyperbaric supervisor because of the need for the supervisor to be in direct control of the operation at all times.

*Note: the guidance for offshore commercial diving projects on first aid and oxygen administration training given by HSE at https://www.hse.gov.uk/diving/aid.htm is considered appropriate for non-sat exposures.*

#### 7.5.3. First aid – saturation exposures

All workers making saturation interventions should have an appropriate current first-aid qualification, an oxygen administration certificate 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 those fulfilling the roles in cl 4.7 above. 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.

*Note: the guidance for offshore commercial diving projects on first aid and oxygen administration training given by HSE at https://www.hse.gov.uk/diving/aid.htm is considered appropriate for saturation exposures.*

### 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 infections of the ear, nose or throat which are normally a bar to entry into compressed air should undertake saturation exposures. Skin infections and transmissible gastro-intestinal infections are an additional bar to saturation work.

Consideration should be given to the need for those in saturation to have covid vaccinations at least until the level of infection in the community is considered sufficiently low not to require them.

### 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 little or 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 procedures if considered equally effective can be used. 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 in accordance with local guidelines or if none exist in accordance with the criteria in paragraph 11.8 of the BTS Guidance. 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-saturation exposures, monitoring should be undertaken after each exposure, until the effectiveness of the decompression regime has been established.

For saturation exposures, the effectiveness of the final decompression following the end of each period in saturation should be established. The need for more frequent monitoring such as during the final decompression, should be identified by the CMA as necessary. In addition, the effectiveness of decompression associated with excursions should be established using the criterion "no detectable bubbles" or other criteria set by the CMA.

The monitoring procedure should ensure that each person exposed is subject to monitoring during their exposure history on a contract. The CMA should advise on the required frequency.

#### 7.7.3. Assessment of DCI risk based on 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. As well as monitoring results for individuals, the CMA should regularly review all results to assess the ongoing effectiveness of the decompression procedures on an overall contract basis. In the absence of clinical symptoms, high bubble scores are not *per se* a reason to give that person a prophylactic recompression treatment or to exclude them from further exposure.

#### 7.7.4. Other monitoring

Techniques other than Doppler monitoring which become equally accepted by the hyperbaric medical community during the lifetime of this document may be considered as a substitute monitoring technique.

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 saturation exposures, regular monitoring of MGSWs for heat stress and weight loss through dehydration, can 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.

### 7.8. MEDICAL CAPABILITY

#### 7.8.1. Medical facilities

Guidance on the provision of medical facilities for saturation work is given in the current revision of DMAC 28 (currently Rev 2) "The Provision of Emergency Medical Care for Divers in Saturation".

DMCA 28 notes that the ability to access medical advice by means such as a video link, from a remotely located specialist with experience of saturation work may be more useful than deploying a local medical specialist without experience of work in saturation. DMAC 28 also notes the need for such specialist expertise occurs very rarely.

#### 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. INCIDENTS ASSOCIATED WITH COMPRESSION AND DECOMPRESSION

#### 7.9.1. Compression incidents

Medical supervision should be sufficiently good, and pressure change rates should be sufficiently low that barotrauma does not occur during compression in either non-saturation or saturation exposures.

Joint pain during compression known as "Compression arthralgia" and which can be severe in some cases, has been recorded during compression in diving at pressures around 6 bar(g) and over. It is attributed to rapid compression and could conceivably occur during poorly managed non-saturation exposures.

For the slow compression rates associated with saturation diving, onset if at all, is more likely around 9 bar(g) but as with most hyperbaric-related ill-health there is significant human variation in onset and symptoms. There is no difference between compression in a surface habitat for tunnelling or diving hence the occurrence of compression arthralgia should be similar.

Symptoms are relieved by reduction in pressure which differentiates it from pain only DCS. It has been reported that breathing trimix rather than heliox reduces susceptibility to compression arthralgia but the supporting evidence is limited.

Due to lack of exposure data from HPCA tunnelling activity there is no tunnelling-specific history of its occurrence.

High pressure nervous syndrome (HPNS) is a neurological and physiological disorder manifesting at pressures of around 15 bar(g) and over when breathing heliox. Its severity can be correlated to higher compression rates and inadequate stabilisation stops. Breathing trimix instead of heliox appears to reduce its severity.

#### 7.9.2. 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 non-routine decompression such as required after failure of the oxygen supply during routine oxygen assisted decompression.

The Contract Medical Advisor should advise on the treatment 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 the CMA's agreement to treat. The medical lock attendant should proceed with treatment whilst trying to contact the CMA.

### 7.9.3. Decompression sickness and saturation exposures

It is important to remember that DCS in saturation diving is rare. In theory there are three circumstances when DCS from decompression in saturation exposures is foreseeable – as the result of decompression at the start of an excursion to pressure lower than storage pressure; as a result of decompression at the end of an excursion to pressure greater than storage pressure and during or following the final decompression to atmospheric pressure. However, the planning of all excursions and decompressions during or following them, should ensure the pressure differential between storage pressure and excursion pressure along with the rate of change of pressure is sufficiently low that the formation of bubbles detectable by Doppler is avoided.

The CMA should prepare procedures for dealing with DCS arising from excursions. In the absence of project specific procedures, a person in saturation reporting DCS 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 as part of a heliox mix 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 separate the remaining chamber occupants to avoid unnecessary exposure risks to them 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 DCS 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 DCS incident.

Any DCS in saturation that does not resolve rapidly with enhanced $O_2$ treatment, will add problems of deployment and overall saturation duration.

## 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. BREATHING AIR AT HIGHER PRESSURE

There are three gases commonly accepted as important when considering high pressure exposures – oxygen, helium and nitrogen. However, it is also important to consider that a fourth gas – carbon dioxide – is the end product of human metabolism and is produced in physiologically significant concentrations in the lungs.

As pressure increases a number of increasingly severe adverse physiological reactions occur in persons breathing air at elevated pressure. Depending on the partial pressure and duration of exposure, oxygen can induce either an acute toxic reaction (central nervous system (CNS) toxicity) or a chronic toxic reaction (pulmonary toxicity). There are three significant adverse reactions from breathing nitrogen at high partial pressures – narcosis, increased work of breathing and the build-up of nitrogen in the tissues which makes effective decompression increasingly challenging. The increased work of breathing leads both to increased production of carbon dioxide and to carbon dioxide retention as well as to fatigue. In turn carbon dioxide retention can be linked to a heightened narcotic effect from nitrogen exposure, increased susceptibility to acute oxygen toxicity and to an increased risk of DCS which in turn has been linked to dysbaric osteonecrosis.

Apart from decompression, the effectiveness of which is largely a function of the profile chosen, the other adverse reactions are a direct consequence of exposure and can only be overcome by limiting or reducing exposure. Consequently in this edition of the guidance, in addition to limits on partial pressure and exposure period, limits on the density of gas breathed are introduced, the effect of which is to require an increasing proportion of helium in the gas mix as a low density diluent as pressure increases, thus limiting narcotic effect, carbon dioxide retention and work of breathing.

There is a relatively common misconception in the industry that the decision to go to mixed gas breathing is to counter decompression problems. However, this is not the case and countering nitrogen narcosis, carbon dioxide retention along with limiting the work of breathing are the more important and often determining factors in adopting mixed gas breathing in HPCA work.

Whilst decompression tables for air exposures between 3.5 and 6 bar(g) exist and are used apparently successfully in that they do not result in excessive DCI, such practice ignores the other harmful effects highlighted above and it is strongly recommended such practice should not be used.

### 8.2. GAS PURITY STANDARDS ETC.

Guidance on the purity of individual gases and tolerances on gas mixtures as supplied, is given in EN 12021 which also gives guidance on carbon dioxide, carbon monoxide and moisture content of breathing mixtures. Guidance on testing is also contained in EN 12021.

Guidance on recommended limits for nitrogen contamination of heliox is given in NORSOK U100.

Guidance on contaminant levels in compartments of personnel locks, TUP shuttle and habitats is given in clause 8.3 below.

### 8.3. GAS PROPERTIES AND EXPOSURE LIMITS

Much of the research on exposure limits has been done in the context of diving. However, there are known physiological differences between diving and tunnelling but because of the lack of equivalent research in tunnelling the impact of these differences on exposure limits if any, is still being established. Consequently, there can be little option but to use diving limits for tunnelling applications. Limits of exposure vary depending on whether non-sat or sat exposures are being undertaken.

The properties of gases and exposure limits should be taken into account when designing breathing mixtures. The advice of the Contract Medical Adviser and any hyperbaric advisers should also be followed when selecting breathing mixtures and exposure limits.

Where limits for specific contaminants are not given, the guidance in HSE publication EH75/2 should be followed. For non-sat exposures the long term 8-hour limit should be adopted and reduced proportionally for exposures over 8 hours in duration. For sat exposures the limit to be adopted should be not more than 20% of the 8-hour limit. Limits should be taken as surface equivalent values.

### 8.4. OXYGEN

#### 8.4.1. Minimisation of hyperbaric oxygen exposure

Hyperbaric oxygen dose in terms of partial pressure and duration should be kept as low as possible consistent with good hyperbaric practice.

#### 8.4.2. Symptoms of oxygen toxicity

Oxygen is toxic to both the central nervous system (CNS) and the pulmonary system. A person's response to high $PO_2$ is neither predictable nor consistent. There is considerable inter and intra-individual variation in susceptibility to CNS toxicity. This is in contrast to the symptoms of nitrogen narcosis which progress in severity as PN2 increases. As there are no reliable tests for susceptibility to CNS oxygen toxicity, testing for it is not recommended as part of fitness assessments. Susceptibility to pulmonary oxygen toxicity is also subject to some inter and intra-individual variation.

Symptoms of CNS toxicity are usually acute in onset, and include convulsions, 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 such as by switching to air breathing. Neurological symptoms have not been reported where the $PO_2$ is 1.4 bar or less.

Pulmonary symptoms are more dose-related and are 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. Prolonged and repeated high doses may lead to permanent lung damage. A more detailed description of symptoms and the nature of oxygen damage can be found in most standard hyperbaric medical texts such as “Bennett and Elliott’s Physiology and Medicine of Diving”, 5th edition. Alf O Brubakk MD and Tom S Neuman MD, editors. London: Elsevier Science. 2003. (ISBN 9780702025716).

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

**8.4.3. 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 normally provide the user with oxygen at a minimum partial pressure of 0.2 bar (see cl 8.14 for exceptions).

To minimise the risk of CNS toxicity, an upper limit on $PO_2$ of 1.4 bar is adhered to in diving as nausea or convulsions underwater are frequently fatal. Although research has shown that the threshold for onset of CNS toxicity when immersed in a gaseous environment as in HPCA work, is higher than if immersed in water, the research was diving orientated but a numerical limit for tunnelling or reasons for the difference have not been definitively established. High work-rates are known to increase susceptibility to CNS toxicity. Accordingly in the absence of information to the contrary, it is recommended that the 1.4 bar limit on $PO_2$ is observed in tunnelling.

There is also a time dependency aspect to the onset of CNS toxicity. The higher the $PO_2$ the shorter the exposure period should be. The National Oceanographic and Atmospheric Administration produces recommendations on partial pressure and exposure period. Oxygen exposure during decompression should also be taken into account. For exposures of more than two hours duration, consideration should be given to lowering the limit on $PO_2$ to 1.2 bar.

The increased threshold before onset of CNS toxicity in a gaseous environment along with the controlled environment of a recompression chamber with a tender present, are the reasons that DCI treatments at up to 2.8 bar $PO_2$ can be carried out.

For saturation exposures, sources of diving guidance give a range of $PO_2$ in storage between 0.2 and 0.45 bar. For tunnelling exposures, it is recommended that $PO_2$ in storage is kept between 0.35 and 0.4 bar. This is to reduce the risk of hypoxic conditions arising in the event of a sudden reduction in pressure. During interventions and excursions a $PO_2$ of around 0.45 bar is recommended but with a maximum $PO_2$ of not more than 0.8 bar. This mitigates against pressure loss and hypoxic risk and allows some flexibility to increase exposure pressure during an excursion without having to change gas mix. Due care should be taken to maintain the cumulative dose within the limits given. During decompression from saturation, a $PO_2$ of 0.5 bar is recommended (see also cl 8.4.4).

Pulmonary toxicity is a chronic condition which arises from excessive long-term exposure to hyperbaric oxygen and is cumulative. The currently preferred measure of such exposure is in oxygen tolerance units (OTUs). However, it should be remembered that historically the limits reflected concern over pulmonary toxicity with measurement being in “units of pulmonary toxicity dose” (UPTD). The term “oxygen toxicity dose” (OTD)) is also used in the literature. By definition, exposure to a $PO_2$ of 0.5 bar and below is not considered to induce pulmonary toxicity. Above 0.5 bar $PO_2$, OTUs are accumulated on a non-linear basis. The rate per minute of generating OTUs is given by the formula $(0.5/(PO_2 - 0.5))^{-0.833}$ or tables of OTU rates can be found in guidance such as the US Navy Diving Manual.

Air breaks built into oxygen decompression schedules help to reverse the effects of oxygen exposure.

In order to allow for the cumulative effects of multi-day repetitive exposures with some recovery between exposures each day, a recommended maximum limit for routine exposure of 420 OTUs daily and 2100 OTUs per week based on a 5/2 work/rest cycle (based on HSE research report –R126 - https://www.hse.gov.uk/research/rrhtm/rr126.htm ) should be adhered to.

It should be noted that additional oxygen exposure will be incurred if therapeutic recompression becomes necessary. Most therapeutic recompressions use a $PO_2$ of up to 2.8 bar under appropriately controlled conditions for treatment of DCI in accordance with recognised treatment tables – (a standard US Navy T6 generates 648 OTUs). 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. Treatments should be followed by a period of abstinence from increased oxygen exposure.

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

Currently, research is underway on developing an alternative methodology for evaluating the severity of pulmonary oxygen toxicity based on an index K expressed either as reduced lung function or the incidence of pulmonary toxicity in a group of persons exposed. At present this index is not in routine use in diving or tunnelling.

Oxygen volume concentration in any habitat, chamber, shuttle or personnel lock and its effect on fire safety is covered in cl 8.4.4.

**8.4.4. Oxygen and fire safety**

Measures to mitigate the risks associated with handling oxygen are set out in EN 12110. All mixtures with an oxygen content greater than 23% oxygen by volume should be treated as pure oxygen. This limit should be adhered to in the compartments of habitats during saturation decompression following procedures which require an elevated $PO_2$ of up to 0.5 bar. The 23% by volume limit takes precedence over the partial pressure requirement for decompression from around 1.2 bar(g) to normal atmospheric pressure.

### 8.5. HELIUM

Helium is a light and inert gas with no narcotic potential. It is relatively rare and hence expensive. Helium is less soluble in fat than nitrogen and diffuses into and out of the tissues more rapidly. The more rapid diffusion into the tissues results in a greater degree of tissue saturation being achieved compared with nitrogen under the same exposure conditions. For non-saturation exposures, longer decompression times are required for breathing mixtures containing helium as a consequence of the more rapid diffusion out of the tissues leading to increased bubbling.

Because of its low density adding helium to the breathing gas reduces the work of breathing (see Cl 8.6.2). This is especially important for compressed air work at high work-rates.

Helium has high thermal conductivity which makes temperature control of the living and working environment more complex in saturation exposures.

Voice distortion can be expected from helium based mixtures but can be countered by the use of signal processing equipment.

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.

### 8.6. NITROGEN

Exposure to high partial pressures of nitrogen results in narcosis, increased work of breathing and more challenging decompression requirements.

#### 8.6.1. Nitrogen narcosis

Nitrogen is a narcotic gas with signs of narcotic response being detectable from air breathing at pressures of 3 bar(g) upwards. Unconsciousness and death occur above ~9 bar(g). The narcotic response is more predictable and graduated than the oxygen toxicity response. Whilst some adaptation to narcosis is possible allowing simple routine tasks to be undertaken apparently competently, it is the underlying impairment and response to the unpredictable, such as emergency situations, where narcosis will impair performance and threaten safety. The nature of impairment has been likened to the narcotic response to alcohol consumption. Drug and alcohol testing on-site in construction, with zero or near-zero tolerance, is now routinely undertaken in many countries as part of human error prevention hence the deliberate exposure of workers to nitrogen narcosis in a high risk environment such as a TBM excavation chamber, cannot be justified. Accordingly, it is recommended that the partial pressure of nitrogen for non-sat exposures should be limited to 3.6 bar (i.e. equivalent to air at 3.5 bar(g)). Although the "Martini Law" features in the literature, from the limited comparative research published, the $PN_2$ limit recommended here equates to a blood/alcohol level similar to that considered sufficient to render someone legally unfit to drive.

Although exposure to compressed air at up to 5 bar(g) is permitted in tunnelling in some jurisdictions and in diving, being legally compliant does not necessarily imply being safe. The narcotic effect of nitrogen which results in increased likelihood of human error and hence increased risk to persons who are not obviously physically impaired, should not be underestimated. Workers suffering from the equivalent level of narcosis due to the effects of alcohol or drugs would not be permitted to enter HPCA.

Indicative narcotic effects of nitrogen exposure whilst breathing a compressed air atmosphere are summarised in Table 1. High work-rates can exacerbate the narcotic effects.

| 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.<br>• Reasoning and immediate memory affected more than coordination of limbs.<br>• Calculation errors and wrong choices.<br>• Idea fixation.<br>• Over-confidence and sense of well-being. Euphoria more pronounced to the point of laughter on loss of self-control.<br>• Noticeably talkative. |
| **5 – 7 bar** | • Sleepiness, impaired judgment, confusion, hallucination, dizziness.<br>• Severe delay in response to signals, instructions and other stimuli.<br>• Pronounced euphoria including uncontrolled laughter or hysteria.<br>• Terror in some. |
| **7 – 9 bar** | • Increasing mental confusion, hallucination leading to stupefaction accompanied by some decrease in dexterity and judgment as pressure increases.<br>• Memory loss and increased excitability. |
| **> 9 bar** | • Euphoria, manic or depressive states, loss of awareness of surroundings and time.<br>• Incapacitation.<br>• Unconsciousness.<br>• Death. |

*Table 1*

#### 8.6.2. Work of breathing

The work of breathing is a combination of physiological work of breathing within the body and mechanical work of breathing within the breathing apparatus. In extreme circumstances it is possible for this combination to exceed the breathing capacity of the individual, who can then suffocate due to carbon dioxide build up.

Nitrogen is a dense gas and the proportion of nitrogen is the dominant factor in determining breathing mixture density. As the pressure increases so the density of the gas being breathed increases in proportion to the increase in absolute pressure. Increased density increases the physical effort required to move gas into and out of the lungs which in itself increases carbon dioxide production as well as inducing fatigue. Dense gas also results in greater turbulence and hence greater flow resistance in the airways. Additionally, there will be flow resistance from any breathing apparatus worn.

The increased density, turbulence and resistance together lead to a significant reduction the volume of gas inhaled and exhaled – around 50% at 3 bar(g). As the lungs are at the end of the flow path from the nose and mouth and where carbon dioxide is generated, any reduction in exhaled volume will lead to a build-up of carbon dioxide.

#### 8.6.3. Limiting gas density

Current thinking is that it is important to set limits on gas density as a control on the work of breathing. To achieve this as pressure increases, requires helium to be added to the breathing mixture replacing nitrogen. This also has the additional effect of reducing narcosis and limiting carbon dioxide retention.

The density of air at sea level varies depending on atmospheric pressure and temperature but can be taken as ~1.27 g/l at sea level and atmospheric pressure. Expired air is slightly denser than inspired air as it contains more carbon dioxide and water vapour. It is strongly recommended that the maximum density of inspired gas should not exceed 5.7 g/l. As a consequence it is recommended that air should not be used as the breathing gas at pressures above 3.5 bar(g) as its density would then exceed this limit. Above that pressure it is necessary to include helium in the mix to maintain its density below the 5.7 g/l limit.

Tunnelling experience has shown that for saturation exposures a maximum $PN_2$ of 2 bar should be adhered to as a means of preventing long term fatigue from work of breathing. The maximum density of breathing mixture during storage in saturation should be 3.8 g/l.

The fact that exposure to compressed air at up to 5 bar(g) is permitted in tunnelling and diving in some countries does not necessarily imply it is safe, as the fatigue from work of breathing at such pressures should not be underestimated.

#### 8.6.4. Decompression

The higher the pressure at which air is breathed the more nitrogen which is taken on by the body during an exposure. In some countries e.g. France, separate tables are applicable for decompression from pressures of up to 5 bar(g) in compressed air work and diving which demonstrate the physiological differences inherent in the two activities. This report clearly recommends that air mode exposures should not be undertaken above 3.5 bar(g).

With the current state of mathematical modelling of decompression profiles, tables are available for apparently effective oxygen assisted decompression following air exposures at 6 bar(g). However, at these pressures the productive time is short and the decompression time is long. Such long decompression in the cramped confines of a personnel lock is very uncomfortable for those involved and should be avoided. Considering the use of such procedures totally fails take account of the dangerous levels of narcosis, the excessively strenuous work of breathing and carbon dioxide retention inherent in air breathing at such pressures discussed elsewhere in this report and should not be undertaken.

### 8.7. OXIDES OF CARBON

#### 8.7.1. Surface equivalent value and limits on exposure

Surface equivalent value (SEVs) is the measure of the maximum permitted concentration of a contaminant such as carbon dioxide in the breathing gas at 1 bar(a). SEVs should be maintained as pressure is increased. The volume concentration of the contaminant gas has to be reduced proportionately as pressure increases to maintain that partial pressure at all exposure pressures.

#### 8.7.2. Carbon dioxide

Carbon dioxide is often overlooked as it is not one of the three breathing gases commonly associated with breathing mixtures for hyperbaric exposure – oxygen, helium and nitrogen. Carbon dioxide is a dense, narcotic and asphyxiant gas in its own right. Excessive exposure to the gas causes hypercapnia. Symptoms of hypercapnia include confusion, lethargy, breathlessness, involuntary hyperventilation, headache, extreme panic and on to unconsciousness. In air breathing, symptoms of hypercapnia associated with hard work can be detected at pressures around 3.5 bar(g) in diving – as there is no data from air immersion the diving figure should be accepted for tunnelling also.

There are two sources of carbon dioxide which should be considered – from inspired air or gas and from the human metabolic process.

Scrubbing or flushing with clean gas are the preferred methods of controlling it in a chamber or compartment atmosphere.

#### 8.7.3. Carbon dioxide from inspired air or gas

Carbon dioxide is present in inspired air or breathing mixture. It occurs at a level of no more than 500 ppm in natural air. It is a component of exhaust from internal combustion engines and can also be generated from combustion of oil lubricants in compressors. Although the use of compressed air in HPCA work is limited, nevertheless it can be used such as in the initial pressurisation of habitats. Carbon dioxide can also be present as a trace contaminant in mixed gas cylinders. It is therefore important to ensure that levels of carbon dioxide in compressed air or breathing mixtures supplied for respiration do not exceed the relevant limits in EN 12110:2014.

Permissible limits on carbon dioxide in gas reclaim systems are given in HSE Diving Information Sheet No 9 (https://www.hse.gov.uk/pubns/dvis9.pdf )

**8.7.4. Carbon dioxide from the metabolic process**

Carbon dioxide is generated as the end point of metabolic processes in body tissues irrespective of the composition of the breathing mixture breathed. The function of the lungs is not just to oxygenate the blood but also to remove carbon dioxide from the blood. As carbon dioxide is released into the lungs through the alveoli, it is exhaled towards the end of the breathing cycle so anything which curtails or restricts the cycle will lead to carbon dioxide retention and build-up in the lungs. On average around 4 – 5% of exhaled breath is carbon dioxide. At high work-rates the percentage of carbon dioxide in the exhaled breath increases as does the breathing rate thus generating an even greater volume of carbon dioxide.

Increased work of breathing, elevated work rates and reduced tidal volumes all result in the build-up of carbon dioxide. Hypercapnia causes disruption to normal respiration resulting in failure to expel carbon dioxide from the lungs which in turn exacerbates the problems due to the work of breathing.

Carbon dioxide from the exhaled breath, will accumulate naturally in any enclosed compartment or chamber such as a personnel lock, TUP shuttle or habitat. The build-up should be controlled by scrubbing the carbon dioxide from the compartment or chamber atmosphere or by flushing with clean gas. However, given the cost of helium, scrubbing is often the cost effective option.

Carbon dioxide build up and restriction on breathing are also consequences of poor mask design where excessive dead space and high breathing resistance can occur. Internal dead space in the facepiece should not exceed 200 ml.

Remedial action to be taken in the event of hypercapnia depends on the nature of the occurrence. Where breathing apparatus is being used, the MGW/MGSW should stop work and the helmet should be flushed with fresh gas to counter the build-up of carbon dioxide. If no immediate improvement occurs, then a return to the personnel lock and possible decompression should be initiated. In compartments or chambers, ventilation of the space with fresh gas should be undertaken along with checks to ensure the scrubber mechanism is functioning effectively and not in need of replacement of the scrubbing medium.

Consequences of hypercapnia are considered to include an increased risk of CNS oxygen toxicity, increased narcosis from nitrogen exposure and an increased risk of decompression illness.
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Research has been undertaken over many years into the adverse effects of exposure to high partial pressures of oxygen and nitrogen along with high concentrations of carbon dioxide. Much of that work relates to diving exposure and does not take account of the physiological differences in exposure between diving and compressed air work.

**8.7.5 Limits on exposure to $CO_2$.**

The atmospheric concentration at the surface is around 500 ppm which is equivalent to a partial pressure of 0.5 mbar. Within lock compartments, shuttles and habitats where mask-off breathing is the norm and regenerative atmospheric control is undertaken, a surface equivalent value of 5000 ppm or $PCO_2$ of 5 mbar should not be exceeded.

**8.7.6 Carbon monoxide**

Carbon monoxide is a toxic gas. It can be present in compressed air due to incomplete combustion of oil lubricants in the compressor or a as trace contaminant in compressed air cylinders. It can also be present in very small quantities in the exhaled breath particularly of smokers. As with carbon dioxide there are few times that compressed air is used for respiration in HPCA work except for example in the initial pressurisation of a habitat. The limits on carbon monoxide in oxygen/nitrogen, oxygen/helium and oxygen/helium/nitrogen mixtures as given in EN 12021:2014 should be adhered to.

Although symptoms of carbon-monoxide poisoning are the same irrespective of pressure, at high pressures the symptoms may be severe and rapid in onset. Symptoms include headaches, agitation, confusion, breathlessness on exertion and loss of consciousness. The severity of symptoms increases in proportion to the partial pressure and as a consequence to any increase in absolute pressure. Levels of contamination which at atmospheric pressure, are likely to be asymptomatic can produce severe symptoms at increased pressure that can prove fatal in the high risk environment of the excavation chamber.

The vastly greater affinity of haemoglobin to bind with CO and form carboxyhaemoglobin, compared to its affinity for oxygen to form oxyhaemoglobin, should also be considered as a reason for maintaining low levels of CO contamination. Haemoglobin is constantly combining with oxygen in the lungs and giving off oxygen as it passes through the tissues in the course of normal metabolism. Carbon dioxide formed is off-gassed in the lungs and the cycle repeats. With carbon monoxide in the lungs there is the action of bonding to the haemoglobin to form carboxyhaemoglobin which then accumulates and is retained in the body thus decreasing the proportion of the body's haemoglobin available to bind with oxygen.

Within lock compartments, shuttles and habitats where mask-off breathing is the norm and regenerative atmospheric control is undertaken, a surface equivalent value of 0.2 ppm as in EN 12021 should not be exceeded.

As with carbon dioxide, scrubbing is the preferred method of controlling carbon monoxide levels in a chamber or compartment atmosphere.

## 8.8. COMMONLY USED GAS MIXTURES

### 8.8.1. Heliox

Oxygen helium mixtures (heliox) form 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 the risk of nitrogen narcosis. The breathing mixture supplied by umbilical should be nitrogen free as should the breathing mixture for flushing and routine pressure make-up in the habitat and other chambers.

However, the heliox atmosphere in a habitat or other chamber is likely to contain some nitrogen as a result of initial compression procedures and subsequent locking in/out operations. It is normal practice when running a habitat at a $PO_2$ of ~0.45 bar to compress the habitat initially to around 1 bar(g) on air and then top up the pressure with diving grade helium. This results in an initial $PN_2$ of around 1.6 bar depending on the partial pressure of oxygen required. Although some of this nitrogen could be lost through flushing, further nitrogen will be gained through locking operations. Contamination with nitrogen could be significant with storage pressures of below 6 bar(g) but becomes proportionally less significant at higher storage pressures.

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

Heliox is also used for the treatment of DCI.

### 8.8.2. Trimix

Trimix is an oxygen, helium, nitrogen mixture which has been used on a number of HPCA contracts in tunnelling at pressures above 3.5 bar. The helium content acts as a diluent to nitrogen thus reducing, but not eliminating, the narcotic effects of nitrogen. The helium content also leads to some reduction in gas density and hence the work of breathing. However its use introduces the complication of having to consider the diffusion characteristics of two inert gases when their partial pressures in the breathing gas are changed for operational reasons. There is limited experience of trimix exposures in both tunnelling and diving as well as a lack of verified decompression tables.

Taking account of these conflicting factors, it is recommended that trimix is not used for any exposure, including as part of an excursion to a pressure greater than storage, with a maximum pressure exceeding 6 bar(g). It is also recommended that the $PN_2$ should be kept constant throughout the exposure irrespective of whether it is of a non-saturation or saturation nature. The limit on $PN_2$ in non-sat exposures is 3.5 bar. For saturation, the chosen value for $PN_2$ should not exceed 2 bar(g) and the instantaneous value of $PN_2$ should not vary from the chosen value by more than +/- 0.1 bar.

Further limits which should be observed are that for non-saturation exposures the gas density should not exceed 5.7 g/l and that for saturation exposures the gas density of the trimix should not exceed 3.8 g/l in storage and 4.2 g/l during working periods.

Given that a $PN_2$ of ~1.6 bar can arise in a habitat from initial compression and the exposure still be considered “heliox” saturation, there is little difference between heliox with such a $PN_2$ and trimix with a $PN_2$ of 2 bar.

As it requires less helium than heliox, trimix can be cheaper than heliox thus making its use more commercially attractive. Although trimix can have commercial benefits for non-sat exposures, the limit on $PN_2$ in saturation restricts the attractiveness of trimix for saturation exposures.

Helium reclaim is undertaken in diving, but that technology has not yet been taken up by the tunnelling industry (see Cl 6.36). There is a cost to the technology.

### 8.8.3. Nitrox

Nitrox which is an oxygen nitrogen mixture other than natural air can be used for exposures at pressures around the interface between the intermediate and high pressure range. However nitrox is of little use in normal HPCA work because of the relatively limited range of pressures over which it can safely be used. Nitrox is widely used in amateur diving and to a lesser extent in commercial diving. Standard nitrox mixtures used in diving contain 32% or 36% oxygen by volume. Nitrox 40 is also available. Advantage can be taken of the reduced nitrogen content to have longer exposures and/or safer decompressions. However, the high oxygen content means that preventing CNS oxygen toxicity, limits the pressure range over which nitrox can safely be used.

Nitrox can be used in the treatment of DCI.

## 8.9. LIMITS ON AIR BREATHING

Taking account of all the adverse physiological effects of air breathing this report strongly recommends that the limit on air breathing should be 3.5 bar(g) above which non-air breathing mixtures should be used to limit the combined risk from oxygen toxicity, narcosis, work of breathing and carbon dioxide exposure. The risks from decompression following air breathing exposures remain but the other risks are considered to be more significant in determining this limit.

Although the corresponding limit in diving is 5 bar(g), experience shows that reputable diving companies often switch to mixed gas breathing well below this limit for safety reasons.

## 8.10. COMPRESSION OF HABITAT

### 8.10.1. Procedure for compression of habitat

There should be a procedure for initial compression of the habitat. It should cover pre-compression checks, initial seal and compression, leak testing, compression rates, gas mixtures to be used, gas quantities required and stabilisation periods. A leak test of at least 20 minutes duration should be carried out at a pressure of around 1 bar(g). The compression rate should not exceed 0.1 bar/min. Reclaimed gas should not be used for the initial compression as it can have higher levels of contaminants.

As the habitat contained air at the start of compression, there will be an initial $PN_2$ of 0.8 bar in the habitat. Thereafter compression on air to around 1 bar(g) is the normal way to raise the $PO_2$ to required levels.
Where trimix is being used as the storage mixture, this nitrogen content is not a problem. Otherwise the nitrogen is a contaminant for which, according to NORSOK U100, the $PN_2$ should be routinely kept below 1.5 bar and further reduced to 0.8 bar and <10% by volume during decompression.

During compression, care should be taken to prevent pockets of irrespirable gas forming in the habitat. Scrubbers should be in operation to assist with thorough mixing of the pressurising gas in the chamber atmosphere. Chamber inhabitants should remain visible to the lock attendant during the compression phase.

On completion of compression there should be a rest period to allow for stabilisation at pressure.

On arrival at storage pressure the $PO_2$ in the habitat should not exceed 0.55 bar and the $PCO_2$ should not exceed 5 mbar. The $PO_2$ can be reduced through normal breathing.

### 8.10.2. Aborted compression

Procedures should be developed in advance, for dealing with an aborted compression. These procedures should lead to the safe return to atmospheric pressure of those being compressed. The procedures are likely to depend on the pressure reached and the duration under pressure.

## 8.11. MINIMUM OXYGEN CONTENT IN CYLINDERS AND CHAMBERS

It is important to ensure that no gas cylinder containing an irrespirable gas such as pure helium or nitrogen is put into use for supply. The quantity of oxygen in a cylinder of diving helium is normally taken as a minimum of 2% oxygen by volume. Pure nitrogen in cylinders is not normally required in HPCA work. Where pure inert gas is required on site, the procedures in IMCA document AODC 038 should be followed.

Care is also needed with heliox and trimix use as these mixtures can have an oxygen concentration of significantly less than 20% which would prove irrespirable if used at low or intermediate pressures. Until the $PO_2$ for those in a compartment being pressurised comfortably exceeds 0.2 bar, masks with a respirable gas supply should be used or be immediately available in the compartment being pressurised.

## 8.12. OXYGEN CONTENT - FIRE SAFETY

Measures to mitigate the risks associated with handling oxygen are set out in EN 12110. All mixtures with an oxygen content greater than 23% oxygen by volume should be treated as pure oxygen. This limit should be adhered to in the compartments of habitats during saturation decompression following procedures which require an elevated $PO_2$ of up to 0.5 bar. The 23% by volume limit takes precedence over the partial pressure requirement for decompression from around 1.2 bar(g) to normal atmospheric pressure.

## 8.13. 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 use of air for initial compression to set the $PO_2$ is also relevant to the decision. Again the advice of specialist hyperbaric advisors and the 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. It is recommended that trimix should not normally be used at pressures greater than 6 bar(g). The gas mix should be chosen so that the risks from carbon dioxide retention, the work of breathing, gas density, risk of nitrogen narcosis and decompression are minimised so far as reasonably practicable.

Intervention and excursions are both likely to involve the use of different mixtures for storage/resting and when at work. The number of breathing mixture formulations required should always be minimised.

## 8.14. BREATHING MIXTURE SELECTION

### 8.14.1. Non-saturation exposures

For non-saturation exposures a 20% oxygen by volume breathing mixture should be used for exposures up to 6 bar(g). A single heliox or trimix formulation can be used over the full range of pressures between atmospheric pressure and 6 bar (g) and this avoids having a gas switch. For exposures to pressures between 6 and 8 bar(g) heliox should be used and a gas switch should be undertaken to maintain the 1.4 bar limit on $PO_2$. However when agreed by the person in charge, heliox with a reduced oxygen volume fraction – never less than 16% - may be used in the breathing mixture for exposure to pressures between 6 and 8 bar(g) but breathing such a mixture should not be undertaken with a lock pressure below 0.25 bar(g).

### 8.14.2. SATURATION EXPOSURES

Compression of the habitat is covered in clause 8.10.

Limits on partial pressure, cumulative dose and gas density in clause 8 should be adhered to. The contract medical adviser and specialist hyperbaric advisers as necessary, should seek to optimise the various mixed gas formulations involved to minimise the risk and discomfort to the MGSWs along with the number of breathing mixture formulations required.

In order to remain within limits on $PO_2$, breathing mixture formulations with an oxygen concentration below 20% will be required for use at pressure. Care must therefore be taken to ensure that at all times the MGSWs receive the minimum $PO_2$ of 0.2 bar required to sustain normal life.

**8.15. CHOICE OF EXPOSURE TECHNIQUE**

The choice of exposure technique depends on a number of safety-related factors including the space available on the TBM for shuttle transfer as well as on the working pressure and the breathing mixture to be used. The amount of work to be done and gas usage are significant commercial factors influencing this choice.

Non-saturation exposures at high pressure only allow for relatively short working periods depending on the decompression tables used (typically 45 minutes at 6 bar (g)). Such exposures permit inspection or limited maintenance only to be undertaken. All exposures at pressures greater than 6 bar should normally be undertaken using saturation techniques (see 8.17 below).

When considerable productive work is required e.g. to maintain cutters on a large cutterhead, saturation techniques should be used. Saturation exposures allow up to 5 – 5½ hours of productive work per shift. The time required to set up access facilities in the excavation chamber and to clean the cutterhead prior to tool change should also be factored into the non-saturation/saturation decision. By removing the need to decompress daily, saturation exposures also remove much of the decompression risk associated with multiple exposures. Saturation techniques can be used from exposure pressures greater than 1 – 1.5 bar(g).

The advice of specialist hyperbaric advisors and the contract medical adviser should be sought on the hyperbaric safety issues associated with the decision making process.

**8.16. EXPOSURE LIMITS NON-SATURATION EXPOSURES**

**8.16.1. Typical exposure procedures**

For typical non-sat exposures the MGWs would enter the personnel lock, don masks for a supply of breathing mixture while the lock would be compressed to working pressure using air. The MGWs still breathing from masks would transfer to the working chamber pressurised with air. At the end of the working period the MGWs would transfer to the personnel lock and be decompressed. At some stage during the decompression it would become safe to breathe air and masks would be removed. Decompression on air would continue until the first oxygen breathing stage is reached at which time the MGWs would don masks with overboard dump capability for the oxygen breathing phase of the decompression. Air breaks would be factored into the oxygen phase of the decompression in accordance with the tables being used.

**8.16.2. For personnel locks less than 1.8 m internal diameter**

For reasons of worker comfort and control of hyperbaric exposure various limits should be observed.

- A single exposure in 24 hours which requires a decompression time in the personnel lock of not more than 2 hours and 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. The CMA at his professional discretion may alter the 5/2 pattern to a 7/3 pattern or similar if he considers that would lead to improved wellbeing overall for those affected e.g. improved opportunities for long distance travel home, at no detriment to their health.

**8.16.3. For a personnel lock of at least 1.8 m internal diameter.**

For reasons of worker comfort and control of hyperbaric exposure various limits should be observed.

- There should be an internal volume of at least 1.5 $m^3$ per occupant.
- A single exposure period of not more than 2 ½ hours with the exposure period and decompression time combined not exceeding 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 duration 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 stretching movements during decompression., During decompression the MGWs should have access to food and drink along with basic welfare facilities. Where it is possible to access the intermediate chamber for gentle exercise this should be considered.

**8.17. 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 8.16 apply. No one should undertake more than 14 such exposures in a 35-day period.

**8.18. SATURATION EXPOSURES**

Typically MGSWs would enter the habitat and be compressed to storage pressure followed by a period in the habitat to establish saturation. When an intervention or excursion is required the MGSWs would transfer under pressure to the TBM personnel lock and then through the intermediate chamber to the working chamber. The personnel lock would be pressurised with working mix. Masks would be donned in the personnel lock and transfer into the intermediate chamber could be achieved by connecting the emergency umbilical core to a mixed gas manifold in the personnel lock, entering the intermediate chamber then connecting the primary core to the primary supply manifold in the intermediate chamber followed by transferring the emergency core to the emergency supply manifold in the intermediate chamber.

MGSWs in the intermediate and excavation chambers which are air pressurised, would breath working mix through umbilical-fed masks. Umbilicals would be connected to manifolds in the intermediate chamber so that in an emergency the MGSWs would evacuate from the excavation chamber and the bulkhead door closed.

Periods not in the excavation chamber for re-caking the face or mid-shift mask-off breaks should be taken on working mix in the personnel lock. At the end of the working period the MGSWs should return via the intermediate chamber to the personnel lock before entering the shuttle for transfer under pressure back to the habitat. A final decompression to atmospheric pressure should be undertaken in the habitat at the end of the saturation run which should not exceed 28 days in duration.

Only where there is no intermediate chamber and in order to permit rapid access in an emergency to the personnel lock from the excavation chamber but still maintain the composition of the breathing mixture in the personnel lock atmosphere, the connecting lock door opening should be covered by a flexible non-flammable curtain to minimise gas transfer. Very slight over-pressurisation of the lock can be used to assist in preventing contamination of the personnel lock atmosphere by air from the intermediate chamber.

As saturation exposure techniques typically give productive working periods of around 5 - 5 ½ hours during a typical intervention or excursion, saturation techniques should be undertaken where significant working time is required for major maintenance. Although saturation techniques are normally associated with higher pressures, they can also be undertaken at pressures below 3.5 bar(g) to limit the decompression risk.

In many tunnels it is likely that the working pressure will increase and/or decrease as the tunnel drive progresses. Guidance on scheduling storage pressure is given in clause 8.20 below.

**8.19. LIVING IN SATURATION CONDITIONS**

For saturation working, the HPCA contractor must extend the safe systems of work to cover the occupational health, welfare and general well-being of those in the habitat. 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 or bettered.

**8.20. PLANNING AND MAINTAINING STORAGE PRESSURE.**

**8.20.1. Selection of 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 pressures 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 hyperbaric supervisor or 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.

*Note: on a tunnel below a river or estuary, the vertical alignment will usually be such that working pressure will increase from the launch shaft towards mid channel and then decrease as the tunnel rises towards the reception shaft. This can result in a need for an increasing storage pressure followed by a decreasing storage pressure.*

**8.20.2. Increase in storage pressure.**

It is good hyperbaric practice to increase the storage pressure to reflect increases in working pressure rather than to depend on excursions. The pressure increase should preferably be no more than to the excursion limit for the storage pressure in use. If compression is done when MGSWs are in the habitat the rate of compression should be in accordance with initial habitat compression procedures.

Compression of the habitat can be undertaken when the habitat is unoccupied with all MGSWs excurting to a greater pressure. In this case the new storage pressure should not exceed that of the excursion being undertaken. Compression of the habitat should not be undertaken during excursions to pressure less than storage.

**8.20.3. Reduction in storage pressure**

Although reductions in storage pressure should be avoided during a saturation run this is not always possible. This can present scheduling problems in a tunnel below a river or estuary when the drive is rising back towards ground surface level. A reducing working pressure profile can be achieved by undertaking a series of progressively smaller excursions to pressure greater than storage.

When a reduction in storage pressure has to be undertaken during a saturation run, it should be done in accordance with the relevant section of the decompression tables and respecting any limitations on interim decompressions associated with the decompression table being used. In the absence of restrictions associated with the table being used, there should be at least 5 days between successive reductions in storage pressure. The reduction in storage pressure should not follow within 12 hours of an excursion to pressure greater than storage pressure. An excursion to pressure less than storage should not be undertaken until a stabilisation period equal to the time to decompress in accordance with the procedures set out in the table to the excursion pressure, has elapsed since the reduction in storage pressure.

**8.21. 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 day/night regime. The minimum rest period in the living complex should normally 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 priod 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 (see also clauses 8.25 and 8.26).
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.

**8.22. DURATION OF SATURATION EXPOSURES AND SURFACE INTERVALS**

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

*Note: the imposition of a 7/14/21-day progressive limit on experienced saturation workers as part of a build-up to full 28-day working does not necessarily 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.*

Following a saturation run, an MGSW should not undergo further saturation exposure until at least an equal interval of time at atmospheric pressure as that spent in saturation has elapsed. However if permitted by the saturation decompression tables used, after 48 hours at atmospheric pressure that person can again become involved in hyperbaric works but only for non-sat exposures.

A person's cumulative saturation exposure should not exceed 13 weeks in any 26-week period.

**8.23. INTERVENTIONS**

Because interventions are work periods undertaken at storage pressure, they do not involve decompression and therefore are to be preferred to excursions. Duration and work/rest periods for interventions should be the same as for excursions.

**8.24. 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. Pressure changes should be no faster than 0.5 bar/min.

For excursions to pressures greater than storage pressure, compression to working pressure and decompression back to storage pressure should be undertaken immediately before and then immediately after the transfer between the shuttle and the personnel lock respectively, to minimise time at the greater pressure.

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 TUP from the habitat. The safety of an excursion to pressures less than storage pressure, can be adversely affected by an excursion to pressures greater than storage pressure in the previous 24 hours. Where there is significant risk of the excursion being aborted before entry into the excavation chamber has begun the pressure reduction can be planned to be done at the TBM lock.

Where possible when planning excursions MGSWs should consistently excurt either to pressures greater than storage pressure or to pressures less than storage during a saturation run but should preferably not undertake both. Where, MGSWs have to undertake both they should excurt to pressures less than storage pressure before undertaking excursions to pressure greater than storage pressure. MGSWs should not excurt to pressures both less and greater than storage within a single excursion. Only one excursion per 24 hours should be undertaken.

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, duration of excursion of 6 to 8 hours, immersion in water and work-rates which can be lower than in tunnelling and hence should be used with caution in tunnelling. Excursion limits when breathing trimix in tunnelling will need to be developed and verified for the specific trimix formulations being used on site.

*Note: European practice is to limit a single excursion to either greater or less than* *storage pressure and is to be preferred, however the US Navy Diving Manual sets out a procedure for a single excursion to comprise both greater than and less than storage pressure phases.*

Pressure or gas mix changes required for excursions should not be undertaken whilst the shuttle is in transit.

## 8.25. INTERVENTION OR EXCURSION DURATION

The time away from the habitat for an intervention or excursion 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 time away should normally be 8 hours in any 24- hour period. No more than one intervention or excursion per day should be undertaken. Exceptionally for long travel distances, the time away from the habitat may be increased with the agreement of the CMA, to a maximum of 10 hours allowing up to two hours TUP each way. To avoid extended time at increased pressure for excursions at pressures above storage pressure the compression and decompression associated with the excursion should take place at the TBM.

## 8.26. WORK/REST PERIODS DURING INTERVENTIONS OR EXCURSIONS.

As personnel are involved in strenuous physical work during interventions and excursions, they should have at least one mid-period rest and refreshment break of at least thirty minutes. This should be undertaken with masks off. Before masks are removed, care should be taken to ensure that the atmosphere in the space where masks are to be removed is of the intended composition. Means should be provided to check if contamination has occurred and to flush the space with an appropriate gas mixture to restore the intended atmospheric composition before masks are removed. Masks should be removed one at a time.

The work period during any intervention or excursion should not normally exceed 6 hours in total including the rest period. The rest period should preferably be taken in the TUP shuttle or personnel lock. The work period duration may need to be reduced or the rest period extended for very heavy work.

In bad ground conditions, there can be a need to recake the face with bentonite to control air loss, one or more times during a work period. During recaking operations the MGSWs should rest in the personnel lock. In these circumstances the safety of the overall tunnelling operation should be considered, and it can be necessary to extend the intervention or excursion to allow essential maintenance to be completed and the TBM to be restarted. Provided the total work period in the excavation chamber does not exceed 6 hours, the time away from the habitat may be extended by up to a further two hours i.e. to 8 hours at the TBM with exceptionally a total of 4 hours of travel time. A supply of food and drink should be provided. Basic toilet facilities should be provided possibly in the intermediate chamber. An extended period away from the habitat of more than 10 hours should be followed by at least a 24-hour period resting in the habitat. Again, the CMA should oversee this procedure to ensure MGSWs are not excessively fatigued. Extended excursion time for pressures above storage pressure will increase the inert gas load and hence increase the risk of bubbling during and after decompression back to storage pressure.

## 8.27. 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 pressure, excursions to pressures above and below storage pressure can be used to achieve the required differential in working pressure. One crew should always excurt to pressures greater than storage with the other excurting to pressures less than storage. Alternating excursions to pressures greater/less than storage should be avoided. Alternatively, a split habitat catering for two storage pressures or two separate habitats at different storage pressures can be used.

## 8.28. FINAL DECOMPRESSION

Starting the final decompression whilst bubbles are present can be a factor in initiating DCS. To ensure that any bubbles formed during excursions have totally resolved, it is important that there should be a period of rest or stabilisation at storage pressure before starting final decompression. Requirements for this are normally set out as part of the decompression tables. Recommended $PO_2$ levels during decompression are normally around 0.5 bar except when the <23% by volume criterion kicks in but again should be set out within the tables.

## 8.29. 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 and exposure techniques being used.

Tables with a proven history of effectiveness are to be preferred. There is probably no need for the use of un-proven tables but if the use of such tables is proposed, they should initially be compared with tables of known effectiveness and then be subject to a verification process as described in clause 3 of this report before they are put into routine site use.

Heliox tables commonly used in diving should be assessed for their likely effectiveness if proposed for use in tunnelling. It will depend on the table being applied as diving heliox decompression tables are normally based on a significant level of contamination by nitrogen in the habitat (see cl 8.10). Consequently the difference between “heliox” with a $PN_2$ contamination level of 1.5 bar and trimix where the limiting $PN_2$ is 2 bar is small.

Although a $PN_2$ contamination of 1.5 bar in heliox is considered acceptable for storage, that contamination limit drops to 0.8 bar during decompression. Consequently when trimix is being used, consideration could be given to reducing the $PN_2$ to 1.5 bar long enough in advance of decompression starting for saturation with “heliox” to be established before dropping the $PN_2$ further to 0.8 bar and undertaking a decompression as if using heliox for storage.

A plan should be developed to treat any DCI occurring during the gas switch or if DCI should occur after the gas switch. The appropriateness of treatment tables for use in saturation under such circumstances should also be taken in consideration. Appropriate arrangements should be made to transfer a casualty to another compartment in an emergency situation. The impact of a gas change on the emergency procedures involving shuttle transfer or a living habitat with different storage pressures should also be considered.

Physiological monitoring should be used to monitor all decompressions for effectiveness. The frequency of monitoring and monitoring outcome criteria should be taken from clause 11.8 of the BTS Guidance.

**8.30. TREATMENT TABLES, OMITTED DECOMPRESSION TABLES, OVER RUNNING PERMITTED EXPOSURE PERIOD ETC.**

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 exceptional exposure periods. Use of exceptional exposure periods allowed by tables should not be a routine activity used to compensate for insufficient numbers of suitable workers or inadequate work planning.

In addition, procedures for dealing with the use of incorrect breathing mixtures during exposure should be drawn up.

**8.31. LOSS OF OXYGEN SUPPLY DURING DECOMPRESSION**

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

**8.32. 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.

**8.33. MASK-OFF BREAKS.**

**8.33.1. Period without use of masks in non-sat exposures.**

Decompression tables which include one or more stages or air breathing where masks are not required to be worn, may be advantageously taken as mask-off breaks to permit communication, rehydration, and comfort breaks for the workers as well as facilitating medical monitoring.

**8.33.2. Air-breaks during oxygen decompression in non-sat exposures.**

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

**8.33.3. Loss or removal of masks**

Loss or unintended 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.

The higher the air pressure, the greater the risk to the wearer from the unintentional loss or removal of their mask. The main risk is from the rapid onset of narcotic symptoms and if the pressure is high enough, loss of consciousness (see Table 1). In such circumstances, the compressed air environment in the working chamber can be toxic or irrespirable. The risks resulting in the 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.

Masks and helmets should include a device allow for equalising pressure in the ears.

**8.33.4. 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 limit contamination of the habitat atmosphere by air. However, during transfer between shuttle and personnel lock and personnel lock to the working chamber it can be difficult to prevent contamination of the trunking atmosphere by air unless adequate flushing with breathing mixture is undertaken.

Persons should be able to transfer through the trunking between PVHOs without having to wear masks by maintaining a mixed gas atmosphere in the personnel lock, shuttle and trunking. Likewise masks should not be required in the shuttle during TUP.

Periods of air breathing between periods of mixed gas beathing should be avoided. 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 a hyperbaric operation, the upper pressure for such activities should be 3.5 bar(g) 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 by one worker at a time.

#### 8.34. 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.

#### 8.35. 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 parameters will increase the risk however the fire 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" (generally taken as below 6% by volume) 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 which 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 Guidance along with any additional requirements of the national regulatory authority.

### 9.2. RECORDS OF NON-SATURATION EXPOSURES

The normal records for non-saturation air mode exposures as set out in the BTS Guidance should be kept.

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.

The records to be kept by each party to the compressed air work including persons exposed, should be as for air mode exposures.

### 9.3. RECORDS OF SATURATION WORKING

#### 9.3.1. 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 or excursion undertaken. On termination of employment, each person exposed should be given a full record of 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.

#### 9.3.2. Exposure log

There should be a full record kept of the saturation run including details of supervisory and life support personnel, all changes of pressure, gas mixture, gas analysis records, chamber atmosphere composition, interventions and excursions, incidents, illness or injury, DCI treatments, decisions of a safety critical nature and other relevant issues. It should be retained on site until the end of the contract period. It should be signed off at the end of the contract period by the senior representative of the HPCA contractor and thereafter kept by the HPCA contractor for a period of 40 years.

#### 9.3.3. Individual logbooks

All personnel exposed should be given a full record of their saturation exposures.

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.

### 9.4. 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.

### 9.5. 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.

### 9.6. 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/personnel lock/TUP shuttle
- Fire in working chamber, personnel 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 or face instability
- Inundation
- Lifting equipment failure
- Life support personnel taken ill or otherwise no longer available
- 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
- Contamination or incorrect formulation of any gas used
- 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, when the CMA deems the risk to the patient from decompression illness to be less than the risk from the illness or injuries suffered, 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.

*Note: information on accelerated emergency decompressions which have been undertaken in commercial diving operations is given at https://www.dmac-diving.org/guidance/Imbert-AcceleratedDecompression.pdf .*

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

The requirements of the BTS Guidance 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

When the pressurising medium in the shuttle, personnel locks or working chamber is compressed air, the fire risk will be high due to the elevated mass concentration of oxygen. All practicable steps through design, construction and systems of work should be taken to eliminate sources of ignition and fuel sources from the shuttle, personnel locks and working chamber. Where possible 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 include electronic cigarettes or vaping.

### 10.5. FIRE PROTECTION IN SHUTTLE, PERSONNEL LOCKS AND HABITATS

Every shuttle, personnel lock or habitat should have a self-contained, permanently pressurised fire suppression system. The system for each compartment should comprise a reservoir tank of water constantly pressurised by high pressure gas and feeding fixed discharge nozzles in the compartment to which it is connected. Although it should not be possible for the pressurising gas to break through into the compartment, that gas should be respirable at storage pressure in case of an unintended breakthrough.

Activation, operation and duration of the suppression system should be in accordance with the requirements of Section 14.2.8 of NFPA 99 "Health Care Facilities Code" published in 2021. Activation of the system should be possible from both the inside and outside of the compartment and activation should automatically trigger a fire alarm warning at the personnel lock 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. The system should work on the "kill and quench" principle. The vehicle should use HFDU hydraulic fluids.

*Note: a CEN standard for multi-service vehicles for use underground is in preparation.*

## 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 each lock attendant or life support person on duty.

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.

Fire suppression by means of a water sprinkler system should be provided in the enclosure.

## 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 for 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 excavation chamber, intermediate chamber, accessible cutterhead or personnel lock 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, for gas planning purposes assume that the external rescue personnel will follow the same exposure profile as 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 personnel locks, one can be used for mating the shuttle whilst the other provides access for the emergency personnel. Where there is only one personnel lock then the shuttle should be designed to act as a two compartment personnel lock in an emergency. The external rescue personnel should follow a non-saturation profile if possible.

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The provision of specimen drawings by IHC Hytech BV and Submarine Manufacturing and Products Ltd for inclusion in Clause 14 is gratefully acknowledged.

# 12 >> Appendix 1 – The Use Of Sonography In Decompression Management – Recommendations On Procedures From BTS CAWG

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 workers, 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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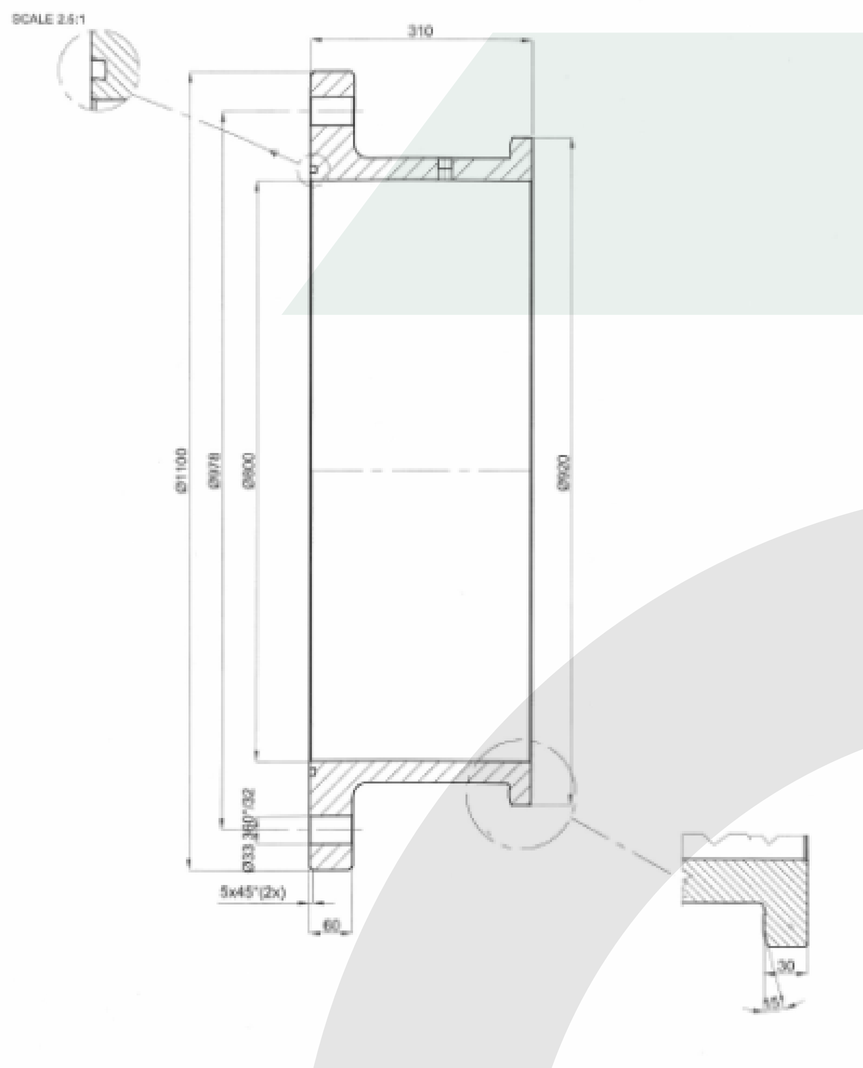
## APPENDIX 2: CONTENTS OF SUBMISSION

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 – air locks, 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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**ITA Secretariat - c/o MIE2** – Chemin de Balexert 9 - CH-1219 Châtelaine (GE) - Switzerland
Tel. : + 41 22 547 74 41 - Email : secretariat@ita-aites.org - Web : www.ita-aites.org