HPCA Work Client Guide

ITA Working Group 5
'Health & Safety in Works'

Guide to ITA/BTS CAWG Report 10 for Clients and others not familiar with High Pressure Compressed Air Works

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British Tunnelling Society

ASSOCIATION INTERNATIONALE DES TUNNELS ET DE L'ESPACE SOUTERRAIN
AITES
ITA
INTERNATIONAL TUNNELLING AND UNDERGROUND SPACE ASSOCIATION

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with High Pressure Compressed Air Works

In Association with

The British Tunnelling Society Compressed Air Working Group

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Association Internationale des Tunnels et de l'Espace Souterrain AITES | ITA International Tunnelling and Underground Space Association

1. HIGH PRESSURE COMPRESSED AIR

Work in a High Pressure Compressed Air environment is defined in Report 10 as “work in compressed air at pressures above historical statutory limits, which in most countries are between 3 and 4 bar(g), and which involves the use of breathing mixtures other than compressed natural air and can involve the use of saturation techniques”.

This Guide provides information for those new to the topic to better understand some of the concepts covered by Report 10 and its current revision.

2. BACKGROUND TO THIS GUIDE

In 2024, a third revision of ITA/BTS CAWG Report 10 “Guidelines for Good Working Practice in High Pressure Compressed Air” was published. This is a highly technical and prescriptive document, which comprehensively covers undertaking high pressure compressed air (HPCA) works in tunnelling. It is intended primarily for use by those planning and undertaking HPCA works and who have knowledge of hyperbaric procedures and tunnelling techniques.

Following publication of the second revision of Report 10, published in 2018, it was felt that a simplified guide to HPCA work should be produced aimed at clients and their professional advisers with no prior knowledge of the technique but who would likely encounter it at the planning or design stage of a project before an experienced contractor had been appointed. They should refer to the glossary of terms in Report 10 for clarification of terms used in this guide. This revision of Report 20 reflects the recent revision of Report 10.

This guide does not advocate the use of HPCA but provides background information on hyperbaric principles and compressed air tunnelling procedures once the use of HPCA is being considered. In this respect, attention is specifically drawn to clause 1.3 of Report 10 and clause 9.2 below.

This guide addresses commonly held misconceptions in the tunnelling industry over the breathing of non-air mixtures and experiencing saturation as a medical condition. It is not widely recognised in tunnelling that saturation is a physiological phenomenon related to the dynamic equilibrium between the partial pressure of gases breathed and those in the tissues and is not limited to diving or experiencing similar conditions. In addition, the guide highlights the decisions that need to be made before work begins on site to ensure HPCA works could safely be undertaken, or to allow adequate provisions for the installation of equipment for HPCA works as a subsequent contingency measure. This allows clients and their professional advisers to understand what HPCA work entails and the provisions which need to be made for it. Also, it would allow them a certain confidence level in making decisions about whether to include the provision of full HPCA functionality or only to require the capability to undertake HPCA works once the need for those arises based on actual site conditions. This Guide is intended to complement Report 10 in this decision-making process.

There are no textbooks which cover in detail the topic of compressed air works in tunnelling. Therefore, reference must be made to industry guidance, standards and regulations. The 2021 edition of the British Tunnelling Society “Guidance on good practice for Work in Compressed Air Regulations” provides comprehensive guidance on the basics of compressed air work up to statutory limits and is available for free download at https://britishtunnelling.com/pages/work-in-compressed-air. Report 10 addresses the additional requirements for working at high pressures and should be read in conjunction with the BTS Guide.

3. STATUS OF REPORT 10

Report 10 is a set of guidelines providing recommendations on good practice in HPCA work. It is not a standard; however, it does refer to numerous relevant standards. It is the only known document published to date on its topic. ITA and BTS CAWG recommend its use on all HPCA contracts. It is also recommended to regulatory authorities to inform enforcement of the stated practices, or to be the basis for enforcement.

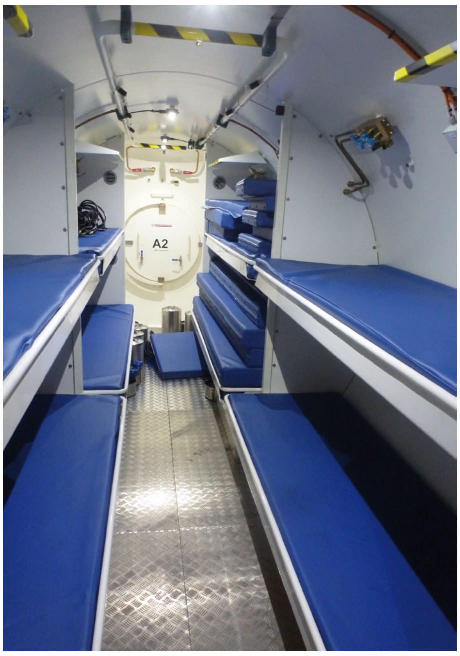

Figure 1 : Interior of habitat

Figure 2 : TUP shuttle being mated to TBM lock

4. DIFFERENCES BETWEEN TUNNELLING & DIVING

HPCA works involve the use of air as the pressurising medium combined with the use of non-air mixtures containing oxygen, helium and nitrogen for breathing, and can include the use of saturation exposure techniques. Such techniques are also used in the offshore commercial diving industry. However, there are major physiological differences affecting a tunnel worker operating in HPCA and experiencing air immersion and a diver exposed to water immersion. The latter experiences buoyancy effects that are absent in tunnelling. Buoyancy significantly alters the distribution of blood around the body and the physical effort required to move around is reduced. Also pressure distributions are different. Thus to use terms such as "bounce dive" in the context of tunnelling and "saturation diving in tunnelling" is to show a lack of understanding of the differences.

Technically it is possible to pressurise the excavation chamber with mixed gas to avoid the need for tunnel workers to wear breathing apparatus; however, due to the high costs of helium it is not commercially viable to do so. Instead, air is used as the pressurisation medium as a less expensive and more practical alternative; the pressurized air at high pressures, however, becomes irrespirable and as in the case of divers, breathing apparatus must be worn.

The difference with immersion is that a tunnel worker in HPCA does not experience the buoyancy effects of immersion in water but importantly also does not experience the various involuntary physiological responses by the human body when immersed in water. These include pooling of blood in the thoracic cavity, a degree of vasoconstriction and hence reduced blood supply in the extremities along with immersion diuresis. Buoyancy results in a significant reduction of use of the lower limbs for weight-bearing support, which further alters tissue perfusion in these lower extremities. Additionally, divers in water tend to orientate themselves in a much more horizontal position which alters the breathing mechanisms.

The fundamental difference with pressure distributions is that the air pressure distribution in the excavation chamber of a TBM is assumed constant with depth whereas were the chamber to be filled with water for a diver, the pressure would increase hydrostatically with depth. This presents restrictions on a diver in saturation over the extent of vertical travel in the chamber which are not presented to a tunnel worker.

STRUCTURE & CONTENT OF REPORT 10

5.1. Glossary and terms of reference.

Clients should refer to this as necessary. Some of the terms in the glossary are explained in more detail in this guide where it is felt this would facilitate their understanding by clients.

5.2. Clause 1 – Introduction.

Clients should take due account of the contingency planning for HPCA work in clause 1.8.

5.3. Clause 2 – Legislation, standards, guidance etc.

Clients can find details of relevant information sources.

5.4. Clause 3 – Notifications, exemptions, and approvals.

Clients should familiarise themselves with this important clause before contacting the regulatory authority. Given that the regulator may not be familiar with HPCA work the client may have to draw the regulator's attention to this Guide, the Report 10 and in particular to its Clause 3. Much of the contact with the regulator prior to work beginning on site, is likely to relate to this clause.

5.5. Clause 4 – Organisation of works in HPCA.

Clients should be cognisant of the planning of the works along with the main appointees required by this clause. Clients should also note the recommendations regarding planning for HPCA works from the earliest stages of planning onwards.

5.6. Clause 5 – Safe systems of work and operational procedures.

Clients should be aware of the contents of clause 5.4 as the information in it is likely to inform early decisions over TBM design.

5.7. Clause 6 – Plant, equipment and gas supply.

Clients should be aware of the contents of clause 6.1 as the information in it is likely to inform early decisions over TBM design.

5.8. Clause 7 – Occupational health.

Clients should be familiar with this clause.

5.9. Clause 8 – Hyperbaric procedures.

Clients need to be familiar with this important clause as the information in it is likely to inform early decisions over exposure techniques to be used. Exposure techniques dictate the equipment required which in turn dictates the working space required.

5.10. Clause 9 – Record keeping.

Clients should be aware of the importance of keeping proper records.

5.11. Clause 10 – Emergency procedures and fire.

Clients should be aware that any emergency affecting the tunnel works whilst HPCA works are underway could cause them reputational damage. It could also lead to scrutiny of their role in ensuring the health and safety of those undertaking the works.

5.12. Clauses 11 – 13 and Appendices.

Clients can treat these as "for information only" until a contractor has been appointed.

6. INDEPENDENT ADVICE

When Clients without prior experience of HPCA works are advised by their designers that such techniques might be needed for their project, they are strongly recommended to engage specialist advisers as soon as practical.

7. REGULATION & STANDARDS RELATING TO WORKS IN COMPRESSED AIR.

7.1. REGULATION OF WORK IN COMPRESSED AIR

Many countries regulate works in compressed air and typically these regulations date from the 20th century. Often, the regulations impose limits on the maximum working pressure and may require the use of air breathing only. The limits are normally in the range 3.5 to 4.5 bar (g) and reflect the requirements at the time the regulations were made and not the maximum pressure humans can safely withstand.

The regulations might potentially prohibit HPCA works in some countries unless some form of exemption, approval, or variance can be obtained from the regulatory authorities. Detailed guidance on recommended procedures for this process are contained in Report 10.

As the procedure for obtaining regulatory approval can be time consuming it is recommended clients establish a dialogue with their national regulator as soon as the potential use of HPCA becomes known. Leaving this to the contractor, after it had been appointed, could result in significant schedule delays.

In some countries there can be regulatory obstacles to acquiring bulk supplies of oxygen and helium or even certain medicines. The client is advised to check whether such obstacles exist since these are likely to impact the project.

7.2. RELEVANT STANDARDS

There are three European standards particularly relevant to work in compressed air which are also widely adopted outwith Europe. Clients should be aware of them and incorporate them in contractual documents. They are EN 16191 "Tunnel boring machines – safety"; 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" and 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".

The 2014 versions of the standards are currently under revision and the revisions are available as provisional European standards with publication of the harmonised standards expected in late 2024 or 2025.

8. DOCUMENTATION FROM CONTRACTOR

The approvals, exemptions, variances, and procedure are likely to make considerable demands for documentation to be produced and maintained. Clients should therefore be careful not to place additional demands on contractors to provide unnecessary documentation at any stage of the HPCA works.

Figure 3 : TUP Shuttle at factory test

Figure 4 : Habitat control panel

9. PRINCIPLES OF COMPRESSED AIR TUNNELLING

9.1. HOW COMPRESSED AIR ACTS ON THE GROUND

Compressed air is used to counter the groundwater pressure acting on a tunnel face in permeable soil thus controlling water inflow and consequent stability/instability of the tunnel face. It is predominantly used in soft ground tunnelling below the water table. Fine grained soils are more responsive to the application of compressed air whereas in coarse grained material considerable air loss can occur through the ground. Further stabilisation measures such as a filter cake or slurry/bentonite membrane on the face may be necessary in more permeable soils.

9.2. MINIMISING EXPOSURE TO COMPRESSED AIR

Clients should be aware that it is often a legal requirement that all reasonably practicable measures should be taken to minimise the number of people exposed to pressure along with minimising the pressure and duration of each exposure, commensurate with minimising the overall risk to the health and safety of those exposed. This requirement should not be taken as a reason to avoid accessing the excavation chamber for routine inspection and maintenance as lack of regular inspection and maintenance can lead to breakdown and the consequent need for more extensive maintenance. The solution is the selection and execution of appropriate hyperbaric access techniques.

9.3. HISTORY OF THE USE OF COMPRESSED AIR

Compressed air was first used in the mid-19th century. Until late in the second half of the 20th century the whole tunnel was pressurised with air and miners worked under pressure to hand excavate and support the ground to form the tunnel. Pressure was maintained by one or more bulkheads in the tunnel with passage of people and materials through airlocks in the bulkheads.

In the final quarter of the 20th century open face Tunnel Boring Machines (TBMs) took over from hand miners in excavating and erecting lining. On occasions these open face TBMs were installed within the pressurised tunnel. In both hand mining and TBM operations the application of compressed air facilitated excavation in wet ground.

As TBM technology progressed, closed face TBMs were developed incorporating a bulkhead with integral airlock(s) in the machine structure. Typically, these machines support the face by maintaining a pressure within the cutterhead and excavation chamber of the TBM in front of the TBM bulkhead. The pressurising medium can be air as with air pressurised shields or excavated spoil as with earth pressure balance machines or slurry as with slurry TBMs. In all TBMs, periodic access for face inspections and cutterhead maintenance is essential.

To maintain face support while accessing the excavation chamber, the spoil or slurry is displaced by compressed air. Compressed air workers can then enter the cutter head or excavation chamber to undertake inspection or maintenance. This is a slightly different application of a traditional technique.

Compressed air can also be required for caisson sinking and shaft construction and very occasionally for groundwater control in rock tunnelling.

9.4. ALTERNATIVE TO COMPRESSED AIR FOR MAINTENANCE

Attention is drawn to clause 1.3 of Report 10. Options to avoid entry under compressed air for TBM maintenance include the formation of stabilised blocks of ground whilst those being developed include the use of robotic tool changers or tool change from within the spokes of the cutterhead under atmospheric pressure conditions.

Stabilised blocks of ground limit the locations at which maintenance can be undertaken. Whilst the robotic options being developed have limitations in terms of the size of TBM on which they can be undertaken; they also have limitations on the extent of coverage of the cutterhead which can be achieved and the type of maintenance which can be carried out.

9.5. HIGH PRESSURE COMPRESSED AIR WORK.

HPCA work was almost unheard of prior to the start of the 21st century. Since then a small number of tunnels with theoretical pressures of up to 15 bar(g) have been built or are being planned. Nevertheless, this pressure is still significantly below that to which commercial divers are routinely exposed in offshore projects which can be between 20 and 30 bar(g).

In HPCA work, compressed air is still the pressurising medium at the face. However, for reasons which are set out in this Guide and Report 10, compressed air as a breathing mixture for workers becomes increasingly hazardous to their health and wellbeing as pressure is increased, to the point it becomes toxic and irrespirable. Hence those in the compressed air environment must breathe a non-air breathing mixture for which the supply through masks attached by umbilicals to a gas supply manifold somewhere on the TBM is the commercially viable approach.

9.6. DETERMINING AIR PRESSURE REQUIRED

The air pressure required is related to the depth of ground water above the face. The simple rule of thumb is 1 bar(g) of air pressure for every 10 m of groundwater. From its first use in the 19th century till the end of the 20th century the tunnelling industry did not find it necessary to work at pressures exceeding 3.5 to 4.5 bar(g) and this was reflected in the regulations covering such work in many countries.

10. HYPERBARIC CONCEPTS

10.1. ABSOLUTE PRESSURE

Humans have evolved to survive in air at atmospheric pressure. For convenience when measuring pressure in most applications it is normal to measure pressure above atmospheric i.e. gauge pressure. At atmospheric pressure gauges display a zero reading i.e. 0 bar(g). Although strictly this should be referred to as "gauge" pressure the word "gauge" is normally omitted. However, in hyperbaric work it is absolute pressure (bar(a) = gauge pressure plus one atmosphere) which is often required for calculations.

10.2. PARTIAL PRESSURE

Atmospheric pressure is made up of the pressure of oxygen, the pressure of nitrogen and the pressure of the other gases in the atmosphere. The pressure of each individual gas is known as the partial pressure (P) of that gas. P = volume fraction of a gas x absolute pressure (Dalton's Law). Partial pressure is an important concept in hyperbaric work and many limits in hyperbarics are based on partial pressure.

10.3. GAS PROPERTIES

10.3.1. Air

Air is a mixture of ~20% oxygen, ~79% nitrogen and ~1% other gases. Included in the other gases is a very small percentage of helium. Hence, we already breathe trace quantities of helium in everyday life without experiencing any harmful effects. For simplicity in calculations, air is often approximated to a 20/80 O_2/N2 mix. Based on that simplification, air at atmospheric pressure has a partial pressure of oxygen $PO_2 = 0.2$ bar and for nitrogen, $PN_2 = 0.8$ bar.

10.3.2. Oxygen

Oxygen at atmospheric pressure is essential for life. It is not commonly understood in construction, that it is the partial pressure of oxygen not the volumetric percentage being breathed, which is important to sustain life.

Oxygen at high partial pressures can be acutely toxic to the central nervous system, prolonged oxygen exposure at elevated partial pressures leads to chronic pulmonary toxicity. Extensive information on oxygen breathing is set out in clause 8.4 of Report 10.

10.3.3. Nitrogen

Nitrogen is an apparently harmless inert gas at least in air at atmospheric pressure. However, breathing elevated partial pressures of nitrogen results in a build-up of the gas in the tissues, which must be released in a controlled manner by the decompression process. Another safety-critical adverse effect, which becomes ever more pronounced as pressure increases is the narcotic effect which leads to human error and ultimately to loss of consciousness and death. Although some consider acclimatisation to narcosis can be developed, it is more to do with the development of coping strategies for routine situations which is developed but when the abnormal strikes, incapacity due to narcosis can often prove fatal. Further information on nitrogen narcosis along with the limits on inspired partial pressure of nitrogen are set out in Report 10.

A further adverse effect arises from the relatively high density of nitrogen which when compressed makes breathing laborious. The effect on breathing, normally referred to as "the work of breathing", has been likened to breathing through a drinking straw. Limiting the work of breathing through limiting breathing gas density is a further control measure which has been introduced into Report 10. The limits recommended are considered to represent good practice.

10.3.4. Helium

Helium is another apparently harmless gas at least in air at atmospheric pressure. It is a low-density inert gas which is used to reduce gas density in breathing mixtures and acts as a diluent to reduce both the oxygen content to counter toxicity effects and to reduce or eliminate the nitrogen content to counter the narcotic effect – see clause 8.5 of Report 10. At pressures greater than 15 bar(g) breathing helium can result in adverse neurological effects.

10.3.5. Carbon dioxide

Carbon dioxide is the largely forgotten gas of hyperbaric activity. It can be inspired from contaminated gas supplies but is largely generated in body tissues as the waste product of human metabolism and off-gassed into the lungs. It is exhaled towards the end of the breathing cycle so anything which curtails or restricts the cycle such as increased work of breathing, can lead to carbon dioxide retention and build-up in the lungs. Carbon dioxide retention results in high levels of CO2 in the blood otherwise known as hypercapnia which manifests as a range of complex physiological responses in the body and is considered to lead to an increased risk of CNS oxygen toxicity, increased narcosis from nitrogen exposure and an increased risk of decompression sickness.

10.3.6. Gas density

As any gas is compressed its density increases in proportion to the increase in absolute pressure. The increased density results in the lungs having to shift a greater mass of gas with each breath and also in greater turbulence and hence resistance in the airways. In Report 10, limits are placed on gas density as a means of limiting work of breathing and fatigue. This limits the nitrogen content of the breathing mixture which in turn limits nitrogen narcosis, carbon dioxide retention and hence oxygen toxicity risk along with DCI risk.

10.3.7. Work of breathing

Work of breathing is the physical effort of inhalation. With breathing apparatus it includes the effort to open the demand valve and maintain inwards gas flow along with exhalation - the effort to push exhaled breath through the regulator casing and past the exhaust valve. Any increase in the work of breathing due to increased physical activity or increased gas density results in fatigue and can lead to pulmonary oedema. It also leads to increased production of carbon dioxide in the lungs. Exposure to pressure leads to a reduction in the volume of air inhaled/exhaled. A reduction in the volume of gas exhaled by the lungs leads to increased carbon dioxide retention in the lungs.

10.4. BREATHING MIXTURES

Once the physiological properties of oxygen, helium and nitrogen are understood it is possible to design breathing mixtures, also referred to as mixed gas, to minimise the adverse effects of the individual component gases. Breathing mixture density can also be a limiting consideration in the mix design – see clause 8 of Report 10.

10.5. AIR TO GAS SWITCHING

10.5.1. Air breathing limits

There is no specific pressure at which it becomes unsafe to breathe air. The harmful effects increase from atmospheric pressure upwards and are well documented as in Report 10. Report 10 recommends the switch from air breathing to mixed gas breathing should take place at 3.5 bar(g). This is based on expert assessment of the increasingly adverse health effects of air breathing with increasing pressure including nitrogen narcosis, work of breathing, gas density, CO2 retention. Physiological effects are a consequence of the partial pressures of gases being breathed and cannot be altered. Clients should make it clear in the tender documents that air breathing at pressures above 3.5 bar(g) would not be acceptable and that they were prepared to bear the costs which would arise from the use of helium.

Air breathing is legally permissible up to the limits on compressed air working which are normally in the range 3.5 – <5 bar(g), under national regulations. Many of these national regulations were made decades ago and reflect the state of knowledge and industry practice of their time. A contractor can undertake such work at his discretion despite the guidance in Report 10 unless contractually bound to comply with Report 10 but would have to accept responsibility for any adverse safety or health incidents arising from that decision. National health and safety regulators can also opt use Report 10 as the basis for enforcement.

Whilst decompression must be effective, sufficient is known about decompression theory for bespoke decompression profiles to have been developed for air exposures up to 6 bar(g). Consequently decompression is not necessarily the primary factor in determining when air breathing is no longer acceptable.

The construction industry has adopted a conservative approach towards working under the influence of narcotic substances such as alcohol and recreational drugs. It would therefore be inappropriate to allow someone to work in compressed air with a higher level of impairment due to nitrogen narcosis than the impairment resulting from the equivalent effects of drink or drugs. Although there is no formal comparison, the level of impairment from breathing air at ~3.5 bar is considered to be similar to that from alcohol consumption at a blood/alcohol level which would constitute unfitness to drive in law. Additionally, high physical work rates can exacerbate the narcotic effects of nitrogen.

10.5.2. Fluctuating pressures

It is foreseeable that occasionally a project will arise on which the majority of exposures are predicted to be at pressures just below 3.5 bar(g) but due to fluctuating groundwater conditions a minority of exposures are predicted to be between 3.5 and < 4.0 bar(g). Periodic or irregular changes between air breathing and occasional mixed gas breathing in non-sat mode under such circumstances could lead to problems of unfamiliarity with procedures, changes in personnel undertaking the work etc. The client should therefore require a comparative assessment of the risks involved in changing between exposure modes and the health risks from consistently breathing air in the 3.5 - < 4.0 bar(g) range. Site specific factors such as TBM characteristics should also be assessed. Based on that assessment the client should instruct the contractor on how to proceed as the Client is likely to have to bear any commercial consequences arising from that decision. The national health and safety regulator for the country concerned should be consulted to confirm they are content with the decision reached.

Given the long term nature of saturation mode and the undesirability of frequent changes in storage pressure, should such a situation arise in saturation working, exposure pressure fluctuations should be accommodated as excursions from a storage pressure which would remain constant.

10.6. SATURATION

Saturation is a physiological condition in which the partial pressures of inert gases in the body tissues are in dynamic equilibrium with those being breathed. For people not experiencing hyperbaric environments, life is one long saturation exposure at atmospheric pressure during which they are saturated with a PO_2 of 0.2 bar and a PN_2 of 0.8 bar.

Any change in either the composition of gas breathed and/or its pressure will result in a change in its partial pressure along with a corresponding change in the gas in the tissues. That change is not instantaneous but takes place over time; the period to re-establish saturation depending on the gas involved and the properties of the body tissues themselves. Vital organs respond much more quickly than fat, muscle and bone. The speed of response is quantified as the “half-life” of the tissue concerned. Once saturation has been re-established no further net gas exchange with the tissues occurs unless the mix or pressure changes.

“Saturation” can be categorised as exposures to pressures less than 18 bar, “deep saturation” to pressures less than 30 bar and “extreme saturation” to pressures less than 34 bar.

10.7. NON-SATURATION EXPOSURES

These are defined in Report 10. Because of the relatively short duration of mixed gas non-saturation exposures not all body tissues are fully saturated before decompression begins. However, the length of time taken to decompress is largely governed by the gas load in muscle tissue and body fat. The restrictions on time at atmospheric pressure before subsequent exposures are to allow the residual inert gas which can remain in the body after return to atmospheric pressure to dissipate. If subsequent exposures begin before all tissue gas has dissipated, gas will accumulate in the tissues and lead to a progressively greater risk of DCI on decompression.

Mixed gas non-sat exposures are completed within a single working shift so the amount of productive work which can be carried out is in the range of 30 – 90 minutes depending on exposure pressure and decompression tables used. Each decompression presents a risk of DCI. For a similar amount of productive work, non-sat exposures present a greater overall risk of DCI than saturation exposures because of the large number of exposures required and the more aggressive decompression profiles used.

Report 10 limits the maximum pressure for mixed gas non-sat exposure to 8 bar(g) on safety grounds. Although the requirement in commercial diving is for the use of saturation techniques above an exposure pressure of 5 bar(g), the higher limit in tunnelling recognises that HPCA work may be required in TBMs which are too small to accommodate the space envelope required by the shuttle for transfer under pressure as part of saturation procedures.

10.8. SATURATION EXPOSURES

With saturation exposures, saturation is established in all the body tissues after a few hours in storage and provided storage pressure is not changed, no further gas is taken on or given off no matter how long the exposure period. A saturation decompression is done very slowly over a period of days and hence presents a much-reduced risk of DCI. This, coupled with the significantly longer period of productive work per day makes saturation the preferred technique when frequent interventions and/or extensive work under pressure is required. Saturation techniques are not restricted to pressures above 3.5 bar – their use below 3.5 bar is a matter for commercial judgement.

10.9. SURFACE HABITAT

A surface habitat comprises one or more interconnected chambers on the surface in which those undertaking saturation exposures live whilst not at work on the TBM. Ideally there is at least one large chamber divided into two compartments for living and sleeping as well as a separate wet chamber containing toilet/showering/washing facilities.

As part of the surface facilities there should be an emergency chamber available into which those in the habitat can be transferred in an emergency affecting the habitat itself. This chamber can also be used for treatment of DCI or of non-pressure related injuries.

10.10. STORAGE

This is the term for living in the surface habitat under saturation conditions. This is a very important part of the hyperbaric procedures and includes the provision of “hotel services” for those undertaking saturation work. It is necessary to provide food and drink, laundry, personal hygiene, as comfortable a living and sleeping environment as is possible in the circumstances, maintain a comfortable level of temperature and humidity and to maintain an environment which is free from bacterial infection.

10.11. STORAGE PRESSURE

Preferably those undertaking saturation should be kept at a storage pressure which is the same as the working pressure on the TBM. However, it can be necessary to work at a different pressure to storage. Storage pressure should be chosen and adjusted to minimise the difference between storage and working pressure. It should also be chosen to avoid the need to work at a pressure below storage pressure or to reduce storage pressure during a saturation run, both of which carry a slightly increased risk of DCS. Should either prove to be necessary the guidance in Report 10 on excursions and reduction in storage pressure should be adhered to.

10.12. TRANSFER UNDER PRESSURE.

Transfer under pressure (TUP) is a characteristic of saturation exposures. It involves the transfer of mixed gas saturation workers (MGSWs) between the habitat and TBM personnel lock using a pressurised transfer shuttle (EN 12110-2 term) which is basically a mobile personnel lock. TUP allows the MGSWs to remain under pressure and hence remain saturated. The TUP process depends on being able to clamp the shuttle to a docking flange and trunking on the habitat at one end of the transfer and to a similar docking flange and trunking on the TBM personnel lock at the other. Once docked and a pressure tight seal has been achieved, the MGSWs move through the trunking between the vessels.

It is very important to ensure there is sufficient space on the TBM to allow the shuttle to be transported from the rear of the TBM to the personnel lock along a shuttle path (term used in EN 16191). This is a responsibility of the contractor and TBM designer. Providing sufficient clear space for a shuttle path obviously limits the size of TBM on which saturation exposures can be carried out. If saturation exposures are required, a fundamental issue for the client and designer is to ensure the size of the tunnel is adequate to accommodate a TBM capable of supporting the TUP process. It is essential that where the adoption of saturation techniques and TUP are foreseeable, they must be planned for at design stage and the size of the tunnel made sufficiently large to accommodate a shuttle path. Retrofit is unlikely to be successful.

10.13. GAS RECLAIM.

The recovery of exhaled gas and its purification to separate out the helium for re-use should always be considered as helium is a scarce resource. There are currently two competing techniques – reclaimed gas is stored in a large gas bag for subsequent filtration and scrubbing outside the tunnel, before being compressed and fed into a gas mixing plant or exhaled gas is recycled at pressure in the tunnel through a regenerative filtration and scrubbing device before being fed back into the breathing circuit. Whether to reclaim gas and how to process it are commercial decisions for the contractor.

11. INTERVENTIONS & EXCURSIONS

11.1. INTERVENTIONS

Interventions are periods of work away from the habitat at pressures the same as storage pressure. Thus, no additional compression or decompression is required and hence no additional DCS risk. Interventions are to be preferred to excursions.

11.2. EXCURSIONS

Excursions are periods of work away from the habitat at pressures different to storage pressure. Thus, additional compression and decompression is required. Excursions to pressures greater than storage pressure are to be preferred over excursions to less than storage pressure. European practice requires excursions to be in one direction only per day. It also does not allow for decompression stops as part of the excursion procedure which limits the excursion pressure differential considerably particularly at what is comparatively low saturation storage pressures in comparison to diving.

11.3. STORAGE PRESSURE CHANGES

Pressure profiles for saturation runs with a constant or increasing storage pressure are fairly straightforward. Pressure profiles with decreasing storage pressure are more challenging. They can be achieved by setting a storage pressure and undertaking successively less extensive excursions as working pressure decreases. Reducing storage pressure is normally undertaken in accordance with the relevant part of the final decompression profile.

12. DECOMPRESSION PRINCIPLES

12.1. EXPOSURE TO PRESSURES

The human body can withstand pressures of 30 bar(g) and more provided the increase in pressure (compression) and the reduction in pressure (decompression) is done in accordance with well recognised procedures. Unlike exposure to noise or vibration it is not the exposure to pressure per se which is harmful but the inappropriate reduction in the pressure of exposure which results in harm. This is a very important difference.

12.1.1. Compression

Compression for non-saturation exposures in tunnelling work is typically undertaken at a rate of around 0.5 bar per minute. This is much slower than in diving. During compression the body is in a state of partial saturation until saturation has been re-established. Compression for saturation exposures is slower and includes one or more periods of stabilisation.

12.1.2. Decompression

During decompression, excess inert gas from the tissues is released into the bloodstream and hence to the lungs where it is off-gassed from the body through breathing. However, if the rate of pressure reduction is too rapid, bubbles can form which lodge in the tissues and as pressure is reduced these bubbles expand, become trapped and cause trauma which manifests as DCI.

Decompression from non-saturation exposures is normally undertaken in accordance with stage decompression principles including oxygen assistance. During decompression the body is in a state of supersaturation with the controlling principle for non-saturation decompressions being to control inert gas bubble formation to recognised relatively safe levels.

On the other hand, decompression from saturation exposures is a long slow linear reduction in pressure often with stabilisation periods which typically takes days to complete safely – typically 2 - 3 days from a storage pressure of around 5 bar(g). In the case of decompression from saturation exposure the principle is to prevent the formation of detectable bubbles.

12.2. DECOMPRESSION TABLES

Decompression should be undertaken following a recognised decompression table (a time-pressure profile) to ensure the rate of gas release does not exceed the capacity of the circulatory system and lungs to release that gas back into the atmosphere. Whilst there are various decompression tables available for mixed gas use in diving, there are few tables available with a published history of use in mixed gas tunnelling exposures. This is particularly the case for trimix and specifically for trimix saturation which is little used in diving at the pressures currently used in tunnelling.

Decompression tables are a compromise between prevention of DCI, making allowance for variations in human response to pressure and commercial expediency (minimising unproductive time). For this reason, decompression tables are not 100% effective at preventing the occurrence of DCI.

Getting regulatory approval for the decompression tables to be used is covered in clause 3 of Report 10. This can be a slow process. Clause 3 sets out recommended procedures. Hyperbaric trials should be avoided on the grounds they are not particularly cost-effective and additional monitoring of actual exposures undertaken instead.

12.3. STAGE DECOMPRESSION

Stage decompression following non-saturation exposures follows a stepped pattern of rapid drops in pressure followed by a soaking period at constant pressure. As the decompression proceeds, successive pressure drops become smaller and soaking periods longer. Oxygen or high oxygen breathing mixtures can be introduced in the final stages of decompression to increase its effectiveness.

2.4. LINEAR DECOMPRESSION

Linear decompression following saturation exposures is a long slow reduction in pressure. The rate of pressure reduction is constant for much of the decompression, but slower rate of reduction is introduced towards the latter stages of the decompression. Typical pressure reduction rates average around 0.1 bar per hour.

Oxygen partial pressures of around 0.5 bar are maintained during the decompression until a limiting volume concentration of 23% is reached after which this limit is followed for fire safety reasons. Stabilisation periods can be introduced to the decompression profile to coincide with sleep periods.

12.5. DECOMPRESSION ILLNESS

Decompression illness is the collective name for a range of acute and chronic illnesses presenting a continuum of symptoms and severity resulting from decompression i.e. the removal of exposure to pressure. Because of variation in human susceptibility, it is difficult to predict the occurrence of DCI.

The more commonly occurring acute symptoms in tunnelling are pain affecting the limbs often the lower limbs (Type 1 decompression sickness also referred to as "pain only" DCS), however occasionally neurological symptoms affecting the spinal cord or brain (Type 2 decompression sickness also referred to as "serious" DCS) can dominate which may present as paralysis or loss of consciousness.

Bone necrosis (dysbaric osteonecrosis) is a chronic form of DCI affecting the long bone joints, which can manifest itself months or years after exposure. The terms "Type 1" and "Type 2" decompression sickness are no longer preferred within the hyperbaric medical community but remain common in tunnelling practice.

12.6. DECOMPRESSION RISK

DCI risk increases with increasing duration of exposure and/or exposure pressure. In particular, non-saturation tables should give the same level of DCI risk over their full pressure and time range however many commercially available tables are less effective at higher pressures/longer exposures. When assessing the effectiveness of decompression tables, it is the risk of DCI as determined objectively by physiological monitoring which should be considered, not the actual incidence of DCI as this can be subjective and disproportionately influenced by variations in human susceptibility.

12.7. TREATMENT OF DCI

Symptoms of acute DCI following exposure can normally be resolved through therapeutic recompression and there are standard treatment regimes for this purpose. Acute DCI occurring during saturation is rare and can be treated by recompression and a change to a richer oxygen breathing mixture. However incapacitation of a team member through DCI, can lead to the saturation run having to be aborted or terminated prematurely. Acute symptoms can sometimes be hidden or masked so that the decision to seek treatment can be subjective. For chronic DCI, surgical replacement of affected joints is the normal treatment for bone necrosis.

12.8. INCIDENCE OF DCI

Use of the incidence of acute DCI arising from non-saturation exposure as a measure of effectiveness of decompression is commonplace in the tunnelling industry but often proves to be unreliable. The very low incidence of DCI in saturation practice makes it totally meaningless as a measure of effectiveness of saturation decompression. An objective physiological monitoring procedure for DCI risk, should be adopted instead.

12.9. POST DECOMPRESSION ATMOSPHERIC PRESSURE BREAK.

On return to atmospheric pressure following a decompression, the level of bubbling should have been reduced sufficiently to pose an acceptably low risk of DCI. Excess inert gas in the tissues will continue to be given off for some hours afterwards. This is why with all exposures, a period at atmospheric pressure is required before further exposure to pressure. The likelihood of residual gas in the tissues is greater after non-saturation exposures because of the more aggressive and hence less efficient decompression regimes used.

13. PROCUREMENT

HPCA work is expensive because it is a high-risk activity which requires considerable sophisticated equipment along with highly competent personnel to undertake it safely. Additionally, there is the cost of helium for use in the breathing mixture. However, HPCA work can be the preferred option in terms of health and safety because of the lower risk of DCI and the flexibility it gives to carry out routine and reactive TBM maintenance other than at pre-planned locations.

Saturation working requires much more equipment than non-saturation techniques but normally allows for more productive working. Non-sat requires less equipment but with the short productive working periods and restrictions on subsequent exposures, can require large numbers of MGSWs for continuity. Saturation can therefore be cost-effective overall.

As clients ultimately bear the cost, they should be involved in the decision-making process regarding exposure techniques and working patterns from an early stage of the project.

Clients should appreciate that deviations from the good practice recommended in Report 10, are likely to have a negative impact on the health and safety of those undertaking what is high risk work activity. This is particularly the case when a tenderer proposes the use of air breathing up to around 5 bar or higher pressure, in lieu of the more expensive but lower risk option of mixed gas breathing.

Clients should always take account of competence when appointing a contractor. Accordingly, clients should consider seeking specialist hyperbaric advice when they become aware that HPCA is possible on the project and to assist in contractor pre-qualification as an essential part of the tender procedure.

When assessing tenders, a two-stage approach is recommended. Clients should consider fully the health and safety risk attached to the proposed working procedures of each tenderer including choice of breathing mixture and exposure technique before considering tender prices.

CLIENT DECISIONS REGARDING CHOICE OF EXPOSURE TECHNIQUEPOSURE TECHNIQUE

The decisions which the client needs to ratify and act on in the planning, design and procurement of a project are:-

Is HPCA going to be used during tunnelling operations?

- If "yes" - the type of exposure technique should be determined
- For non-saturation exposures only
  • Provision must be made at TBM design stage for plant and equipment required.
  • Approaches should be made to the regulatory authority to discuss approvals, exemptions etc.
- For saturation exposures
  • Tunnel diameter must be large enough to accommodate a TBM with TUP capability.
  • Provision must be made at TBM design stage for plant and equipment required.
  • Approaches should be made to the regulatory authority to discuss approvals, exemptions etc.
- If it is foreseeable that HPCA may be required as part of the tunnelling operations or a contingency –then the type of exposure technique should be determined.
- For non-saturation exposures only
  • Provision must be made at TBM design stage for capability to install plant and equipment when required.
  • Approaches should be made to the regulatory authority to discuss approvals, exemptions etc.
- For saturation exposures
  • The tunnel diameter must be large enough to accommodate a TBM with TUP capability.
  • Provision must be made at TBM design stage for capability to install plant and equipment required.
  • Consultation with regulatory authority regarding the potential for HPCA work should be made to discuss how approvals will be achieved for the tunnelling operations especially the time and requirements for any independent specialist reviews.
- If HPCA is not anticipated under any foreseeable circumstances, then there should be clear acceptance by the Client that there may be no option for retrofit once tunnelling has begun. (This is also relevant for alternative tender submissions - see for example WG5 "Planning for Health and Safety", May 2020)
- If the client approves and accepts the use of any work under pressure, they should be made aware of the medical staff and chamber operatives requirement needed to promote and ensure safe exposure and decompression.

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