



## Hyperbarics The Logistics: Planning Behind a Successful Intervention

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### ABSTRACT

To execute a hyperbaric intervention successfully and safely, all aspects of project planning must be carefully considered. Maintaining worker safety under pressure requires knowledge of industry best practices and procedures directly related to the unique conditions of each hyperbaric worker, adequate forethought of each stage of the project, process and procedure, supervision, and management.

Hyperbaric interventions can be successfully planned and safely performed in varying hyperbaric environments: from routine maintenance inspections to complete tooling replacement and/or complex repairs. However, hyperbaric safety and logistical requirements must be engaged not only at the design phase of the tunnel project, but continuously throughout the project's life cycle.

When planning for hyperbaric interventions, it is very important to understand the following fundamentals: hyperbaric safety, compressed air regulation compliance, risk assessment, best practices, hyperbaric experience, dedicated hyperbaric life-support systems, resource availability, training, qualification, fitness, and correctly applied hyperbaric intervention methodologies specific to the tunnel's geological conditions and pressure.

*Note: The topics and discussion within this paper are deliberately focused on hyperbaric requirements within Canada, some international and North American best practices have been incorporated.*

### 1 INTRODUCTION

It is important to have a thorough understanding the functionality of specialized equipment required for hyperbaric interventions. As an example, an earth pressure balance (EPB) or slurry tunnel boring machine is a machine developed to operate in a pressurized environment combating against the natural opposing pressures of the ground which the tunnel boring machine (TBM) is mining. When conducting hyperbaric interventions, air pressure is introduced into the working chamber of the TBM slightly higher than the opposing ground pressure resulting in a pressurized space or hyperbaric environment that allows workers to perform routine inspections, maintenance, and repairs working under pressure.

There is an infinite number of variables to consider when planning for hyperbaric interventions. From the obvious variables directly associated with the tunnel's geology and TBM type, to the not so obvious variables of physical effects on the human body working while under pressure. Other planning variables to consider are regulation compliance, the availability of resources and equipment, training and qualification, variables imposed by financial restraints and/or time limitations. With good project planning and forethought, most variables can be identified, discussed and successfully controlled.

## 2 TUNNEL AND TBM DESIGN (HYPERBARIC CAPABILITIES)

If soft ground has been identified, discussions for hyperbaric interventions details should take place at the beginning of the tunnel design phase. These discussions may include routine planned maintenance interventions or simply a contingency/stand-by requirement and the systems required to support the work under pressure.

There are two significant systems required to support hyperbaric interventions: the TBM's airlock and the compressed air supply system/plant. Without these two essential components operating to compliance and functioning safely, hyperbaric interventions cannot occur. Deliberate planning and discussion regarding these two components; their capabilities or limitations, must transpire at the onset of the tunnel project.

Early planning factors for the airlock are the design and manufacturing compliance with ASME-PVHO (pressure Vessel Human Occupancy) standards, Provincial Regulations and CSA Standards. Airlock design suitability is dependent on TBM project requirements, working pressure and worker decompressions needs. If prolonged or lengthy decompression is planned for higher pressure interventions, the airlock must be suitable to safely support each decompression need. The airlock's access and egress capabilities must be understood for evacuation preparedness, and the airlock's capability to support the use of mix breathing gas supply (for > 4.5bar interventions) and/or ability to make a shuttle system for saturation intervention support must be considered.

Other important consideration for the compressed air supply plant is, the compressor(s) supply capacity and redundancy requirements, provincial regulation compliance specific to compressed air supply and compressed air filtration with certified breathing air compliance. Discussion should include detailed calculations to ensure the compressed air supply has sufficient capacity CFM/CMM (cubic meters per minute/cubic feet per minute) and pressure to support the face during interventions, as well as adequate worker ventilation at pressure throughout the interventions.

Table 1 shows three basic examples of proactive planning discussion. Hyperbaric operations are exceptionally high risk and require detailed safety work plans, regulatory approvals and notifications. In some cases, variance approvals pending the scope of work being undertaken is necessary. These requirements need time for preparation and acceptance to avoid potential project delays and cost overruns.

Table 1. Example Proactive Planning Discussion

Proactive Planning	Proactive Result	Non-proactive Result
Hyperbaric consultation on TBM airlock design and compressed air supply/plant for project compliance and suitability.	<ul style="list-style-type: none"> <li>• systems built to regulation compliance.</li> <li>• enhanced safety</li> <li>• additional project costs can be identified early.</li> <li>• compliant systems can eliminate potential project delay</li> </ul>	<ul style="list-style-type: none"> <li>• unsuitable systems or poorly designed systems that risk fail testing and compliance requirements.</li> <li>• project delay due to non-compliances and modifications</li> <li>• unplanned project costs to accommodate modifications and compliance.</li> </ul>
Pre-project planning discussions, realistic work efforts and proficiencies in relation to the anticipated working pressure and scope.	<ul style="list-style-type: none"> <li>• suitable decompression tables identified with realistic understanding of capabilities.</li> <li>• resources planned and scheduled without delay.</li> <li>• hyperbaric intervention costs can be estimated for budgetary planning.</li> </ul>	<ul style="list-style-type: none"> <li>• project delays</li> <li>• additional costs</li> <li>• failure to meet project schedule and budget.</li> </ul>
Understanding decompression obligations and resource schedule capabilities.	<ul style="list-style-type: none"> <li>• intervention schedules are planned and scheduled, minimizing TBM stoppage time.</li> </ul>	

Proactive Planning	Proactive Result	Non-proactive Result
Flexible planning of hyperbaric methodologies to support variable hyperbaric intervention pressure and scope scenarios.	<ul style="list-style-type: none"> <li>• preparedness with flexibility to quickly adapt to variable pressure or scope scenarios.</li> <li>• no delays as labour resources and equipment can be identified and planned for the intervention scenario to be readily prepared and available.</li> <li>• no unexpected costs or budget overages.</li> </ul>	<ul style="list-style-type: none"> <li>• no practical understanding of what is achievable causing potential delays.</li> <li>• last minute planning resulting in project delay and cost overruns.</li> </ul>

### 3 REGULATION ADHEARANCE

Compressed air work, now commonly known as hyperbaric intervention(s) has evolved over the past 20+ years, not only here in Canada but also in the United States, Europe, Australia and Asia through the adoption of commercial diving practices and disciplines. This evolution has transpired due to stricter health and safety requirements and project liabilities. The comparable nature of this pressure related work, along with its physical similarities to commercial diving is the main contributing factor. Fundamentally, the adaptation of commercial diving practices has elevated health and safety awareness levels and requirements within the tunnelling industry for compressed air work. Throughout all stages of hyperbaric planning, staging and execution, there must be adherence to Provincial regulations and Canadian Safety Standards as a minimum best and safe practice. Planning a hyperbaric intervention cannot start without first understanding and adhering to regulated requirements.

The following are the current Provincial regulations citing compressed air work in Canada, CSA Standard Z275.3:

- British Columbia – OHS Reg., Secs. 20.122 and 20.123
- Manitoba – WSH Reg., Sec.27
- New Brunswick – OHS Regs, Sec. 90
- Nova Scotia – Occ Safety Gen Regs, Sec. 156
- Ontario – O. Reg 213/91, Const. Projects, Secs. 332 to 397
- PEI – OHS Regs, Sec. 47.1
- Saskatchewan – OHS Reg, Part XIX
- NWT / Nunavut – OHS Regs, Part 19

Provinces without a specific regulation will typically default to the CSA Standards as a best and safe practice.

The following are examples of standards and best practices to be utilized for planning hyperbaric operations:

- CSA Standard Z275.3-09 Occupational Safety Code for Work in Compressed Air  
(Currently under review for re-publication 2022)
- CSA Standard Z275.1-16 Hyperbaric Facilities (currently under review for re-publication 2022)
- CSA Standard Z275.4-12 Competency Standard for Diving and Hyperbaric Chamber Operations
- ASME PVHO – 1 – 2019 Safety Standards for Pressure Vessels for Human Occupancy
- ASME PVHO – 2 – 2016 Safety Standards for PVHO (In Service Guidelines)
- ITA – International Tunneling and Underground Space Association. Working Group No. 5 Health and Safety in Works “Guidelines for Good Working Practice in High Pressure Compressed Air”. (V3 March 2018)
- Canadian DCIEM Diving Manual – Decompression Procedure and Tables

### 4 HYPERBARIC RISK ASSESMENT AND RISK MANAGEMENT

Hyperbaric interventions are high-risk activities executed in extremely high-risk environments. Accidents are caused by an unsafe action or condition that could be avoided with proper pre-planning, risk assessment and prevention. The recognition and elimination of unsafe actions and conditions should substantially reduce any

accident rate. Accident prevention is not separate – it is the combination of safe working conditions, proper functioning equipment and safe work procedures woven into every phase of the hyperbaric operation and its planning. The duty to provide a safe workplace is the obligation of everyone involved with the project.

A project-specific hyperbaric Hazard Risk Assessment (HRA) must be implemented as a first step to any hyperbaric intervention project. This formal hazard risk assessment will identify all conventional and hyperbaric related risks not only to personnel but also to the associated life support equipment/systems and the TBM. The initial HRA is a good baseline for the development of Field Level Risk Assessments (FLRA – see Figure 1) and safe work plans, allowing all project personnel involved with a clear understanding of the risks and control measures associated with the specific hyperbaric environment and scope of work being performed. The HRA must account for the intended compression and decompression profiles, anticipating all potential adverse effects on the body while working under pressure and/or breathing different gases. It must account for the overall well being of the workers while working under pressure.

Soft ground tunnel projects are faced with variable pressures scenarios and unreliable geologies. Risk assessment and risk management should always remain flexible throughout hyperbaric planning. It is good practice to perform a FLRA whenever there is a situational or condition change. This process will identify any new risks allowing for additional controls to be established before proceeding. Another good practice is to research past projects with similar geology and pressures and utilize lessons learned.

Hyperbaric intervention planning must first and foremost consider the health and safety of the workers performing their duties under pressure. There are many good documents and references regarding risk assessment that can be adopted during the planning phase of a hyperbaric intervention.



Figure 1. Process for Carrying out FLRA<sup>1</sup>

## 5 EMERGENCY PLANNING AND PREPAREDNESS

During a hyperbaric intervention, several pressures-related illnesses or conditions can present themselves if there is poor planning and no awareness. Failure to identify and treat a hyperbaric injury can result in fatality and/or physically debilitating injuries with long term health effects. Two examples of hyperbaric injuries (pressure injuries) are Decompression Sickness (DCS) also known as the 'Bends', and gas embolism (lung trauma). Worst case lung trauma is an Arterial Gas Embolism (AGE). Both examples have varying levels of injury severity related to them however, they can be prevented with proper planning and the utilization of approved decompression tables and procedures. Other good control measures are to ensure workers have the correct training and knowledgeable awareness of the signs and symptoms of these varying hyperbaric injuries. Project management must also take into consideration the requirement for workers to be medically

<sup>1</sup> Tunneling Health and Safety Best Practices, Ontario Tunneling Sector LMHSC: page 13, 2016

examined and deemed fit to perform hyperbaric work in accordance with the governing regulation. Project managers must be cognisant of the potential risk of conventional injuries i.e., cuts and lacerations, breaks and sprains. Conventional injuries should be controlled in addition to the hyperbaric related injuries.

Good emergency planning and protocols must include the following:

- access to a hyperbaric treatment facility on site (medical lock) and/or access to the closest general hospital with hyperbaric treatment facility (if available),
- communication protocol identifying key emergency contacts with roles and responsibilities,
- coordination with the tunnel rescue team for injured worker extraction and rescue coordination with the local fire department if they are involved with rescue responsibilities for the project.

Good emergency preparedness planning ensures the implementation of detailed procedures that will facilitate the removal of an injured worker from a pressurized environment and subsequently provide access to a hyperbaric physician and treatment facility. Emergency planning should be contingent of the HRA and FLRA. Provision should be made for emergency preparedness and emergency response from within project resources. For remote tunnel project locations, planning consideration should be given to medical evacuation means via helicopter or designated emergency vehicle to the closest town or city with a hyperbaric facility.

## 6 HYPERBARIC RESOURCE AVAILABILITY

A TBM necessitating planned or unplanned hyperbaric interventions for inspection, maintenance and/or repair means it has stopped and is subsequently no longer mining. This can be a risky situation for a project pending the geology the TBM has stopped in. Time is typically of the essence to conduct the required inspection, maintenance and/or repair work on the TBM. To ensure minimal delays, project managers should identify the availability of qualified personnel, resources, and equipment, including all redundancy. A typical hyperbaric support team will comprise of a hyperbaric supervisor, hyperbaric workers (minimum 2), air lock attendant (minimum 1), diver medical technician and chamber operator. A designated hyperbaric physician and hyperbaric safety director should be on call or onsite as needed for safety oversight.

Planning consideration should be given to supporting 24-hour hyperbaric rotations, minimizing the stoppage time for the TBM. Pending face pressure, hyperbaric crews can be rotated through different shift scenarios covering 24 hours. It is particularly important to understand what can be achieved under pressure in accordance with the prescribed decompression table and working pressure. For rotating shifts, total time under pressure must be understood (working time + decompression time). This will be a factor with respect to ensuring enough resources (qualified personnel) are available to achieve effective and safe working time at the face of the TBM for a prolonged duration.

Table 2. Example of Planning Rotating Interventions @ 3.5 bar

Personnel		Shift Breakdown	Hours	Working Time at Face
Hyperbaric Safety Director (on call)	1	Pre-shift prep & meeting	1	
Hyperbaric Physician (on call)	1	Intervention (#1) including decompression	2	50 min
Hyperbaric Supervisor	1	Intervention (#2) including decompression	2	50 min
Chamber Operator (CO)*	1	Intervention (#3) including decompression	2	50 min
Airlock Attendant (ALA)	3	Shift handover	1	
Diver Medical Technician (DMT)	1			
Hyperbaric Worker (2 per intervention) *	6	One Shift	8	2.5 hours
Personnel per shift	14	Three Shifts	24	7.5 hours

\*Three interventions per shift

Consideration must also be given to ancillary support equipment i.e., medical lock availability onsite, availability of a transfer under pressure (TUP) shuttle lock to support planned decompression and shift rotations. If higher pressure interventions are planned and necessitate the use of mixed breathing gas, breathing consumption rates must be calculated and bulk gas supplies pre-arranged with redundancy.

Individual sub-planning efforts are needed for each hyperbaric intervention shift. This will address more specifics related to the scope of work conducted including availability of required tooling and rigging, tool air and water supply, welding supplies if needed, as well as any specialty PPE that may be required. The most challenging planning factor is to ensure personnel working under pressure are provided the ability to maximize their time working on the face of the TBM, eliminating down time or lost time as each intervention is limited.

## 7 VENTILATION PLANNING / FACE SUPPORT AND AIR LOSS MAINTENANCE

Before a hyperbaric intervention commences, the stability of the ground must be confirmed; first establishing stability and second, maintaining stability throughout the interventions. A plan for the use of bentonite slurry to seal the face must be developed to ensure the slurry has the correct properties required to consolidate the existing ground conditions. Any specific requirements related to the EPB or Slurry machine and the existing materials within the excavation chamber should also be considered. Additionally, a refilling plan is also important pending the duration of the interventions and potential for loss of pressure and face support.

When scheduling for the TBM's stoppage duration, it is important to recognize that the bentonite flooding and face sealing process typically requires 24 hours of preparation prior to the hyperbaric intervention. Post flood or post the 24 hours, the faces capability to hold pressure will be tested and monitored for at least one-hour prior to the working chamber before deemed safe for entry by hyperbaric workers. During this 24+ hour period, other preparations will be underway, such as equipment and support systems testing, final FLRA and briefing, and final decompression planning based on the known working pressure, scope, and conditions.

Once face stability is achieved, control and maintenance of the face pressure will be handed over to the hyperbaric team. The hyperbaric team must have planning and procedures in place to ensure the correct air pressure has been calculated and maintained, mitigating the risk of excessive air loss or over pressurization. An air loss monitoring procedure should be developed and maintained throughout the hyperbaric intervention, along with a ventilation plan (for air interventions) in compliance with appropriate confined space regulations.

## 8 PLANNING THE CORRECT INTERVENTION METHODOLOGY

When hyperbaric interventions have been identified as an essential requirement in support of tunnelling operations, it is particularly important to recognize and understand the different methods available to ensure safety and productivity. Understanding these will facilitate planning efforts at the onset of the project. They can be considered 'tools in the toolbox' to successfully support work requirements with variable pressure and scope scenarios. Three key factors defining what methodology will be most efficient, productive, and best suited are:

1. Pressure: Requirement for the use of air or mix gas, define decompression requirements, requirement for the use of saturation
2. Airlock: Access, functionality for a TUP/shuttle lock
3. Scope: Time required for inspection, cleaning, obstruction removal, tool replacement, repair

### 8.1 Methodology – Single Bounce Intervention

Bounce interventions can be performed in a shorter time frame with or without decompression commitment based upon the intervention pressure. Note: > 3.5 bar will likely require decompression planning; however, the decompression obligation can be prearranged as a minimal requirement. Typically bounce interventions will use air only, though they can be planned using mix gas at higher pressures with minimum commitment to decompression. The optimal outcome for a bounce intervention is to allow hyperbaric planning and execution with limited risk and resources.

## 8.2 Methodology – Multiple Rotating Interventions

Rotating interventions afford planning for longer extended hours and/or days of hyperbaric operations. This intervention planning is suited for tooling replacement, debris removal or larger scale repairs that need multiple days of effort. Workers remain under pressure for the maximum safe allowable time and are committed to decompression at the end of their working shift. These interventions can be planned using air (typically <3.5bar) and mix gas (typically >3.5bar). Worker's swap shifts at the airlock and rotate through multiple interventions over the shift period to provide continuous 24-hour coverage with maximum efficient working time under pressure. Shift scheduling can be 3 x 8-hour shifts, 2 x 10-hour shifts, or 2 x 12-hour shifts, all providing a continuous 24 hours of work coverage.

Where practicable, rotating interventions should utilize a TUP/shuttle lock to transfer the workers and air lock attendant post shift from the airlock to the designated medical lock on site. The transfer system will keep workers at a designated decompression pressure and be incorporated into the decompression schedule planned for each intervention. If the transfer option is not feasible, decompression obligations must be planned and performed within the airlock. For efficient and safe decompression planning, consideration of the workers wellness must be accounted for due to the cramped and uncomfortable conditions within the airlock. The project hyperbaric physician and hyperbaric safety director must be consulted on this planning. Consideration should also be given to airlock modifications at the design phase of a project if the utilization of a TUP/shuttle system is not optional. This process will identify possible modifications required to support longer duration decompression requirements and enhance the safety of personnel decompressing.

## 8.3 Methodology – Saturation Interventions

Saturation extends capabilities to implement long duration hyperbaric operations over multiple days and weeks. Furthermore, saturation allows the planning of hyperbaric interventions at very high pressures i.e., 6bar and above. These high-pressure interventions preclude the use of decompression on a rotational basis. Saturation will allow workers to remain under pressure for an extended period, e.g., up to 20 days, working on the TBM for uninterrupted 4/6hour shifts. In saturation, workers typically breathe a mixture of Helium and Oxygen (HeO<sub>2</sub>) throughout. They rest and live under pressure in a saturation habitat facility. The saturation habitat can be designed to accommodate 4 or more workers with sleeping quarters, toilet facility and shower. In support of saturation operations, the airlock system must be designed to operate with a mating TUP/shuttle lock system. Worker's swap shifts in the airlock, then are transported under pressure back to the saturation habitat via the TUP/shuttle lock system for rest when not on shift.

## 8.4 Additional Planning

In support of the above three methods, additional planning is needed for the design and availability of the tunnels multi-service vehicle to accommodate/mount the TUP/shuttle lock system. Design planning may be needed to identify a means to support the TUP's ability to be elevated and connected to the TBM airlock. Other items to consider during planning include:

- Regulated planned maintenance of TBM airlock and systems throughout the project
- Regulated planned maintenance of compressed air plant and quality air testing throughout the project
- Airlock and/or working chamber modifications to support HP and LP water supply, tool air, welding leads, mop line etc.
- Diving option for flooded working chamber interventions with airlock modification to support
- Laydown area for medical lock and/or saturation habitat with power, potable water, grey water removal

## 8.5 Hyperbaric scheduling assumptions for planning

Below is a table identifying high-level scheduling timelines to consider for hyperbaric planning and scheduling.

Table 3. High Level Schedule Planning Timelines

Action	Task	Estimated Duration
Develop	Hyperbaric Intervention Procedure Manual (HIOP) with approvals	3-4 months
Complete	Variance applications related to hyperbaric work	4-6 months
Schedule	Logistics meetings, i.e., hospital/hyperbaric staff, provincial regulators, emergency support	4-8 weeks
Test	TBM airlock modifications as/if needed, with modification testing	4-6 weeks
Assess	TBM compressed air system and airlock with compliance testing	3-5 weeks
Train	Pre-launch cutterhead familiarization for all hyperbaric workers	2-3 days
Mobilize	Medical lock and TUP/shuttle with ancillary hyperbaric support equipment. Duration includes 2-3 days onsite for required systems set up and compliance testing	2-3 weeks
Prepare	Medical lock, TUP/shuttle with ancillary hyperbaric systems prior to interventions	2-3 days
Mobilize	Saturation habitat and TUP/shuttle with ancillary support equipment. Duration includes 1-2 weeks onsite for systems set up and compliance testing	4-6 weeks
Activate	Prepare saturation system and bring online prior to interventions	3-5 days

## 9 CONCLUSION

As we continue to respond to an increasing demand for underground infrastructure, EPB and Slurry TBM technology is evolving allowing for soft ground tunnels to be designed and constructed in challenging geology with varying pressure environments. Parallel with the evolution of tunnel construction capabilities is the requirement for hyperbaric interventions to support and mitigate the challenges inherent with soft ground tunnel construction and ground pressure. Hyperbaric intervention planning demands a proactive and practical approach at the commencement of every soft ground tunnel project.

Working in conjunction with design engineers, construction management teams, TBM manufacturers and tunnel contractors, hyperbaric specialists can ensure the TBM's airlock and air supply system are practicable and compliant, and ensure hyperbaric interventions are planned safely and performed with minimal impact to the tunneling schedule and budget.

Quality planning is a requirement for all project activities. Hyperbaric interventions can be performed with optimal success through proper allocation of resources. Proactive hyperbaric planning demonstrates that hyperbaric risks can be mitigated with formal assessment, risk management and emergency preparedness. Project budgets and schedules can be successfully attained with suitable hyperbaric methodology planning. Preventative maintenance inspections and tooling changes can be completed safely with minimal interruption to mining. Full cutter head repairs involving structural welding can be accomplished under pressure with great success. "If you fail to plan, you are planning to fail!" (Benjamin Franklin)

## 10 REFERENCES

- American Society of Mechanical Engineers (ASME) "PVHO-1-2019: Safety Standard for Pressure Vessels for Human Occupancy"
- Canadian – Defence and Civil Institute of Environmental Medicine Decompression Procedure and Table "DCIEM Diving Manual"
- Canadian Standards Association "CSA Standard Z275.1-16 Hyperbaric Facilities"
- Canadian Standards Association "CSA Standard Z275.3-09 Occupational Safety Code for Work in Compressed Air Environments"
- Canadian Standards Association "CSA Standard Z1002-12 – OHS – Hazard Elimination and Risk Assessment"

ITA – International Tunneling and Underground Space Association. Working Group No. 5 Health and Safety in Works “Guidelines for Good Working Practice in High Pressure Compressed Air” (V3 March 2018)

Ontario Infrastructure Health & Safety Association’s (IHSA) Labour Management Committee Tunnelling Sector – Labour Management Health and Safety Committee (LMHSC) 2016 “Tunneling Health and Safety Best Practices”