12th U.S./North American Mine Ventilation Symposium 2008 – Wallace (ed)
ISBN 978-0-615-20009-5

Ventilation and atmosphere control inside a 3-bar compressed air TBM heading

B.R. Zernich
Traylor Brothers Inc., Los Angeles, California, USA

M.A. Krulc
Traylor Brothers Inc., San Diego, California, USA

ABSTRACT: Advances in tunneling technology, such as Earth Pressure Balance and Slurry Shield methods, have allowed the tunneling industry to construct tunnels in increasingly difficult ground conditions. In recent years, a number of civil projects including large diameter train tunnels, subway tunnels, water tunnels, sewer tunnels, and combined sewer tunnels have been successfully completed deep beneath the water table in soft ground conditions utilizing modern day Tunnel Boring Machines (TBM). With the increase in difficult ground conditions and higher water pressure comes the inherent need to utilize compressed air to gain access to the TBM's cutterhead and cutting tools. This paper focuses on one such instance in Los Angeles, CA in which Traylor Brothers Inc. performed a cutterhead intervention by compressing the heading of an 11-foot diameter tunnel to approximately 3 bar gauge pressure. This paper focuses on the environmental controls used to manage ventilation, oxygen levels, temperature, and pressure, as well as discusses the problems associated with toxic gases and the increased risk of fire. The paper will also cover the physical science of the environment and the increased risks of performing basic job functions while in a compressed air heading.

1 Background

The use of compressed air for ground water control was introduced to the world with the advent of the modern day "air lock", patented by Admiral Sir Thomas Cochrane in the year 1830 (Hewett and Johannesson 1922). Since its' inception, compressing the atmosphere within subaqueous excavations has been used as a tool for tunneling and caisson development throughout the world. The primary purpose is to balance the hydrostatic pressure within an excavation, reducing the inflow of water and thereby stabilizing the ground.

The first application of tunneling, using a shield and compressed air in conjunction, occurred in 1886 during the construction of the London and Southwark Subway. Shortly thereafter, the combination of shield tunneling with compressed air became increasingly effective with the completion of the Sarnia tunnel beneath the St. Clair River, connecting the United States and Canada. Other projects quickly followed suit, such as the Blackwall tunnel under the Thames in London and the completion of the Hudson tunnel, connecting New Jersey and Manhattan.

However, the use of compressed air for tunneling was often very dangerous and not without limitations and adverse side effects. Often, work within a compressed air environment led to de-compression illness or "bends" and other health related complications. This prompted the advent of modern day earth pressure balance (EPB) tunnel boring machines, followed by the slurry and mixed chamber shields. These machines do not require a compressed air atmosphere as a medium for controlling ground water while mining. They counter-balance water and ground pressure by utilizing a sealed chamber within the front of the shield, whereby workers are protected in normal atmospheric conditions within the tunnel.

Nevertheless, even with the use of modern day EPB, slurry, and mix-chamber shields, compressing the atmosphere is still a necessary and convenient method for gaining access to the cutterhead or mixing chamber of a soft ground TBM, but not without risks. Not only are maintaining oxygen levels adequate for human survival and monitoring for toxic gas of extreme importance, but human performance and comfort factors must not be neglected either. Contingency plans must be well thought out ahead of time, and systems for monitoring and controlling the environment within a compressed air TBM heading must be in place before starting any compressed air operation.

2 Case History

2.1 NEIS Project – Los Angeles, CA

In 2002, Traylor Brothers Inc., of Evansville, Indiana (Traylor) was contracted to excavate an 8,000 meter long, 4 meter diameter tunnel for the City of Los Angeles, Department of Public Works. The project replaced an aging main-artery brick lined sewer that was in desperate need of repair. Expected ground pressure was on the magnitude of 3-bar, or the equivalent of 30 meters of water. Traylor procured two Lovat EPB-TBM's to mine two separate soft ground drives along the alignment. One of the significant challenges of the project was the excavation of a rather long section of tunnel between two drilled shafts, where access to the cutterhead chamber was severely limited due to the high groundwater pressure, alluvial geology, and the densely populated urban environment (Zernich et al. 2005).

2.2 Planned Cutterhead Intervention

Within the described section of alluvial geology and high water pressure, and based on previous experience, Traylor decided that the TBM would not be able to mine the 1200-meters needed to reach non-earth pressure conditions without at least one cutterhead intervention. Traylor decided to perform a planned intervention about half way through the section by jet grouting an area of ground ahead of the TBM where the City of Los Angeles had provided an empty lot where access for grouting was possible.

The intended purpose of this jet grout plug was to create a "refuge" that would encapsulate the TBM and protect the cutterhead chamber from the high ground water pressure. Since the use of compressed air as a means for intervention was not desirable at this high pressure, Traylor intended to use the jet grout method first and only use compressed air if it became absolutely necessary. Once the TBM was parked within the grout zone, access could be gained in normal atmospheric conditions. After extensive chemical grouting, crews were able to gain access to the cutterhead even though water was still infiltrating around the TBM at 150 to 190 lpm.

2.3 Why Compressed Air?

During the initial intervention, small voids in the jet grout plug were immediately noticed in the face and on occasion these voids would burst pressurized water. Nevertheless, approximately 40% of the cutterhead tools were replaced before a substantial water inflow occurred bringing with it methane gas, and force the crew out of the cutterhead. After additional grouting attempts failed, Traylor chose to use compressed air as a means of completing the intervention safely.

2.4 Compressed Air Intervention

During the summer of 2004, the working chamber was compressed to 2.6 bar (38 psi) (see Figure 2). The first entry was conducted with 5 people, using a 3 hour work time and a 4 hour/2.76 bar (40 psi) decompression table. The second entry was increased to a 4 hour work shift using a 4 hour/2.76 bar (40 psi) decompression table. However, after the second entry a worker complained of knee pain, and was diagnosed and treated for Type I decompression sickness. Thereafter, Traylor reduced the working time back to 3 hours, using an adjusted Cal-OSHA 3 hour/2.76 bar (40 psi) decompression table. Traylor continued compressed air operations using three crews per day, six days per week for

Figure 1 – Caisson Gauge

the following three weeks. During that time two other workers complained of decompression illness symptoms, but doctors ruled that it was not decompression sickness but more likely anxiety. In total, over 200 entries were conducted during this intervention, with only one confirmed case of decompression sickness.

2.5 TBM Airlock Configuration

The Lovat TBM was affixed with a dual chamber airlock, which was incorporated into the trailing gear and towed behind the TBM shield. This lock was not attached directly to the mixing chamber of the TBM due to space limitations within the shield. Therefore the airlock chambers were quite large compared to typical airlocks and were relatively comfortable during the longer decompression cycles.

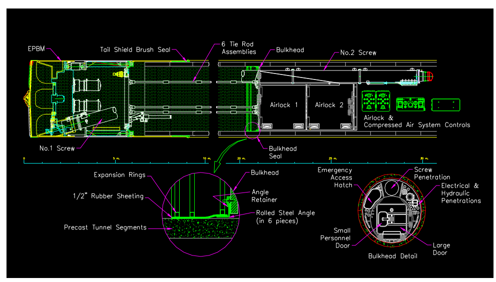

Figure 2 – Heading Arrangement Drawing

3 Engineering Controls

During a compressed air operation, environmental control can be easily overlooked with so much effort being placed on the primary task of changing cutterhead tools. However, ventilation and environment control within a


Figure 3 – Hyperbaric Chamber – Installation

compressed air heading need to be well thought out and resolved with unconventional methods to ensure that proper ventilation is still being achieved. Obviously, a concern for the workers comfort and well-being through proper ventilation and environment control can make work more productive and ultimately more successful. The goal for any compressed air engineer, especially at higher pressures, is to limit the exposure to the human body by completing the assignment as quickly as possible without compromising overall safety. By controlling the environment, mainly temperature, humidity, and air flow, a compressed air entry will be safer, more relaxing, less stressful to the body, and ultimately more productive. This type of work can put un-ordinary stress on the ordinary worker, so the better prepared and comfortable the work environment is, the more likely a successful operation will be achieved.

3.1 Ventilation

Many compressed air headings have natural air flow as a result of air being absorbed into the ground due to the geology. Also, within a lower pressure operation (i.e. <1bar), it doesn't take as much differential pressure to overcome the hydrostatic water pressure, thereby easily pushing more air into the ground and, in turn, ventilating the heading.

The following example shows that the same variation in heading pressure has more impact in a 1bar heading than in a higher pressure, 3bar heading:

Ph = 1 (bar)
Pw= 1.1 (bar)
1.1bar > 1 (bar) ≈ 9.1% higher than hydrostatic pressure

Ph = 2.9 (bar)
Pw = 3 (bar)
2.9 > 3 (bar) ≈ 3.3% higher than hydrostatic pressure

Where:
Ph = Hydrostatic Water/Ground Pressure
Pw = Working Pressure

For obvious reasons, at higher working pressures (>1.5bar) one can not afford to compress the heading any higher than one has to. If the ground is not absorbing enough air to properly ventilate the heading, then other measures have to be taken. Also considering the situation that Traylor was in, with the face being entirely made up of jet grouted ground, air absorption into the ground was not occurring. In fact, once the working pressure was reached, the heading required very little additional air to maintain pressure. In order to exchange the air and create flow within the working chamber a scavenger line had to be installed to achieve a steady exchange of air while maintaining pressure. It should be noted that in a situation like this, a scavenger line must be located at the opposite side of the workings from the air inlet point. There will not be adequate circulation within a heading by simply removing the air near the entrance point because the air will short-circuit between the inlet and outlet.

3.2 Temperature

Heading temperature can have many adverse effects on worker's safety and comfort. Working within high ambient temperatures can cause fatigue, exhaustion, and de-hydration, which can lead to other complications during the compressed air exercise. The ambient temperature within a heading must not be overlooked while planning for compressed air work.

From thermodynamics, we learn that compressing air generates heat from the friction between moving gas molecules as they consolidate. Considering an isentropic compression of an ideal gas as a reversible and adiabatic process, we can approximate the temperature rise during air compression from Eq. 1 (Cengel and Boles 2002).

$$\frac{P2}{P1} = \left(\frac{T2}{T1}\right)^{k/k-1} \qquad (1)$$

Where:
T1,2 = temperature (C)
P1,2 = pressure (Bar)
k = specific heat ratio for an ideal gas

As an example of the estimated temperature rise we will assume the following.

T1 = 21.1°C
P1 = 1bar abs.
P2 = 3.7 bar abs.
k = 1.4

The factor for k was gathered from the specific heat table for air with an assumed average temp of 27°C. Thus, solving for T2, the new temperature is 30.7°C. From measurements taken during operations compared with the values given above, the results matched fairly closely, which indicates this was a good approximation.

During decompression the previous logic holds true, and we expect a decrease in temperature with nearly the same variation. During both compression and decompression, the temperature changes can create an uncomfortable work environment.

Compression generally occurs as fast as possible in order to increase work time during the operation. Thus, it can be a challenge to control the temperature during the short amount of time compression takes place and often it is neglected. In Traylor's case, air dryers were installed to prevent an abundance of humidity; however it was still relatively warm during compression.

The working chamber on the other hand, is a larger body of air already maintained at a specific air pressure, where cooling can be achieved by creating flow and introducing cooler air from the system with air chillers. This can provide a more comfortable work environment and increase productivity. In Traylor's case, the heading was generally warm, with temperatures exceeding 27^{o}C. Air coolers would have been the next step to bring working temperatures down inside the heading.

Ambient air temperature during long decompression cycles should not be overlooked either. Over the course of a work shift, employees' bodies have exerted a fair amount of energy and core body temperatures have become high. However, during decompression the body is required to generally relax, and as temperature levels begin to fall inside the hyperbaric chamber, the body can become quite cold, especially to someone covered in sweat and wearing wet clothes. This isn't healthy for the body, and workers can become sick, which in turn causes delays to the intervention and loss of production. To combat this, Traylor implemented several controls. Workers were required to bring a change of clothing for the decompression cycle, and electric space heaters were built into the airlock to counteract the effects of the temperature change. These measures proved to be an effective way to deal with temperature decline and should be thought about before starting a technical operation like this.

3.3 Oxygen De-compression

While performing higher pressure compressed air work it becomes necessary to use oxygen during decompression to reduce the likelihood of developing decompression illness. Oxygen helps the body dissolve inert gases, such as nitrogen, which are absorbed by body tissues and blood during compression. However, oxygen in concentrations higher than 22% can cause hypoxia and become lethal if absorbed by the body exposed to pressures greater than 0.7bar. For this reason, 100% oxygen must not be administered until the lower pressure stages of decompression are reached.

For this intervention, Traylor used a Built-In Breathing Systems (B.I.B.S.).mask with 100% oxygen that was plumbed through the airlock using single stage regulators. B.I.B.S. masks with vacuum exhaust lines are available and should be used in hyperbaric chambers to prevent accidental build up of oxygen within the environment. Traylor was not able to procure these masks in time, and had to allow discharge straight into the chamber. Either way, control measures have to be taken to ensure that oxygen levels do not reach dangerous levels. Traylor implemented the following procedures; first, direct sampling oxygen sensors were installed and monitored to ensure oxygen build up was not occurring inside the lock. Second, oxygen storage tanks were kept on the free air side of the chamber where lock tenders could control their use. No oxygen was made available to the workers until the chamber pressure was below lethal levels for 100% oxygen to be administered. If the oxygen detectors alerted the lock tenders that levels were too high, the oxygen could be discontinued until the problem was resolved. Third, oxygen technicians were introduced during the final stages of decompression to assist workers with their B.I.B.S. mask and prevent malfunctions and oxygen leakage. Forth, extra masks were made available inside the hyperbaric chamber in case of failure. Finally, ventilation was created by exhausting and maintaining air flow through the chamber during the entire decompression to ensure an adequate exchange of air. This type of system should be in place and strictly adhered to during technical compressed air work.

Figure 4 – Workers during oxygen decompression. (Notice the technician without a B.I.B.S mask within the airlock assisting workers during decompression.)

4 Compressed Air Atmosphere

4.1 Physical Nature

Within any compressed air heading the physical make up of the atmosphere has changed from its original state. During compression, additional air molecules have been added to a specific volume to create pressure. The molecular ratios of gas within the air, mostly oxygen and nitrogen, have not changed, but the total amount of gas molecules has.

As an example, within a specific volume of air at sea level, the absolute pressure exerted on the body is equivalent to 1 atmosphere or roughly 1bar. If the absolute pressure increases to 2 bar (1bar-gauge) the amount of gas molecules has doubled within the same volume of air. If it increases to 3 bar-absolute it has tripled, and 4 bar absolute has quadrupled the amount of gas molecules within that volume of air.

In Traylor's case, the pressure within the heading was increased to nearly 3bar-guage and so the amount of gas molecules within that heading had multiplied by a factor of 4. This means that while the percentages or ratios of oxygen to nitrogen were the same as normal atmospheric conditions, there were four times as many oxygen molecules within the heading. This can have serious effects if it is not addressed.

4.2 Fire

Fire in a compressed air heading is a serious risk with potentially deadly consequences. After ignition, fire needs two things to burn; oxygen and fuel. As described above, there was an abundance of oxygen within the heading, so extreme care was taken not to cause any unnecessary ignition or fire. Fire suppression equipment was installed in strategic locations prior to starting work, including inside the working chamber, the cutter head, and within the hyperbaric chambers. Keep in mind that a tunnel water system's pressure is reduced equally by the effects of the atmosphere pressure within the heading, and if normal operating pressure is not sufficient, a secondary pump must be installed. This should be checked prior to starting work.

4.3 Cutting and Welding

Cutting and welding are obvious sources of ignition, which as stated above, can have lethal consequences. Precautions have to be taken in order to perform these tasks in compressed air headings without accidents.

First, the use of common acetylene for burning/cutting is not permitted within any pressurized condition, including underwater diving. Acetylene (C_2H_2) is considered a hydrocarbon of the alkyne group and is an unsaturated organic compound. Acetylene is fundamentally unstable because of its molecular carbon-to-carbon triple bond, which, when subjected to pressure, will decompose to benzene with an exothermic reaction. As a gas it can explode with a violent reaction when subjected to pressure above 1 bar and therefore it is often replaced in compressed air work with Mapp gas. Mapp gas is a tradename for a cutting gas from the Dow Chemical Company, and is a liquefied petroleum gas mixed with methylacetylene-propadiene. It does not burn as hot as acetylene, but is safe under pressure.

Due to the risk of running separate hoses and exposing more gas and oxygen to the heading, Traylor decided to only use an air arc for cutting within the cutterhead chamber instead of Mapp gas. An air arc uses electric welders high current output combined with a special carbon rod mixed with compressed air to create high temperatures to cut steel. Air arcing is generally a very clean cut, but on thicker surfaces can take extra time compared with traditional oxygen-acetylene cutting. Nevertheless, Traylor believed this extra cutting time outweighed the risk of cutting with Mapp gas and oxygen.

Welding was done with an electric arc welder as normal. However, during all cutting and welding exercises a gas tester was in place to test the atmosphere for explosive or toxic gas as well as make sure that the air within the heading was moving and ventilating properly. It should be noted that it can be very easy to rid the environment of the smoke and fumes from welding within a compressed heading by simply installing a scavenger hose near the source of emission that is routed to the free air exhaust system.

4.4 Hygiene

It must not be neglected that hygiene and overall sanitation is of utmost importance inside both the airlock and the heading. Measures must be taken to ensure that the worker's health is not compromised by poor sanitation. Facilities should be well thought out and set up before starting any operation. Traylor made great efforts to ensure that the locks were disinfected and sanitized each day while operating. Tunnels in general are inherently dirty; however sanitation has to be maintained during this operation.

4.5 Gas

The infiltration of gas, such as methane and hydrogen sulfide are greatly reduced within a compressed air environment. Methane and dissolved gas within ground water is pushed away right along with water and thus becomes less likely to infiltrate a heading. If compressed air headings are kept at levels higher than acting hydrostatic pressure and water and gas are not allowed to enter the heading, the likelihood of gas infiltration decreases greatly. This should be addressed when determining the operating pressure of a heading if the presence of gas is already known. For Traylor the presence of methane was a concern along the entire alignment and even within the compressed air heading it had to be addressed, thus the operating pressure was increased to a level where no water was allowed to enter the heading. Nevertheless, a gas tester must be present at all times during the exercise.

5 Conclusion

Though the use of compressed air over the course of history has ultimately proven to safely facilitate mining through difficult ground below the water table, numerous hazards still exist, especially with regard to inadequate ventilation. Mitigating factors must be foreseen well ahead of time and operational flexibility must be maintained to assure safe and economical accomplishment of the work.

This project was an example of a successful tunneling experience demonstrating the importance of ventilation and atmosphere control in a compressed air environment.
Though very much a challenge for Traylor management and engineers, this cutterhead intervention and tunnel

project was ultimately completed while gaining a great amount of respect and experience for working within a compressed air heading. Because this type of work is not undertaken on a regular basis, it is important to review and carefully plan and account for each of the factors discussed in this paper as well as additional factors that may be required to successfully complete future compressed air work. Worker safety and comfort must be given the utmost thought and planning when executing this type of work.

References

B. Zernich, M. Krulc, and B. Robinson, 2005, Northeast Interceptor Sewer Case History, pp 357, *RETC Proceedings*

B.H.M. Hewett and S. Johannesson, 1922, Shield and Compressed Air Tunneling (McGraw-Hill Book Co. Inc., New York)

E. Campbell, MD, 2006. http://www.scuba-doc.com Oxygen Toxicity

http://64.78.42.182/sweethaven/BldgConst/Welding/lessonmain.asp?lesNum=4&modNum=1,2001-2006, Sweet-Haven Publishing Services