Boring Deep Tunnels

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The process of digging tunnels deep underground has changed in the last three decades, due largely to the Tunnel Boring Machine (TBM). This has revolutionized the compressed air mining and tunneling industry, creating a whole new world. The TBM consists of a circular, rotating, cutting head or face, which may be from 5 to more than 10 metres in diameter. This is pushed forward as it cuts, while a tunnel is cemented behind it. The modern pressure-shielded TBM allows compressed air workers to work most of the time in a relatively safe one-atmosphere environment behind the face. Occasional excursions (interventions) into the pressurized head space through a man-lock are performed to service the cutter head. These interventions may involve only two or three workers at a time and may last minutes to a few hours, in sharp contrast to the traditional "sand hog" operation where dozens of workers worked shifts as long as could be managed within a normal work day. Another fundamental new development is the extensive use of oxygen. Oxygen breathing is limited in some jurisdictions, but there is no doubt that oxygen can greatly improve both the speed and the reliability of decompression. Its use requires following well-established safety procedures. TBM depths may exceed the narcotic limits for effective work using air as a breathing gas, so operators may use breathing mixtures containing non-narcotic helium. Wide experience with such mixtures in diving is finding its way into tunneling practice. Modern TBM techniques allow work at pressures much greater than those considered normal for traditional compressed air methods, and as a result the rules and requirements may not be appropriate. For example, the maximum pressure allowed by the U.S. OSHA rules is 50 psi, or about 3.5 bar gauge. Variances from these rules may require physiological and medical as well as political expertise to manage. These techniques are being used in the 22 km, 8 bar Brightwater Project north of Seattle, WA.

Introduction

Tunnel and caisson work in the old days involved hordes of sandhogs, digging with the muscles of their shoulders and backs. The image that should come to mind is that of the Brooklyn Bridge, which left its engineer a cripple. Categorically, compressed air work has caused a lot of injury. In fact, the organizer of this meeting, Dr. Kawashima, has devoted much of his life to helping these workers with bone necrosis and other problems.

More recently automatic machines have been used for digging caissons; a diagram of one is shown in Figure 1. Several years ago some attendees at a meeting in this series actually got to visit a caisson in Tokyo, although we did not go under pressure. Digging was being done using remotely controlled tools. Workers only entered the caisson pressure when repair was needed. An earlier example is the Maiko West Bridge. As I recall Dr. Mano was consultant on one side of the river and Dr. Nashimoto on the other (2, 3). In any case these caissons were done in the same manner. In fact, we saw a lovely young lady sitting at the controls in the surface control room operating the machine remotely with great skill.

Workers had to enter pressure only when something went wrong or changes were needed. There were few workers under pressure, but because of archaic rules they still had to decompress in many cases without benefit of oxygen. Decompression is still a major factor in tunnel and caisson work. In Japan the caisson master or operator often performs the decompressing in an empirical manner based on his experience. Where decompression tables are used the ones available from the government are woefully inadequate.

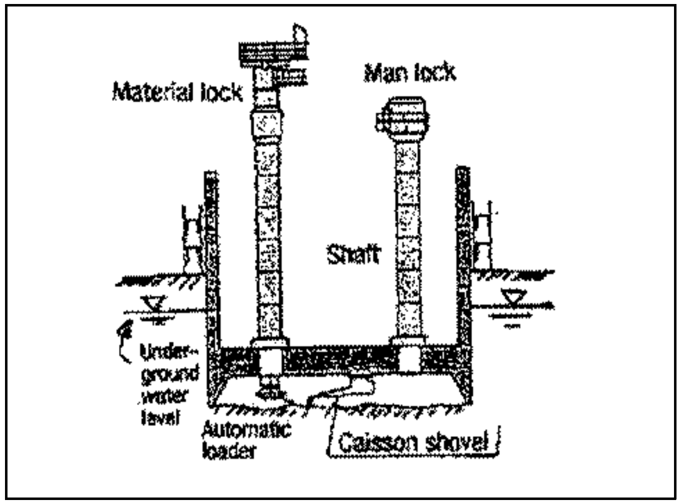

Figure 1. Sketch of automatic caisson system. Remotely controlled shovel digs out, and caisson is lowered. From (1).

Use of Oxygen

It is not necessary to tell the readers of this document about the benefits of breathing oxygen during decompression. Oxygen makes decompression a great deal more reliable—"safer" if one wants to use that term—with far less decompression sickness and the subtle subclinical disturbances that may have lasting effects but that seldom get treated. Among these decompression disorders is aseptic bone necrosis, also known as dysbaric osteonecrosis since it is caused by changes in pressure. And decompression with oxygen is much faster and therefore less expensive. Japan still does not allow oxygen officially, but Dr. Mano has used it successfully by getting special permission, a "variance," allowing a deviation from the rules.

In the USA not only is oxygen not allowed, but the decompression tables required by the Occupational Safety and Health Administration are not at all adequate at the higher pressures, leading to substantial dysbaric osteonecrosis. This has been well described by Dr. Kindwall (4). These are the so-called "Duffner" or Washington State tables. Although the US Department of Labor rules do not allow use of oxygen on a regular basis, it is possible to get variances allowing its use because it makes the work safer.

Oxygen has been used in the US, however, for compressed air work on an experimental basis. Jones (5) got permission to study the use of oxygen in some 14,000 decompressions, without serious incidents and with outstanding success. The successful use of oxygen in Hong Kong is reported by Ronson in this symposium (6). Oxygen has been used with such success in Germany that it is now mandatory for compressed air decompressions. Oxygen has finally become approved for use in Great Britain. However, at least until recently some doctors in the UK have continued to try (!) to treat decompression sickness with air and without oxygen. Other places where oxygen has been used successfully for compressed air decompression include Brazil and France. Results with oxygen have been excellent, reducing DCS and injury, and making decompression shorter and more efficient. Oxygen was tried with good results in Japan in 1959, but inadequately trained workers caused a fatal fire and its use has been prohibited since then (7).

Kindwall and his colleague Peter Edel have produced a set of laboratory-tested compressed air decompression tables that use oxygen breathing (Kindwall et al, 1983; Kindwall, 1994). A sample Kindwall-Edel table is shown in Figure 2.

PO_2 on bottom breathing air at 36 psi = 0.72 atm

36 psi

Exposure time	Time to 1st stop	Decompression stop pressures, psi.							Total deco time
		Breathe air					Oxygen (breaks)		
min	min	32	28	24	20	16	12	08	min
30	6							10	18
60	6						5	15	29
90	6						5	35(1)	54
120	5					5	5	50(2)	79
150	5					5	10	70(3)	109
180	5					5	15	85(3)	129
240	4				5	10	20(1)	110(4)	179
Tables below for contingency only, > 8-h day									
360	3			5	5	15	55(3)	140(5)	269
480	2		5	5	35(1)	45(2)	60(2)	180(7)	399

Figure 2. Sample Kindwall-Edel caisson decompression table using oxygen breathing. Breathing gas during work (exposure time) is air. Pressure units are pounds per square inch, psi; time in minutes. Oxygen is breathed in the shaded stops. Small figures in parentheses show number of air breaks at that stop. The two rows below the divider are for contingency situations, not for regular workdays. (Ref 8)

Issues with oxygen

Oxygen is not without its price. For one, there is the fire risk, which is the main reason oxygen has been prohibited. But compressed air alone, even without extra oxygen, increases the fire risk; this is well known in the compressed air community. Dealing with oxygen requires proper training, an overboard dump system for the breathing masks, and continuous on-line oxygen analysis in order to make it safe. Further, for long exposures to prevent lung toxicity it may be best to have workers breathe oxygen intermittently or in "cycles," such that after every 25 minutes of oxygen breathing the workers breathe atmospheric air for 5 min.

Other decompression factors

Many individual factors affect the susceptibility of an individual to decompression sickness. One main factor is acclimatization. Compressed air workers who have been exposed regularly are more tolerant of decompression. In Navy diving this is called "work up." It has been found to be a major factor in both tolerance of compressed air exposures and of dives.

Use of helium as "trimix"

Helium has been used as a component of divers' breathing gas in commercial and military diving for well over half a century. There are two main objectives. Helium is lighter and easier to breathe, but its main benefit is that it does not cause narcosis. While a diver can do rote or simple work while breathing air at pressures up to 7 or so bars, at greater than about 4 bars memory and the ability to do detailed work or multi-tasking can be severely impaired. In recent years high-end recreational divers have begun using helium to reduce narcosis in the form of an oxygen-helium-nitrogen "trimix" for diving beyond about 4 bars. Trimix has also been used in caisson work. The technique was worked out by Dr. Nashimoto's team, with the help of Dr. Wouter Sterk (10). The pattern is to use the appropriate oxygen level for the pressure of the exposure and to put enough helium in the mixture to reduce the narcosis to an acceptable level for the work being done. Experience with decompression from trimix comes from diving.

Brightwater and the Tunnel Boring Machine

The authors are working as consultants in a major tunneling project in the Seattle area known as Brightwater. One of us (EK) is the project physician, responsible for examination of workers prior to their going under pressure and for treating any injuries, including of course decompression sickness should it occur. The first author (RWH) is participating in the selection and use of the decompression tables for work with compressed air, and for preparing trimix tables for interventions beyond 3.5 atm. Much of this is concerned with getting approval to do this work from the Department of Occupational Safety and Health of Washington State (DOSH). This is necessary because much of the work will be done in situations outside the rules of the US Department of Labor. Interestingly, another consultant to the DOSH is Dr. Sterk, known to many of this audience and one of the authors of the reference on trimix (10).

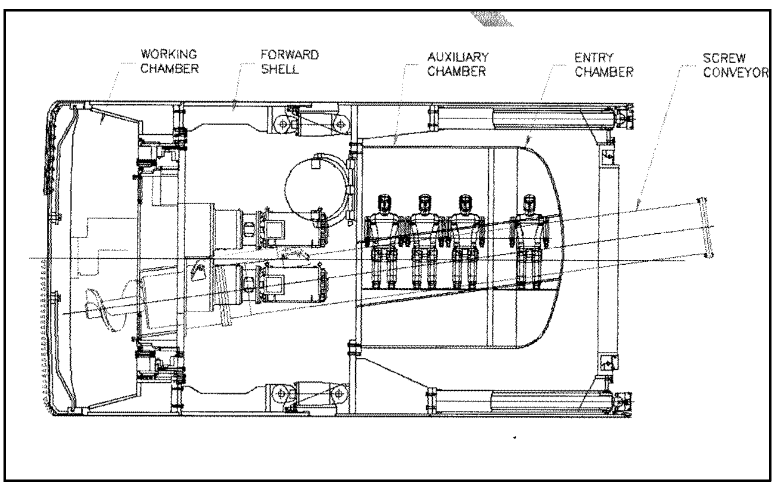

Figure 3. Drawing of the "machine room" of the Brightwater West Tunnel Boring Machine. Cutting face is on the left side. The machine room itself is at working pressure.

The work involved is to drill a tunnel for use as a sewer outfall. It involves work to pressures well beyond those allowed by the occupational safety rules. These rules were developed during the "sandhog" days mentioned above. The exposures are very different and use Tunnel Boring Machines (TBMs, Figures 3 and 4). Like the caisson work in Japan just mentioned, workers are not exposed to pressure unless they are needed for an "intervention" to make repairs or change the teeth on the working face of the machine. The face of the specific TBM used on this job is about 5 metres in diameter; others may be much larger (e.g., the TBM face shown in Figure 4).

The arrangement of the TBM starts with the face, then behind the face is the machine room which has mechanisms to turn the face, and a spiral feed mechanism. This moves the tailings out of the face area where they are dumped into small rail cars that carry the materials to the open end of the tunnel. Pressure in the machine room is the same as that of the face, but behind the machine room pressure is essentially atmospheric. The face is rotated and pushed along, digging several metres per day depending on the terrain. This is a Pressure Balanced Shield Machine. In another type of TBM the excavated soil is mixed with a high-density slurry which is pumped out through pipes. Both types are involved at Brightwater.

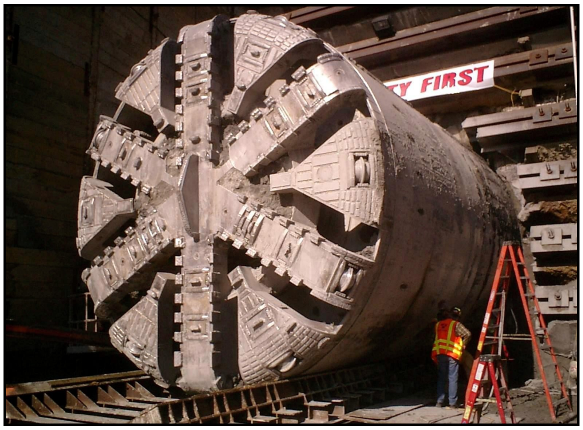

Figure 4. Face of a TBM (Tunnel Boring Machine) similar to that used on the Brightwater West project. (Ref 11).

When an intervention is needed a team of 2 or 3 workers transfers into a “man lock” which is in the corner of the machine room. The lock is pressurized to the pressure of the machine room and the workers transfer through the lock into the machine room. Sometimes the intervention is to do work on the machinery, but when work in front of the face is needed the team enters the face area through a door in the face. They may be wet, but with this arrangement they are normally not totally immersed.

Once work is complete the workers transfer back into the machine room, where they clean off and transfer into the man lock. The hatch is sealed and they begin the proper decompression profile for their exposure.

TBM decompression

If the pressure is in the air range, up to 50 psi (3.45 bar), the decompression will be performed with the Kindwall-Edel tables for Air With Oxygen. The Kindwall-Edel tables go only to 46 psi (3.2 bar) so as an option we generated tables for the gap between 46 and 50 psi using Hamilton Research’s DCAP computational program with parameters that match the profile of the Kindwall-Edel tables. Decompressions are not performed with air tables except in the contingency that for some reason oxygen cannot be used. The workers in this range are “miners” experienced in compressed air work.

For interventions at pressures greater than 50 psi (3.45 bar) we use a set of trimix tables generated with DCAP for a mixture of 20 % oxygen, 25% helium, balance nitrogen. These are designated the Kindwall-Edel-Hamilton Tunnel/Caisson Decompression Tables. They cover the range 48 to 88 psi (3.31 to 6.1 bar). These Trimix tables use an intermediate mix of 36 % oxygen and oxygen breathing after 12 psi (0.83 bar). A basis for the trimix decompressions is considerable experience in successful use of trimix tables by recreational and scientific divers. including a set of trimix tables for the US NOAA organization. The Brightwater West workers for the trimix range are commercial divers accustomed to breathing helium-rich mixtures.

For all the oxygen breathing, with both the K-E Air With Oxygen tables and the Brightwater West K–E–H Trimix Tables the workers breathe the oxygen in cycles of 25 min on oxygen and 5 min on air.

Summary

The methods described here enable miners and divers to perform work supporting the Tunnel Boring Machine, using air with oxygen decompression in the range to about 50 psi, and for interventions at higher pressures using trimixes containing helium. For work in the air range, to 50 psi, decompression is with the Kindwall-Edel laboratory tested Air With Oxygen decompression tables, and for work at higher pressures trimix decompression tables based on diving experience are used.

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