37 Decompression options for tunnel work at more than 3 bars (gauge) pressure

R.W. Hamilton*, J. Vollbrandt, M. Heineke and G. Luther
**Hamilton Research Ltd., Tarrytown, USA*
GKSS Forschungszentrum Geesthacht, Germany

This paper is dedicated to the memory of the late Albert R Behnke to whom the word's compressed air workers owe a great deal

Abstract
The most cost effective way to prepare for compressed air work at greater than 3 bars (gauge) pressure is to plan the decompression procedures to suit the operational situation rather than to attempt to fit a tunnelling operational or engineering plan to current diving tables. Special decompression procedures are needed when work is required at pressures greater than this. We have compared a variety of decompression approaches to this task using the *DCAP Plus* computer program; most of them take advantage of the benefits of oxygen for improved decompression, but also consider that the control of oxygen exposure is a major planning factor. Work in air with air decompression is inefficient, but is not limited by oxygen exposure. The most effective approach and one on which there is some experience is work in air with oxygen breathing during decompression. Even more effective decompressions are possible with oxygen-enriched air, but this becomes limiting due to oxygen exposure when used for the more stressful exposures, and requires breathing of prepared gas mixtures. For jobs requiring many man-days of work at high pressures the benefits of saturation techniques may offset the cost of the equipment. Saturation-excursion techniques can improve safety and make the final decompression shorter. An important aspect of using innovative decompression techniques is the requirement to validate their reliability; a new set of consensus guidelines makes it feasible to introduce into the workplace new techniques based on documented experience with little or no laboratory validation. It will be less efficient hence more expensive to work at higher pressures, but this can be done with no increase in risk, and for many situations will be the most cost effective approach.
Keywords: Decompression, Decompression tables, Oxygen, Oxygen tolerance, Tunnel work, Compressed air work.

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1 Introduction

When the opportunity presents itself for advanced engineering and construction work well below the water table, a major consideration in project planning is whether or not workers will have to be exposed to pressure. When the projected pressure exposure is greater than that of about 3 bars (gauge) the concerns include that of how to do the decompressions. Both lore and past experience would suggest that risks of decompression sickness, DCS, become greater as pressure exceeds about 2 bars using currently legislated 'tables', and beyond 3 bars there are few existing compressed air tables or procedures for performing the decompressions, whether prescribed by regulations or not.

Considerable experience from various modes of diving, aerospace, and medical activities, suggest that trouble-free decompressions from pressurised construction operations in the range of 3 bars and beyond are not only possible, they may very well be the most cost-effective way of performing the work. We have performed an analysis of how some techniques familiar in other fields but relatively new to compressed air work might be brought to bear to improve the reliability of tunnel decompression procedures. Some established decompression techniques, many based on creative use of oxygen and oxygen-enriched mixtures, might be adapted for tunnel work. Methods compared include:

- Work in air with air decompression.
- Work in air with air and oxygen decompression.
- Work in air with an intermediate oxygen rich mixture ('enriched air') and oxygen for decompression.
- Work breathing oxygen-enriched air by mask, with or without oxygen during decompression.
- Saturation and saturation-excursion techniques.
- Use of rebreather apparatus.

In order to use new methods several problems may need to be solved. Among these are those of acquiring suitable decompression tables, securing acceptance of the tables in the particular jurisdiction, and managing the use of oxygen. And some provision has to be made to accommodate the legal and ethical aspects involved with introducing new decompression procedures.

Our approach here has been to 'model' these options for comparison. This has been done by calculating a series of comparative profiles with a common set of conditions. We chose an arbitrary 3.6 bars (gauge) as pressure for the worksite, and have selected work periods (called 'bottom times' in diving terms) so that decompression can, where appropriate, be completed in an 8-hour work day. We have tried to deal with both decompression and oxygen exposure.

Many tunnel decompression procedures consider that the duration of the decompression cannot exceed the work time, because of utilisation of the chambers/locks. For the extra deep jobs different schedules may be necessary to accommodate the need for longer times in decompression, and this analysis is not limited to those situations where decompression time is less than work time. One straightforward method of dealing with this is to provide additional decompression chambers or locks.

Other considerations should not be forgotten, although they are not specifically addressed here. A major issue is fire safety, both in handling oxygen in containers and pipes as a gas, and the possibility of increasing the oxygen level in the compressed air atmosphere. Others are the possible use of mask breathing while working, logistics of mixing, handling, and administering breathing mixtures, the need for special training, and the possible use of 'decanting', a procedure of transferring the worker from the work lock to surface pressure and into another lock for decompression. These are not considered here, but not forgotten either.

2 Methods

2.1 Decompression computations

Many methods are available for computing decompression schedules or tables, but virtually everything that works has an empirical basis and can be traced to laboratory and field experience with decompression. One of the accepted and widely used methods, a variation of the Haldane-Workman-Schreiner computational algorithm (Schreiner and Kelley, 1971), is available to us by means of the *DCAP Plus* computer program ('Decompression Computation and Analysis Program', Hamilton and Kenyon, 1990). Using DCAP as a tool, we have examined a variety of approaches based on the use of oxygen and air-oxygen mixes, specifically to establish the comparative merits of the different approaches. For ascent limits we used an algorithm developed for deep air dives followed by air decompression that has been successful in practice; the 'matrix' of ascent-limiting M-values which stages the profiles is designated MM11F6 (Hamilton, Muren *et al.*, 1988). The procedures calculated with this method are quite conservative in relation to many other computational methods, but the samples presented are not necessarily ready for use. They are intended for comparison only; actual procedures for a particular worksite might vary in either direction.

We considered two types of profile, the maximum time that can be worked in a normal 8- or 9-hour day, and the 'intervention' profile that will be done only occasionally. For the normal work periods we chose the longest time that could be worked and still allow decompression to be completed before the end of the day. For the intervention excursions we arbitrarily chose a 2-hour work period.

When planning decompression from long-duration daily exposures to high pressures of nitrogen, it is necessary to consider the 'multiday' effects. 'Gas loading', a significant but quite hypothetical component of the computation, is found to build up over several days, and this may increase the calculated decompression time. For this reason all the full day calculations reported were done as if carried out over a 5-day work week. Exposure to oxygen was considered on a multiday basis as well.

We 'staged' the decompressions at 0.3 bar intervals, after the pattern used in diving. The results would be essentially the same using linear depressurisation, which would be more in keeping with tunnel practice; operational advantages may result from choosing one method or the other, but there is not much difference in the physiology. The practice of 'decanting', or decompressing to surface pressure followed by repressurisation and execution of a planned decompression profile is not considered here.

2.2 Validation of decompression procedures

An attractive new approach is now offered for dealing with the ethical questions of introducing new decompression tables and procedures without extensive (and expensive!) laboratory testing. A 1987 workshop sponsored by NOAA, U.S. Department of Commerce, brought together many of the leading workers in the field of decompression physiology, medicine, and operations along with administrators, lawyers, the clergy, military leaders, and others, to address the matter of validation of decompression tables (Schreiner and Hamilton, 1988). This workshop came up with guidelines for the validation process, including ways of dealing with such things as 'interpolative' modifications – those within the realm of valid experience – and conservative changes. Many recommendations are what common sense or current validation practice would dictate, and much of what was recommended was recognised as already being current industry practice.

The Validation Workshop protocol calls for documenting a data base for new procedures such that 'new' practices are not extrapolations but rather are interpolations of known experience. Really new ideas call for dedicated laboratory research, done with 'informed' subjects, and under medical control. Interpolative advances are within the job description of the workers, but should be done with special care and training, documentation, feedback, medical backup, and with competent judgement where indicated. A mechanism for making the judgmental decisions (such as when enough tests have been performed, or when to make a change in a procedure) is specified. Since many new tunnel procedures would be conservative compared to the existing ones, it is likely that considerable progress can be made and justified without extensive laboratory testing. Further, in tunnel work the risks of something going wrong leading to a more serious event such as drowning are not much of a factor; most conditions specified by the Workshop are met during any well managed compressed air job. There is now a recognised rationale for making these improvements.

2.3 Oxygen exposure

Virtually all innovations that improve decompression are based on creative use of oxygen. A major aspect of the methods discussed here is tolerance of oxygen exposure and avoidance of oxygen toxicity. This has to be considered as an integral part of any new oxygen-based decompression plan.

Oxygen exposure in these calculations was handled generally according to the Repex algorithm (Hamilton, 1989; Hamilton, Kenyon, and Peterson, 1988). This method uses an empirically determined set of limits based on a the number of days of exposure. Exposures are calculated in Oxygen Tolerance Units; one unit is about the equivalent of an exposure to a partial pressure of oxygen (PO_2) of 1 bar for 1 min (OTU is derived from and equivalent to the earlier UPTD, Unit Pulmonary Toxicity Dose). The breathing gases and other factors were adjusted to keep the exposure within the Repex limits. For 5-day work weeks on a continuous basis Repex allows a maximum of about 420 OTUs per day. This is based on 300 units per day, with 5 days of work and 2 days off each week ((300*7)/5=420). Operational experience in the same configuration has shown this to be acceptable, but for jobs of more than a few weeks of continuous exposure a slightly lower daily dose is recommended. In a long exposure adaptive changes of the same nature as those of acclimatising to life at high altitude will occur, but the acclimatisation will be in response to an excess of oxygen rather than a deficiency. Incidentally, if in a real life situation a continuous daily exposure level is set slightly too high it may be noticed after some time by a few of the workers; it can be adjusted downward at that time without having to make other changes and without any lasting injury or other risk.

2.4 Saturation and saturation-excursion

The term 'saturation' applies to the method highly exploited in diving of maintaining the workers under pressure around the clock for a number of days, then performing a final decompression at the end of the time. This has long been advocated as a possible method for some types of tunnel work, but to our knowledge it has not been implemented. Living full time at work for a couple of weeks is not an uncommon practice, since it is the pattern for ships' crews and offshore platforms, for example. One difference between working at sea and at 3.6 bars, however, is that at the higher pressure with air as the breathing gas the working time is limited by oxygen exposure and only a few hours can be worked each day.

We investigated two saturation options, one of having the living chamber at the pressure of the worksite, here 3.6 bars (gauge) pressure, and the other to have the living chamber at the shallowest pressure from which the workers could make pressure excursions to the worksite without need for decompression stops on return to the living chamber.

For the saturation exposures the time spent breathing air at the hypothetical 3.6-bar worksite is the limiting factor, due to oxygen exposure. For this we assumed the workers would be working every day for at least 10 days and would not take weekends off. The daily exposure should then be about 300 units instead of the 420 used for a 5-day week, and allows about 320 min of work each day; this limit applies no matter what saturation decompression pattern is used.

We chose 2.1 bars as the lowest pressure from which a 320 min excursion to 3.6 bars can be made each day, with no decompression stops required on return to the living chamber. Another set of procedures from CIRIA's Underwater Engineering Group, UK, gives much the same results (Hennessy *et al.*, 1985). For the excursion times and final decompressions we used the Repex procedures for nitrox saturation (Hamilton, Kenyon, and Peterson, 1988).

3 Results

The results of the calculations are given in Table 1.

3.1 Work in air with air decompression

This is the traditional method of performing compressed air work. Using air throughout is the least efficient method as far as working time per day is concerned, but it has the benefit of being familiar, requiring no special equipment or gas handling. At 3.6 bars it requires more than twice as much decompression time as the work time, and even then allows only a little over two hours of work time in a day. If more than one transfer lock (pressure chamber) is available so that alternate shifts can be run then this might become feasible. This option is the only one at 3.6 bars that is not oxygen limited.

3.2 Work in air with air and oxygen decompression

This is the easiest oxygen modification to implement, and gives the most time for the effort. Here the decompression time is about 50% greater than the working time, with a useful working time of greater than 3 hours per day. In practice each worker, in the lock, breathes oxygen by mask for part of the decompression period. For the run listed here oxygen breathing is started at a pressure of 0.9 bar during decompression, and is breathed in continuous cycles of 30 minutes on oxygen followed by 10 minutes off, breathing air from the chamber during the 'off' periods. We also tried oxygen starting at 1.2 bars; it reduced the decompression time but made the oxygen dose even higher. The oxygen breathing and decompression pattern can usually be optimised with respect to decompression time and oxygen exposure.

3.3 Work in air with an intermediate oxygen-rich mixture and oxygen for decompression

This procedure calls for increasing the oxygen earlier in the decompression to reduce gas uptake at the higher pressure stops by breathing an 'enriched air' mixture (sometimes called 'nitrox'). The final oxygen breathing pattern used here was in cycles of 30 min on O_2, 30 min on air. It would require mask breathing earlier in the decompression (since higher levels of oxygen cannot be used in a chamber for fire safety reasons) and would in this case gain very little over just oxygen in the later stages of decompression.

3.4 Work breathing enriched air by mask, with oxygen during decompression

This method offers considerable advantage in decompression time for a short (here 2 h as an example) work period, but is not of much value for daily work because the exposures are limited by oxygen exposure. For short interventions, however, especially where the atmosphere might be contaminated and breathing by mask is required, this method should be considered. The techniques for mixing the enriched air 'EANx' or 'nitrox' mixtures are well established (see for example, Bøe and Hartung, 1983; Mastro and Butler, 1990; Wells, 1989).

Table 1. Calculations for various methods of working at 3.6 bars. All options were started at 0800. DCAP calculations used matrix 11F6 without additional conservatism factors. Work times (min) and gas patterns were adjusted to limit O_2 exposure to about 420 units for 5 runs per week and 300 OTUs for continuous work in saturation, and to make surfacing occur between 16:00 and 17:00. Pairs of values show effect of small changes. Daily runs were taken from the maximum decompression time reached during a 5-day week, calculated continuously. EANx = enriched air, here 34% O_2. Work times for all options except the basic air are oxygen limited.

Type	Work time (min)	Decom. time (min)	Surface (clock) time	OTU
Air, air decompression	120	324	15:24	116
	130	354	16:04	126
	140	399	16:59	136
Air, O_2 decompression	190	309	16:19	402
	200	314	16:34	432
Air, O_2 & EANx decompression	200	299	16:19	416
EANx, O_2 decompression	120	79	11:19	344
Rebreather, 1.4 bar PO_2	120	74	11:14	326
Saturation at 3.6 bar	320	*0	13:20	300
Saturation at 2.1 bar + excursions	320	**0	13:20	300

* decompression at end of saturation = 94 h
** decompression at end of saturation = 46 h

3.5 Use of constant PO_2 rebreather apparatus.

This method considers using devices that supply a constant PO_2 (partial pressure of oxygen) by mask, with a backpack that recycles the gas and maintains the oxygen level. Here this method presents essentially the same decompression picture as breathing enriched air during work; in this specific situation it offers no decompression advantage over the use of enriched air nitrox, but for work at higher pressures it will. Rebreathers may be attractive for interventions. Rebreathers may offer operational advantages because they can reduce the complexity of having to mix gases and supply them by hose, but the complexity of the apparatus may offset this. A rebreather for tunnel work need not have the reliability or redundancy of one used underwater, but it would surely have to be sturdy and simple.

3.6 Saturation at 3.6 bars

Saturation will become more attractive as working depths increase for situations requiring many hours of work each day. The workers can breathe air, and the limitation of daily work duration is oxygen exposure. These decompression techniques are well established and, although time consuming and slow, can be made trouble free. It is not likely to be most effective to have the workers live at the full working pressure, unless the job layout dictates. Having the workers live at working pressure imposes a long final decompression, but no more work time is achieved because the limitation is daily oxygen exposure.

3.7 Saturation-excursion techniques; saturation at 2.1 bars

This is the saturation technique that should be most useful. The 'storage pressure' of the living chamber is chosen so as to require no decompression stops after a work period. Having it at a lower pressure reduces the fire risk, makes it easier to maintain the atmosphere, offers lower risk due to pressure anomalies, and makes the final decompression much shorter. The final decompression does have to take the excursions into account, and both Repex and UEG offer methods for that. The final decompression is too long to consider doing it every weekend.

4 Discussion

In due course the options chosen for further investigation will have to be compared to available tunnel and caisson experience in what does and does not work well (see, for example, Kindwall *et al.*, 1983).

Oxygen breathing has, of course, been used for decompression in diving with great success, and has been used for some compressed air work as well. A notable example of that is the Kiel Supply Tunnel in 1989 (Faesecke, 1990). There the medical authority for the state implemented decompression procedures based on oxygen breathing that met the criteria of the UHMS Validation Workshop, although without that specific intent at the time.

Another possible approach to saturation should be mentioned. Since the daily work time is oxygen-limited and cannot be increased except by providing a low-oxygen breathing mixture, the extra time available each day might be used to decompress back to a living chamber located at a lower pressure than the 2.1 bars used in the example. If the living chamber were at less than 1.4 bars (gauge) then it could be filled with air and the atmosphere controlled by flushing with air instead of controlling oxygen and scrubbing CO_2 as is normally done (1.4 bars gauge = 2.4 bars absolute, which with the volume fraction of oxygen in air of 0.21 gives a PO_2 of 0.5 bar, the threshold for O_2 effects). Special decompression procedures could be generated for this option.

For deeper work than the 3.6 bars used in this example it may be necessary to consider the use of helium mixtures. We have looked at this in detail for work at 80 msw, and satisfactory intervention techniques are available (Luther *et al.*, this conference).

Our purpose here is to point out that manned work and intervention is entirely feasible for tunnel work in the range of 3 bars and beyond. It requires attention to physiology for effectiveness and safety. It will be more expensive to implement than for lower pressures, but it may nevertheless offer the most cost-effective approach. Although this paper focuses primarily on the range of pressures higher than 3 bars, some techniques such as those explored here might also be applied to the higher end of the 'legislated' range of less than 3 bars.

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40 Procedures for safe working at high pressures in a TBM chamber using special breathing gas mixtures

G. Luther, R.W. Hamilton*, M. Heineke, G.A. Nietsch** and J. Vollbrandt
GKSS Forschungszentrum, Geesthacht, Germany
**Hamilton Research Ltd., Tarrytown, USA*
***Dyckerhoff & Widmann AG, Hamburg, Germany*

Abstract
Strait crossing by means of a tunnel boring machine is becoming more frequent and will continue in the future. The normally automatic tunnelling progress needs occasional human intervention in the pressure-exposed part of the shield even at pressures beyond those considered acceptable for breathing air. It is important to establish that with due attention to the physiological and human exposure requirements, this work can be done safely, and it may be less expensive than doing it by other methods. The need is likely to be for short (<2 h) interventions by specialists, but could involve multiple shifts of an entire team. In addition to the usual considerations of working with a tunnel boring machine, the high-pressure work situation involves many other factors like selection and management of breathing gases and breathing equipment, later re-use of pressure chambers, effects of gases on human performance, selection of decompression patterns, fire and oxygen safety, mobilisation time and integration with normal work shifts and training at several levels. Many of the risk factors and redundancies necessary for diving are not applicable here. Decompression procedures are better if designed for the operational situation, not the reverse. Partial saturation profiles not commonly used in diving for economic reasons may work well in the tunnel situation.
Keywords: Tunnel work, Partial saturation, Decompression computation, Heliox, Nitrox, Storebælt-tunnel.

1 Introduction

The Storebælt tunnel will be part of the fixed link between the islands of Funen and Zealand in Denmark. It consists of two tubes with a length of about 8 km each and its deepest point is approx. 80 m below sea level. Only little experience is available about tunnelling beneath straits with comparable depths and water pressures. Although there have been reasons for the management of the tunnelling works to expect largely impervious underground conditions one has to be prepared to encounter water-bearing layers at full pressure corresponding to the depths below sea

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level. Indeed a fatal water inflow happened during the tunnelling works in 1991. In order to make human intervention at hyperbaric conditions in the work chamber at the shield front possible, ground treatment was foreseen by the designer of the tunnel. However, the contractor wanted to investigate additionally the methods, measurements, and equipment for an access to the work chamber under high hyperbaric conditions. Since both the tunnelling technology and the underwater technology have to contribute their specific knowledge to this task, Dyckerhoff & Widmann AG as a partner of the joint venture for Great Belt Tunnelling and GKSS were asked for a study, which deals with hyperbaric 'dry' intervention in the work chamber of a tunnel boring machine when deeper than 30 m below sea level under consideration of the tunnelling environment.

This paper gives some of the conclusions of that study and points out some of the advantages and problems of the sub-saturation approach. It relates to tunnel work:

(a) in depths deeper than 30 m and/or
(b) with heliox and nitrox as breathing gas mixtures.

2 Basic design aspects using partial saturation

Any work at great depths or pressures must consider the risk of pressure loss. The work chamber behind the Storebælt boring machine has a volume of about 100 m³. The maximum pressure corresponds to 80 m (9 bar). If there should be an opening in the shield or a rupture of a pipe should occur the first pressure drop will be very high. The same effect is true for diving facilities. In Figure 1, the theoretical pressure drop is shown for free openings of 20, 40 and 100 mm diameter. Having an opening of 100 mm, no supply of air for compensation, and an elapsed time of one minute the pressure in the work chamber will drop from 9 bar to about 4 bar. Regarding the tightness of the system this effect should be considered during the design and operation periods.

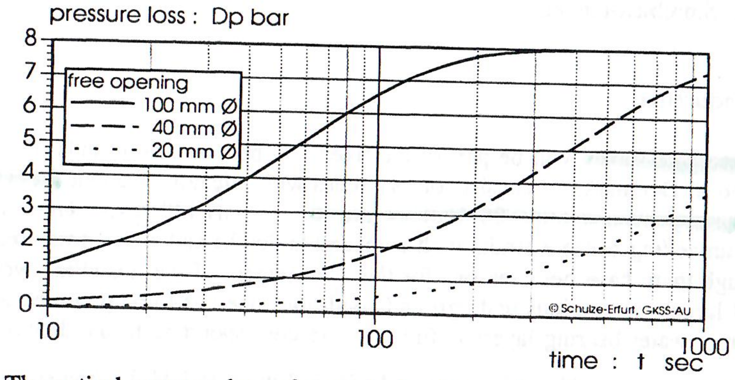

Fig.1. Theoretical pressure loss of a work chamber as function of time (initial air pressure of 8 bar; work chamber volume of 100 m³)

It is possible to use air in all chambers as chamber gas up to a pressure of depth 80 m. The lock chamber, which is directly connected to the shield, should be pressurised starting at 2 bar absolute with helium as backup for a break in gas supply to the built-in-breathing system (BIBS) (first safety arrangement). In case of a dangerous situation like an unforeseen pressure loss in the work chamber the pressure crew has to hurry into the lock chamber. In order that at depths greater than 50 m the crew remains clear thinking, it is recommended that there should be a lower nitrogen concentration in the chamber by adding helium during the preceding compression period (second safety arrangement).

Having air in the work chambers and in the lock chamber means a partial pressure of oxygen of about 1.9 bar. Fire protection has to be integrated into the design. Pressurising the lock chamber with helium is a convenient solution for this chamber. A concept for smooth evacuation of the pressure crew or for transfer to an ill pressure worker has to be established in detail before construction starts.

3 Operational limits of partial saturation

After a stay of 24 to 48 h under pressure the external inert gas pressure is in all tissues of the human body. In this case the human body is saturated. Now it is possible to stay as long as necessary in this depth without any further prolongation of decompression time. This technique can be safely used up to pressures of 60 bar (Luther *et al.*, 1988).

If the time in pressure is shorter than 24 h the tissues of the human body are only partly saturated by the inhaled inert gas (Workman *et al.*, 1975). The pressure in the tissues will increase very quickly in the first hours. That is even true for slow tissues with a theoretical degree of saturation of 99.99% after stay of 24 h in air with 9 bar environmental pressure (see Figure 2). For occasional single interventions which may require one or two hours work it may be much more efficient to use partial saturation, the tunnel equivalent of 'bounce dive'.

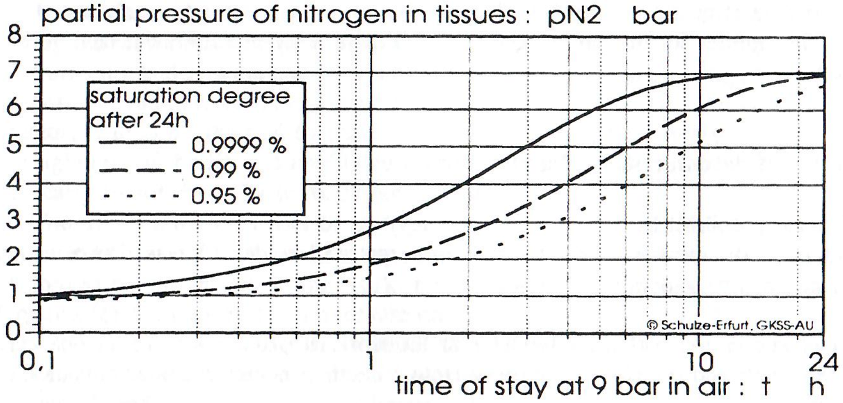

Fig.2. Theoretical saturation curves with nitrogen

If a task will take more than two hours, two or three pressure crews should do the work. If the work requires pressure exposure of more than 6 hours per day over a prolonged period, then saturation techniques may be the solution. Using saturation, decompression profiles over a time of up to 5 days (depending on the pressure behind the shield) should be kept in mind.

4 General demands of compression and decompression profiles

At full saturation the pressure crew lives for a long period in an accommodation/decompression chamber waiting for their missions. Three shifts are necessary to support the locked saturation crew at the surface. Many of the required tasks can be done in a short time (less than 6 hours per day). For the performance of those tasks partial saturation is the right and economic technique, but the decompression procedure has to fit into the work of the tunnel boring process. The partial saturation crew is a part of the tunnel boring crew and has to work under pressure only on request. The following demands are recommended for the integration of the partial saturation technique in the tunnel process. The compression and decompression procedures should:

- be safe regarding time and pressure accuracy
- be simple regarding change of breathing mixtures
- be simple regarding crew transfer between chambers
- offer the use of air as chamber gas wherever possible
- use only one special breathing mixture per compartment
- reduce heliox breathing as far as possible
- regard the qualifications standards and
- regard the experience of tunnel crews.

At partial saturation, safety reasons require a gas storage capacity for full saturation dive at maximum depth to decompress the crew in case of a substantial delay. This applies for the gas storage only, no extra crew or equipment have to be provided.

5 Location of decompression chambers

5.1 General possibilities

Depending on the location where the pressure crew will be decompressed two possibilities can be generally discussed:

1. Decompression within the tunnel near the work site, and
2. Transport and transfer under pressure to a decompression chamber outside the tunnel.

5.2 Decompression in the tube

Decompression of the pressure crew near the work site can be performed in the lock chamber or after transfer in a separate decompression chamber located near the shield.

Decompression in the lock chamber is possible if this chamber and its auxiliaries are equipped for all needed gas mixtures and for saturation decompression, too. Decompression with transfer of the pressure crew to a decompression chamber located near the shield is an excellent system configuration. The transfer between the lock chamber and the separate decompression chamber can be performed by surfacing and recompression, by a trunk system connecting the hatches at the lock chamber and at the decompression chamber or by a 'Shuttle'. The 'Shuttle' is a movable chamber that allows workers to be transferred near the shield from the lock chamber to the well equipped decompression chamber. The transfer in a 'Shuttle' is the best method regarding safety of the pressure workers and efficiency of the tunnel boring requirements.

5.3 Decompression outside the tube

Decompression at the outside can be performed by transport of the pressure crew under pressure to an outside area where the needed logistic support for a safe decompression is located. In this case the workers will be transferred first by the 'Shuttle' to a 'Transfer Chamber' and afterwards by the 'Transfer Chamber' to the outside area. A part of the decompression can be performed during the time the pressure crew is on its way to the tunnel entrance. Figure 3 contains a schematic view of such a system configuration. Two other options for decompressions are to use an existing diving support vessel moored near the tunnel end, or to take workers to an existing hyperbaric complex elsewhere.

5.4 Main disadvantages of single system variants

Decompression of the worker near or at the shield leads to larger restrictions of the tunnel boring process. During decompression periods no boring is possible and if the work behind the shield is not completed, the second or third crew have to wait during the total decompression period.

Surfacing and recompression is an unsafe method especially at higher pressure ranges. A trunk system interconnected to the lock chamber through the arms of the erector, able to be attached to another chamber is a time-consuming procedure and the tightness of the flanges might cause problems. Transfer of an ill worker would be nearly impossible, if a trunk system is used.

The use of a diving vessel or an hyperbaric complex usually involves considerable loss of time, more manpower, dependence on weather conditions, prolonged restrictions or boring work, restricted medical care of and additional logistics for the transport of a pressure crew. This possibility can only be applied in very special cases and is not discussed in this paper as standard procedure.

Decompression on the outside with workers transferred by a special 'Transfer Chamber' leads to a higher establishment cost, but in terms of productivity the overall costs will be lower. The decompression system itself can be used at later

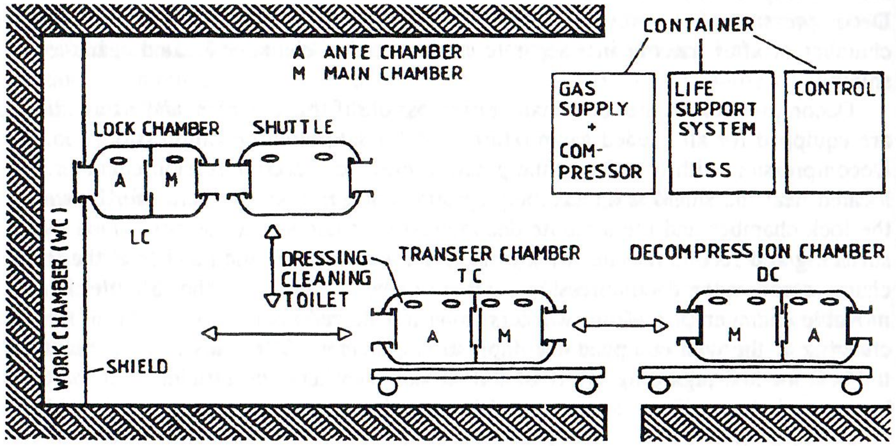

Fig.3. Chamber system for transfer and decompression

tunnel contracts, too. Regarding the health of the worker such a system also provides a higher safety level.

6 DCAP Program as an engineering tool

DCAP stands for decompression computation and analysis program (Hamilton *et al.*, 1987).

6.1 Short introduction into DCAP-Program

For the decompression computation GKSS has a comprehensive computer program called DCAP, which is designed to facilitate the computation of all types of partial decompression tables. DCAP is primarily a computational tool, and although it handles this step of the decompression development process quite effectively, for its output to be useful it has to rely on a basis of experience. More on the background of DCAP as a tool is presented by Hamilton *et al.* in their paper to this conference.

One curious point about the tables being generated is that exposures with air have a shorter decompression than those with heliox. Intuitively one would expect the heliox tables to require less decompression time. Helium is less soluble, therefore less gas has to be unloaded, and experience shows this. For example, decompression from heliox saturation can be 2 to 3 times as fast as from saturation with nitrox. There are several reasons for this apparent discrepancy.

First, the algorithm used has not been optimised for helium. It is more conservative than needed in some areas, but to change it would require that analysis and integration that has not yet been done. Second, because helium moves faster than nitrogen a short exposure results in picking up more helium. At some point as

exposures get longer the times will be more advantageous for helium. Mixtures of helium, nitrogen and oxygen might well be found to be optimal.

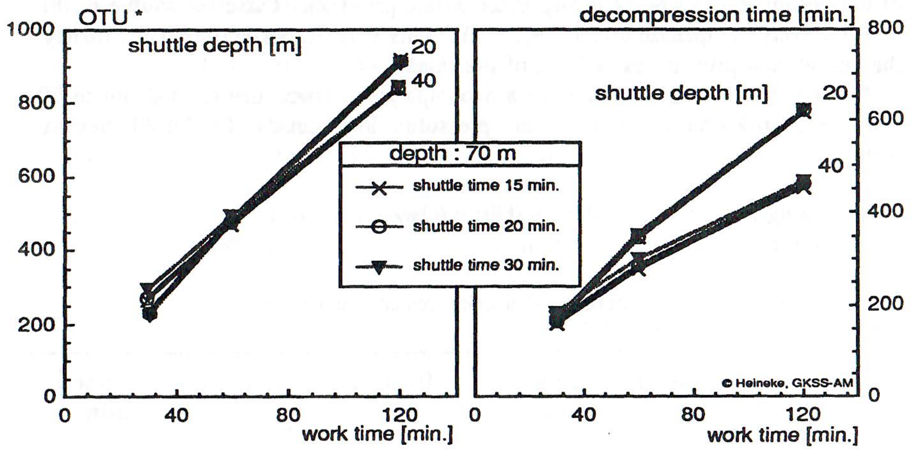

Fig.4. Influence of work time, 'Shuttle' depth and 'Shuttle' time on OTU* and decompression time

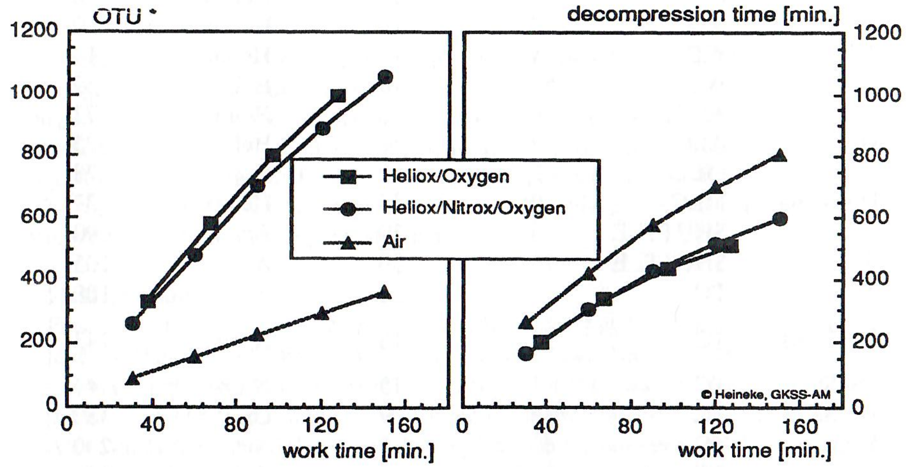

Fig.5. Influence of work time and breathing mixtures on OTU* and decompression time

* OTU: Oxygen Tolerance Units, Hamilton (1989) and Hamilton *et al.* (1991)

6.2 Use of DCAP Program for the tunnel boring process

As pointed out, GKSS is using the DCAP program. This program gives the chance to the engineers to arrange the decompression procedure (stops, oxygen level, decompression time) according to the possibilities of a tunnel boring process. The results of the DCAP calculation laid down in Figures 4 and 5 give a good impression of the optimising capability incorporated in the program. Different shuttle times can be effectively compensated (see Figure 4). This is an important point for managing the operational procedures in front of the shield.

Table 1 contains an overview of a decompression procedure for a depth of 70 m and a real work time of 55 min under pressure. Prerequisites for DCAP calculations were:

Breathing mixtures	Heliox/Nitrox/Oxygen
Shuttle transfer time	15 min

Table 1. Example of an operational decompression procedure

Activity	Chamber	Time demand min	Depth m	gas mix	Time total min
T	MLC	0	0	Air	0
C	MLC	1	10	Air	1
C	MLC	4	50	Heliox	5
T	ALC	3	50	Heliox	8
C	ALC	2	70	Heliox	10
T	WC	4	70	Heliox	14
Work	WC	55	70	Heliox	69
T	ALC	4	70	Heliox	73
D	ALC	2	50	Heliox	75
T	MLC	3	50	Heliox	78
D+Stops	MLC	9	30	Heliox	87
T	SHUTTLE	3	30	Air	90
S	SHUTTLE	15	30	Air	105
T	TC	3	30	Air	108
D+Stops	TC	35	18	Nitrox	143
D+Stops	TC	1	15	Nitrox	144
D+Stops	TC	36	9	Oxycyl.	180
Stops	TC	60	9	Air	240
D+Stops	TC	155	0	Oxycyl.	395

T Transfer of pressure crew, C Compression, D Decompression,
S Shuttle procedures Oxycyl. = Oxygen breathed in cycles
For chambers see Table 2.

7 Operational aspects for partial saturation intervention

7.1 Breathing gases

The chamber gas in all chambers is air. Breathing gases are supplied by BIBS (built-in breathing system) or by rebreather. The gases have to be mixed according to the needs of the decompression profile. In Table 2, types of breathing gas mixtures related to single chambers are listed. The concentration of breathing gas mixtures for work in depths deeper than 30 m depends on the partial saturation profile for compression and decompression. For the higher depths of the Storebælt project the heliox breathing gas might contain 18% oxygen and the intermediate enriched air or 'nitrox' mix might contain 50% of oxygen.

Table 2. Distribution of breathing gas mixtures for chambers used for transfer and decompression

Chamber		Heliox 1	Air	Nitrox	Oxygen
WC	Work chamber	x	(x)		
ALC	Ante lock chamber	x			
MLC	Main lock chamber	x			(x)
	Shuttle		x		(x)
TC	Transfer chamber		x	x	x
	Decompression chamber*		x	x	x

* if available

7.2 Optimal plant configuration and plant operation for tunnel boring work requiring longer work periods

Long interruptions for the tunnel boring process can be avoided if two transfer chambers (TC-1 and TC-2) and one outside decompression chamber (DC) are integrated in the design and operation of such a project. Using this prerequisite 3 shifts can work up to six hours per day behind the shield. The overall procedure corresponds to the following transfer plan.

First pressure crew

First crew is compressed in the lock chamber (LC) at the shield to the pressure level of the work chamber (WC) and works for two hours. First decompression stops are performed in the main compartment of the lock chamber (MLC) to the pressure level of the 'Shuttle'. All inhabitants are transferred to the 'Shuttle'. Afterwards the 'Shuttle' itself is disconnected and transferred to TC-1 without decompression. Further decompression of the pressure crew down to surface pressure is initiated directly after connection and pressure balance between 'Shuttle' and TC-1.

Second pressure crew
About 2 h after the first crew has left MLC the second crew can enter MLC for compression to the pressure behind the shield. The second TC-2 is used for decompression of this crew. Transfer and decompression procedures are the same as for the first crew.

Third pressure crew
About 8 h after the start of the compression of the first pressure crew the third crew can enter MLC for compression. Decompression of this crew is afterwards possible in TC-1. If each crew has to work one hour under pressure behind the shield and needs one hour for tunnel transfers, 11 h after the first crew has entered MLC the tunnel is free for normal operational work, while the third crew is decompressed further at the outside base.

7.3 Gas consumption for 3 shifts

During partial saturation procedures the TCs and one decompression chamber are used for decompression. Maximum consumption of gas is needed at max. depth (80 m) and at max. working time under isobaric conditions.

Table 3. Gas storage for intervention at 80 m in m^3 (1.08 bar, 0°C)

Breathing gas	Demand			Total
	1 Crew	3 Crews	ALC	
Heliox	200 m^3	600 m^3	50 m^3	650 m^3
Nitrox	50 m^3	150 m^3	-	150 m^3
Oxygen	30 m^3	90 m^3	-	100 m^3
Air	yes	yes	yes	

The consumptions in Table 3 are based on two TCs, 3 shifts and a 16 h period under pressure. Gas reserves are included for some delays and 120 min at pressure. ne repressurisation of the lock chamber is included. If Heliox is supplied by a closed circuit breathing system (CCBS) or rebreathers to the pressure worker the consumption of Heliox can be reduced to less than 25% of max. value (150 m^3/day instead of 600 m^3/day).

7.4 Personnel requirements for partial saturation work

A surface crew of 12 people is needed to perform short intervention in 3 shifts using partial saturation techniques. The shifts can be the normal tunnel boring crew, if the crew members are trained for such a job. For each shift 3 people are needed for pressure work. At least 12 people out of the total workforce of one tunnel should be licensed to work in pressure. Additional training for using partial saturation technique is needed.

The surface crew for the operation and supervision of the pressure work is normally a part of the standard tunnel boring crew. Thus the shift engineer A might be the supervisor A and the senior foreman D the chamber operator D. Table 4 demonstrates how the distribution can be arranged.

Table 4. Distribution of personnel per 3 shifts

	Shift 1 (8h)			Shift 2 (8h)			Shift 3 (8h)		
	LC	E*	TC	LC	E*	TC	LC	E*	TC
Supervision	A	A	A	B	B	B	C	C	C
Chamber op.	D		D	E		E	F		F
Erector op.		G			H			I	
Transfer technician		G			H			I	
Chamber operation			G			H			I
Life support	K		K	L		L	M		M
Surface personnel		4			4			4	
Pressure crew		3			3			3	

* Erector operation

At full saturation the pressure crew is living under pressure waiting for their missions behind the shield. This possibility is only necessary if a lot of pressure work is assumed for the boring period. Full saturation capability means a surface crew of 11 people additionally needed during stand-by periods for each tunnel side. 15 people are needed to operate the system during pressure work periods.

8 Operational support for a safe decompression

It is essential for the decompressing crew to remain relaxed and limber during decompression. If possible they should get up and move around every half hour or so, moving all limbs and joints and activating the circulation. Cramped conditions are detrimental to decompression. However, most decompression chambers contain bunks or cots, and most experts consider that this gives the crew the best practical conditions for maintaining good circulation. We recommend bunks, with flameproof mattress covers and bedding.

The pressure crew should not be allowed to become cold, but should not be too hot either. Sleeping is acceptable, but should be interrupted by the operator for moving around at least every hour. Intensive or strenuous exercise during decompression is not beneficial and should be avoided.

Dehydration appears to be detrimental to reliable decompression. Individuals decompressing should remain well hydrated, and to do this should make a conscious effort to drink plenty of liquids. Too much coffee is not recommended because it is a diuretic. Juices, soda, sports drink, etc. are good – whatever liquids taste good, will result in a lot being consumed. Milk, if used, should be low fat. For these decompressions prevention of dehydration can be an important factor, and should be identified in the operational plan. Provision should be made for the regular supplying of fluids before starting the operation, and the 'topside' operators should be trained to encourage the crew to drink plenty of appropriate fluids.

9 Conclusion

Partial saturation can efficiently support tunnel boring work. In order to get the maximum benefit of this possibility, partial saturation technique should be integrated in a very early stage of design into the tunnel boring concept, including needed operation procedures. GKSS uses DCAP program as a powerful software program. This program delivers safe prerequisites for an excellent optimising process regarding both the tunnel boring possibilities and decompression needs.

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41 Unmanned excavation systems in pneumatic caissons

S. Shiraishi
Shiraishi Corporation, Tokyo, Japan

Abstract
This paper describes the principal features of a recently developed unmanned excavation system (UES) for pneumatic (compressed air) caissons. Traditional hand-mined caissons became extremely expensive in comparison with alternative construction techniques, so mechanical excavators were developed (caisson shovels) which, although removing the need for hand mining, still required their operators to work in compressed air. The UES is a further development in which the operator is in an atmospheric capsule. It combines the benefit of mechanical excavation but without the time constraints or potential hazards of men having to work in compressed air.

Keywords: Pneumatic caissons, Excavation, Unmanned systems, Atmospheric capsule, Compressed air.

1 Introduction

Pneumatic (compressed air) caissons are seldom built elsewhere in the world other than in Japan. In USA, no pneumatic caisson has reportedly been constructed for about fifty years and, in Europe, there have only been relatively few in recent years.

The reasons for this are the labour-intensive nature of the excavation and construction works together with the health hazards for workers. Alternative, less expensive methods were often found for substructure work.

Pneumatic-caisson technology in Japan, however, has been in continuous, steady demand and has developed considerably from the traditional techniques in use in the post-war period.

In recent years, in-caisson excavation works have been mechanised in Japan and pneumatic-caisson technology revolutionised. Pneumatic caissons in Japan are now strongly competitive against such newly developed technological rivals such as cast-in-place concrete piles.

This successful improvement has been accomplished by increasing the efficiency of in-caisson excavation in particular, as well as many other aspects of pneumatic-caisson works. This improved efficiency of in-caisson excavation work has been

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