Compressed-air work is entering the field of high pressures

J-CL LE PÉCHON¹, G. GOURDON²

¹JCLP Hyperbarie, Paris, France; ²Hyperbarie SARL, Pierrelatte, France

CORRESPONDING AUTHOR: Jean-Claude Le Péchon – hyperbar@club-internet.fr

ABSTRACT
Since 1850, compressed-air work has been used to prevent shafts or tunnels under construction from flooding. Until the 1980s, workers were digging in compressed-air environments. Since the introduction of tunnel boring machines (TBMs), very little digging under pressure is needed. However, the wearing out of cutter-head tools requires inspection and repair. Compressed-air workers enter the pressurized working chamber only occasionally to perform such repairs. Pressures between 3.5 and 4.5 bar, that stand outside a reasonable range for air breathing, were reached by 2002. Offshore deep diving technology had to be adapted to TBM work. Several sites have used mixed gases: in Japan for deep shaft sinking (4.8 bar), in the Netherlands at Western Scheldt Tunnels (6.9 bar), in Russia for St. Petersburg Metro (5.8 bar) and in the United States at Seattle (5.8 bar). Several tunnel projects are in progress that may involve higher pressures: Hallandsås (Sweden) interventions in heliox saturation up to 13 bar, and Lake Mead (U.S.) interventions to about 12 bar (2010). Research on TBMs and grouting technologies tries to reduce the requirements for hyperbaric works. Adapted international rules, expertise and services for saturation work, shuttles and trained personnel matching industrial requirements are the challenges.

INTRODUCTION
Compressed-air work is an old technology (1850) (1, 2) that was used to prevent flooding of shafts or tunnels under construction. Until the 1980s, the workers were digging shafts to sink caissons or tunnels while under pressure, working in long shifts, as extensively reviewed by Lamont (3). These workers have been called compressed-air workers, caisson workers, or “tubistes” in French.

During the early 1980s in Europe, tunnel boring machines (TBMs) came of age. With the use of these machines, no more digging under pressure is required. However, the cutterhead tools wear out, have to be inspected and, from time to time, need replacement or repair. Qualified technicians who can be compressed via an airlock system are sometimes called to perform those tasks when they cannot be performed at atmospheric pressure.

In a similar manner in Japan, sinking large, deep caissons for bridge foundation has changed to remote-controlled mode, requiring hyperbaric operators only for maintenance and removal of digging equipment before filling the installed caissons with concrete (4, 5). Those workers are qualified technicians and enter compressed-air environments only occasionally.

Caisson sinking underwater or boring tunnels in soft ground with TBMs is nowadays performed at depth, where hydrostatic pressures may reach values as high as 13 bar. That range of pressure is outside the maximum reasonable pressure for compressed-air breathing. A reasonable range for maximum air breathing stands in between 3.5 and 4.5 bar; it has been reached for the first time in 1992 in Japan for shaft sinking and in 2000 in the Netherlands for tunneling (6,7,8,9,10).

Offshore deep diving techniques that were already available since the early 1970s had to be adapted to TBM work. Basically, bounce deep diving technology as well as deep saturation diving have already been used in tunneling or caisson sinking. At least three sites worldwide have used mixed gases in tunnels and in several sites in Japan for caisson work. They are as follows.
St. Petersburg Metro in Russia
(5.8 bars – bounce interventions with trimix).
This is a short tunnel (1 km) joining two
pre-existing metro lines that had never been
connected since the initial construction in the
1930s, because the ground was in the water table
and technology was not yet available.

Seattle flood water control tunnels
They are presently being constructed using
mixed gases at pressure between 4.8 and 5.8 bar.

Western Scheldt Tunnels in The Netherlands
(up to 6.9 bar with bounce interventions and
saturation exposures) (9, 10). This is a twin
tunnel boring operation crossing below the
Western Scheldt Estuary, at a depth of 70 meters
underground with a boring diameter of 11
meters, intended for both legs of a freeway.

Deep caisson sinking for bridges in Japan
(4.6 – 5.4 bar) (11,12,13). Deep caissons
supporting the Nagoya Bridge.

The purpose of this review is to inform the medical
side of the hyperbaric community that such work
is taking place in several countries although
very few scientific publications report on this
type of specific hyperbaric intervention.

BOUNCE INTERVENTIONS

The term “bounce intervention” means that the
workers involved are decompressed back
to atmospheric pressure immediately after they
complete the preset intervention time. Most of the
time this decompression process is carried out in
the airlock system built in the TBM. Eventually
twin locks are used to provide back-to-back in-
terventions: one team decompressing in lock
n°1 while a second team undergoes compression
in lock n°2 for a second working session (14).

This technique using mixed gases is very similar
to standard compressed-air practices in TBMs
with a major difference: The mixed gases must
be breathed through masks as soon as the
pressure is above 2 or 3 bar during compression.
The first phase of compression can be carried out while
breathing ambient air to facilitate ear equilibration.

St. Petersburg
The St. Petersburg metro line hyperbaric works
consisted of performing inspections and repairs
at 5.8 bar. The total number of interventions
has been 46 with teams of three, and with a
working time of 60 minutes (Table 1, facing page).

Seattle
A two-tunnel project in Seattle, Wash. (Vinci,
Fontier, Kamper and Parsons) intended to route
waste waters to Brightwater treatment plant through
two 4.3-meter diameter tubes 3.5 and 6.4 km long
respectively, is already boring at a pressure of 5.8
bar. Trimix breathing intervention procedures have
replaced the compressed-air technique that has been
used successfully up to 4.8 bar. A sample of decom-
pression tables is shown in Table 2 (facing page).
TABLE 1 – Trimix exposure characteristics

<table>
<thead>
<tr>
<th>Site</th>
<th>Type of intervention</th>
<th>Mixture O₂/N₂/He</th>
<th>Nb of runs / man. exposures</th>
<th>Working time/ minutes</th>
<th>Pressure/bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. Petersburg</td>
<td>Standard</td>
<td>23/53/24</td>
<td>46 / 118</td>
<td>60</td>
<td>4.2-5.8</td>
</tr>
<tr>
<td>Seattle</td>
<td>Standard</td>
<td>20/47/33</td>
<td>41 / 123</td>
<td>90</td>
<td>5.5</td>
</tr>
<tr>
<td>Western Scheldt</td>
<td>Standard</td>
<td>25/50/25</td>
<td>52 / 156</td>
<td>60</td>
<td>4.6-4.8</td>
</tr>
<tr>
<td></td>
<td>Exceptional (short)</td>
<td>12/45/35</td>
<td>1 / 3</td>
<td>28</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>Exceptional (long)</td>
<td>18/50/32</td>
<td>1 / 3</td>
<td>240</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Stop time is shown in minutes; the smaller font shows the five-minute air breaks during pure oxygen breathing. An extra table for two hours’ working time is available to cope with an incidental delay if the decompression should start later than 90 minutes.

TABLE 2 – Sample extracted from decompression procedures

| MIXTURE: 20 / 47 / 33 - Oxygen / Nitrogen / Helium - PRESSURE: 5.5 Bar |
| STOPS PRESSURE | 3.3 bar | 3.0 bar | 2.7 bar | 2.4 bar | 2.1 bar | 1.8 bar | 1.5 bar | 1.2 bar | 0.6 bar | Total decomp |
| WORKING TIME   | To 1st stop | AIR | 6 | 10 | 15 5 15 | 5 + 51 |
| 20 minutes     | 5 | | | | | | | | |
| 60 minutes     | 4 | 8 | 11 | 12 | 14 | 26 | 25 5 12 | 13 5 25 5 25 5 16 | 4 + 207 |
| 90 minutes     | 3 | 6 | 10 | 12 | 18 | 28 | 31 | 25 5 25 5 3 | 22 5 25 5 25 5 25 5 17 | 3 + 302 |

Stop time is shown in minutes; the smaller font shows the five-minute air breaks during pure oxygen breathing. An extra table for two hours’ working time is available to cope with an incidental delay if the decompression should start later than 90 minutes.

SATURATION INTERVENTIONS

In the range of 6 bar, the decompression time after bounce intervention becomes too long for practical application; the technique called saturation exposure is the only way. The idea of tunneling saturation exposures was first presented by Benkhe (16). However, it was developed only for compressed-air situations, and it was supposed to take place directly in the tunnel. It was never used until mixed gases and high-pressure tunneling became necessary. This technique, derived from saturation diving technology, requires a habitat under pressure where the workers are living and a shuttle (15), installed on a train (Figure 2, page 196), to move the workers to and from the habitat into the TBM airlock system. Saturation in tunneling has been used on one work site only: the Western Scheldt Twin Tunnels construction in the Netherlands in 2001-2002 (15,17).

The gases used were very specific since the pressure of up to 6.9 bar allowed excursions from
a habitat pressure of 4 bar, with air breathing in the airlock during the transfer as well as in the shuttle during transfer back (Figure 3 and Figure 4). In addition, the transfer back was carried out with two stops at 5 bar and 4.5 bar according to the decompression profile calculated by Sterk (15).

Table 3 (facing page) shows the overall statistics for both tunnels. The total number of runs for the train has been 134, and the total time spent working in the cutter head is 464 hours, 39 minutes for a team of three, each time (15).

**PRESENT SITUATION**

Several tunnel boring projects that may involve higher pressure are in progress or being prepared: In Sweden, Hallandsås twin tunnels – bored for high-velocity trains to go through the Hallandsås mountain – required some advanced preparation for interventions in saturation using a heliox mixture of up to 13 bar. Half of the tunnel is now perforated, and it appears that hyperbaric interventions may not be necessary until the completion of the second tube (Figure 5, facing page).

In a very ambitious project below Lake Mead, near Las Vegas, a tunnel boring project is planned for 2010-2013. The project is designed to open an extra water intake in the middle of the lake as deep as 120 meters. The tube will penetrate as deep as 140 meters below the lake surface; boring may require manned interventions to about 14 bar in some digging areas.

The saturation atmosphere in the habitat will be heliox at a pressure close to the working pressure; the shuttle atmosphere will be similar. In the airlock system and in the working chamber the atmospheres will be compressed air. Workers will breathe from masks supplied via twin umbilical lines, with heliox from in-tunnel pre-mixed gas storages. A detailed evaluation of the potential risks of through skin isobaric counter diffusion shows that there should not be adverse effects for the workers. An evaluation of the safety package associated with that very exceptional operation is under way by Nevada local authorities (Sept. 2009).

Several projects have been awarded in the range of 5-8 bar pressures (London – 8 bar) or are at the stage of bid evaluations. A construction site is due to start in 2010-12 in Hong Kong (5-6 bar), and a bid process is ongoing in New York for another project.

**WHAT COULD BE THE NEXT STEPS?**

Research on improvement of the TBM cutterheads and grouting techniques are in progress to try to reduce the requirements of hyperbaric works. Development of expertise and services to provide saturation equipment, shuttles, personnel and
TABLE 3 – Performance in saturation at Western Scheldt (15).

<table>
<thead>
<tr>
<th>Saturation #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitat pressure bar</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3.7</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Saturation at pressure days</td>
<td>7</td>
<td>7</td>
<td>12</td>
<td>11</td>
<td>10</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Working pressure bar</td>
<td>6.6</td>
<td>6.9</td>
<td>6.7</td>
<td>5.9</td>
<td>5.9</td>
<td>6.4</td>
<td>6.2</td>
</tr>
<tr>
<td>Numbers of excursions/runs</td>
<td>13</td>
<td>12</td>
<td>12</td>
<td>22</td>
<td>20</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Team working time hr:min</td>
<td>41:11</td>
<td>37:30</td>
<td>44:20</td>
<td>79:47</td>
<td>72:11</td>
<td>88:34</td>
<td>101:06</td>
</tr>
</tbody>
</table>

additional training to safely match the industrial needs is the present challenge. A very high safety standard, acceptable internationally, is required.

In all cases, however, those operations must remain in a competitive cost frame that includes direct costs of the hyperbaric operations as well as the cost of production time lost. The alternative method involves atmospheric pressure work after grouting or eventually freezing the ground, the preparation of which may take longer than the organization of a straightforward hyperbaric repair when the personnel, the equipment and the procedures are readily available and prepared – and basically already paid for.

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