

What safety options are available for compressed air tunnelling at working pressure higher than 3.45bar?

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Decompression Illness in CA workers

- ▶ While tunnel workers working at depth with compressed air, the **discrepancy between nitrogen absorption and elimination resulted in the occurrence of Decompression Illness** (DCI) in the compressed air (CA) workers.



Skin bend –
scarlatiniform
rash



Joint bend, bone
necrosis



DECOMPRESSION TABLES
TABLE 1

WHERE THE WORKING PERIOD IS NOT OVER 1/2 HOUR

Basic pressure (Pounds per square inch)	Stage pressure (Pounds per square inch) (see Note 2)							Total time-(minutes) (See Note 3)
	28	24	20	16	12	8	4	
14 to 16								----
16 to 18								----
18 to 20								----
20 to 22								----
22 to 24								----
24 to 26								----
26 to 28								----
28 to 30								----
30 to 32							5	5
32 to 34							5	5
34 to 36							5	5

TABLE 8

WHERE THE WORKING PERIOD IS OVER 4 HOURS BUT UP TO AND INCLUDING 8 HOURS

Maximum working pressure (Pounds per square inch)	Stage pressure (Pounds per square inch) (see Note 2)							Total time-(minutes) (See Note 3)	
	28	24	20	16	12	8	4		
14 to 16								15	15
16 to 18								30	30
18 to 20								45	45
20 to 22							5	55	60
22 to 24							15	60	75
24 to 26							30	60	90
26 to 28						5	35	60	100
28 to 30						10	45	60	115
30 to 32						20	45	60	125
32 to 34					5	30	45	65	145
34 to 36					10	35	45	70	160
36 to 38					20	35	45	80	180
38 to 40				5	25	40	50	85	205
40 to 42				10	30	40	50	90	220
42 to 44			5	15	30	40	55	100	245
44 to 46			5	20	35	40	60	110	270
46 to 48			10	25	35	45	65	120	300
48 to 50		5	10	30	40	45	70	130	330

Notes:

1. Decompress at a rate not faster than 5 pounds per square inch per minute.
2. Decompress between stages at a rate of 5 pounds per square inch per minute.
3. Not including time between stages.
4. Where alternative decompression procedures are given (e.g., 46 pounds per square inch) the longer decompression procedure should always be chosen.

Decompression Tables with **oxygen** for decompression

- Employed and modifier regularly worldwide to **reduce Decompression Illness**.
- In Europe, such as France, adding oxygen for decompression in compressed air work within **3.0bar** had been employed since 1974 and became mandatory in **1992**, application **up to (4.0bar) in 1997 Sydney airport link**, similar mandatory requirement applied in **Germany up to 3.6bar (1997)** and **U.K. up to 3.45bar (2001)**

Current known Air Decompression Tables on CA work regulations

- In U.S., U.K, France, China Mainland does not have any **approval tables** which allow working pressure over **3.45bar (3.6bar in Germany)**.
- When compressed air work beyond 3.45bar, the usual compressed air containing 80% **nitrogen** would generate **neurological narcosis, affect tunnellers orientation and work capability**.
- Simply increasing the percentage of **oxygen** is unsafe as it would **increase the risk of fire and becomes toxic to the body in high concentrations**

French Oxygen Decompression Tables

Working Pressure up to 3.6 Bar (Rev 1)

Working Time	Mins. to first stop	1.8 Bar Air	1.5 Bar Air	1.2 Bar Air	0.9 Bar OXY	0.6 Bar OXY	Total Decomp	Total Intervention
0h 20	10					10	20	0h 40
0h 25	9				5	10	24	0h 49
0h 30	9				5	15	29	0h 59
0h 45	8			3	10	15 s 10	51	1h 36
1h 00	7		3	10	20	5 s 25 s 10	90	2h 30
1hr 30	7		10	20	25 s 5	20 s 25 s 20	147	3 h 57

Working Pressure up to 3.9 Bar (Rev 1)

Working Time	Mins. to first stop	1.8 Bar Air	1.5 Bar Air	1.2 Bar Air	0.9 Bar OXY	0.6 Bar OXY	Total Decomp	Total Intervention
0h 15	11					10	21	0h 36
0h 20	11					15	26	0h 46
0h 25	10				5	15	30	0h 55
0h 30	10				5	20	35	1h 05
0h 45	9			5	15	10 s 20	64	1h 49
1h 00	8		3	15	20	5 s 25 s 15	101	2h 41
1h 30	7	3	15	25	25 s 10	15 s 25 s 25 s 10	180	4h 30

10/01/97
TP450598 DOC
Transfield Bouygues Joint Venture
New Southern Railway
Technical Procedure

1.4.1

77-ST-TP-054
Revision 3

Operating Procedures for
Compressed Air Work

Working Pressure up to 4.2 Bar (Rev 1)

Working Time	Mins. to first stop	1.8 Bar Air	1.5 Bar Air	1.2 Bar Air	0.9 Bar OXY	0.6 Bar OXY	Total Decomp	Total Intervention
0h 15	12					10	22	0h 37
0h 20	11				5	10	26	0h 46
0h 25	11				5	15	31	0h 56
0h 30	10			3	10	15 s 5	48	1h 18
0h 45	9		3	10	15	10 s 25	77	2h 02
1h 00	8	3	10	15	25	5 s 25 s 25	121	3h 01

German Oxygen Decompression Tables

Compressed Air Ordinance

Working Normal Operation (Cont.)

When the pressure in the personnel lock is lowered down to 1.0 bar, excess pressure going beyond the atmospheric pressure.

Time at Stop Pressures during Decompression in minutes	Oxygen			Total Decompression Time
	1.2 bar	1.0 bar	0.5 bar	
				hrs. min.
13	63	32		2:01
10	56	25		1:42
8	49	21		1:26
4	43	16		1:11
2	35	13		0:58
	27	9		0:44
	23			0:31
	15			0:23
11	58	27		1:48
9	51	22		1:32
6	44	17		1:15
2	37	13		1:00
	29	9		0:47
	24			0:33
	16			0:25
12	61	28		1:56
9	53	23		1:37
8	45	18		1:20
4	38	14		1:04
1	30	10		0:49
	21	4		0:34
	16			0:26

In commercial diving industry

- In to reach greater working depths without suffering from nitrogen narcosis or oxygen toxicity, **helium** is used in place of nitrogen. With years of research & development resulted in the successful application of varies **mixed gases (Trimix – O₂/N₂/He)** for deep diving.

Available options for TBM tunnelling - I

- Mixed gases technique (Trimix) as commercial diving with **modified Trimix Decompression Tables for CA work**
- Applicable in short working time, usually within 2 hours

HYPERBARIE SARL TRIMIX TABLES

MIXTURE : 20 47 33 - Oxygen, Nitrogen, Helium PRESSURE : 5.0 Bar

STOPS PRESSURE		4.5 bar	4.2 bar	3.9 bar	3.6 bar	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											OXYGEN		
20 min	4											2	10	15 5 10	4 + 42
50 min	3								5	11	14	16	25 5 7	18 5 25 5 24	3 + 160
60 min	3							1	9	12	14	17	25 5 12	13 5 25 5 25 5 11	3 + 184
80 min	3							5	11	13	17	32	25 5 17	8 5 25 5 25 5 23	3 + 221
90 min	3						1	4	11	24	31	35	25 5 23	2 5 25 5 25 5 25 5 20	3 + 276

Te rate of compression to the first stop shall not exceed 0,9 bar/min

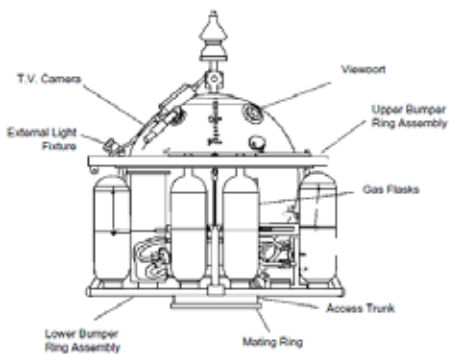
Air Break

Available options for TBM tunnelling - II

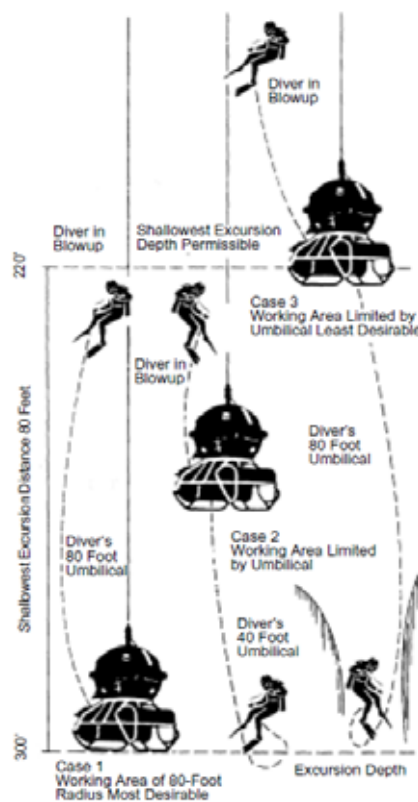
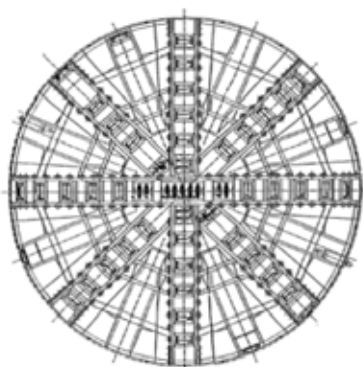
Mixed gases diving in **Saturation mode**

- A diver (CA worker) when exposed to a constant pressure of 24 to 48 hours, body tissues become **“saturated”** with inspired inert gases; **further time at depth requires no additional decompression time - known as “saturation”,** avoid the stresses of multiple decompressions where **long working times** are needed.
- There are set of **“Unlimited Duration Excursion Tables”** which **allow safe multiple excursions (downward diving) to be conducted during the course of a saturation,** allow **a large vertical range of working depths without time limits**

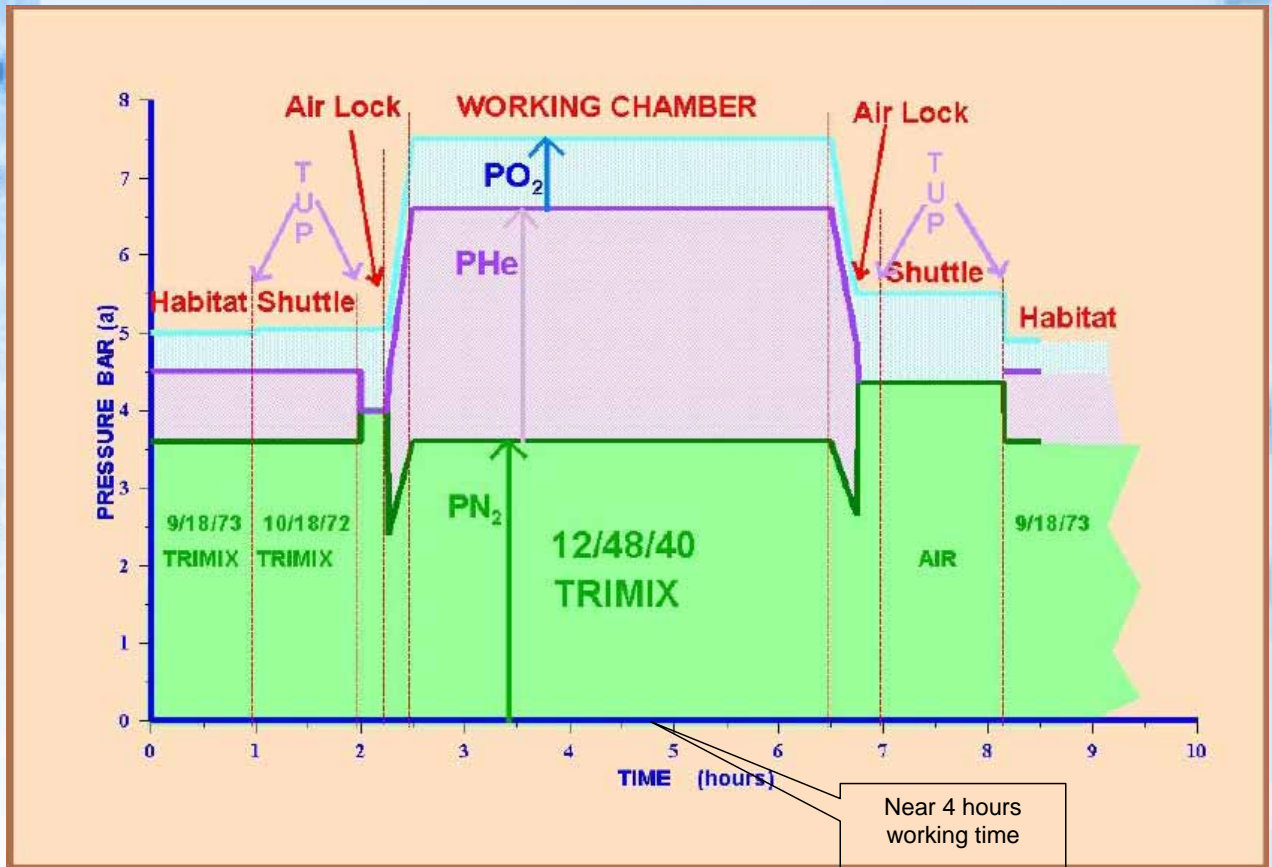
Mixed gases diving – saturation mode, for prolonged working time



The diving shuttle in Saturation dive



Storage Depth (fsw)	Deepest Excursion Distance (ft)	Deepest Excursion Depth (fsw)
0	29	29
10	33	43
20	37	57
30	40	70
40	43	83
50	46	96
60	48	108
70	51	121
80	53	133
90	56	146
100	58	158
110	60	170
120	62	182
130	64	194
140	66	206
150	68	218
160	70	230
170	72	242
180	73	253
190	75	265
200	77	277
210	78	288
220	80	300
230	82	312
240	83	323
250	85	335
260	86	346



(Oxygen/ Nitrogen/Helium as 9%/18%/73% ~ 10%/18%/72%)

Realistic validation of trimix tables for model TBM & compressed air work

Netherlands Western Scheldt TBM Tunnel up to 6.9bar



Employing mixed gases for caisson in *Japan*

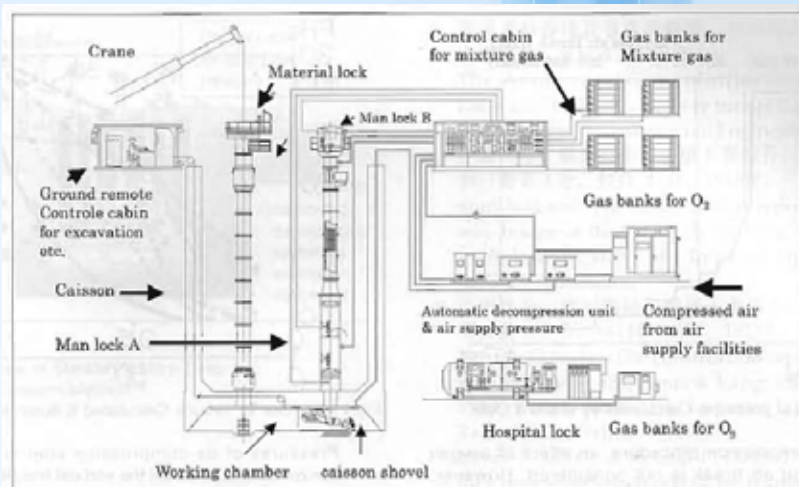


Fig.2 Component of equipment in the mixture gas-breathing



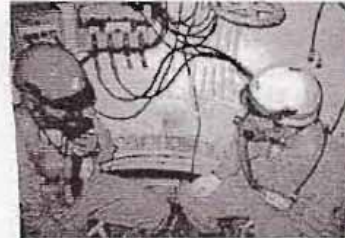
Samples of built-in breathing system (BIBS) with full face mask inside DDC/PTC



Picture.1 Unmanned excavation in the working chamber



Picture.2 Ground remote control cabin in unmanned excavation



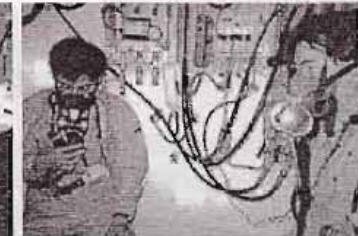
Picture.3 Personnel in Man Lock A



Picture.4 Control cabin for mixed-gas breathing system



Picture.5 Personnel servicing excavation equipment in the working chamber



Picture.6 De-compression with oxygen breathing in Man Lock B

On going deep TBM tunnel with mixed gases for compressed air work

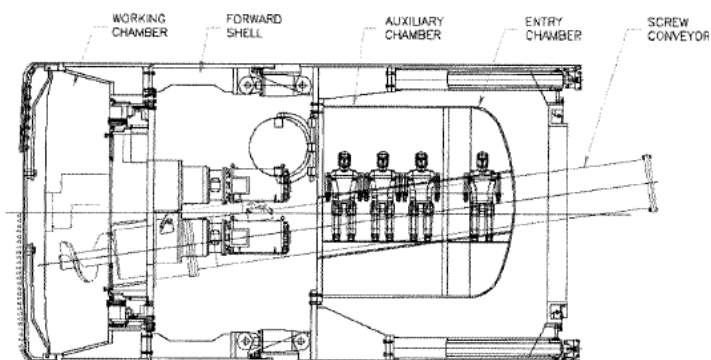
Russia St Peterburg TBM Tunnel up to 5.5bar



In Sweden Hallandsås Tunnel



U.S. Seattle Brightwater Tunnel up to 6.1bar



Advantage of adding **Oxygen for Decompression**

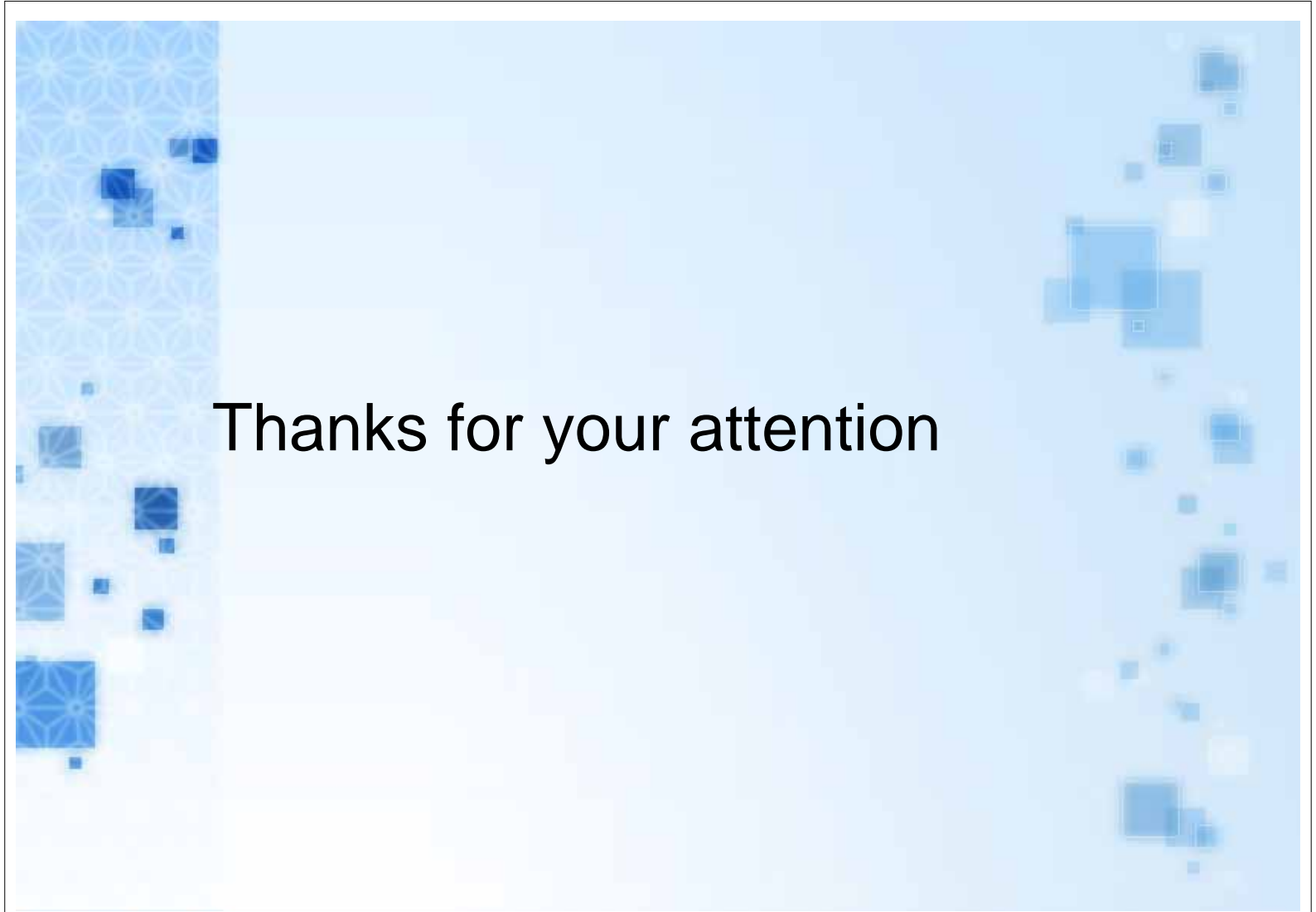
- **Zero decompression illness recorded in two KCRC tunnels** with oxygen decompression in KCRC West Rail DB 320 & West Rail LBD-201 (working pressure < 3.45bar)
- May prevent late bone necrosis

Advantage of **Mixed gases (Trimix) Decompression**

- **Zero decompression illness recorded** in Netherlands Western Scheldt Tunnel & Russia St Peterburg (working pressure >3.45bar)

Limitation in Mixed gases & Oxygen Decompression

- In Hong Kong, you must **first obtain approval** from Labour Department
- The TBM man-lock is small, hot and humid, delivery oxygen by mask is difficult, these problems must be **solved from TBM design and build**
- Risk of fire safety must be complied with applicable safety standards **with proper risk management plan**
- Risk of oxygen toxicity **need experience Diving & Hyperbaric Medical Physician support for advisory, medical management**



Thanks for your attention