Procedures to Minimise the Incidence of Decompression Sickness for Compressed Air Cutterhead Interventions

Russell Connors[1]
[1]*John Holland Pty Ltd, Singapore. Email: russell.connors@jhg.com.sg*

ABSRACT:

Compressed air Cutterhead Interventions (CHIs) are manned interventions into the working chamber of a Tunnel Boring Machine (TBM) to perform maintenance work on the cutterhead, check ground conditions and clear obstructions. Compressed air CHIs can be either planned or unplanned, regardless, attention is needed to ensure works are planned adequately and procedures implemented by the project team to minimise the incidence of Decompression Sickness (DCS).

KEYWORDS: Compressed Air; Cutterhead Intervention; Health and Safety; Decompression Sickness; Hyperbaric Oxygen Treatment

1 INTRODUCTION

Contract T208 involved the construction of Springleaf Station, and associated Tunnels. The construction of the 4.4km of bored tunnels in the challenging Bukit Timah Granite Formation using Mixed Shield Tunnel Boring Machines (TBMs) required the extensive need for compressed air CHIs.

This paper briefly summarises the use of compressed air to facilitate Mixed Shield TBM CHIs on Contract T208, health and safety requirements, working in compressed air, and the procedures that were developed by the Leighton-John Holland Joint Venture (LJHJV) project team to reduce the incidence of DCS. This paper will also make recommendations relating to the use of compressed air work in Singapore, and how to better manage the health, safety and wellbeing of the workforce to minimise unnecessary safety incidents and project delays.

2 CASE STUDY: CONTRACT T208

Leighton Asia and John Holland, forming a Leighton John Holland Joint Venture (LJHJV), were appointed to deliver Contract T208 of the 43 km Thomson East-Coast Line (TEL) in November 2013 by the Singapore Land Transport Authority (LTA). It involved the construction of Springleaf Station, Tagore Cut and Cover Tunnels, over 4.4 km of segmentally lined bored tunnels, six cross passages and two in-line sumps.

Figure 1: Location of Contract T208 within the TEL Alignment in Singapore

1. Compressed Air Cutterhead Interventions

Pressure is used during a CHI to maintain face stability by counteracting water and overburden pressures. The initial pressure used for a CHI is pre-calculated. Air loss from the excavation chamber into the face must be prevented by forming a bentonite cake across the face. The bentonite cake properties will vary depending on the ground conditions encountered.

If upon initial inspection it is found that the face is stable, there may be scope to reduce the intervention pressure which will allow for longer intervention working times, shorter compression and decompression times, more comfortable working conditions and a reduction in the risk of air loss, and DCS. This reduction in intervention pressure needs to be carefully considered and must not result in face instability or uncontrolled water ingress.

All compressed air CHIs were initiated from the TBM dual manlocks which provided direct access into the working chamber to perform compressed air works, as shown in Figure 2. A dual manlock allows for one intervention team to be under compression while another intervention team is undergoing decompression procedures. These certified manlocks on the TBM were under the direction of authorised Manlock Attendants to compress and decompress Compressed Air Workers (CAW) as they enter and egress the working chambers.

Any intervention that showed signs of face instability and air losses was immediately aborted, and the excavation face re-pressurised by the application of a pressurised bentonite slurry.

Figure 2: Dual manlocks provided direct access into the working chamber for CAWs. Prior to the start of a CHI, both manlocks need to be pressure tested for any leakage as shown above.

2. Regulations for Compressed Air Cutterhead Interventions in Singapore

All compressed air works and procedures developed for Contract T208 were in accordance with the following regulations:

- Maximum of 3.5 bar working pressure for any CHI
- Compressed air working and decompression times as per the Blackpool Tables
- Compression rates of no more than 0.1 bar/min
- Decompression rates of no more than 0.4 bar/min
- Workplace Safety and Health (Chapter 354A) Workplace Safety and Health (Construction Regulations 2007: Part XII Compressed Air Environment
- Workplace Safety and Health (Chapter 354A) Workplace Safety and Health (Medical Examinations) Regulations 2011
- Workplace Safety and Health (WS&H) Guidelines: Compressed Air Works – Prevention of Compressed Air Illness and Barotrauma

- BS 6164:2011 Code of Practice for Safety in Tunnelling in the Construction Industry
- ITA Working Group No. 5: Health & Safety in Works in Association with the British Tunnelling Society Compressed Air Working Group
- LTA General and Particular Specifications

3. Statistics for Compressed Air Cutterhead Interventions

In total, 18,599 man hours were spent in compressed air for Contract T208. Of the 4,535 personnel entries averaging 1.9 bar of pressure, a total number of 11 nos. of Type 1 DCS and 6 nos. of Reportable Barotrauma were recorded, affecting 15 nos. of CAWs. It should be noted that 1 nos. CAW experienced 2 nos. of Type 1 DCS and 1 nos. CAW experienced both a Reportable Barotrauma and a Type 1 DCS.

All works in compressed air can be summarised in Table 1. In addition to the table below, refer to Appendix A for a complete summary of compressed air CHIs on Contract T208.

Table 1: Summary of T208 Compressed Air Statistics

Total Number of CA Hours	18599	personnel hours			
Total Number of CA Entries	4535	personnel entries			
Average CA Exposure	04:05	hours:minutes per each entry			
Maximum Working Pressure	2.6	bar			
Average Working Pressure	1.9	bar			
Total Number of CA Medical Incidents	17	Frequency	0.37%		(1 in 267 entries)
Type 1 DCS	11		0.24%		(1 in 412 entries)
Type 2 DCS	0		0.00%		
Reportable Barotrauma	6		0.13%		
Description	**No.**				
Light headed/dizziness	1				
Knee Pain	7				
Shoulder Pain	3				
Ear/Sinus problems	6				
Total	**17**				

3 HEALTH AND SAFETY REQUIREMENTS FOR WORKING IN COMPRESSED AIR

As per Singapore regulations and LJHJV procedures, no CAW was allowed to work in a compressed air environment if any of the following applied:

- There is no Medical Lock Attendant present for compressed air CHIs above 1.0 bar or will be for a period of 24 hours after the compressed air CHI
- Dry bulb temperatures exceed 29° Celsius inside the working chamber
- There is not a minimum of two (2) CAW for the compressed air CHI
- They are feeling fatigued, suffering from any illness or under the influence of alcohol
- Failed their last medical check-up (annual or fortnightly)
- Their last medical check-up was more than 14 days old
- They have not been in a compressed air environment above 1 bar for more than 14 consecutive days
- It has been less than 12 hours since their last compressed air CHI
- They have been involved in 6 consecutive days of working in compressed air
- It has been 1 year since their initial pre-employment or annual medical review

Due to the high frequency of compressed air works on Contract T208 and the stringent health and safety regulations governing fitness for work, LJHJV employed a total of 91 CAWs over the period of bored tunnelling works. It was paramount that the health, safety and wellbeing of all CAWs was constantly monitored and maintained to reduce any delays that might arise due to the unavailability of workers to perform a compressed air CHI on the TBM.

1. Medical Check-ups and Fitness for Work

Following the pre-employment medical, familiarisation and safety training, a CAW would undergo a bounce dive that involved an intervention for 30 minutes at 1 bar of pressure, considerably less than the actual working conditions on Contract T208. The purpose of which is to determine if the potential CAW understand the risks and procedural avoidance of barotrauma by equalising the pressure difference of the gas filling spaces of the eustachian tube that connects the middle ear to the throat by performing the Valsalva manoeuvre, and their ability to work in a compressed air environment.

At the successful completion of the pre-employment medical and bounce dive within 30 days of employment, the new CAW is issued with a log-book and certified fit to commence a compressed air CHI. The new intervention worker will perform the first of several CHIs at reduced working times and pressures (no greater than 1.8 bar at 3 hours) while paired with a more experienced CAW until they are gradually acclimatised to conditions of working in compressed air.

CAWs were required to attend fortnightly medical reviews at the T208 contractor's office by the Appointed Medical Practitioner (AMP). Where a CAW has recently suffered or is suffering from a cold, flu or has symptoms that affect the sinus or respiratory tract, they were ruled unfit to dive in compressed air. The CAW is only allowed to perform compressed air works again if their symptoms are cleared and the AMP has ruled them medically fit to dive.

In addition, LJHJV would routinely toolbox and educate CAWs on the requirements of fitness for work, the signs and symptoms of a DCS and what not to do 12-24 hours after an intervention i.e. no consumption of alcohol, carbonated beverages, strenuous exercise or ascending to altitude (flying).

2. Reportable Barotrauma

A Reportable Barotrauma is defined as tissue damage caused by the inability of the body to equalise the pressure of gas filling spaces during changes in ambient air pressure. According to Boyle's law, increases in ambient pressure will decrease the volume of gas filled spaces. Blockages of the gas filling space of the eustachian tube that are not properly cleared during compression or decompression may cause pain, discomfort or a ruptured eardrum. [1]

Where a CAW suffered from any pain or discomfort in the ears or sinus while undergoing and was unable to clear away the blockages, the dive was aborted. Likewise, where a CAW had suffered from any pain or discomfort in the ears or sinus during a decompression, the decompression was halted, and the pressure slowly increased a to the last decompression step as per the decompression tables. The pressure was the held until the worker had successfully cleared the blockage. Once the CAW was comfortable, the decompression was recommenced as per the decompression tables.

For both instances, the CAW was sent to the Appointed Medical Practitioner (AMP) for a review to determine if a Reportable Barotrauma had occurred. For reoccurring compressed air CHIs where the same CAW experienced pain or discomfort during either compression or decompression, the CAW was barred from conducting any further work in compressed air.

All Reportable Barotrauma as summarised in Table 2 was investigated and determined to be from the decompression of the CAW at a rate greater than 0.4 bar/min between decompression steps. Measures taken to address this include the retraining of the Manlock Attendants and CAWs on the correct decompression rates and proper communication techniques. All CAWs who experienced a Reportable Barotrauma on Contract T208 were barred from further work in compressed air.

Table 2: Summary of Reportable Barotrauma on Contract T208

Date	Time In	Working Pressure (bar)	Working Time in Compressed Air (hrs:min)	Decompression Time Commenced	Decompression Time Finished	Decompression Time (hrs:min)	Total Working Time in Compressed Air (mins)	TBM
08/12/2015	12:20 PM	2	02:40	3:00 PM	4:50 PM	01:50	270	TBM C1
13/07/2016	10:45 AM	0.9	02:20	1:05 PM	1:15 PM	00:10	150	TBM C2
17/09/2016	3:25 AM	2.35	01:20	4:45 AM	6:15 AM	01:30	170	TBM B
01/03/2017	10:55 AM	2.4	02:30	1:25 PM	3:15 PM	01:50	260	TBM B
09/03/2017	11:55 AM	2.1	03:10	3:05 PM	5:05 PM	02:00	310	TBM B
21/03/2017	6:00 AM	1.95	03:00	9:00 AM	10:25 AM	01:25	265	TBM B

4 WORKING IN COMPRESSED AIR AND DECOMPRESSION SICKNESS

All compressed air interventions on Contract T208 were carried out utilising Blackpool Tables for intervention and decompression times. The selection of the correct decompression tables is important in reducing the incidence of a DCS, which are the symptoms that arise from the formation and accumulation of oxygen and nitrogen bubbles in the circulatory system due to a rapid reduction in ambient air pressure. [2]

WSH guidelines dictate that at the completion of each compressed air CHI, pure oxygen is to be administered in a timely manner to CAWs after exposures exceeding 1.5 bar to assist with the purging of nitrogen bubbles from the circulatory system. It should be noted that the administration of pure oxygen during decompression, which is currently not covered under Singapore regulations or was undertaken on Contract T208, has been found to be beneficial in reducing decompression times and the incidence of a DCS due to the enhanced effect of purging nitrogen bubbles from the circulatory system. [3]

In addition, all compressed air CHIs were undertaken below 3.5 bar as per Singapore Regulations. Due to the harmful effects of oxygen toxicity from breathing oxygen at increased partial pressures, compressed air CHIs would have required the use of breathing mixtures and advance saturation diving techniques that are currently not available to the tunnelling industry in Singapore. [4]

1. Decompression Sickness

While oxygen bubbles are readily utilised by the body, the formation of nitrogen bubbles can lead to DCS which is either categorised as Type 1 or Type 2. Type 1 DCS generally involves dizziness, pain in the joints, muscles and limbs. The more serious Type 2 DCS can involve a loss of consciousness, collapse from shock, breathing difficulties, weakness and paralysis. No Type 2 DCS was encountered on T208. [5]

Typically, the onset of a Type 1 DCS that occurred on Contract T208 commenced not more than 12 hours after the intervention and at the workers dormitory. At the onset of developing DCS type symptoms, CAWs are immediately returned to the T208 medical lock for treatment. For all Type 1 DCS that were documented on T208, all CAWs underwent the United States Navy Table 6 Procedures in the medical lock under the direction of the AMP and the guidance of the Medical Lock Attendants. The CAW was then re-examined again after 2-4 weeks by the AMP to see if they could continue working in compressed air. All CAWs on Contract T208 who experienced a Type 1 DCS were cleared to continue working in compressed air after adequate rest.

For Contract T208, LJHJV experienced that the majority of DCS cases were found to occur above 1.8 bar exposures and during working times greater than 4 hours (240 mins), as shown in Table 3.

Table 3: Summary of Type 1 DCS on Contract T208

Date	Time In	Working Pressure (bar)	Working Time in Compressed Air (hrs:min)	Decompression Time Commenced	Decompression Time Finished	Decompression Time (hrs:min)	Total Working Time in Compressed Air (mins)	TBM
14/12/2015	8:10 PM	2.15	03:26	11:36 PM	1:36 AM	02:00	326	TBM C1
14/12/2015	8:10 PM	2.15	03:26	11:36 PM	1:36 AM	02:00	326	TBM C1
18/12/2015	11:26 AM	2	02:40	2:06 PM	3:56 PM	01:50	270	TBM A
02/02/2016	11:20 AM	1.9	03:05	2:25 PM	4:05 PM	01:40	285	TBM C1
03/02/2016	11:15 AM	2.35	02:45	2:00 PM	4:03 PM	02:03	288	TBM A
30/04/2016	11:21 PM	0.8	03:33	2:54 AM	3:00 AM	00:06	219	TBM A
26/10/2016	1:55 PM	1.95	02:30	4:25 PM	6:05 PM	01:40	250	TBM B
23/11/2016	2:00 AM	2.27	02:53	4:53 AM	7:00 AM	02:07	300	TBM C2
03/12/2016	12:15 AM	2.3	02:45	3:00 AM	5:01 AM	02:01	286	TBM C2
17/12/2016	2:45 PM	2.3	03:00	5:45 PM	7:46 PM	02:01	301	TBM C2
13/02/2017	11:50 PM	1.75	03:35	3:25 AM	4:45 AM	01:20	295	TBM C2

2. Administration of Oxygen

The administration of pure oxygen was performed at the medical lock on the surface by certified Medical Lock Attendants in accordance with the WSH guidelines at the completion of a compressed air CHI, as shown in Figure 3.

It was the responsibility of the Shift Supervisor that once the CAWs had completed their intervention, they were to be transported from the TBM to the surface with minimal physical effort or exertion, changed into clean clothes and present at the medical lock in a timely manner.

The Medical Lock Attendants were required to be on standby at the medical lock until 24 hours after the last intervention had been completed. In addition, regardless of the working pressure, CAWs that had completed their oxygen administration were to remain on site for a one-hour bends watch period before they were allowed to leave.

Figure 3: Administration of pure oxygen for 30 minutes after an intervention

5 PROCEDURES IMPLEMENTED TO REDUCE THE INCIDENCE OF DECOMPRESSION SICKNESS

Due to the increase of Type 1 DCSs proceeding the three months leading up to December 2016, LJHJV developed a set of Hyperbaric Oxygen Therapy (HBOT) procedures to enhance the washout of nitrogen bubbles in the bloodstream for interventions above 1.8 bar. In lieu of existing oxygen administration procedures, these new HBOT procedures were developed in consultation with the AMP to reduce the likelihood or incidence of a DCS occurring, as shown in Table 4.

Contract T208 HBOT procedures involved the administration of pure oxygen within 30 minutes of completing a compressed air CHI to the CAWs for 30 minutes at 0.6 bar of pressure inside the medical lock. The pure oxygen was administered to the CAWs by a Built in Breathing System (BIBS). The BIBS allowed for the supply of pure oxygen whilst also removing exhaled gases from the pressurised environment inside the medical lock. HBOT procedures could not start until all CAWs involved in the compressed air CHI were present at the medical lock on the surface and ready to commence.

The HBOT procedures were first implemented on the 7th of December 2016 until the completion of the final TBM tunnel drive on the 7th of July 2017. The HBOT procedures in total covered an adequate sample of 6,253 personnel hours in compressed which was representative of 1,498 personnel entries.

From the information gained, it can be seen that the HBOT procedures developed by LJHJV in conjunction with the AMP, reduced the frequency of Type 1 DCSs on Contract T208. Refer to Figure 5, Table 5 and Table 6. Based on this reduction of frequency we can say that if these HBOT procedures were implemented from the beginning of the project, then the number of Type 1 DCSs experienced on Contract T208 would again have been reduced, as shown in Figure 6.

Table 4: Contract T208 HBOT Procedures

Table	Pressure	Total Working Time				
		≥1hrs	≥2hrs	≥3hrs	≥4hrs	≥5hrs
5	**1.8 – 1.95**	x	x	x	HBOT	HBOT
6	**2.0 – 2.15**	x	x	HBOT	HBOT	HBOT
7	**2.20 – 2.35**	x	HBOT	HBOT	HBOT	HBOT
8	**2.40 – 2.55**	HBOT	HBOT	HBOT	HBOT	HBOT
9	**2.60 – 2.75**	HBOT	HBOT	HBOT	HBOT	HBOT
X = 30 mins surface oxygen HBOT = oxygen @ 0.6 bar for 30 minutes						

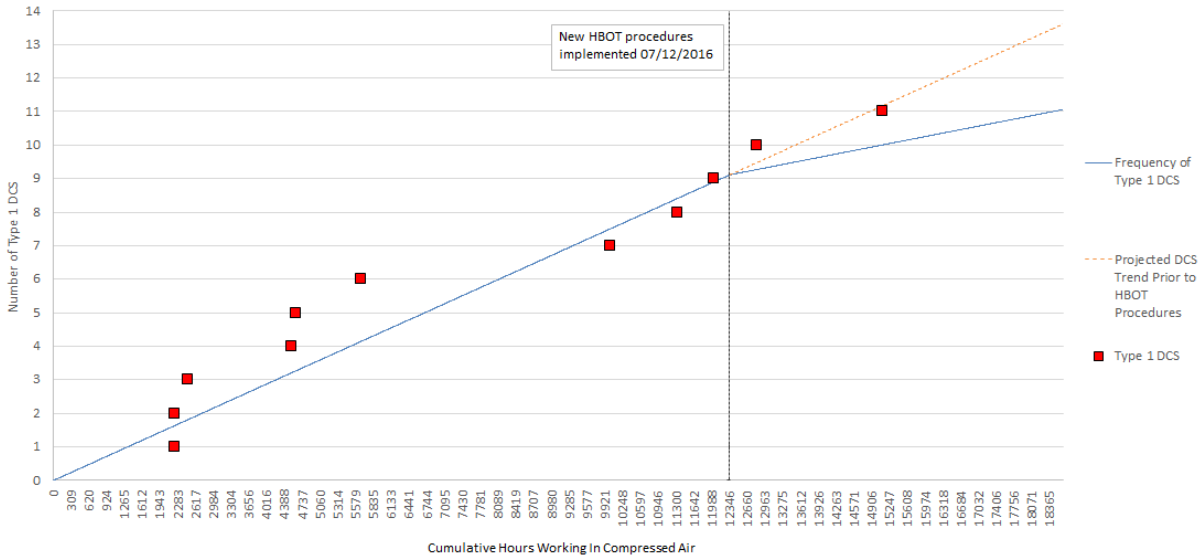

Figure 5: Frequency of Type 1 DCS on Contract T208

Table 5: Summary of T208 Compressed Air Statistics prior to the implementation of the HBOT procedures

Total Number of CA Hours (from beginning to 07/12/16)	12346	personnel hours			
Total Number of CA Entries	3037	personnel entries			
Average CA Exposure	04:01	hours:minutes per each entry			
Maximum Working Pressure	2.6	bar			
Average Working Pressure	1.9	bar			
Total Number of CA Medical Incidents	12	Frequency	0.40%		(1 in 304 entries)
Type 1 DCS	9		0.30%		(1 in 434 entries)
Type 2 DCS	0		0.00%		
Reportable Barotrauma	3		0.10%		

Table 6: Summary of T208 Compressed Air Statistics following the implementation HBOT procedures

Total Number of CA Hours (from 07/12/16 until finish)	6253	personnel hours			
Total Number of CA Entries	1498	personnel entries			
Average CA Exposure	04:09	hours:minutes per each entry			
Maximum Working Pressure	2.6	bar			
Average Working Pressure	1.9	bar			
Total Number of CA Medical Incidents	5	Frequency	0.33%		(1 in 300 entries)
Type 1 DCS	2		0.13%		(1 in 749 entries)
Type 2 DCS	0		0.00%		
Reportable Barotrauma	3		0.20%		

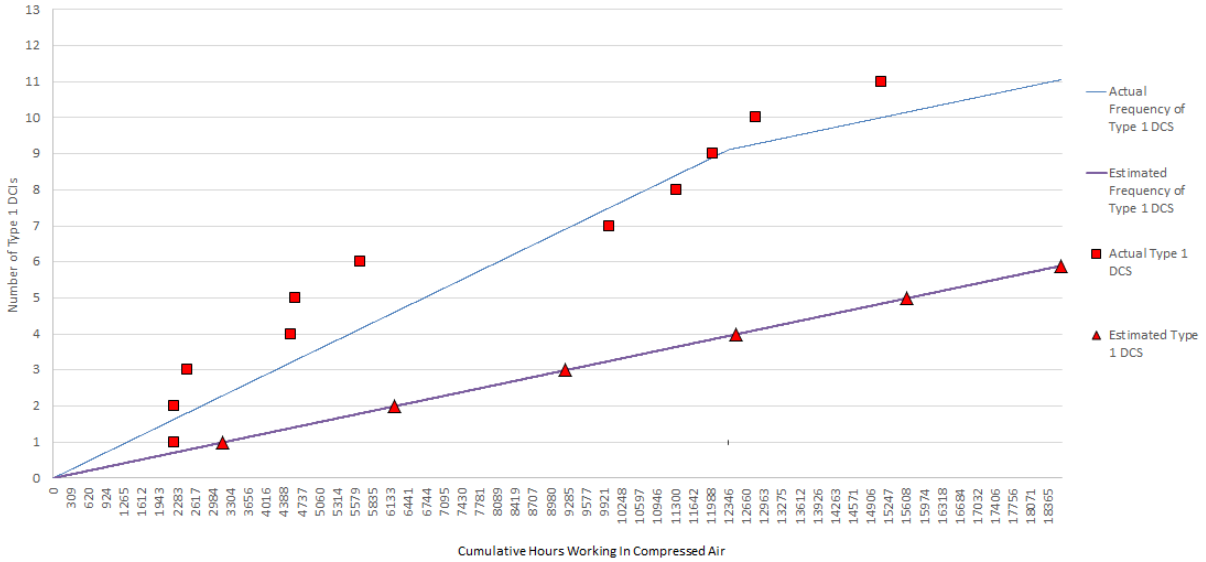

Figure 6: Estimated frequency of Type 1 DCS if HBOT Procedures were implemented from the beginning of the project

CONCLUSION AND RECOMMENDATIONS

In total, 18,599 man hours of work in compressed air representing 4,535 personnel entries were completed on Contract T208. It has been determined that the HBOT procedures developed by LJHJV in consultation with the AMP, reduced the frequency of CAWs developing a DCS for compressed air CHIs under 3.5 bar by over half (57%) from 0.3% to 0.13%

It is recommended that on future projects in Singapore, HBOT procedures developed on T208 are implemented for compressed air works where intervention pressures are less than 3.5 bar, and where the use of oxygen during decompression on the TBM has been ruled out. These HBOT procedures should be implemented in line with the existing project specific Work Method Statements (WMS), Standard Operating Procedures (SOPs) and relevant Singapore regulations.

In addition, adequately trained, rested and experienced CAWs should understand the requirements surrounding fitness for work, speak up if they are feeling unwell and understand the signs and symptoms of a DCS.

REFERENCES

[1] J H Lynch, A A Bove, *Diving Medicine: A Review of Current Evidence*, Journal of the American Board of Family Medicine, July-August 2009; Vol 22 No. 4

[2] J How, A Vijayan, T M Wong, *Acute Decompression Sickness in Compressed Air Workers Exposed to Pressures Below 1 Bar in the Singapore Mass Rapid Transit Project*, Singapore Med J 1990; Vol 31: 104-110

[3] Hamilton and Kay, *Boring Deep Tunnels*, for 3rd NEW UJNR, 2008 Nov

[4] US Navy Diving Manual, 6th revision. United States: US Naval Sea Systems Command. 2006

[5] R. D. Vann, F. K. Butler, S. J. Mitchell, R.E. M, *Decompression Illness*, The Lancet; Volume 377, Issue 9760, 8-14 January 2011, Pages 153-164

APPENDICES

A Summary of Contract T208 Compressed Air Cutterhead Interventions

APPENDIX A: SUMMARY OF CONTRACT T208 COMPRESSED AIR CUTTERHEAD INTERVENTIONS