DECOMPRESSION ILLNESS AND ITS REGULATION IN CONTEMPORARY UK TUNNELLING

- AN ENGINEERING PERSPECTIVE

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Synopsis

This thesis records the findings of a retrospective study of decompression illness (DCI) in the UK compressed air tunnelling industry since the mid-1980s.

The thesis describes how the study arose, its scope and objectives, along with an overview of tunnelling and shaft-sinking. The development of compressed air working techniques is reviewed along with a description of decompression practice and DCI, and an outline of relevant legislation and guidance.

The acquisition and manipulation of data to form a number of databases and spreadsheets on which the analysis was performed is discussed. That analysis examined measures of DCI incidence and quantified that incidence using these measures. Also considered is the variation in tolerance and susceptibility to DCI in the workforce, and the phenomenon of acclimatisation. An examination of the extent to which men worked on multiple contracts and the variation in their susceptibility to DCI on these contracts is included.

Options are then considered for reducing the incidence of DCI. The first retained air-only decompression through the application of restrictions on exposure. The second related to the use of oxygen decompression.

Finally the adequacy of the existing Regulations and Guidance is considered and recommendations made for possible changes to them, arising from the study.

The main conclusions are that a number of measures of DCI incidence were identified, some more appropriate than others and that the incidence of DCI when so measured was high, disproportionately so in shift workers. No reasonably practicable restrictions on exposure were identified which would have allowed the retention of air-only decompression. Oxygen decompression looked promising but had yet to be used sufficiently extensively to generate enough data for analysis.

Recommendations included one that an alternative technique for monitoring the effectiveness of decompression should be developed. The thesis ends with recommendations for further research.

Key words:- hyperbaric environment, acclimatisation, oxygen decompression.

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> **"Engineers were possibly rather absorbed in the engineering nature of their own occupation and overlooked or at any rate underestimated the importance and seriousness of the illness occasionally arising from compressed air"**.
>
> Dr. E. Hugh Snell,
> London County Council Medical Officer,
> Blackwall Tunnel 1894 – 86.
> (Preece *et al*, 1897 - 98; p 83)

Contents

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List of Acronyms and Abbreviations

The acronyms and abbreviations below are used in the text:-

(the) Addendum - *Addendum to "A Guide to the Work in Compressed Air Regulations 1996 - Guidance on Regulations" Guidance on OXYGEN DECOMPRESSION and the use of Breathing Mixtures other than Compressed Natural Air in the Working Chamber*, (HSE, 2001).

Atkins – W.S. Atkins, Consulting Engineers and contractors to HSE for data transcription.

BSI – British Standards Institution.

BGI – Bubble Growth Index (Lambertsen *et al*, 1999).

c. - circa

CAC – Compressed Air Contractor (Work in Compressed Air Regulations 1996 – Regulation 5).

CAWG – Compressed Air Working Group of the British Tunnelling Society (successor body to the "Panel").

CBR – Crude Bends Rate.

CIRIA – Construction Industry Research and Information Association.

CMA – Contract Medical Adviser (Work in Compressed Air Regulations 1996 – Regulation 9).

CTRL – Channel Tunnel Rail Link.

Current data – data used in this study - from contracts after 1985.

DCS – Decompression Sickness.

DCI - Decompression Illness.

DCI/HW – DCI per hour worked.

DON – Dysbaric osteonecrosis.

DP Index – Decompression Penalty Index (Shields and Lee, 1986).

DSM – Diving Safety Memorandum.

Evans' data – Newcastle Registry Data used by Dr A. E. Evans (CIRIA, 1992).

(the) **Guidance** – Guidance accompanying the Work in Compressed Air Regulations 1996, (HSE, 2001).

GYPP – Great Yarmouth Power Project.

HS – Hyperbaric Supervisor.

HSE – Health & Safety Executive.

HSW Act – Health and Safety at Work etc Act 1974.

ICE – Institution of Civil Engineers, London.

JLE – Jubilee Line Extension.

LA – Lock Attendant.

LTA – long term average.

LWRM – London Water Ring Main.

MLA – Medical Lock Attendant.

MRC – Medical Research Council.

NI (Number) – National Insurance (Number).

NNC – number needed to compress (Bennett and George, 2002).

OSD – Offshore Safety Division (of HSE).

(the) **Panel** - Medical Research Council Decompression Sickness Panel.

PDSOB - Post Decompression Surface Oxygen Breathing.

SBR – Standardised Bends Ratio.

SERF – Single Exposure Risk Factor.

TBM – Tunnel Boring Machine.

UHMS – Undersea & Hyperbaric Medical Society.

WCA Regulations or **1996 Regulations** – Work in Compressed Air Regulations 1996 (Great Britain, 1966).

1958 Regulations - Work in Compressed Air Special Regulations 1958 (Great Britain, 1958).

1958 Tables - decompression tables in the Schedules to the **1958 Regulations.**

Glossary

Comprehensive glossaries of tunnelling terminology can be found in BS 6100:1990 Section 2.2.3 "Tunnels" (BSI, 1990), which is currently being revised, and on the website of the International Tunnelling Association (www.aites.org). Compressed air working and decompression illness utilise a vocabulary which includes both engineering and medical terminology and for which an excellent, comprehensive glossary and list of abbreviations was complied by Jardine (Jardine and McCallum, 1994). There are glossaries of the more esoteric terms found in the hyperbaric research literature in Robertson and Simpson (1996) and Andrews (1998).

A limited glossary of terms, including terms not defined elsewhere, which are frequently used in the text, is set out below for convenience.

Air deck – a horizontal bulkhead in a shaft or caisson.

Appointed Doctor – doctor appointed by HSE to undertake statutory medical examinations of compressed air workers (Work in Compressed Air Regulations 1996 – Regulation 10).

Balance point – the horizon on the tunnel face where the air and water pressure are balanced. The balance point can be raised or lowered by reducing or increasing the air pressure.

Blackpool Tables – decompression tables, first published by CIRIA (1973), and named after the contract on which they were first used. The Blackpool Tables form the basis of decompression procedures currently approved by HSE for use in UK.

Bubble Growth Index – index relative to an assumed initial size of a bubble during exposure, decompression and afterwards (Lambertsen *et al*, 1999; Appendix A).

Caisson – a structure, which is sunk vertically into the ground by progressively excavating material from within the structure (see Section 1.5.1).

Compressed Air Contractor – a contractor appointed under Regulation 5 of the Work in Compressed Air Regulations 1996 to undertake work in compressed air and the principal duty holder under these Regulations.

Contract Medical Adviser – a doctor appointed by the Compressed Air Contractor under Regulation 9 of the Work in Compressed Air Regulations 1996, to advise the Compressed Air Contractor on all aspects of occupational health in compressed air work.

Cross passage – a small diameter tunnel for access or emergency purposes, connecting two parallel tunnels.

Crude Bends Rate – a measure of the incidence of DCI expressed as a percentage of exposures.

Decanting - rapid decompression to atmospheric pressure in the manlock of the working chamber followed promptly by transfer to another manlock in which the pressure is quickly increased to that of the working chamber or marginally higher, before a timed or stage decompression is carried out in the second manlock. In diving the equivalent technique is surface decompression.

Decompression threshold – the exposure pressure at or above which, stage decompression is required in a decompression table.

Decompression Penalty Index – a measure of the severity of exposure based on the exact decompression time theoretically required, interpolated from the **US Navy tables**, (after Shields and Lee, 1986).

Decompression stress – the physiological stress on the body resulting from exposure to a hyperbaric atmosphere.

Diving Safety Memorandum – a formal information sheet on diving safety, originally issued by the Department of Energy, now by the Offshore Safety division of HSE, which sets out aspects of its enforcement policy for commercial diving.

Exposure period - the time from start of compression to the start of decompression.

Exposure number – the sequential number of an exposure in a man's exposure history

Free air – normal atmospheric pressure.

Head access – access to the cutterhead of a **TBM** for maintenance or inspection purposes.

Kentledge – concrete or steel blocks placed on top of a caisson to increase its weight and thus assist the sinking process.

Lock test – a short exposure to compressed air, undertaken under medical supervision to confirm a person's suitability for work in compressed air.

Newcastle Registry – the (now defunct) Registry of compressed air tunnelling exposure data established by the Medical Research Council Decompression Sickness Panel in 1964 at the University of Newcastle upon Tyne (Griffiths, 1967).

Normal decompression – stage decompression carried out immediately following exposure to compressed air, (term used by Evans (CIRIA, 1992)).

Open faced tunnelling – excavation by hand or by backacter/cutter boom in a shield, which provides limited mechanical support to the face being excavated.

Pipe jack – a structure similar to a tunnel but one in which the lining is installed as pipes, lowered into a shaft, which are progressively jacked forward to follow the excavation.

Phase decompression – a decompression technique, part of which – the walkout to the pit bottom from an intermediate manlock - is spent at an intermediate pressure and thus counts as part of the decompression.

Post Decompression Surface Oxygen Breathing – the routine administration of pure oxygen at atmospheric pressure following normal decompression on air.

P√T or **PrT (or Exposure Index)** – index of decompression stress expressed as (absolute) pressure x square root of exposure time, (Hempleman, 1993).

Royal Navy Tables – Decompression tables for diving and therapeutic recompression published by the Royal Navy (Whistler and Larne, 1984).

Shaft - a vertical structure usually giving access to a tunnel.

Single Exposure Risk Factor – a measure of the risk of DCI arising from a single exposure of a given pressure/time combination.

Standardised Bends Ratio – a comparative measure of DCI in which the actual number of DCI events arising from a given group of exposures is compared with the expected number of DCI events for a group of exposures of similar pressure and time from a reference dataset.

Stage decompression – decompression in which pressure is reduced to a number of predetermined stages and is held for increasingly long periods at each successive lower pressure stage.

Tunnel - a horizontal structure in the ground constructed without open excavation from the surface. The lining is installed behind the face as excavation progresses.

Uniform decompression – decompression in which the pressure is reduced at a constant rate throughout the decompression.

US Navy Tables – Decompression tables for diving and therapeutic recompression published by US Navy (Whistler and Larne, 1984).

Chapter 1 – Introduction to the Study

1.1. Introduction

For around 170 years, compressed air working has been used on infrastructure projects to facilitate the sinking of caissons and the driving of tunnels. Millions of people have benefited from the bridges founded on these caissons and the tunnels driven under land and water features with the aid of compressed air.

The technique was first applied to caisson sinking and was initially used in the UK around 1851. The most spectacular caisson to be sunk in the UK in recent years was a single 50m square by 25m high concrete monolith weighing around 25,000 tonnes, which formed a new dock entrance structure at Ramsden Dock, Barrow in Furness to facilitate the passage of nuclear submarines from a local shipyard (see Figure 1.1).

Figure 1.1 – Aerial view of Ramsden Dock Caisson

(©Monk/Weiss & Freitag JV)

In recent years, perhaps the best known UK tunnelling projects on which compressed air working was used were those for the extension to the Jubilee Line on London Underground where it was used on three contracts including the Thames crossings at Canary Wharf and most recently on Phase 2 of the Channel Tunnel Rail Link (CTRL).

Over the past two decades the public has also benefited from less well known infrastructure tunnelling projects on which compressed air working was also required.

These included improvements to the water supply to much of the Greater London area through the London Water Ring Main tunnels; tunnels at Bacton and Yarmouth where pipelines from the offshore gas fields had their landfall and London Cable Tunnel which carried electricity cables to improve the robustness of the national grid. Environmental benefits have arisen from major tunnel sewer schemes such as those at Fylde Coast, Hull, Hastings, Swansea and Weston super Mare; where in each case, bathing beaches or urban waste water discharges have been brought up to European Community standards. The local community benefited from flood relief from the tunnel at Swanage.

Unfortunately however, the benefits to society have been gained at great cost to many of those working in compressed air - pain, disability and in the past even death, all from decompression illness (DCI).

The tunnelling industry is not alone in having to address the problems of decompression. Divers also work under pressure and are at risk as they decompress during their return to the surface. A century ago and more, divers and caisson workers both suffered (literally) from the lack of medical and scientific knowledge about the effects of pressure and the techniques for safe decompression. At that time, experience from the tunnelling industry was being utilised by the diving industry. Since then however, the diving industry has been much more active in addressing the challenge of safer decompression, first for military diving and marine salvage work but later for deep diving associated with the commercial exploitation of oil and gas reserves in the North Sea and elsewhere. Decompression illness, which was prevalent in UK offshore diving up to the late 1980s, has been significantly reduced (Robertson and Simpson, 1996). Much of this improvement has been as the result of research driven by the high commercial value of the oil reserves, which has resulted in money being made available.

Unfortunately similar sources of funding have not been available to the tunnelling industry. Techniques and practices for compressed air working in the UK construction industry have changed but slowly in recent decades and it is only now that the tunnelling industry in the UK is beginning to embrace modern (diving) hyperbaric practices. It would appear that this reluctance to change is not confined to the UK as Phillips variously noted in his account of the history of American compressed air legislation:

> "By the 1920s, caisson workers and naval divers adhered to completely different schedules for decompression"; ".... there was little if any collaborative effort between writers of decompression tables for tunneling workers and those for navies. This divergence has

> continued to this day as the naval and private commercial diving firms have continued to develop ultramodern decompression techniques while tunneling and caisson workers still follow outmoded timetables" and "While many fields of industry, including mining, textiles, agriculture, and farming were closely studied and improved, the tunneling community seemed to escape public and bureaucratic scrutiny" (Phillips, 1965: p134 & 140).

Knowledge about the causes of and cures for DCI has developed over the past hundred years or so. In that time relatively few significant changes in decompression practice in the tunnelling industry have been made in an attempt to reduce the risk of decompression illness. The relative scarcity of references to relevant literature in Section 2.1 provides evidence that decompression illness arising from tunnelling and caisson sinking has been a neglected area of occupational health concern even by comparison with the construction industry's already poor attitude towards occupational health (HSE, 2002b).

1.2. The study – its conception and form

This study arose from the author's interest and involvement in compressed air tunnelling and was conceived to reflect the link between engineering and medicine in the DCI, which results from such work. It was specifically designed to make use of exposure data which was available within HSE, and to be informed by the author's experience of the different approaches to decompression practice in diving and compressed air tunnelling from the regulatory perspective.

1.2.1. The "Engineering perspective"

DCI in compressed air tunnellers is a medical condition arising directly from engineering activity. It is a manifestation of the human body's response to reduction in ambient atmospheric pressure following hyperbaric exposure such as in compressed air tunnelling and diving.

DCI, as an occupational disease in tunnelling, has long been associated with formal guidance and statutory control through the specification of ever more restrictive but effective decompression regimes. Any reduction in the incidence of DCI requires cooperation between engineers, who have traditionally sought to maximise working time and to minimise time spent in decompression, which represented an unproductive overhead on a contract, and medical professionals who have sought to reduce its incidence. Medical expertise is required to relieve its symptoms.

Engineers determine the working pressure and manage the working environment in compressed air tunnelling. They are thus well placed to examine what they can do to reduce the incidence of DCI.

The information available to engineers includes the history of the development and use of compressed air working through literature such as the proceedings of the Institution of Civil Engineers; current and previous legislation, standards and industry guidance. It also includes the work of specialist industry groups such as the Compressed Air Working Group (CAWG) of the British Tunnelling Society. Engineers have direct access to lock attendant's registers and understand the use of decompression tables. Engineers can restrict the use of the more extreme exposures permitted by a table but are not competent to modify the profiles within the tables. Engineers need to know if a man is fit to work in compressed air but are not competent to make that assessment or to treat DCI.

The "Engineering perspective" is intended to reflect one side of the division between the engineering and medical aspects of DCI arising from compressed air tunnelling and thus to define in part, the scope of the study.

1.2.2. Quantitative v qualitative studies

Patton (1990) differentiated between quantitative and qualitative studies. Quantitative studies use standardised measures to assign information to a limited number of categories, which can be analysed in a statistically rigorous fashion. Data accuracy depends on the design of the experiment, the precision of the measurement tools and on adherence to predetermined measurement procedures. In qualitative studies, the researcher is the measurement tool and the validity of the study depends on the interpretive skill of the researcher.

In part this is a quantitative study. The data available for analysis were not the product of carefully designed experiments but were the best available from industry within the constraints of statutory requirements. Often data were in a format not specifically designed to facilitate research. In part also there is a qualitative aspect to the study particularly in respect of data manipulation where the author's knowledge of the industry enabled him to recognise how inconsistencies in the recorded data had arisen and allowed the elimination some of these inconsistencies.

1.2.3. Participation v observation

In some studies the researcher participates in the activity, in others the researcher merely observes the activity.

Gill and Johnson (1997) cited by Saunders *et al* (2003; p 224) identified the four combinations of participation and observation, depending on whether the researcher observed or took part in the activity and whether or not the researcher's identity was revealed (see Figure 1.2). They gave no guidance as to what they meant by "takes part in activity".

How does their classification apply to this study? The author has worked very intermittently in compressed air throughout most of the period under study. For much of this period the author was a regulator of the industry whose identity was known within the industry but at that time he was not a "researcher". The author played no direct part in record keeping but observed the process – perhaps being an "Observer as participant". Section 3.6 and Appendix 4 sets out how the author used his knowledge of compressed air working techniques to eliminate many of the inconsistencies in the data, perhaps in the process becoming a "Participant as observer". One aspect which Saunders *et al* did not consider however, was that in which the researcher was a regulator of the activity being researched, which perhaps leads to a fifth and unique category - participant **and** observer!

Researcher takes part in activity

Researcher's identity is revealed	Participant as observer	Complete participation	Researcher's identity is concealed
	Observer as participant	Complete observation	

Researcher observes activity

Figure 1.2 – Typology of participant observer researcher roles

(after Gill and Johnson in Saunders *et al,* 2003)

Patton (1990) considered the credibility of the observer and concluded that an observer should declare the experience, training and perspective he brought to a study. Both the positive and negative effects should be addressed. Additionally, the effect that the presence of the observer/participant had on those being studied should also be evaluated. This study should question if the author's role as a regulator within the industry affected the study outcome.

As a regulator, the author helped set the framework within which work in compressed air was undertaken both through inspection and through involvement in the drafting of the 1996 Regulations and the Guidance. Indirectly he influenced data quality in that he introduced the use of computer software for data recording exposures. A contract by contract comparison of the amount of work required to be done to improve data quality (see Appendix 4) shows that most of the contracts on which electronic record keeping was undertaken required significantly less work to be done on them than on contracts with manual recording systems. Accordingly, it was concluded that the author influenced the outcome of the study through introducing changes in industry practice which had the effect of improving the quality of data recorded. Had this study been planned when many of these contracts were in progress, the site inspections undertaken by the author would have been somewhat more rigorous in respect of record keeping procedures!

1.2.4. The author's experience of compressed air tunnelling and diving

My experience of compressed air tunnelling began in 1981 when I was Resident Engineer on the construction of two small diameter tunnels on the Garnock Valley Sewer at Dalry, Ayrshire. Both tunnels were built with the aid of low-pressure compressed air.

Since 1987 I have been the Health & Safety Executive (HSE) national specialist in a range of civil engineering topics including tunnelling and work in compressed air. As tunnelling topic specialist, I have had some involvement in most of the compressed air tunnelling work in the UK during this period.

I was extensively involved as the principal engineering author in the revision of the Work in Compressed Air Special Regulations 1958, the outcome of which was the Work in Compressed Air Regulations 1996 and associated guidance (HSE, 1996). Later, I drafted the addendum dealing with oxygen decompression and the use of non-air breathing mixtures (HSE, 2001). I remain responsible for HSE's technical policy in compressed air tunnelling matters.

Electronic recording procedures were established in the industry during the mid-1990s to improve the quality of records and to aid future analysis. I simultaneously instigated a programme of locating and collecting exposure records from earlier contracts and having them transcribed into electronic format.

Through my work, I developed the view that levels of DCI in UK tunnelling were unacceptably high and I set out to change HSE policy on decompression practice. I drove forward the programme of research, which resulted in the change to oxygen decompression in 2001 (Lamont, 2002; (reproduced in Appendix 1)).

As a result of my position in HSE, I am a member of CAWG and I chair British Standards Institution (BSI) committee B/513/2 – "Drilling, piling and tunnelling – safety" and through B/513/2, I am also a member of the UK delegation to the European Standards committee CEN/TC151/WG4 "Construction machinery safety - tunnelling machines". This committee is responsible for drafting four harmonised standards covering the safety of tunnelling machinery including EN 12110, available in the UK as BS EN 12110:2002 "Tunnelling Machinery – airlocks – safety requirements" (BSI, 2002).

Between 1989 and 1994 I was also responsible for the technical aspects of inshore commercial diving within HSE. Part of that role required me to inspect commercial diver training courses, for which I required some knowledge of diving physiology. During this time I became familiar with decompression practice in diving which included the use of oxygen for decompression and the routine use of various non-air breathing mixtures.

I hope that through my technical knowledge and experience, I can add value to this study.

1.3. Scope and Objectives.

The scope of this project covers exposure data from caisson sinking and tunnelling contracts driven under compressed air in the UK since 1986. Most of the data were from contracts where the pressure was 1 bar gauge or over, however, data from a number of more recent contracts at pressures below 1 bar were included in the study.

Previous studies have focussed mainly on individual contracts such as the Tyne tunnel (Paton and Walder, 1954) and Dartford (Campbell Golding, 1960), apart from the HSE-funded study by Evans, of data in the Newcastle Registry data from 1948 to 1980 (CIRIA, 1992). HSE records show that there were few compressed air contracts in the period 1980 – 1986 (HSE, 1998).

The study has been designed to utilise information and data sources, which are readily available to the engineer, and to strike a balance between the engineering and medical aspects of DCI. Although the study covers the period from 1986, attitudes and behaviour, working practices, and statutory requirements have been influenced by the evolution of compressed air techniques over the decades. The scope of the study therefore includes an assessment of historical information on the development of compressed air working to inform and contrast where appropriate.

Unlike previous studies, which have been wholly restricted to caisson sinking and tunnelling, this study will be informed by experience from the UK diving industry where appropriate.

The objectives of this study are set out below, cross-referenced to the chapters in which these objectives are addressed:-

- obtain and make suitable for subsequent analysis, exposure data and records of DCI arising from compressed air tunnelling in the UK since the mid 1980s	Chapter 3
- identify measures of the incidence of decompression illness	Chapter 4
- analyse the data collected to provide information on the incidence of decompression illness both in the population exposed and at an individual level and make comparisons with historical data – principally the work of Evans (CIRIA, 1992)	Chapter 4
- examine the tolerance of individuals to DCI	Chapter 5
- examine the susceptibility of individuals to DCI	Chapter 5
- examine if an acclimatisation effect can be demonstrated in the workforce as a group and in individuals	Chapter 5
- determine if individuals experiencing DCI do so equally on more than one contract	Chapter 5

- examine if there is the potential to make a significant reduction in the incidence of decompression illness using air-only decompression regimes	Chapter 6
- determine the benefits (if any) of oxygen decompression in the UK to date	Chapter 6
- be informed by experience from the diving industry where appropriate	Chapters 4 – 7
- review the regulation of compressed air working in the UK and make recommendations for its revision if appropriate	Appendix 5

Whilst osteonecrosis (chronic DCI) may be more disabling than some forms of acute DCI (see Section 2.3.1), the lack of data on cases of osteonecrosis meant than this study focussed on acute DCI only (see Chapter 4).

1.4. Units

Metric units have been used throughout the text. Imperial equivalents given in brackets alongside indicate that the figure was originally in imperial units but was converted to metric units for consistency in this text.

1.4.1. Units of pressure

A variety of units of pressure are used, sometimes inconsistently, in papers on hyperbaric work depending on whether the author is a scientist, a tunnelling engineer, a diver or a doctor. Scientists prefer to work in absolute pressure units. Engineers, divers and doctors tend to work in terms of gauge pressure. Flook (2001: p2), a scientist, noted that:-

> "of all the scientific units in common use, those for pressure remain apparently almost a matter of personal preference. Nowhere is this more true than where hyperbaric pressure is used"

Prior to metrication under the Construction (Metrication) Regulations 1984 (Great Britain, 1984) pressure was measured in pounds per square inch (psi) (lbs/in^2). Since metrication, the pressure unit of choice within the industry has been the bar (decimal fractions of bars are preferred to millibars) however some use of imperial units persisted until the mid 1990s. Throughout this text, pressure is given in bar. Imperial equivalents given in brackets alongside (see Table 1.1) indicate that the pressure in bar represents a conversion from such units.

The following definitions can be found in Longman's "Dictionary of Physics" (Gray & Isaacs, 1990):-

> **bar** – A CGS unit of pressure equal to 10^5 pascal. It may be used with SI units and SI prefixes may be attached to it. The millibar (Symbol: mbar or mb) is a commonly used unit of pressure in meteorology.
>
> **standard atmosphere** – An internationally established reference for pressure, defined as 101325 pascals. Although this was formerly used as a unit of pressure - the atmosphere, symbol: atm – the standard atmosphere should not now be regarded as a unit. Atmospheric pressure fluctuates about the standard value.

Other units which are used occasionally include (kilo)Pascals ((k)Pa), which appear in research reports by Flook and atmospheres and atmospheres absolute (ata). In diving-related references, feet/metres of (sea)water (f/msw) are used. A useful conversion table for units of pressure can be found in the journals of the Undersea & Hyperbaric Medical Society (e.g. UHMS, 2002).

In UK tunnelling industry practice, pressure is implicitly stated as gauge pressure (absolute pressure = gauge pressure + atmospheric pressure). Throughout this text, gauge pressure (in bar) is used unless stated otherwise.

1.4.2. Metrication

In most circumstances a single conversion factor would have been used for all pressure data. However in compressed air work the Construction (Metrication) Regulations 1984 (Great Britain, 1984) set out the statutory equivalents for certain pressures, rounded off in mbar, between imperial and metric units. Table 1.1 shows these equivalences along with interpolated conversions for intermediate pressures. The figures in Table 1.1 were extrapolated as required to obtain conversions for pressures above 3.5 bar and below 0.7 bar. Current HSE policy is that exposure pressures should be rounded off to the nearest 0.05 bar above the actual pressure.

Regulations		Interpolated	
Metric (bar)	**Imperial (psi)**	**Metric (bar)**	**Imperial (psi)**
0.7	10	-	-
0.95	14	-	-
1.05	15	1.00	14.5
1.10	16	-	-
1.15	17	-	-
1.25	18	1.325	19
1.40	20	1.450	21
1.50	22	1.575	23
1.65	24	1.725	25
1.80	26	1.875	27
1.95	28	2.00	29
2.05	30	2.125	31
2.20	32	2.275	33
2.35	34	2.425	35
2.50	36	2.575	37
2.65	38	2.70	39
2.75	40	2.825	41
2.90	42	2.975	43
3.05	44	3.125	45
3.20	46	3.25	47
3.30	48	3.375	49
3.45	50		

Table 1.1 - Metric conversions

1.5. Principles of caisson sinking, tunnelling and compressed air work

This text is not about caisson sinking or tunnelling. However it is considered important to include a description of basic caisson sinking and tunnel construction techniques and compressed air equipment to facilitate an understanding of the environment in which compressed air is used and the changing pattern of compressed air working over the years.

1.5.1. Caisson sinking

A "wet" caisson is sunk by progressively excavating material from within and around the base of the caisson structure, thus allowing it to sink into the void created. As material is removed from inside its base, the caisson sinks under its own weight or it forced down with the assistance of jacks or kentledge if necessary. The caisson is allowed to flood with groundwater. Where problems are encountered during excavation, an air deck is built across the caisson to allow compressed air to be introduced below the air deck to maintain a pressurised working chamber in which the excavation takes place in the dry.

A "dry" caisson is constructed progressively downwards from the surface using underpinning techniques and does not normally require compressed air working.

Caissons may be used as foundations e.g. for a bridge, and caisson sinking techniques are used to sink shafts for tunnel construction.

1.5.2. Tunnelling - machines and methods

It is common in the construction of a tunnel to encounter a range of varying ground types and groundwater conditions over the length of the tunnel. Because of this, tunnelling machines are normally designed for the conditions likely to be encountered on a specific tunnel. To accommodate a range of ground types, they frequently incorporate characteristics from more than one generic type of machine. Indicative methods of excavation in various ground conditions are set out in Table 3 of BS 6164:2001 (BSI, 2001). It is important to remember one of the basic rules of tunnelling - each tunnel is unique.

Tunnels are normally classified by the type of ground through which they are driven and by the excavation method used.

Soft ground tunnels include those in sand, gravel, silt, clay and soft rock. Excavation is by shield machine or by hand. The face is progressively excavated for a distance equivalent to the length of one ring of lining with the shield being shoved forward as excavation progresses. A ring of lining is built in the tailskin of the shield and the cycle repeated. The shield provides temporary ground support until the permanent lining, precast concrete or occasionally cast iron segments, has been constructed.

Shield machines come in a number of generic types, classified by their mode of operation. Mechanisation in tunnel excavation has increased considerably in the past two decades with the development of ever more sophisticated machines.

"Open mode" machines have a cutter boom or backacter for part-face excavation or a rotating cutterhead through which excavated material passes (see Figure 1.3). Excavated material is removed from the machine by conveyor belt.

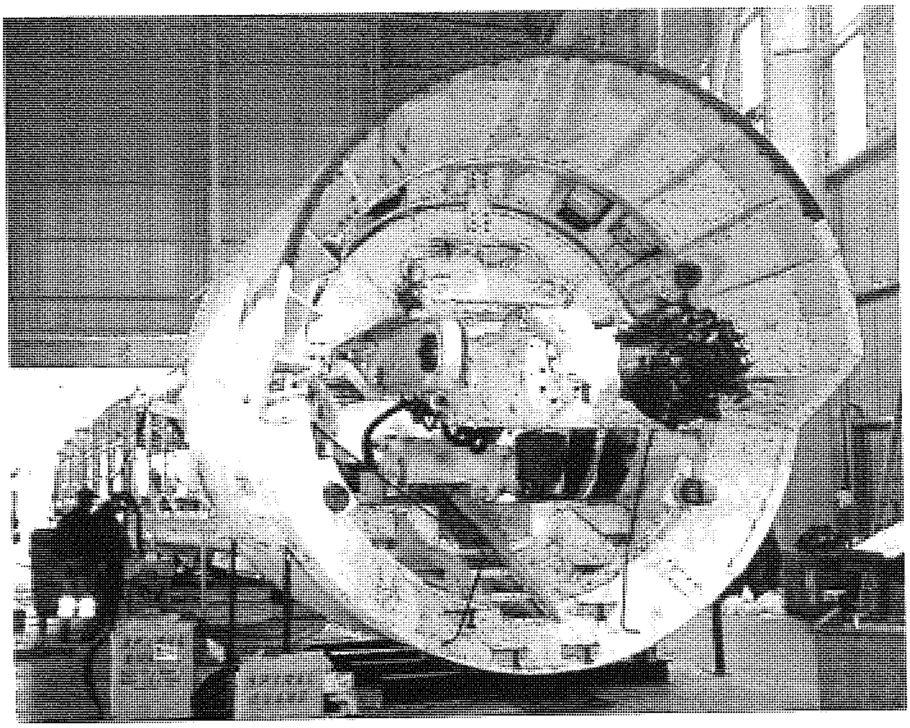


Figure 1.3 – Typical cutter-boom TBM during factory assembly

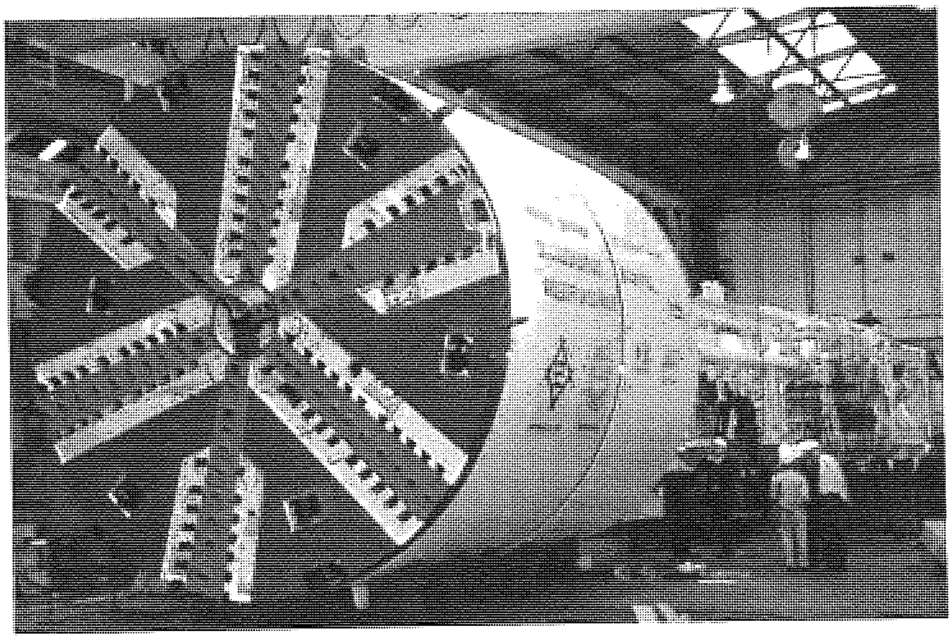


Figure 1.4 – Typical slurry TBM during factory assembly

"Closed mode" machines include earth pressure balance machines, slurry machines (see Figure 1.4) and air-pressurised shields. In these machines, a bulkhead separates the cutterhead from the rest of the machine and the tunnel, and therefore these machines can operate successfully below the water table. Compressed air is usually applied to allow access to the cutterhead for maintenance. Only the cutterhead has to be pressurised.

Prior to the development of closed mode machines, it would have been necessary use an open mode machine and to pressurise the entire tunnel. The use of closed mode machines has considerably reduced the number of exposures undergone to drive a given length of tunnel.

Hand excavation (Figure 1.5) is now limited to small diameter tunnels, backshunts, machine build chambers, breakouts and tunnels which are too short or too geometrically complex to be capable of being machine driven. In addition, the demand for tunnels in ever more challenging geotechnical conditions necessitates the use of sophisticated machines.

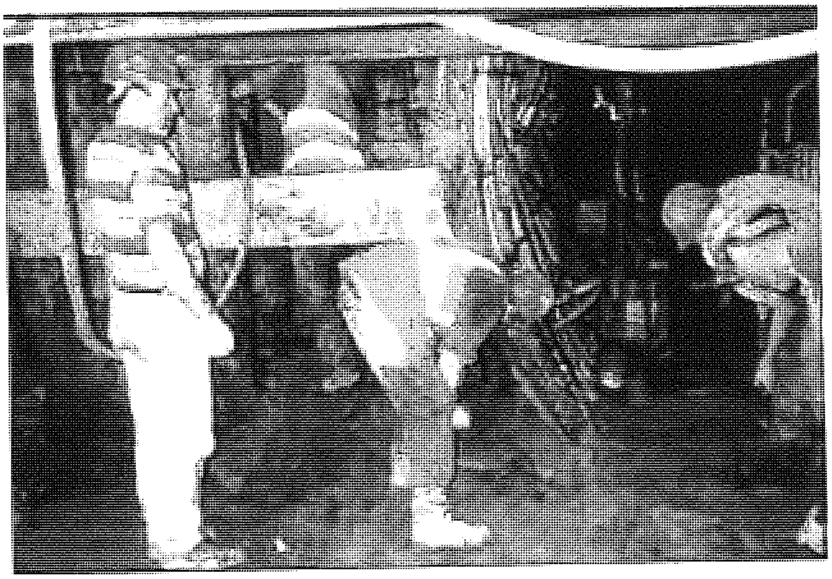


Figure 1.5 – Hand excavation of station tunnel enlargement – JLE 105

Hard rock tunnels in which excavation can either be by tunnel boring machine (TBM) or drill and blast techniques and where little ground support is required following excavation, rarely require the application of compressed air to control ground water infiltration.

King (2000) in the Harding lecture of 2000, gave a much fuller description of the development of tunnelling techniques.

1.6. Compressed air working

Even within the tunnelling industry, the use of compressed air is considered by many to be something of a black art (King, 1989). This is not the case. The principles behind its use are straightforward.

1.6.1. Effects of compressed air on the ground

Compressed air is normally applied at a pressure which is sufficient to balance water pressure - either pressure from water coming through the tunnel face or from the ground at the base of the caisson. Balancing water pressure with air pressure controls water ingress. By controlling water ingress, ground stability can be controlled thus preventing face collapse or invert boiling. This allows construction to be carried out safely and with minimal settlement. It is the essential simplicity of balancing pressures, which makes compressed air effective. Javadi (2002), provided a simple description of the mechanisms by which water is controlled through the application of air pressure, whilst a more comprehensive review of these mechanisms was given by Holzhäuser (2002).

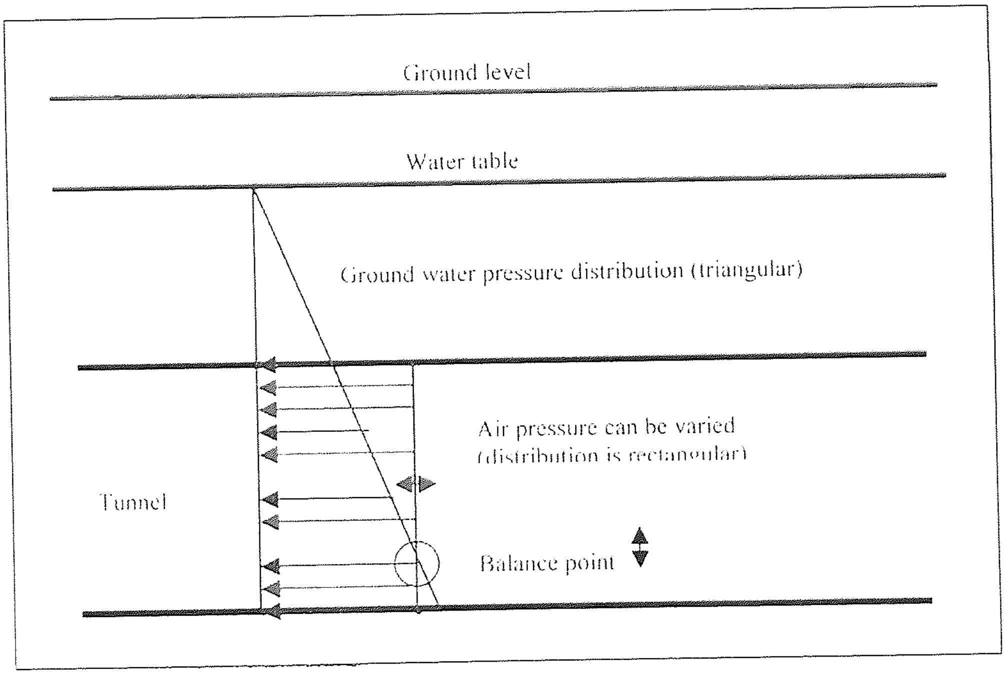


Figure 1.6 – Hydrostatic v air pressure diagram
(pressure distribution colour code - air pressure, ground water pressure)

Ground water pressure increases linearly with depth across the tunnel face to give a triangular pressure distribution. It is normal industry practice to ignore the density of air.

Air pressure is therefore taken to exert a constant pressure on the face – a rectangular distribution. Consequently there is only one horizon on the tunnel face where the air pressure equals the water pressure – the balance point (see Figure 1.6). By altering the air pressure, the balance point can be maintained at the required level. In machine driven tunnels, the air pressure will be determined with the aid of instrumentation on the machine. In hand excavated tunnels, the balance point is usually determined by the pit boss or leading miner on the basis of his assessment of the stability of the face. It is usually set slightly above tunnel invert level. The hydrostatic/air pressure imbalance across large diameter faces can lead to instability or blow out with catastrophic consequences for anyone in the working chamber.

1.6.2. Bulkheads and airlocks

Bulkheads are used to maintain pressure in the working chamber and airlocks. In caisson sinking, a horizontal bulkhead known as an air deck is used whilst in tunnelling, air pressure is normally maintained by a vertical bulkhead across the tunnel. Air locks in shafts are known as vertical locks (Figure 1.7) whilst in-tunnel locks are known as horizontal locks. Where a vertical lock gives direct access to a horizontal lock above, the combination is referred to as a "T" lock.

Airlocks allow the passage of men and materials through the bulkhead, between the pressurised working chamber and the free air part of the workings. Locks for the passage of men are normally referred to as manlocks, whilst those for materials used to be called muck locks but are now more commonly referred to as materials locks. Both types of airlock can be formed from a number of bulkheads built into the tunnel lining (see Figure 1.8) or from a self-contained pressure vessel attached to the air deck or to a single bulkhead in the tunnel.

Closed mode TBMs have integral manlocks (see Figure 1.9) to allow access through their forward bulkhead to the plenum chamber behind the cutterhead.

Figure 1.7 – Vertical lock, Weston-super-Mare

Figure 1.8 – Tunnel manlock and lock attendant's station, Portsmouth

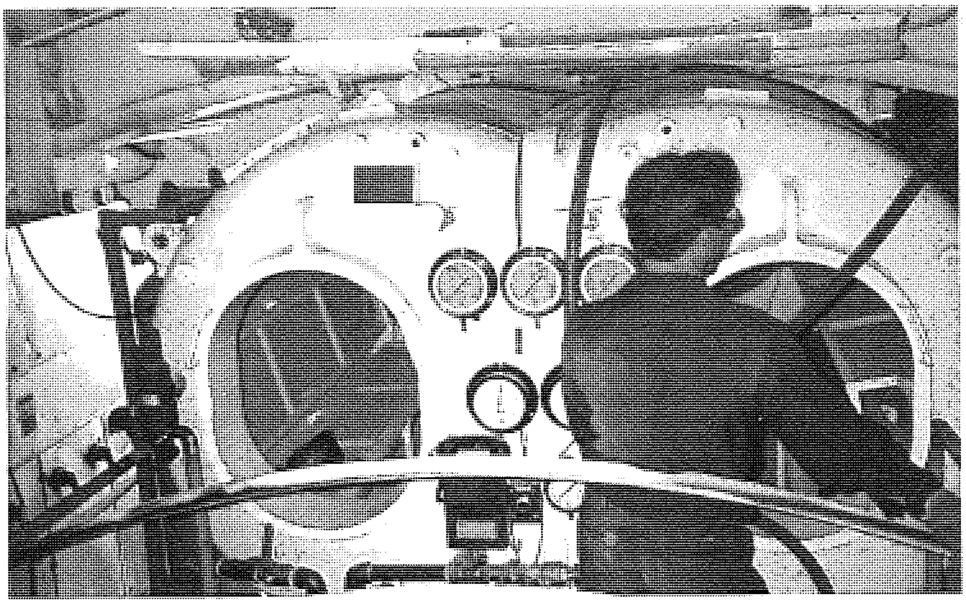


Figure 1.9 – Typical two-compartment manlock on TBM

1.6.3. Alternatives to the use of compressed air for ground stabilisation

There are alternatives to the use of compressed air for ground support. The most common are the use of grouting techniques and ground freezing. Grouting involves the injection of cementitious or chemical mixtures into the ground. The nature of the ground and in particular its permeability have considerable influence over the success of any grouting operations.

In ground freezing operations, liquid nitrogen or an ammonia/calcium brine system is used to form an ice block in the ground. Ground freezing can also be used in shaft sinking operations particularly where unacceptably high air pressures would otherwise be required. Apart from the health hazards arising from the materials used, there is further risk as the effectiveness of both techniques is susceptible to ground permeability and groundwater flow.

Grouting can be used in conjunction with compressed air to reduce air loss through the ground such as on the Garnock Valley Sewer - Dalry to Dalgarven contract in Ayrshire, for which the author was Resident Engineer in 1981. When considering the reasonable practicability of the use of grouting or freezing to avoid the use of compressed air, the not inconsiderable costs of these techniques must be balanced against any health and safety benefit. Shutter (1992) reviewed the use of ground freezing (Figure 1.10) or grouting (Figure 1.11) as alternatives to the use of compressed air but concluded that there were circumstances where compressed air would remain the technique of choice for ground stabilisation. That being the case, he recommended that whatever measures were necessary to ensure its continuing use should be taken.

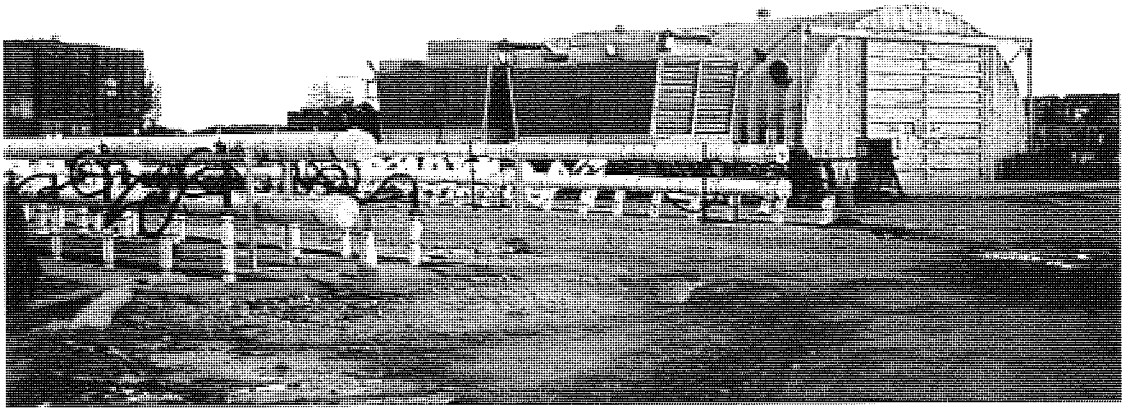


Figure 1.10 – Ground freezing installation, Portsmouth

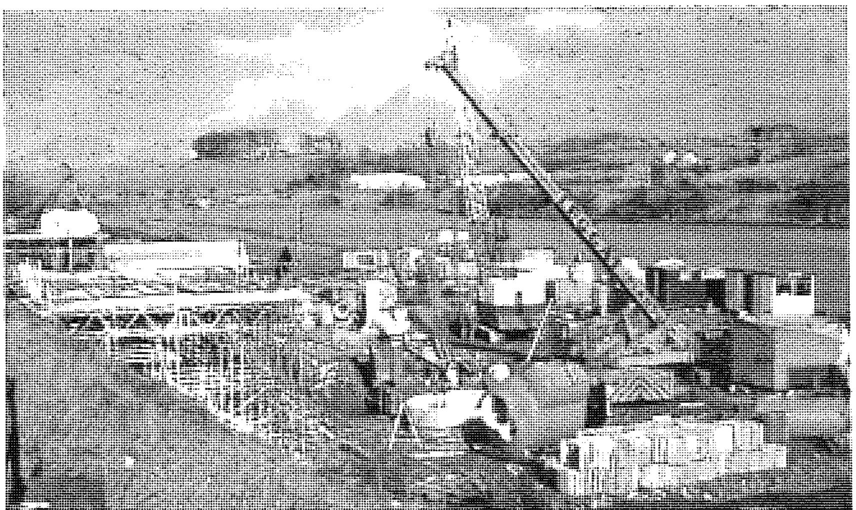


Figure 1.11 – Grouting operations, Garnock Valley Sewer, Dalry

1.6.4. Pressure variations

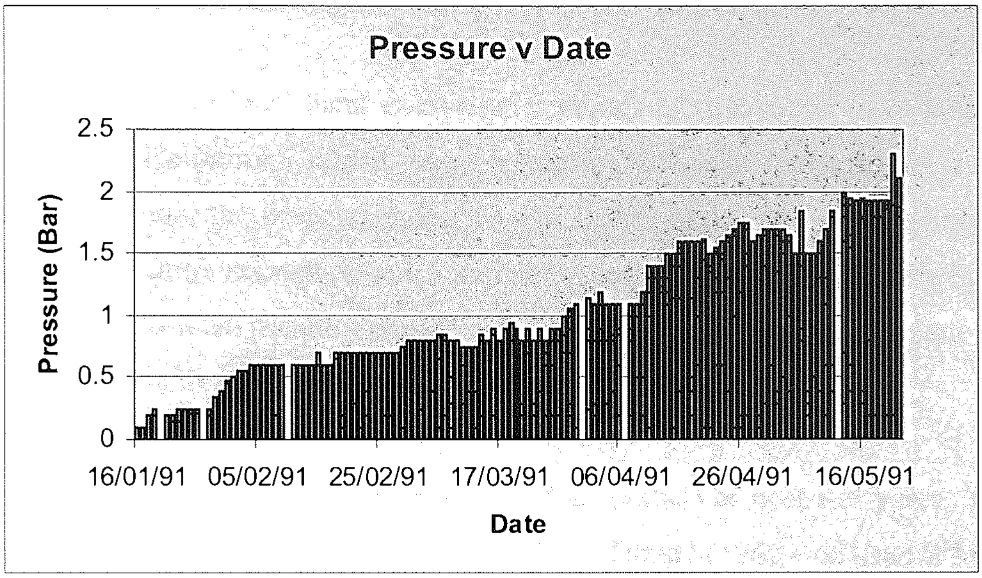


Figure 1.12 – Contract pressure profile – Ramsden Dock

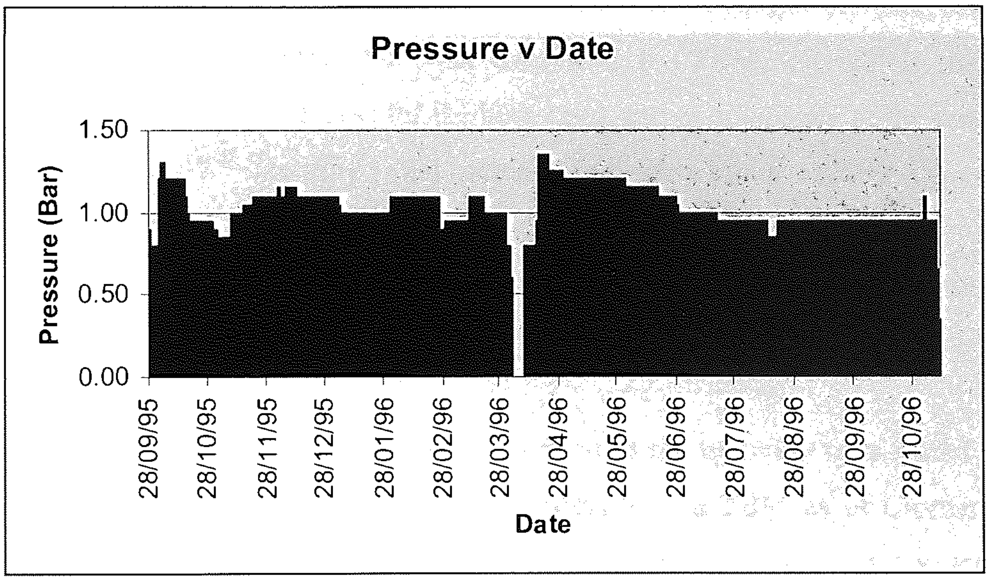


Figure 1.13 – Contract pressure profile – JLE 105

When caisson sinking, exposure pressure normally increases with time/date as sinking continues. This is illustrated in Figure 1.12 by the contract pressure profile for the Ramsden Dock contract. However when tunnelling, exposure pressure tends to be constant or slowly varying as can be seen by the contract pressure profile for JLE 105 (Figure 1.13).

Tidal effects can sometimes be observed in caissons or tunnels being constructed under the sea. These introduce pressure fluctuations, which follow the tidal cycle but which are usually considerably less than the pressure change equivalent to the full tidal range.

1.6.5. Changes in the tunnelling industry affecting compressed air working

As noted in 1.5.2, traditional hand excavation methods of excavation have largely been replaced by mechanisation, which uses increasingly more sophisticated tunnelling machines. In addition, the ever-increasing cost of labour makes the considerably greater productivity of machine excavation much more commercially attractive. Action by HSE to address the occupational health hazards of hand excavation, which include manual handling, noise and vibration has also reduced its occurrence.

The hand excavation of the great UK compressed air tunnels of post-war years, including Dartford (1957 – 58), Clyde (1959 - 63), Tyne Road Tunnel (1962 - 66) and 2nd Dartford (1974 – 77) is a thing of the past.

In 2003, twin tunnels were completed under the Thames at Dartford as part of CTRL Phase 2 Contract 320 (see Section 6.2.2). Each CTRL tunnel was of similar diameter and length to the 2nd Dartford road tunnel but was excavated by TBM, on which the use of compressed air was limited to access for the inspection and maintenance of the cutter head. The hand excavated 2nd Dartford road tunnel required around 122000 exposures to complete excavation, whereas the CTRL tunnels together required a total of around 250 working exposures. Mechanisation in this case reduced the number of exposures by a factor of around 1000.

Compressed air has long been invaluable in assisting in the recovery of a tunnel after an incident such as collapse as at Hull, major breakdown of a TBM as at Cromer, or the encountering of expectedly poor ground conditions or obstructions as on London Water Ring Main (LWRM). This is unlikely to change in the future as long as incidents occur.

1.7. Decompression illness

The major occupational ill-health condition arising from hyperbaric exposure is DCI. Unlike exposure to other physical agents in tunnelling – heat, vibration etc – it is the ending of the exposure rather than the exposure itself, which causes the illness.

DCI is the generic term for a range of acute and chronic ill health conditions resulting from hyperbaric exposure, now accepted within the hyperbaric medical establishment. The aspects of DCI which are relevant to this study are discussed in Section 2.3.

1.8. Overview of text

Chapter 1 – provides an introduction to the text and describes how the study arose, its scope and objectives, along with an overview of tunnelling, shaft sinking and compressed air working practice.

Chapter 2 – presents an overview of the development of compressed air working techniques along with decompression theory and practice through a review of relevant literature. There is also a description of DCI, its classification, and treatment; a brief outline of legislation and guidance and an overview of relevant research from the diving industry.

Chapter 3 - reviews the acquisition and manipulation of data to form a number of databases and spreadsheets and reviews the work done to improve data quality.

Chapter 4 – summarises the available data, examines a number of measures of the incidence of DCI and quantifies that incidence using these measures.

Chapter 5 – considers the variation in response by the workforce to exposure to compressed air and any resulting DCI. It looks at the extent to which some compressed air workers are more tolerant of DCI whilst others are more susceptible to DCI. The phenomenon of acclimatisation is reviewed both in the workforce as a whole and in the individual. The chapter concludes with an examination of the extent to which men work on multiple compressed air contracts and how this affects their susceptibility to DCI.

Chapter 6 – considers options, determined by HSE prior to this study, for reducing the incidence of DCI. The first set of options retain air-only decompression through the application of a range of restrictions on exposure. The second relate to the use of oxygen decompression which replaced the air-only decompression regime in 2001.

Chapter 7 – sets out general conclusions from the study

Chapter 8 – contains recommendations for HSE to consider when it next reviews the legislation, guidance and policy on the regulation of work in compressed air along with recommendations for research which have developed during the course of this study, some of which have already been acted upon.

Appendix 5 – considers the adequacy of the 1996 Regulations, Guidance and Addendum and makes recommendations for possible changes to them which have arisen as a result of this study.

Chapters 1, 2 and 3 are common to the whole study. Chapters 4, 5, and 6 run in parallel, each with its own discussion and conclusions, although both Chapters 5 and 6 utilise results obtained in Chapter 4. Chapters 7 and 8 summarise the findings from Chapters 4 – 6 and complete the study with general conclusions and recommendations. Appendix 5 draws on results from the study to make recommendations to HSE regarding possible changes to legislation etc.

Chapter 2 - Historical Overview and Review of Literature and Legislation

The ability to work in compressed air has developed independently of the knowledge of the physiological processes associated with hyperbaric exposure. The tunnelling and diving industries have evolved through taking advantage of this ability to work in hyperbaric conditions whilst mitigating the physiological risks through the application of empirically derived rules and procedures. Knowledge of the physiology of DCI has often lagged behind the application of hyperbaric technology.

2.1. Overview of work in compressed air – the principles, practices and problems

The development of knowledge about work in compressed air and the effects of exposure to it, is reviewed below in roughly chronological order.

2.1.1. Origins of the technique

Many of the practices and problems still current in compressed air working had their origins around the late 19th or early 20th century but the reasons for them have been lost with time. Basic techniques have changed little, but restrictions on exposure times and decompression practices have evolved over the years. It was therefore considered important to review the history of compressed air working on the UK, better to understand how current practice has evolved.

According to Snell (1896) the invention of the diving bell by Sturmius in the early 16th century was the first situation in which men had worked in compressed air. Hill (1912) and Watson (1945) amongst others, suggested that caisson sinking under compressed air developed as an extension of the use of the diving bell. Hill and Watson both recorded that Smeaton used a diving bell in 1778 to aid the repair of bridge foundations near Newcastle upon Tyne. West (1988) gave a similar account of the origins of compressed air working.

King (1989) noted that diving for salvage and compressed air tunnelling operations had been considered in the late 17th century. Both King (1989) and Snell (1896; p 2) made passing reference to the work of Edmund Halley (1656 – 1742). His scientific interests apparently extended beyond astronomy to things nautical, including the diving bell. According to Martin (1997), Halley obtained a patent for the diving bell in 1690.

The early diving bells were relatively small but heavy, inverted cast iron boxes, which were raised and lowered by crane. Smeaton incorporated a hand-operated air pump in a bell for use at Ramsgate Harbour (Martin, 1997). Over time, they evolved into structures which extended above the water level to facilitate access and removal of excavated material - caissons. Willotte and Hersent (1880) illustrated the continuing link between caisson sinking and diving bells through their description of a floating caisson which was used for the removal of rock from Brest Harbour in water depths of 5 – 10 metres. The equipment was a caisson in which when ballasted for use, men worked in a dry chamber at its base, having accessed the working chamber through airlocks at base level. Access from the surface was down a spiral stair within an open shaft. Once work was completed, the caisson was floated off to a new location using in-built buoyancy tanks and repositioned on the seabed. The main benefits of the equipment over the diving bell seem to have been the ability to use it continuously without the need to surface periodically and the ability to float it into any required location. From the illustrations reproduced by Watson (1945), the use of heavy diving bells continued at least up to around 1940.

In 1896, Snell published a comprehensive account of compressed air working and hyperbaric medical knowledge at that time, which he claimed was the first volume published in Britain on the topic (Snell, 1896; p 1). He credited Denis Papin, a Frenchman, with developing caisson work from the use of diving bells in 1691.

Phillips (1965), published a similar but more modern text, reviewing the development of compressed air working.

Shield tunnelling had begun in the early 19th century. Copperthwaite (1906) and West (1988) both suggested that Brunel was advised in 1826 by the Swiss physicist Dr Jean-Daniel Colladon, to use compressed air for face support on the Thames Tunnel but did not take up the suggestion. Binnie (Inglis *et al*, 1908-09) also suggested that compressed air working could have been available to Mark Isambard Brunel for use on his Thames Tunnel, but confirmed it was not used. Although Haxton (1959) and West (1988) record this as having taken place in 1828 the date is not totally inconsistent with the comments by Lampe below. The benefits of working under air pressure were obviously known to Brunel as Lampe (1963) made two references to Brunel descending in diving bells to inspect the river bed and tunnel face, following inundation of the tunnel in 1826 and again in 1827. More detailed descriptions of Brunel's frequent use of diving bells on the Thames Tunnel was given by Law (no date), but without any mention of compressed air working. Brunel's son, Isambard Kingdom Brunel, was even reported by Lampe as having taken advantage of the hire of the bell – a massive 4 ton cast iron structure - to descend in it with his sister and her friend for fun. West (1988) suggested that Brunel himself had ideas about the potential benefits of compressed air but may have wished to prove that the tunnel shield, which he had developed for use on the Thames Tunnel, was adequate without the use of air.

It is generally accepted that the first formal record of the idea of using compressed air to facilitate caisson sinking was in 1830 when Patent No. 6018, was granted to Admiral Sir Thomas Cochrane, 10th Earl of Dundonald (Holden, 1997). West (1988) discussed the content of the patent at some length. Binnie (Inglis *et al,* 1908-09) referred to the patent issued to Admiral Cochrane for the idea of using compressed air. Moir (Inglis et al, 1909 - 10) also made reference to Cochrane's invention of compressed air working and to the patent granted in 1830. The grant of another Patent, No 2221, to a Mr. G. T. Bousfield in 1873, relating to "A compressed air-lock like that used continually from 1845 onwards", was recorded by Copperthwaite (1906: p 33) but no other information was given about it.

Credit for the first actual non-diving application of work in compressed air is generally given to Triger (Griffiths, 1959; Snell, 1896). It was for the construction in 1839, of a shaft through quicksand, at Chalones in France in connection with a coal-mining project. Triger reported the work in 1841 to the French Academy of Sciences (Triger, 1841; cited by Snell, 1896). The technique was repeated in 1846 at Douchy in north-east France by Blavier and reported by him in "Annales des Mines, Vol ix" (Blavier, nd; cited by Snell, 1896).

Use of the technique seems to have spread throughout Europe during the late 19th century. It was used on the Kattendyk Tunnel in Antwerp, in 1879, (West, 1988; Haxton, 1959). This was a small rectangular tunnel 1.45m (4ft 10ins) x 1.17m (3ft 10ins) in cross-section (Greathead, 1895 - 96). Compressed air working was also used in Germany in 1896 (Hewett and Johannesson, 1922) in addition to its continued use in France (Copperthwaite, 1906) as well as being used internationally where expatriate European engineers worked (Bayley, 1908 – 09; Hewett and Johannesson, 1922).

CIRIA (1978) provided a comprehensive but not necessarily complete list of UK contracts between 1851 and 1978, on which compressed air was used. Hewett and Johannesson (1922) listed examples of early compressed air tunnels in Europe and America along with comprehensive bibliographic references. Lamont (1996) compiled a list of more recent UK contracts, based on HSE records.

2.1.2. Early UK experience

Simms (1844) in his manual on practical tunnelling made no reference to compressed air working. The first recorded use of compressed air in the UK was for caisson sinking in 1851 (CIRIA, 1978) when it was used to facilitate the construction of bridge foundations at Chepstow and on the Medway at Rochester. Similarly, the first record of a UK tunnel to be built with the assistance of compressed air was for the City and South London Underground Railway at Stockwell in 1886 (Haxton, 1959) or 1887 (CIRIA, 1978). By then the construction of at least eight major UK bridges had benefited from caisson sinking under air. Pressures of up to 2.75 bar (40 psi) had been used. Given these pressures, it was not surprising that ill health resulted. "Many" bends were recorded at Saltash Bridge in 1855 in compressed air work up to 2.75 bar (40 psi) while "five deaths" were reported as having occurred at pressures up to 1.95 bar (28 psi) on the Foyle Bridge contract in Londonderry in 1861(CIRIA, 1978; List A).

This accords with the results of a search of the Proceedings of the Institution of Civil Engineers (www.iceknowledge.com) which indicated that the first paper presented to the Institution, relating to a project in which compressed air was used to facilitate caisson sinking, was in 1851 for the Medway Bridge at Rochester (Hughes, 1850-51). In keeping with the "engineering perspective" of the study, a comprehensive examination of the history and experiences of work in compressed air by engineers over the decades was undertaken. The primary source for this was the Proceedings of the Institution of Civil Engineers and other material from its library and archives.

Interestingly, on the Medway Bridge project initial attempts at pile driving had involved the use of a technique – the Potts Method - in which a vacuum was created within the pile casing to utilise atmospheric pressure as the driving force (Copperthwaite, 1906). Hard ground under the toe of the pile forced a rethink and instead the pile was transformed into a caisson, which was pressurised with air to keep out water and enable men to work in it.

Hughes (1850 - 51) described in some detail the development of the airlocks, the problems of maintaining a constant pressure in the caisson and the general effects of work in compressed air noted during the contract. A maximum pressure of 61 feet head of water (~2.05 bar (30 psi)) was applied. A steam-powered reciprocating compressor supplied the air and lighting was by candles. The main effects of compressed air on the miners were reported to be greatly increased appetite for food, better hearing and slight respiratory effects. Candles burned with greater intensity but were consumed more rapidly. Hughes made no mention of symptoms which would resemble decompression illness, despite the relatively high exposure pressure. In his assessment of the work, Hughes wrote,

> "the system appears to promise increased power to the Engineer in combating the difficulties of construction usually encountered in deep water." (Hughes, 1850 – 51: p 365)

The urbanisation and industrialisation in Victorian times had created a demand for railways and bridges. Thus in the final quarter of the 19th century, compressed air working became relatively common-place.

The 19th century was obviously a time when great interest in compressed air working was generated both amongst engineers and in the medical profession. Many interesting issues relating to compressed air working emerge from the records of this period.

Compressed air working is only a technique to facilitate caisson sinking or tunnel driving and as such has no intrinsic engineering value *per se*. Its development in the early years was restricted partly by the lack of suitable compressors to supply the large volumes of air required – steam powered compressors were being used (Morton, 1897) and diesel engines and electric motors were still being developed - and partly by the lack of tunnelling equipment to cope with tunnelling below the water table. Watson (1945) noted the use of water powered reciprocating compressors and water turbine powered compressors around 1860. Further detailed descriptions of tunnelling equipment and machinery from the early 20th century were given by Brunton and Davis (1914).

Biggart (1885) provided an interesting insight into the effects of air pressure on men sinking caissons for the Forth Bridge (see Figure 2.1). Despite working alternate shifts of six hours "each day, Sunday excepted, and then only throughout the day", he noted that no ill effects were experienced when the pressure was held between 0.825 bar (12 psi) and 1.25 bar (18 psi). Above that pressure, sickness, involving pains in the legs and arms occurred which in extreme cases resembled "paralytic shock". Onset of symptoms was noted as "shortly after coming out of the chamber". Biggart further noted that in some cases relief was achieved by returning to pressure whilst in others by "a strong shock of electricity". He recommended reducing shift length above 1.725 bar (25 psi). In his view remaining under air pressure "rarely does visible harm" however "the more seldom one does so the better". Biggart's paper contained a brief report from Dr M'Kendrick, Professor of Physiology at Glasgow University at the time, on the effects of pressure. In his report, Professor M'Kendrick referred to the work of Paul Bert, and recommended that decompression should be undertaken gradually and any sickness treated by immediate recompression. Boycott (1906) recorded that men working on the Forth Bridge caissons and suffering bends were in the habit of spending Saturday afternoons and Sundays in the chamber to relieve their symptoms, presumably as no medical lock was yet available.

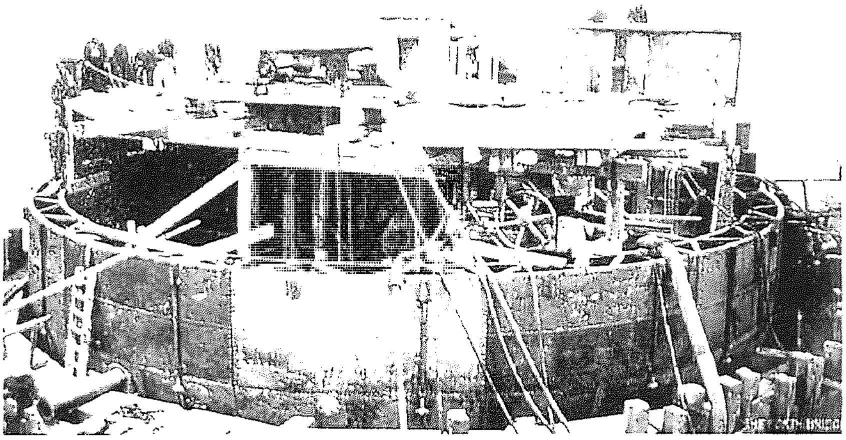


Figure 2.1– Vertical lock, Forth Railway Bridge

(Biggart, 2003)

Beaver (1972), gave an interesting account of other hazards affecting compressed air tunnelling in an article on the construction of the Glasgow Underground from 1891 – 97. He reported that in the five months taken to drive the first 25m (80 feet) of advance under the River Clyde, no fewer that ten blow-outs (sudden loss of compressed air through the river bed followed by inrush of water and mud) occurred, always during breaks, but all apparently without fatalities in the workforce. Morton (1897) attributed this to a failure to adjust the air pressure in line with tidal fluctuations in river level. In an attempt to counter the problem, the Contractor had introduced 24 hour, 7 days-a-week working without meal breaks. Sunday working caused resentment in the workforce. Beaver noted that there was little surprise when in February 1884, a fire occurred in the workings trapping 15 men. The men survived for 20 hours lying in the tunnel invert (Greathead, 1895 - 96) and used the compressed air supply to the grout pan for breathing air whilst a cross passage was dug from an adjacent tunnel through the 1.5m (5 feet) of ground separating the tunnels. This was an amazing and most resourceful rescue.

A second fire occurred on the project a few months later (Shipway, 2002). It was thought to have been started by a candle used for lighting the workings which set fire to timber. From the illustrations of tunnel construction provided by Shipway, there was plenty of timber around as the permanent tunnel lining was erected within a timbered heading. By the time a rescue team had been mustered, a lock attendant had been fatally overcome by smoke. Air was taken off allowing the workings to flood. This extinguished the fire however a second body was subsequently discovered in the workings once they had been recovered (Wright and Maclean, 1997). Compressed air increases the vigour with which a fire burns, reduces the ignition energy required to start a fire and increases the rate of flame spread (Lamont *et al*, 1998). A further two fatalities occurred on the project due to DCI.

The principle of compensation for industrial injury due to hyperbaric exposure was established by London County Council, for men working on the construction of the Blackwall Tunnel. In 1894 it obtained Parliamentary powers to make payments to men afflicted by DCI (Hay and Fitzmaurice, 1897). Hay and Fitzmaurice also noted that only three cases of "permanent illness" (p 78) but no deaths had occurred on that project. This prompted Baker (Preece *et al*, 1897 – 98) to regret that with no deaths there had been no bodies available for post mortem examination and that as similar work without compressed air would have given rise to 20 fatalities, work in compressed air was the "most healthy employment that a workman could be engaged in" (p 91)! Such little DCI was remarkable as 37 men per 8-hour shift were being exposure to pressures, which peaked at 2.425 bar (35 psi). Snell (Preece et al, 1897 – 98) disagreed that cases of illness were few. He recounted that over 200 cases of DCI – "caisson disease" as it was then called - had occurred and many men were so ill they left the workforce and had to be replaced. He also considered under-reporting had been rife. In his book, Snell (1896; Ch III) described in detail, fifty "illustrative" cases from over two hundred which occurred on the project.

Other London County Council requirements on the contractor included the provision of ventilation and resting places in the working chamber (Hay and Fitzmaurice, 1897). The contractor was required to expose only men found to be medically fit.

Snell (1896; p134) attributed "compressed air illness" as he preferred to call it to a number of factors of which he considered excessive carbon dioxide (CO_2) build-up to be the most important factor (Snell, 1896; p221).

Greathead (Greathead, 1895 - 96) reported that no DCI had occurred during compressed air work on the City and South London Railway tunnels. Greathead was another supporter of the CO_2 theory but also believed that chilling during decompression could be a contributory factor. To counteract chilling in the airlock, Greathead had it constructed from mass brickwork, reducing the 3.2m (10ft 6ins) cast iron tunnel lining to form a lock, a mere 1.15m (3ft 9ins) square by 3.7m (12ft) long. Greathead noted that the insulating properties of the brickwork helped maintain a fairly uniform temperature in the lock when compared to the bare cast iron lining.

Moir (Baker *et al*, 1895 – 6) reported that on the Hudson Tunnels, the introduction of his medical lock had reduced the fatalities from DCI, from a rate of 1 death a month amongst a workforce of 45 – 50 men to a total of 2 deaths in 15 months amongst a workforce of 120 men. In describing how spectacular were the effects of recompression, Moir noted that men carried in to the medical lock, unconscious or paralysed were "sent away rejoicing" (p 96). According to Moir the "purity of the air was the great secret of the health of the men" (p 97).

It is not surprising that the quality of air delivered from the steam powered compressors of the day was poor, given that air compressors were much less well developed at the end of the 19th century than they are now. White (1899-90) described the use of crude fish oil and tallow for lubrication. The oil was passed into the air cylinders through the inlet valves using a simple oil can. Lubrication therefore depended directly on the attention and skill of the attendant. The use of poor quality lubricating oil, coupled with inadequate cooling of the compressors could result in the generation of CO_2 from combustion of the lubricating oil in the cylinders of the compressor. Presumably the need to stoke the boilers to maintain steam pressure and to lubricate the compressors was the origin of the requirement for a compressor attendant to be continuously present.

2.1.3. *The early 20th century*

Many of the papers referred to in this section, provide an interesting commentary on compressed air working which is still relevant today. Evolution rather than revolution has been the way forward.

London County Council again appeared to have taken a proactive interest in the welfare of the workforce during construction of the Greenwich Tunnel in 1900. Copperthwaite (1901 – 02) noted that they made provision for the care of the men working in compressed air and that although a compensation scheme was in force, only three payments totalling £20 were made. Two medical officers, Drs Leslie and Macmorran, were appointed for the contract. Copperthwaite (1906) later noted that the doctors had given each ganger a signed list of workers found fit to work in compressed air and only men on that list could be put to work by the ganger. Once more, air purity was an issue and London County Council was reported by Copperthwaite (1906) to have funded research into construction of an air scrubber to remove excess CO_2. Ventilation in the tunnel was achieved by discharging the incoming air near the lock and venting air from near the face. Copperthwaite (1901 – 02) noted that difficulty was experienced in persuading the miners to keep the exhaust inlet sufficiently close to the tunnel face to be effective – a problem, which is still encountered in the course of inspections. Copperthwaite (1906) listed four factors which he considered to be the cause of compressed air illness:- high concentrations of CO_2, excessive air pressure, insufficient fresh air supply and excessively long exposure periods. He noted that the last two were regulated by London County Council, whilst the first was the most critical. This supported his earlier suggestion (Copperthwaite, 1901 – 02) that ideally CO_2 , resulting from the use of poor quality lubricants, should be eliminated from the air supply by purification downstream of the compressor.

Engineers continued to play a leading part both in debating and in combating the cause of DCI. Moir (later knighted presumably for his eminence in civil engineering) and a number of other leading engineers of the day considered that exposure to excessive CO_2 whilst in the working chamber was the main cause of DCI (Moir, 1891). Nearly ten years later, Moir (Matthew *et al*, 1907 – 08) again noted that he had first put forward this idea in the 1880s, and if not CO_2, then some other atmospheric contaminant was the cause of compressed air illness. Davis and Kirkpatrick (1907 – 08) supported that opinion from their experience during construction of caissons for the King Edward VII Bridge in Newcastle upon Tyne in 1903-04.

By 1904 a "telephonic connection" was linking the air lock, compressor station and the tunnel on a sewer project in Aberdeen (Conway, 1908-09). Electric lighting was being used in place of oil lamps or candles, which also helped to improve air quality, but no mention was made of any illness on a contract where pressure up to 1.15 bar (17 psi) was used.

Contractors continued to feed large quantities of fresh air to the working chamber to counter CO_2 build-up. Binnie (Preece *et al*, 1897 – 98) suggested improving air quality by removing moisture and oil mist from the air supply whilst Moir (Preece *et al*, 1898 – 99) stated that 1 – 1.25 parts per 1000 of CO_2 was an acceptable limit for pressures above 1.40 bar (20 psi). On at least two occasions in 1902, Copperthwaite suggested the use of sodium hydroxide scrubbers to reduce CO_2 levels (Hawksley *et al*, 1901 – 02: Copperthwaite, 1901 – 02).

Despite having been aware of the benefits of recompression as a means of relief of symptoms from at least 1885 (Biggart, 1885) engineers had the continuing belief in air quality as the main cause of compressed air illness. Moir (1908: Cruttwell *et al*, 1907 - 08), had even introduced the medical lock for recompression purposes on the Hudson River project in 1890.

The miners on the East River Tunnel in New York were sufficiently appreciative of Moir's medical lock that in 1908 they presented him with a model of it, on completion of the project (Moir, 1908). Later, Moir noted that it had proved a great success and its use had subsequently been adopted by the Royal Navy (Inglis *et al*, 1909 – 10).

Moir (Inglis *et al*, 1909 - 10) recorded what he considered to be the first use of compressed air for tunnelling purposes as opposed to caisson sinking, on the Hudson River tunnels in 1902. This project had been beset by technical problems including inundation and a number of blow-outs through the face. Work had originally started in 1874 and had continued as finance permitted over the following thirty years. The extraordinary lengths to which engineers went on this project to overcome wet ground conditions included the use of kerosene flames in pressures of around 2.35 bar (38 psi), to dry the clay in the tunnel face (Jacobs, 1909 - 10).

Boycott (1906) gave an extensive account of his knowledge and experience of compressed air illness on a major bridge project in Newcastle on Tyne in 1906. 30 to 36 men per shift worked in air on 12-hour nominal shifts. Boycott recorded that up to 1.50 bar (22 psi), a ½ hour break for breakfast and a 1- hour break for dinner were taken, both breaks being increased by ½ hour above 1.50 bar (22 psi). Breaks were taken in free air and decompression was at a constant rate of 0.35 bar (5 psi) /minute.

Boycott concluded that slow decompression was required, proper medical supervision, a recompression lock on site, a compulsory rest on site after decompression and that if properly managed, work at pressures over the 3.20 – 3.50 bar (46 – 50 psi) limit was feasible.

At Newcastle the recommendations of Drs Hill and Macleod for exposure and decompression were followed (Boycott, 1906). They are set out in Table 2.1. By comparison with the Blackpool Tables, the maximum exposure pressure is 3.5 bar (50 psi) for 4 hours 15 minutes followed by 5 hours 45 minutes decompression.

Pressure (bar) (psi)	**Shift length**	**Decompression time**
2.05 (30)	4 hrs	30 – 60 minutes
3.125 – 4.10 (45 – 60)	4 hrs	1 –2 hrs
5.175 (75)	1 hr	1 – 2 hrs
6.15 – 7.2 (90 – 105)	30 – 60 minutes	2 hrs

Table 2.1 - Hill and Macleod recommendations - Newcastle c. 1905

(Boycott, 1906)

Another account of compressed air work at Newcastle was given by Parkin (1905). He recorded that "only men so appointed", were allowed to operate the valves regulating the pressure in the airlocks – a reference obviously to the provision of lock attendants. Parkin reported that as at Blackwall, men occasionally skipped decompression by exiting through the materials lock. He recommended that normally "special receptacles should be provided to prevent the tunnel air being fouled by the excretions of the workmen". However at Newcastle this was not a problem as men could leave the chamber as often as they wished. Parkin also considered that compressed air was beneficial to asthmatics.

Following construction of the Blackwall Tunnel as described by Hay and Fitzmaurice (1898), a second major tunnel under the Thames, was built some ten years later in 1905-07. This was the Rotherhithe Tunnel, the construction of which was described by Tabor (1908 - 09). Large numbers of men were still being employed in compressed air as all excavation was carried out by hand and according to Tabor, sixty men worked on each of three shifts at Rotherhithe.

Copperthwaite (1906) published a number of excellent illustrations of typical caissons and shields of the day whilst Boycott (1909) provided engineering descriptions of the caisson sinking operations themselves.

Whitley (1916 - 17) writing on the construction of the Carmarthen Bridge around 1910, provided useful information on the compression and decompression procedures adopted at that time. Compression was at a rate of 0.35 bar (5 psi) per minute, which is similar to current practice. The decompression table used on the contract is reproduced in Table 2.2. For comparison, the equivalent decompression times from the Blackpool Tables, which are considerably longer, are also shown.

Whitley observed that the five-minute soak at the first stage pressure was not adhered to as the men got cold and wished a shorter decompression. He also provided a detailed breakdown of the typical working shift (see Table 2.3).

Whitley observed that stage decompression was generally considered to be the method to adopt in tunnel works where comfortable air locks could be provided. However as Carmarthen was a caisson sinking project it was undesirable to keep three men for long periods in the cramped confines of a small vertical lock. Furthermore, it was difficult to maintain air purity. Similar reasoning was behind the prohibition of vertical locks for stage decompression in the 1996 Regulations (Guidance, paragraph 90).

Exposure Pressure (bar) (psi)	**Stage Pressure* (bar) (psi)**	**Stop time (mins)**	**Final Time (mins)****	**Total Decomp time (mins)**	**Blackpool Tables (mins)**
1.05 (15)	0	0	0	12	18
1.40 (20)	0	0	0	14	65
2.05 (30)	0.35 ($5^{1}/_{2}$)	5	$16^{1}/_{2}$	$26^{1}/_{2}$	132
2.425 (35)	0.55 (8)	5	24	34	167
2.75 (40)	0.7 (10)	5	30	40	229
3.125 (45)	0.85 ($12^{1}/_{2}$)	5	$37^{1}/_{2}$	$47^{1}/_{2}$	279
3.50 (50)	1.025 ($14^{1}/_{2}$)	5	$43^{1}/_{2}$	$53^{1}/_{2}$	340

Table 2.2 – Decompression times at Carmarthen Bridge c. 1910 (Whitley, 1916-17)

*column 2 – stage pressure after first 5 minutes (note - lock pressure held at this "stage" pressure for the duration of the stop time)
**column 4 – time for decompression from stage pressure to atmospheric pressure @ a rate of 0.07 bar (1 psi) per 3 minutes.

Activity	**Time taken for activity**			
	< 1.40 (bar) (20 (psi))	**1.40 – 2.425 (20-35)**	**2.425 – 2.75 (35-40)**	**2.75 – 3.50 (40-50)**
Preparing for work (06:00 hrs)	0 hrs:15min	0:15	0:15	0:15
Passing through air lock (comp)	0:10	0:17	0:20	0:30
Working	1:30	1:28	1:15	0:30
Passing through air lock (decomp)	0:15	0:20	0:30	0:45
Breakfast	0:30	0:45	0:55	1:30
Passing through air lock (comp)	0:10	0:17	0:20	0:30
Working	3:35	3:18	2:45	2:15
Passing through air lock (decomp)	0:15	0:20	0:30	0:45
Dinner	1:00	1:20	1:30	2:15
Passing through air lock (comp)	0:10	0:17	0:20	0:30
Working	3:20	2:48	2:25	1:00
Passing through air lock (decomp)	0:15	0:20	0:30	0:45
Changing	0:15	0:15	0:15	0:15
Total shift length	12:00	12:00	12:00	12:00
Total exposure time (3 exposures)	8:45	7:34	6:25	4:15

Table 2.3 – Make-up of typical morning working shifts c. 1910 (Whitley, 1916 - 17)

Interestingly, Hill (1912) observed that even at his time of writing, tunnelling was a peripatetic occupation, noting that "caissoniers" as he called them, travelled from place to place throughout England and Europe (Hill, 1912). UK tunnellers continue to travel and in recent years, have worked in Europe, the Middle East and SE Asia.

The preference for stage decompression was not just in the UK. Hill (1912) noted that Bornstein, a leading German expert of the time also favoured stage decompression as a result of his experimental work at the Elbe Tunnel site in Hamburg. Hill's own experiments on goats and pigs led him to believe that individual susceptibility was a factor in DCI.

Hewett and Johannesson (1922), in a book on compressed air working "written for engineers by engineers", considered that the engineer should use such safeguards as experience and science had shown to be necessary. They were quite clear that the nitrogen bubbles formed on decompression, caused DCI and that higher pressure, longer exposure and quicker decompression, all increased the risk of DCI.

Levy (1922) reported on the construction of the East River tunnels in New York from 1914 – 1919. His study of around 1.3 million exposures, although related to a non-UK contract is nevertheless important, not least because of the large number of exposures from that contract. He lamented the lack of thorough research into compressed air illness in the USA, despite compressed air work being of enormous economic importance by allowing tunnels to be built. Levy believed that caisson disease was caused by too rapid decompression leading to the formation of nitrogen bubbles and was not attributable to CO_2. Levy noted an unusual problem at East River - the lack of fit men because of War service. He appears to have introduced the requirement for compressed air workers to wear a badge identifying their occupation and he arranged with the ambulance service that in the event of illness, his workers should be taken directly to a recompression chamber.

Levy recorded 680 DCI events in 1361461 exposures (men worked 2 exposures per day) – a crude bends rate of only 0.05%. Additionally he quoted bends rates for all exposure pressures above 1.05 bar (15 psi) in increments of 0.07 bar (1 psi), which even at 2.75 – 3.50 bar (40 – 50 psi), were around 0.1%. This is considered to be a remarkably low rate given the poor decompression practices which were undertaken.

The importance of the compressor attendant in ensuring correct lubrication was highlighted by Shaxby and McNair (1927) in their report on a catastrophic blow-out which occurred at a shaft being sunk under compressed air at Deptford Green and as a result of which, five men were killed. As part of their investigation, they considered the potential for an explosive mixture of oil mist from the compressors to form in the workings. They noted that similar blow-outs had been recorded on at least three occasions in the preceding twenty years.

Working Pressure (bar) (psi)	**Number of Minutes for each 0.07 bar (1 pound) of Decompression after the first rapid stage**		
	After first 3 hours' exposure	After second or third 3 hours' exposure showing an interval for a meal	After 6 hours or more of continuous exposure
1.25 – 1.40 (18 – 20)	2	3	5
1.45 – 1.65 (21 – 24)	3	5	7
1.725 – 2.00 (25 – 29)	5	7	8
2.05 – 2.35 (30 – 34)	6	7	9
2.425 – 2.70 (35 - 39)	7	8	9
2.75 – 3.125 (40 - 45)	7	8	9

Table 2.4 - Dr Haldane's Rate of Decompression in Caisson and Tunnel Works (1908) (Japp, 1935a; p182)

Japp (1935a) gave a wide ranging review of compressed air practice based on his extensive personal experience of compressed air working both in the UK and America in which he summarised changes in practice which had occurred during the previous forty years or so. He discussed the use of Haldane's tables (see Table 2.4), their modification on site, the acceptable pressure drop to first decompression stage, the pressure below which stage decompression was not required and the ventilation of air locks. He doubted that work in compressed air could be effectively regulated by government but suggested that the engineering institutions should produce guidance on good practice.

It is not surprising therefore that the first formal guidance aimed specifically at UK compressed air working, was the 1936 Report from the Institution of Civil Engineers (ICE, 1936) (see Section 2.4.2). In 1951 Murray (1951) noted that whilst most countries had compressed air legislation, Britain had only the ICE Report and the Admiralty Diving Regulations of 1907.

Following a fairly well documented period in the early 20th century when knowledge was still developing and there was considerable compressed air working, particularly for caisson sinking for bridge foundations, there is a general lack of published information by engineers, on compressed air working until after World War 2. By then, most of the compressed air working was associated with tunnelling rather than with caisson sinking. The post-war boom in the construction of road tunnels and tunnels for power station cooling water supply had begun (CIRIA, 1978). The notable exception to this is the collection of documents relating to the work of the ICE Compressed Air Committee between 1935 and 1962 held in the archives of the Institution of Civil Engineers (Buchanan, 2005b).

2.1.4. The past fifty years

For most of this period, there have been few major changes in compressed air working technique. Instead the major changes have been in the tunnelling techniques themselves, resulting from growing mechanisation.

From 1937 until 1974 when the Health and Safety at Work etc Act (Great Britain, 1974) came into force, the annual Reports of HM Chief Inspector of Factories recorded details of DCI events including comprehensive reports on a number of individual cases of DCI, all severe, some fatal (Lamont, 1996). In addition they reported an irregular range of general statistics about compressed air working such as the number of men medically examined. Notably, no fatality from DCI was recorded after 1963, whereas before then, there was an average of one fatality every three years.

After the war, some of the most extensive compressed air tunnelling projects ever to be undertaken in the UK – Tyne, Dartford, Blackwall, and Clyde tunnels were constructed. Because of the large number of exposures involved, experience from these contracts had a strong influence on compressed air working for much of the period. Engineers no longer seemed to write about the compressed air aspects of contracts, leaving it instead to the medical profession to publish a number of important project-specific reports. Notably the Medical Research Council (MRC) supported this work, eventually forming its Decompression Sickness Panel (the Panel) in 1957 (Elliott, 1992).

The first of the MRC sponsored reports was on DCI during construction of the Tyne pedestrian and cycle tunnels between 1948 and 1950. Paton and Walder in their introduction noted that:-

> " ... the study of industrial decompression sickness has been almost entirely neglected in this country..."; and "... some of the simplest question of facts about such illness in the industrial sphere could not be answered." (Paton and Walder, 1954; pp 1 - 2).

The contractor driving the Tyne tunnels began with decompression based on the recommendations of the 1936 ICE report but soon adopted the tables derived by Damant and Paton which later were to become the 1958 Tables (Paton and Walder, 1954).

Paton and Walder (1954) published an extensive report on the occupational health aspects of compressed air working and DCI at Tyne. Their main areas of research covered the variation in bends rate during the contract period; the susceptibility to DCI of new starts and shift workers; acclimatisation; site of the bends, pressure of relief and recompression profile.

Around the same time, Lewis and Paton (1957) reported on their investigations into DCI experienced during the sinking of caissons for a power station cooling system under the Thames estuary. Their reported bends rate was ~4% which they clearly regarded as unacceptable. The four factors which they considered to contribute to this were faulty decompression – difficulty in maintaining a slow constant drop in pressure; excess CO_2 in the airlock due to poor ventilation; physical work from climbing the ladder from the working chamber into the decompression lock and chilling of the men during decompression.

In 1954 a contract was awarded for major compressed air caisson sinking operations in connection with the construction of a bridge in Auckland, New Zealand (Shirley-Smith *et al*, 1961). This project was also the subject of a major report (Rose, 1962). Decompression procedures were again based on the tables which eventually became the 1958 Tables (see Section 2.4.3) but utilised decanting (see Section 2.2.7) rather then normal decompression procedures. A site modification to the tables was made at high pressures. The report contained extensive analysis of bends rates, data on acclimatisation and on the onset and site of DCI.

Construction of the first Dartford Tunnel had begun in 1936 with a pilot tunnel drive. However, work was interrupted by the war and the main tunnel itself was not constructed until 1957 – 60 (Kell, 1963) and (Kell *et al*, 1963). Around 1200 men were employed at pressures up to 1.95 bar (28 psi). 122000 decompressions were undertaken resulting in 689 cases of DCI (CBR = 0.56%). of which 94.9% were Type 1 DCS. Brand (Kell *et al*, 1963) recorded that the pilot tunnel was driven in accordance with the recommendations of ICE 1936 report. Turner (Kell *et al*, 1963) noted that DCI incidence decreased slightly as the contract progressed in that after 3000 exposures, the incidence was 1.5%; after 10000 exposures it was 1%; and after 50000 exposures it was still 1% but with 1 death. An extensive record of the medical and physiological aspects of this contract was published by Campbell Golding (Campbell Golding *et al*, 1960).

Compressed air working on the Clyde Tunnels between 1957 and 1964 was carried out in accordance with 1958 Regulations although these were still in draft form when work began. Haxton (1965) noted that, as a consequence of pressure being raised from 0.70 – 2.25 bar (10 – 32.5) psi during the sinking of the first shaft, the incidence of DCI rose and this resulted in the decompression times for exposures of over 4 hours duration being lengthened.

An important issue which emerged during the later stages of the construction of the Clyde Tunnels, was the realisation that dysbaric osteonecrosis (DON) had become a major health problem in compressed air tunnelling. Baynes, one of HM Medical Inspectors of Factories, was invited to talk on the subject to a meeting of the Institution of Civil Engineers (Kell *et al*, 1967). Walder, by then researching the problem of DON for the MRC, expressed concern over the emerging problem from the Dartford and Clyde contracts (Morgan *et al*, 1967). DON was also a major topic of discussion by CIRIA (1974).

The third tunnel under the Tyne, the road tunnel, was built between 1962 – 66. This was also the subject of a comprehensive report (MRC, 1971). That report provided some information on DCI but was more oriented towards DON. Once again, site modifications were made to the 1958 Tables.

Around the same time a major advance in tunnel machinery took place with the development of a TBM having an internal bulkhead to separate the pressurised plenum chamber from the rest of the machine, which remained at atmospheric pressure. Although the machine was used without much success when trialed in Paris, and aroused considerable sceptical comment from leading British tunnellers, Bartlett noted that:-

> " attempts to reduce exposure to compressed air should not be belittled. Unless solutions to medical and technical problems could be found some important civil engineering works could be rendered impracticable in the future." Bartlett (Kell *et al*, 1967; p 538).

In 1966 the Blackpool Tables were first trialed, before being published in 1973 (CIRIA, 1973) (see Section 2.4.4).

The final report covering this period arose from a study of data in the Decompression Sickness Central Registry at the University of Newcastle. Following a pilot study initiated by the Compressed Air Working Group (CAWG), the main study was undertaken by Evans (CIRIA, 1992). This was initially funded by industry through the Construction Industry Research and Information Association (CIRIA) "Core Programme". Funding was later taken over by HSE, however the report was published by CIRIA (1992).

This was an important study, which is frequently referred to in this text. Evans' findings related to comparisons between decant and normal decompressions, the derivation of Standardised Bends Ratio (SBR), and factors leading to DON.

UK practice and guidance has continued to influence major compressed air projects abroad. A number of countries have adopted UK legislation and guidance as the basis of their regulation of compressed air working practice (Anderson and Lamont, 1991). This was also reflected in the extensive use of compressed air tunnelling involving UK expatriates in Cairo, Singapore and Hong Kong from the mid 1970s to the late 1980s (Court, 1992; Campbell and Gutteridge, 1992).

The most recent changes in UK practice arose from the coming into force of the 1996 Regulations (Lamont, 1997) and the introduction of oxygen decompression (Lamont, 2002).

2.1.5. The UK conferences on work in compressed air

There have been three major UK conferences dedicated to compressed air tunnelling since the mid 1960s. Each represented a milestone in the topic in its time.

The first was a workshop of international experts held in 1965 and organised by the Panel on the theme "Decompression of Compressed Air Workers in Civil Engineering". Its Proceedings were edited by McCallum (1967) but are now out of print.

The author was privileged to be a member of the organising committee for the second gathering of international experts, which occurred in 1992. This was again sponsored by the Panel and its Proceedings, which were edited by Jardine and McCallum (1992) set another benchmark in knowledge on compressed air working. This event was specifically designed to link the engineering and health aspects of compressed air working and was reflected in the conference title of "Engineering and health in compressed air work".

In 2002, CAWG sponsored the 2nd International conference on "Engineering and health in compressed air work". The Proceedings again provided a benchmark in knowledge and practice in the topic. The author was a member of the organising committee and the lead editor of the Proceedings (Slocombe *et al*, 2003).

2.2. Decompression principles and practices

Even from the "engineering perspective" some understanding of the physiology underpinning the decompression tables and the development of decompression practices is essential to an appreciation of the incidence of DCI, the means by which it can be reduced and before recommendations can be made for future changes to legislation.

A comprehensive account of the development of decompression practices over the past century was given by Hempleman (1993).

2.2.1. Stage decompression

In the 19th century, Bert demonstrated that inert gas bubbles were the cause of DCI, but strategies to prevent and treat DCI remained undiscovered. John Scott Haldane (1860 - 1936), an eminent gas physiologist of the time, became involved with experiments into the physiological effects of pressure. Through this work which was supported by the Admiralty, Haldane developed an understanding of how different body tissues became saturated with nitrogen at different rates. He noticed that the body could tolerate limited supersaturation for a short period of time without adverse effect. Through experimental work, Haldane established that it was safe to go from a compressed state to a decompressed state up to the point at which supersaturation was no longer tolerated and bubbles occurred. Then after a period at that "stop" or "stage" pressure, the process could safely be repeated with ever-smaller pressure drops until atmospheric pressure was reached. This was the principle of "stage decompression" which is still in use today.

On the basis of observation and experimental work, Haldane noted that rapid decompression from 1¼ atmospheres above normal atmospheric pressure to atmospheric pressure – a reduction in absolute pressure by just over half - could be carried out with "complete immunity from symptoms" irrespective of length of exposure and rate of decompression (Haldane and Priestly, 1935: p357). He confirmed by animal experiments that if the pressure drop ratio was 2 : 1, this principle held for all pressures below 6 atmospheres (absolute). Above that pressure, a ratio of 1.75 : 1 was to be preferred.

As a consequence of this work, Haldane was (rightly) highly critical of the then established practice of slow compression and decompression and went on to calculate decompression tables based on his findings.

Hill (1912: p205-206) did not completely support Haldane's pressure ratio theory but noted that in his opinion it was permissible to reduce ambient pressure rapidly to half (absolute) working pressure; to reduce it to one third was acceptable but to reduce it to one quarter (absolute) working pressure was not acceptable.

Levy (1922) was more conservative than Haldane in that he considered the first pressure drop should only be to half gauge pressure, followed by uniform decompression to atmospheric pressure. Japp (1935) discussed both approaches at some length.

2.2.2. Uniform decompression

Hill appeared to have favoured uniform decompression (Behnke, 1969) and undertook a series of not particularly conclusive animal experiments to compare stage decompression with uniform decompression. He acknowledged a number of disadvantages of uniform decompression. Uniform decompression did not take advantage of the time gained by a large initial pressure drop - a uniform pressure drop was too slow at first but became too fast towards the end and the early stages of decompression were effectively further exposure to high pressure (Hill, 1912: pp 207 - 209). Despite his personal preferences, he concluded that stage decompression showed a slight benefit over uniform decompression at least for short exposures, but was doubtful of its benefit for long exposures.

2.2.3. Phase decompression

Japp (1935) described a decompression regime involving the use of an intermediate airlock chamber, the derivation of which he credited to Haldane.

Phase decompression was a major topic of discussion within the Joint Medical Panel of ICE Compressed Air Committee (Buchanan, 2005b). The joint ICE/Ministry of Labour committee in its “Second Interim Report” (ICE, 1949) suggested the intermediate manlock compartment was formed by bulkheads and the tunnel lining so that it could be held at an intermediate pressure equal to that of the first stage after the initial pressure drop on decompression. The time taken by men walking along the tunnel within that manlock towards the pit bottom manlock compartment then counted towards decompression time. This procedure would only have been worthwhile in relatively long tunnels.

There were rules for phase decompression in the 1958 Regulations however CIRIA advised “This form of decompression is not recommended” (CIRIA, 1975 : p 69)

Paton (1967; p 5) reported that there was little interest in the technique by then and no evidence of its use in the UK has been have found.

2.2.4. Application of Haldane’s theory of Stage decompression to UK practice

Haldane’s principles of stage decompression dominated UK practice for many years. As a member of the Admiralty Deep Diving Committee, his stage decompression principles formed the basis of the Admiralty Report (1907) and the Royal Navy Diving Tables of 1908 (Hempleman, 1993). With the passage of time, experience in using Haldane’s tables showed that one table was too conservative whilst another was insufficiently conservative.

The ICE Report (1936) was prepared by a committee which included Prof. Haldane. Accordingly the decompression practices in it were also based on Haldane’s principles. A major point of contention was the threshold pressure above which stage decompression was required and the economic consequences of this to the contractor.

Andrews (1998) and Paton (1967) both reported evidence that doubts had existed over the validity of some of Haldane's assumptions about saturation times. There were also doubts over the safety of the 1.50 bar (22 psi) decompression threshold in the decompression tables. They were however used from 1936 until the introduction of new tables in 1951. These later became the 1958 Tables (Hempleman, 2004). The 1958 Tables reduced the threshold pressure to 1.25 bar (18 psi). A full description of the thinking behind the 1958 Tables was given by Paton (1967).

2.2.5. Theoretical derivations of other decompression tables

In 1966 a new set of decompression tables was trialed on a tunnel sewer contract at Blackpool. These have come to be universally known as the "Blackpool" Tables (see Section 2.4.4).

Hempleman had suggested that gas diffusion in a single slow tissue was the dominant factor in the decompression process. He further suggested that there was a critical amount of gas, which was responsible for all bends (Hempleman, 1993, 2003). From experiments on female goats, Hempleman discovered that there was a mathematical relationship between the pressure and exposure period, after which goats began to display symptoms of the bends. This relationship was defined by an expression of the form $P\sqrt{T}$, where P was the (absolute) pressure and T was the time of exposure. The relationship held for times of up to 2 hours (Hempleman, 2004). His experiments also showed that Haldane's pressure reduction ratio was not constant but reduced with increasing exposure pressure.

The precise derivation of the tables was described by Hempleman (CIRIA, 1982). The threshold pressure for stage decompression was further lowered, this time to 0.95 bar (14 psi), which subsequently became 1 bar on metrication (see Section 1.4.2).

These tables remain in use and they incorporated the addition of oxygen breathing on the introduction of oxygen decompression in 2001.

Other theoretical concepts relating to table development included those of Workman and his "M" values (Baker, 2005) and the Bubble Growth Index (Lambertsen *et al*, 1999). Hempleman (1993) and Andrews (1998) both gave descriptions of these concepts, neither of which has directly influenced UK tunnelling decompression practice.

2.2.6. *Modification of decompression tables*

For a long time, it has been accepted industry practice to make *ad hoc* modifications to the decompression tables in their application on site. Japp – a contractor's man, (1935a) discussed them at length having noted (p 182) that:-

> "These times seemed in 1908 far too long for decompression when compared with the shorter time then in vogue".

Catton (1967a; p 185), observed that "Variations in decompression procedures are numerous" whilst Hempleman commented that *ad hoc* changes to tables were:-

> "typical of the history of compressed air working in tunnels. A decompression procedure is adopted, it is tried and found inadequate in certain respect, and 'on the spot' alterations are made to attempt to remove the difficulties." Hempleman (in Bennett & Elliott, 1993; p 365).

King (1989; p 418) noted that:-

> "all too often the introduction of *ad hoc* safety margins to the established tables not only causes cases, but inhibits adequate analysis of possible causative factors, often because they are not admitted." .

Whyte (1967) recorded that shortly after the introduction of the 1958 Regulations, site modifications were made to the decompression tables to address an unacceptably high incidence of DCI on the Clyde Tunnel.

More recently Contract Medical Advisers (CMAs) and lock attendants, with the tacit agreement of HSE, have regularly tried to improve decompression safety by deviating from the Blackpool Tables through decompressing workers to tables greater in pressure than those consistent with the exposures undergone (see Sections 3.6.6 and 6.1.1).

It is also a common practice in the diving industry to include an *ad hoc* safety factor when selecting the decompression profile to use. This factor, often referred to irreverently as the "Jesus" factor (Shields and Lee, 1983; p12), involves decompressing to the profile for one or more increments of pressure and/or time greater than actually required by the exposure undergone. A similar practice occurs in tunnelling.

One outcome of the study by Flook (1998) was a recommendation against the *ad hoc* use of such practice in tunnelling. Because of the fundamentally different exposure pattern between tunnelling (low pressure, long duration) and diving (high pressure, short duration), the tissue types affected are different. In tunnelling it is gas from the slow tissues – especially fat, which gives rise to DCI whereas in diving it is gas from the fast tissues which causes a problem. Consequently the more common manifestation of symptoms in tunnelling is Type 1 DCS, with a greater tendency towards Type 2 DCS in diving. As a result a slightly extended decompression would have a more directly beneficial effect in diving than in tunnelling. Conversely it would require a considerable increase in decompression time – much greater than would be achieved by the application of safety factors - to have a beneficial effect in tunnelling (see Sections 3.6.6 and 6.1.6).

Flook's recommendation was justified; as an increase in decompression time can increase the amount of gas in the tissues if saturation was not achieved before decompression began. It has been the author's personal experience that that lock attendants would give longer decompression than was required as they were being "careful not to bend" the HSE Inspector.

Another variant of this practice which was justified by experience within the industry, was the introduction of stage decompression from around 0.8 bar. This became accepted practice once the number of DCI events below 1.0 bar was recognised. In effect, Table 1 of the Blackpool tables was extended down to 0.8 bar (see Section 6.1.1).

2.2.7. Decanting

Decanting (see Glossary), was used in caisson sinking operations, where it was not reasonably practicable to carry out long decompressions in the cramped conditions of the vertical lock. It was also used in tunnelling operations, to enable the horizontal tunnel locks to be quickly cleared of men thus expediting production. However tunnelling engineers apparently have a faith in the technique which goes well beyond their awareness of its development and limitations.

According to Hempleman (1993; p 357) surface decompression began in 1914 as a technique to get divers out the water quickly during periods of adverse weather. He reported that Damant had regularly, and apparently successfully, used the technique in conjunction with Haldane's tables. The surface interval was supposedly 1 – 2 minutes.

Paton (1949) reported on experiments using goats undertaken by the Admiralty to determine safety decanting procedures. Again only very high pressure exposures (up to 5.7

bar (85 psi)) for relatively short durations (35 - 50 minutes) were studied and not all the goats survived the experiments.

Normally, in decanting the initial decompression is rapidly to atmospheric pressure. However the ICE Report (1936; p 9) described a decanting procedure which involved a ten minute stop during the initial decompression. Catton (1967a) experimented with variations to the ICE Report procedure for decanting and reported a reduction in DCI as a result.

In papers relating to the drafting of the 1958 Regulations, Damant (1946) gave details of how decanting was practised in the Royal Navy. Although the Navy permitted decanting only for exposures not exceeding 50 minutes at pressures up to 4.0 bar (58 psi), Damant thought engineers should be allowed to experiment and develop decanting. However he advised adherence to a five minute limit from end of the decant decompression to being fully recompressed to working pressure. He warned that decanting should be used in certain limited circumstances only, such as where one lock was available or in a vertical lock.

Paton (1967) on the other hand, advised that the five minute limit should be from the start of decompression to the completion of compression in the decant lock which was the procedure permitted in the 1958 Regulations. Partridge (1967) considered that this was achievable at low and medium pressures but more difficult to achieve at high pressures due to limitations with the air supply. Rose (1962; p 22) recorded that at Auckland, the five-minute limit varied from two to eight minutes.

Although decanting was reported by Paton (1967) to have first been used in the UK in 1914, this may have been intended to be a reference to diving practice. Taylor (Morgan, 1957) reported that his employer Charles Brand, a major tunnelling contractor of the day, first used decanting some forty years later, at Portishead. He noted that the miners did not strictly adhere to the five-minute limit until after the first cases of DCI had occurred on site.

Decanting remained relatively common in UK tunnelling up until the early 1990s when Evans (CIRIA, 1992) showed that it gave rise to a 50% increase in the incidence of DCI. In addition to the increased health risk, at high working pressures the fast rates of change of pressure required to meet the five-minute limit coupled with uncertainty over how that limit was defined, all called into question the safety of the procedure. Decanting was prohibited by the 1996 Regulations, except in an emergency.

Catton (1967b and 1992) was a supporter of the technique for many years. There is some decant data in the HSE database, including data from contracts for which he was the medical adviser, but not sufficient to make its separate analysis statistically valid.

The analysis of records from decant exposures is discussed in Section 3.6.8.

2.2.8. Post decompression surface oxygen breathing

Post Decompression Surface Oxygen Breathing (PDSOB) is a technique in which workers breathe pure oxygen at atmospheric pressure, for a period immediately following decompression. The oxygen is administered by mask. It was introduced in the UK on the Great Yarmouth Power Project (GYPP) contract as a compromise before full oxygen decompression was approved but has now been used on a number of contracts around the world (Ridley and Colvin, 2002). More recently, Ridley (2004) claimed that it was an effective alternative to oxygen decompression at least up to 1.6 bar.

2.2.9. Oxygen decompression

The use of oxygen for decompression purposes is not new. Haldane and others (Admiralty, 1907) recommended the technique to the Admiralty in 1907.

Oxygen decompression was one of the factors included in the comparison of international decompression practice by Anderson and Lamont (1991). Oxygen has been used for routine decompression in tunnelling operations since at least 1972 in Germany and 1992 in France. For many years, HSE was against its use in tunnelling because of the enhanced fire risk (Lamont, 2003) – a view reinforced by the multi-fatal fire in Japan in 1959 (Nashimoto, 1967).

The first change in HSE's position came in the Guidance (HSE, 1996). This required the provision of oxygen in the medical lock, for use at the CMA's discretion in the treatment of DCI (Paragraph 205). The Guidance also contained information for compressed air contractors (CACs) on how to seek approval for routine oxygen decompression (Paragraphs 179 - 180).

In the UK, its routine use for decompression began only in September 2001 when HSE withdrew approval of air-only decompression to the Blackpool Tables and substituted an approved decompression regime utilising oxygen breathing to Blackpool Table profiles (sometimes called the oxygenated Blackpool tables). Oxygen was introduced from the 0.6 bar stage downwards, to be breathed on a cycle of 20 minutes oxygen/5 minutes air. At the same time, stage decompression with the alternative of air or oxygen breathing at the CAC's discretion, became mandatory from 0.7 – 1.0 bar. Detailed guidance on the use of oxygen for decompression purposes was published in the addendum to the Guidance (the Addendum) (HSE, 2001).

HSE undertook an extensive programme of research into both the safety and health aspects of oxygen decompression before making the change. That programme was described in detail by Lamont (2002) and as so much of the information in that paper is of relevance to this text, it is included at Appendix 1.

2.2.10. Medical and physiological aspects of the use of oxygen

It is consider that a detailed description of the medical and physiological aspects of the use of oxygen is outwith the "engineering perspective" but these issues were described in detail by Andrews (1998; Ch 7).

Breathing oxygen during decompression increases the differential between the partial pressure of nitrogen in the tissues and in the inspired breath. The greater the differential in partial pressure, the greater the rate of off-gassing from the tissues. An important aspect of the technique is that part of this partial pressure difference arises from the reduction in nitrogen concentration in the inspired breathing gas and not from a change in ambient pressure. An explanation of the physiology behind this was given by Vann and Thalmann (1993).

Prolonged breathing of hyperbaric oxygen results in adverse physiological responses by the body. These include reduced pulmonary function and are normally countered by the use of air breaks during oxygen breathing (Flook, 1998). Such precautions are included in current UK practice (HSE, 2001).

2.3. Decompression Illness

The major occupational ill-health condition arising from hyperbaric exposure is DCI. Unlike exposure to other physical agents in tunnelling – heat, vibration etc – it is the ending of the exposure rather than the exposure itself, which causes the problem.

Hyperbaric medicine started as the diagnosis and treatment of DCI which then was purely an occupational disease resulting from exposure to pressure in caisson sinking, tunnelling or diving. It has now expanded into a major medical specialism which includes compressed air tunnelling/diving medicine, aviation medicine (strictly "hypobaric" medicine) and hyperbaric oxygen therapy for non pressure-related conditions (Phillips, 1965).

Covering deep commercial diving to space flight, hyperbaric medicine has developed far beyond the relatively straight-forward medical problems of tunnelling work in compressed air. It is not within the scope of this study to give a comprehensive review of hyperbaric medicine. However a brief overview of aspects of hyperbaric medicine relating to DCI in caisson sinking and tunnelling is included.

DCI is the generic term which is now accepted within the hyperbaric medical establishment for a range of acute and chronic ill health conditions resulting from hyperbaric exposure (Francis *et al*, 1991). It is described in many standard texts on hyperbaric medicine including that by Bennett and Elliott (1993) and in texts on occupational medicine including that by Elliott (2000). It is considered that the extensive discussion on DCI and its causes given by Hills (1977) is more in the manner of the "engineering perspective " than those in the standard medical texts.

Early authors referred to the illness resulting from exposure to compressed air by a number of names. The ICE Report (1936) mentions "Divers' palsy" and "caisson disease". Snell (1896) noted that it was unrelated to the caisson but a consequence of exposure to compressed air. He preferred to call it "compressed air illness". Colloquially, DCI in its various forms has been called the "niggles", "bends", "chokes" and "staggers" depending on the manifestation of symptoms. The term "bends" originated around 1894 during construction of the Brooklyn Bridge caissons and compared the posture forced on men suffering pain-only DCI to a fashionable gait adopted by society ladies of the time – the "Grecian Bend" (Hills, 1977; p 12).

2.3.1. Forms of Decompression Illness and their onset.

Acute DCI includes both Types 1 and 2 Decompression Sickness (DCS), barotrauma - typically experienced as pain in the ears or sinuses, pneumothorax and gas embolism. It appears from DCI records that pneumothorax and gas embolism are extremely rare in compressed air tunnelling but are more common in diving.

From the early days up to the introduction of the Blackpool Tables, death and paralysis were accepted outcomes from acute DCS (Snell, 1896: Lamont, 1996). A major success of the Blackpool Tables is that no fatality appears to have occurred as a result of their use, following their introduction in 1963 (Lamont, 1996).

The time of onset for acute DCI normally varies from a few minutes up to around twelve hours after decompression although Levy (1922) quoted onset at up to 23 hours after decompression. White (2002) had knowledge of DCI following air saturation exposures, as long as 24 – 48 hours after decompression.

Chronic DCI manifests as dysbaric osteonecrosis (DON) - a condition in which lesions occur on the shafts and heads of the long bones (McCallum and Harrison, 1993). Where these lesions occur on the load-bearing surfaces of joints such as at the upper end of the femur, bone disintegration leading to severe disability results and surgical replacement of the joint may be necessary. A comprehensive review of DON was given by Walder (1992).

The onset of symptoms of DON varies from months to years however early symptoms may be detected much sooner by MRI scanning or x-ray.

The historic incidence of DON in tunnellers has been quoted as being as high as 19% (Sawatzky, 1998). Evans found that the most significant factors leading to DON were one or more DCS Type 1 events associated with long, high pressure exposures (>2 bar and >4 hours) (CIRIA, 1992). More recently Hutter (2002) advanced a theory that compression-related factors could also lead to DON. Only one or two cases of DON arising from recent contracts are known.

DON is significantly more disabling in miners than acute DCI though less frequent and as such should be more worthy of study. However it has not been included as HSE does not have reliable data on its occurrence (Lamont (discussion contribution) in Slocombe *et al*, 2003: pp 28 - 29).

The significant reduction in DCS in UK commercial diving as a result of restrictions on exposure, has been mirrored by the virtual elimination of DON to the point that HSE no longer requires long bone x-rays as part of diving medical examinations, as the risk from the exposure to radiation is of a similar order of magnitude to the risk from DON (HSE, 2002a). Consequently the current incidence of DON in divers is unknown (Simpson, 1999). Lamont (Slocombe *et al*, 2003: pp 293 - 294) has suggested that the introduction of oxygen decompression to reduce DCI incidence may result in a similar reduction in osteonecrosis in miners. However this reduction may be difficult to prove due to lack of data.

2.3.2. Classification of DCI

Campbell Golding (1960) put forward a classification system based on symptoms, which is still used within the UK tunnelling industry today. In his classification Type 1 Decompression Sickness (DCS) referred to limb pain ("niggles", "bends") whilst Type 2 DCS covered a range of more serious symptoms related to the central nervous system ("chokes", "staggers"). Hills (1977) proposed a development of the Campbell Golding classification – a four category classification in which the third category was vestibular DCI and the fourth category DON however this has never become accepted in the UK.

More recently a number of hyperbaric experts including some associated with the Institute of Naval Medicine, proposed an alternative system of classification (Francis *et al.* 1991). This was based around the premise that there was no clear differentiation between Types 1 and 2 DCS but a gradation and overlap of symptoms between the two. They preferred to use a descriptive classification that included the terms "pain only" DCS and "serious" DCS (Sykes *et al*, 1992).

Within the relatively small hyperbaric tunnelling community in the UK, there remains a general preference for the Campbell Golding classification. Additionally there is an informality in terminology which can confuse the outsider, with the terms "bends"; "hit"; "getting bent" etc frequently being (mis)used in a range of contexts.

The classification of DON was based on work by the Medical Research Council, which established a radiological classification system, details of which were given by Walder (1992) and Sawatzky (1998).

2.3.3. The causes of DCI

Since ill-health arising from work in compressed air was first recognised, doctors, physiologists and engineers have attempted to discover the factors causing DCI. For most of that time the search has focussed on DCS as DON did not become a major issue in UK tunnelling until the post-war compressed air tunnelling boom. As outlined in Section 2.1, the two main causal factors considered over the years were inert gas bubbles and excessive CO_2. Although inert gas bubbles as the causal factor for DCS had been identified by physiologists well before 1900, it is perhaps surprising that engineers have clung for so long to the view that CO_2 was a causal factor.

The earliest opinion could have been in a report by Prof. Trouessart into the results of Triger's work. However Snell (1896; p6) criticised Trouessart's report for being "interesting" but recorded that it "treats little of physiological matters" despite being the first observations on a "man under a pressure of 3 atmospheres in addition to the atmospheric pressure". Copperthwaite (1906, p 35) was more positive in his account of observations by Triger and Pol and Watelle of decompression experiences at Chalones and Douchy.

Although as a result of observations at Triger's mine in Douchy in 1845 (Phillips, 1965) Rameoux may have identified gas bubbles as the likely cause of DCI, the major breakthrough in determining the cause of DCS was made by Paul Bert (1833 – 1886) sometime French Minister of Education and Professor of Physiology at Bordeaux and the Sorbonne. Bert showed that DCS was caused by the formation of bubbles of nitrogen within the body on decompression, a theory which is still accepted today. His publication of his findings in his paper "La Pression Barometrique" in Paris in 1878, is reported in the concise biographical summary of Bert's experimental work which was given by Phillips (1965). A review of early theories on the causes of DCI which were popular in Europe and the USA was authored recently by Butler (2004) in one of the rare papers on tunnelling issues in the diving hyperbaric medical literature. The most popular of these centred around "systemic exhaustion" and "systemic congestion" as well as tissue/vascular bubble formation. In an autobiographical account by a worker on the Brooklyn Bridge caissons, Harris highlighted the supposed role of "foul air" in causing DCI (Harris, 1964; p 67).

Despite Bert's work, a number of early British authors attributed the cause of DCS to a number of factors of which impure air due to the presence of excess CO_2 was the most favoured. Snell (1896; p 134) attributed DCS to five factors:- pressure, length of exposure, inadequate ventilation, too rapid decompression and personal idiosyncrasies (obesity, age, poor health, excessive alcohol consumption, exercise following decompression and lack of acclimatisation). Of these he strongly, but clearly now mistakenly, considered inadequate ventilation resulting in excessive CO_2 build-up to be the most important factor (Snell, 1896; p221). Moir (1891) and Binnie (Baker, 1895-96), both eminent civil engineers of the period, also believed that good health in compressed air working was attributable to air purity and suggested removing moisture and oil mist from the tunnel air supply.

Parkin (1905) discussed five possible causes of DCS – CO_2 which could not be the cause otherwise DCS should develop in the caisson not outside it; "congestion of inner organs" could not be the cause as no change in pulse or blood pressure could be measured; cold and exhaustion which he summarily dismissed along with the possibility of the "abdominal walls becoming compressed and causing congestion"; leaving "air emboli as described by Rameoux" as what he considered the likely cause. In his view, Snell was too preoccupied by CO_2.

Boycott (1906) who was a contemporary of Parkin, also credited Rameoux with the idea that air emboli were the cause of DCS. His view of the mechanism was that the quantity of gas in the blood increased under pressure, according to the laws of Dalton and Henry. Then, on rapid decompression gas bubbles escaped, arresting circulation and causing pressure on tissues. Furthermore, on recompression the gas bubbles went back into solution and the gravity of the symptoms depended on the location of the bubbles. Boycott was aware of variations in tissue saturation, which to him were manifested by the differences in the incidence of DCS between shift and non-shift workers.

Boycott (1906) was also aware that nitrogen not CO_2 was the cause of DCS. At Newcastle, he had compared CO_2 levels and the incidence of DCS but found no correlation. Likewise he reported having done a comparison between data from Newcastle and Blackwall and found no correlation. He concluded that the importance of good ventilation had been much overestimated.

Boycott analysed the patterns of illness and noted the cumulative effect of repeated exposures. He observed that bends normally occurred after the shift but not during meal breaks. He detected no correlation with age or total number of exposures undertaken. In his view, miners experienced less ill health than surface workers. The evidence in support of this view was the lack of payouts by the site sick-pay club, which had originally sought enhanced contributions from miners.

Erdman (1907) discussed the supposed causal factors for DCS of which he was aware. These were gas emboli – the theory Erdman himself strongly supported, not least because he recorded having incised swellings on the legs of two men after decompression, from which he observed air to be discharged from the incisions. He rejected the other theories because none of them accounted for the liberation of air from his incisions. These included excess CO_2 favoured by Snell and others; oxygen toxicity which Erdman rejected because pressures were not sufficiently high; cold - a causal factor which according to Erdman, had been put forward by Triger; the effects of compression on the body – a theory which he noted had been put forward by Pol and Watelle, but rejected by Erdman because he found no physical changes in respiration or circulation on compression.

Interestingly, it is clear that when Moir introduced the medical lock, he was under a serious misconception about the mechanism from which the benefits of therapeutic recompression were obtained. Following an incident in 1891 in which a journalist visiting the Hudson River tunnel required therapeutic recompression, Moir (1891) published an article giving his opinion that DCS was a form of blood poisoning resulting from oxygen starvation due to excess CO_2. DCS arose from the body, having become acclimatised to the enhanced oxygen concentration in compressed air, being starved of oxygen during decompression. Moir believed that air in the medical lock was purer having come straight from the compressor and coupled with a slower decompression, allowed the body to readjust to normal oxygen levels.

By the end of first decade of the 20th century, knowledge within the medical/physiological community on the causes of DCS had advanced. However engineers experienced in compressed air tunnelling continued in their belief that CO_2 was a cause of DCS, despite their knowledge that recompression gave symptom relief.

In relation to construction of the Rotherhithe tunnel, Brown (Inglis *et al*, 1908-09) repeated the view that more fresh air led to less DCS but conceded that Hill (Matthews *et al*, 1907 – 08) had recently attributed the cause of DCS to decompression rate. Likewise Binnie (Inglis *et al*, 1908 – 09) expressed his personal belief in the link between DCS and CO_2 exposure but noted that Haldane had proved him wrong.

According to information give in the contribution by Boycott (Inglis *et al*, 1909 - 10) it was around 1903 when physiologists first began to reject air purity in favour of pressure change as the cause of DCI. Although medical opinion was changing, some engineers' views obviously did not change. Huddleston (Inglis *et al*, 1908-09) noted that on the Rotherhithe project in 1905-07, London County Council still required an air supply of 8000 cu ft per man per hour free air volume.

Hill (1912), a physiologist, provided further insight into developments relating to the physiological aspects of exposure to compressed air. He was clear that nitrogen was the gas in the bubbles causing DCS and was critical of Snell and others who advocated the CO_2 theory. He commented that London County Council, acting on Snell's advice, still required an enormous air supply at great expense and that Snell's views "stand unconfirmed by any large series of actual analyses of the tunnel air" (Hill, 1912; p 151).

Japp (1935a) recorded that Haldane had demonstrated that the effect of CO_2 was a much less significant factor in causing DCI than previously thought and set out guidance for suitable control levels.

As late as 1951, Behnke (1951) noted that empirical evidence pointed to a higher incidence of bends associated with a rise in the CO_2 level. More recently, South (1990) expressed concern over links between excess CO_2 and DCI.

Inert gas bubbles are still accepted as the primary cause of DCI. Body tissues take up air – oxygen and nitrogen - during compression and the subsequent exposure at pressure, with saturation occurring if the exposure is sufficiently long. During decompression, the blood becomes super-saturated and gas bubbles form. Some of the oxygen in bubbles is metabolised or gassed off in the lungs. Inert nitrogen bubbles also form in the bloodstream. Most of these bubbles are removed from the blood during its passage through the lungs. However if they lodge in the fine blood vessels in the tissues they can obstruct the blood vessels leading to local tissue trauma. The nature of the resulting DCI varies with the location at which the bubbles have lodged. Vann and Thalmann (1993) and Elliott (1969) described in detail the physiological basis for DCS. More recently, Andrews (1998) provided a review of contemporary bubble formation theory. The role of venous gas emboli in DCI is much more highly researched in diving hyperbaric research (e.g. the work of Lambertsen et al, 1999). Evans and Walder (2002) suggested that cosmic particles could be the cause of the nucleation which generated the bubbles leading to DCI.

Even the Guidance contained requirements for monitoring and limiting CO_2 in the manlock atmosphere (Paragraph 87). These were drafted long before this study began. This was partly because excess CO_2 increased the breathing rate but also because there was a view in the industry linking excess CO_2 to increased susceptibility to DCS. At that stage the evidence of the long history of opinion linking excess CO_2 and DCS was unknown.

This concern over high CO_2 levels did not however extend to a prohibition on smoking during decompression. Rose (1962) reported measurements of up to 2 ½% CO_2 in the lock atmosphere, but no association between CO_2 and DCS. Presumably carbon monoxide levels would also have been raised due to smoking in the locks, but Rose did not give any information on these.

The effects of CO_2 on respiration and general physiology along with its narcotic effects were described in detail by Schaeffer (1975) however he made no mention of any link to DCS. Cook (1951) suggested that although CO_2 was found in the limbs – the most common site for pain-only DCS in tunnel workers - it was not the cause of DCI as it was rapidly diffused and replaced by nitrogen. Cook reported experiments in which subjects breathed a mixture containing 12% CO_2. He found no statistically significant increase in DCI incidence due to these high CO_2 levels. Cook considered this conclusive proof that CO_2 did not cause DCI. Walder (1975) concluded there was no evidence that CO_2 caused DCS. The evidence from the literature reviewed, would appear to show that high CO_2 levels do not give rise to DCI. To go beyond that into the physiology involved is outwith the "engineering perspective" of the study.

The discussion in the engineering literature on causal factors centred on DCI as DON did not become a matter of concern till relatively recently. DON, being a chronic condition, is also much more obviously a medical issue rather than an engineering one.

DON obviously arises as a result of work in compressed air as that form of necrosis is only found in people undergoing hyperbaric exposure. The condition came to the fore in the UK during the major post-war tunnelling boom particularly because of the work by Davidson (Davidson and Griffiths, 1964) and Walder (1992). It is generally accepted that DON results from inadequate decompression to the extent DON may result from only one bad decompression. The evidence for this is generally considered to have arisen from a submarine escape incident, following which three men who only ever experienced that single hyperbaric exposure, developed DON (James, 1945). More recently, Hutter (2002) advanced a theory that compression-related factors may also lead to DON.

2.3.4. Susceptibility to DCI

Individuals exhibit a varying degree of susceptibility to DCI.

> "Certain individuals when exposed repeatedly to a standard pattern of decompression frequently develop symptoms of decompression sickness whereas other individuals under same conditions rarely do so. This indicates the existence of *individual differences* in susceptibility to decompression sickness" and "In addition given individuals when exposed repeatedly to a standard pattern of decompression may develop symptoms on some occasions and not on others. This indicates the existence of *temporal variations* in susceptibility to decompression sickness" (Gray, 1951; p 182).

This succinctly sums up what is consider in this study to be susceptibility to DCI in tunnelling.

This inter-individual and intra-individual variability in response was illustrated in the findings of research by Flook (1998). The work involved Doppler and ultrasonic monitoring of workers following exposure at Weston super Mare and Swansea contracts (see Section 2.5).

The concept of susceptibility is not new. Since the 19th century, the experts of the day have noted personal characteristics or physical conditions which they considered increased susceptibility to DCI. In the early days, these characteristics were even considered to be possible causes of DCI (see Section 2.3.3). They included exercise following decompression and "personal idiosyncrasies" such as obesity, and age (Snell, 1896; p134) and cold and exhaustion (Parkin, 1905).

Current practice still respects these as factors which could make someone susceptible to DCI. After decompression men should still avoid undue exercise. Obesity is still a major contra-indicator for compressed air work and the medical examination is used to eliminate excessively obese individuals. Age is another factor and CIRIA (1982; p 32), recommended than only those over 35 who are exceptionally physically fit and no one over 40 should undertake strenuous physical work in compressed air. There are requirements in the Guidance for heating in the manlocks and that the seats should be such as to prevent contact with the cold chamber walls (Paragraph 88).

A systematic review of personal characteristics and their influence on DCI susceptibility was undertaken by Gray (1951). A parallel review by Cook (1951) examined the effect of environmental factors on DCI susceptibility. Although both studies were primarily focussed on the problems of hypobaric rather than hyperbaric exposure, Bateman (1951) noted that the idea of a common aetiology for DCI and what he called "altitude sickness" met with few objections at the time. Gray reported correlations between DCI resulting from hypobaric exposure and age and some measures of obesity. Cook reported a correlation between DCI susceptibility and exercise, temperature and fluid intake.

Most recently there was a case control study by Colvin (2003) into factors which could indicate a susceptibility to repetitive DCI. The study used medical data drawn from statutory medical examinations and the HSE database. The controls were matched for work and exposure but had not experienced a DCI event. Colvin looked at a range of over thirty lifestyle or physiological factors including smoking, drinking and obesity, to determine which if any, made the individual susceptible to repetitive DCI events. He found no statistically significant correlation between any factor and DCI. Colvin's results contradict those of Gray and Cook above. However there are many differences between the studies. Colvin used exposure data from working hyperbaric exposures whereas Gray and Cook reported predominantly on hypobaric exposures, many of which were experimental. The significance of this difference is outwith the scope of this thesis but the findings of Colvin are accepted.

Certain occupational groups such as fitters and electricians can undergo regular short exposure without experiencing DCI but go on to experience DCI when their exposure pattern changes such as in response to a major plant breakdown. This issue arose during inspection of certain contracts. Their susceptibility is unrelated to occupation except that occupation dictates exposure pattern.

Relatively little research has been done into the causes and incidence of DON in the UK in recent years because of lack of data. Factors affecting the susceptibility to DON were presented by Evans (CIRIA, 1992). The most significant of these factors was one or more DCS Type 1 events associated with long, high pressure exposures (>4 hours and >2 bar respectively)).

2.3.5. Treatment of DCI

Since the introduction of the medical lock by Moir in 1891, the treatment for acute DCI in tunnelling, has been recompression as soon as possible after the onset of symptoms, followed by slow decompression back to atmospheric pressure.

The statutory notification requiring "Notification of Compressed Air Illness" in 1938 (Home Office, 1938; Buchanan, 2005b) contained some basic advice on the diagnosis and treatment of DCI.

Over the past three decades, tunnelling industry practice has been to use therapeutic recompression, apparently successfully, in accordance with the regime set out in CIRIA (1982). Under this regime, recompression was only to a pressure sufficient to relieve symptoms, which in many cases was below exposure pressure, followed by slow stage decompression on air. This contrasted with the diving industry where treatment was to a predetermined pressure and profile such as in the US Navy or Royal Navy treatment tables (Whistler and Larne, 1984).

Since 1996 HSE guidance has been that therapeutic recompression should, at the CMA's discretion, be on oxygen to predetermined treatment regimes such as US Navy (or RN tables) (HSE, 2001; Appendix 13). The limitations of this approach to treatment, following air decompression to the Blackpool Tables, were set out by Flook (2001).

Administering oxygen to a casualty whilst being transported to a chamber for therapeutic recompression is an appropriate first aid treatment. However any oxygen so administered should be taken into account in assessing the risk from oxygen toxicity during treatment (Clark, 1993).

A typical medical lock is shown in Figure 2.1 with an oxygen breathing installation in Figure 2.3.

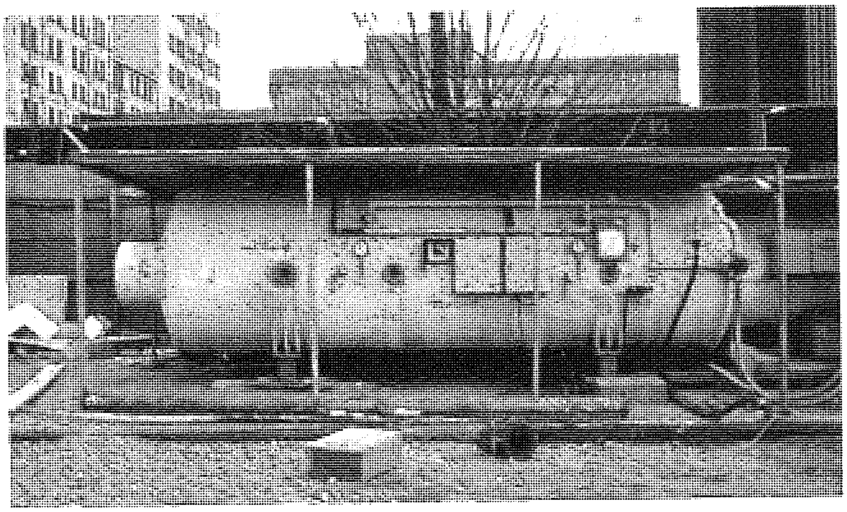


Figure 2.2 – Medical lock

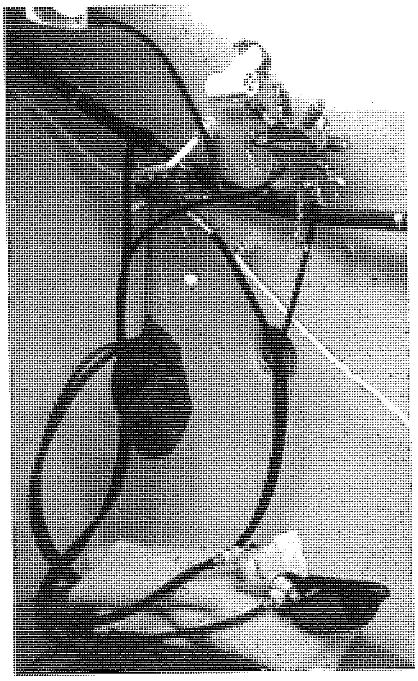


Figure 2.3 –Oxygen breathing installation

Before therapeutic recompression became fully accepted, a range of treatments had been proposed. These included electric shock (Biggart, 1885) (Butler, 2004) and Faradic treatment, coupled with therapeutic recompression for persistent cases (Erdman, 1907).

Parkin (1905) suggested that mild discomfort could be relieved by rubbing the affected area. He considered the use of morphine or ergot to treat severe pain was likely to be unsuccessful as drugs did not counteract bubble formation for which recompression was the best treatment. Norrie proposed the use of an exercise machine to stimulate the affected limb (Groves, 1944). An extensive discussion of treatment options is beyond the "engineering perspective" of this text.

HSE policy has been to create a climate in which the CAC/CMA encourages any worker with symptoms resembling DCI, to return to site for treatment, no matter how slight the symptoms (see Section 6.1.4).

DON is irreversible and its treatment involves the surgical replacement of affected joints. Elsewhere the hope has been expressed that oxygen decompression will reduce the risk from DON by improving the effectiveness of the decompression (HSE, 1999).

2.3.6. Reporting of Decompression Illness as an industrial disease

The first statutory requirement for the notification of DCS to HM Factory Inspectorate was in 1938 when an amendment was made to Section 66 of the Factories Act, 1937 (Buchanan, 2005b) requiring notification of "compressed air illness" to the Chief Inspector of Factories from 1st January 1939. The current statutory requirement is to notify DCI, DON or barotrauma as an occupational disease under the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995 (Great Britain, 1995). Further information on reporting requirements is given in Appendix 5 of the Guidance. During the early 1990s DCS was reportable both as an injury and as a disease. From the author' knowledge, HSE's published figures for DCS/DCI have underestimated the true number of cases in recent years. This was due in part to faults in HSE's internal management of the reporting system.

HSE's current policy which reflects that of Walder (1967; p 65) is that any case or suspected case of DCI for which treatment is given should be reported and counted as a DCI event. CMAs are aware of this policy and have supported it. It is a conservative approach as a small number of persons treated may have suffered physical injury not Type 1 DCS. The HSE database (see Section 3.3.2) was constructed from information obtained directly from CACs, CMAs and LAs aware of this policy.

2.4. UK regulation and guidance relating to work in compressed air

Statutory regulation and guidance has evolved to follow improvements in engineering practice and medical knowledge with major milestones occurring irregularly at intervals of 20 – 30 years.

The legislation covering compressed air working in the UK, changed most recently in September 1996 with the coming into force of the Work in Compressed Air Regulations 1996 (Great Britain, 1996).

2.4.1. Admiralty Deep Diving Report 1907

The first guidance on good practice was the Admiralty Deep Diving Report of 1907 (Admiralty, 1907). Much of this report was concerned with diving and is not relevant to this study. However the report also contained a section on decompression risk in which developments in scientific thinking at the time about the causes of and cures for decompression illness were discussed.

The report acknowledged the work of Bert and described the findings from both animal experiments and post-mortem examinations supporting the view that nitrogen was the principal gas involved in decompression illness. It also gave references to contemporary works on the origins of decompression illness theory.

In the report there were a number of comparisons between tunnelling and diving which are still relevant today – miners work at "much less high air pressure" but "the duration of exposure is far longer"; the "commonest symptoms are 'very acute' pain" but paralysis and asphyxial attacks also occur", there are "variations in individual susceptibility" (pp 31 – 35).

At that time it was standard practice to compress slowly in the (mistaken) belief that slow compression reduced susceptibility to pressure. The report, in describing different tissue saturation characteristics, recognised the error in this practice which resulted in increased inert gas uptake.

The report noted that there were two methods of securing safety in decompression. One of these was to limit exposure time whilst the other was to decompress slowly. For caisson workers, slow decompression from 1.50 bar (22 psi) and over was essential. "Slow" was defined in the report as 12 minutes per atmosphere as proposed by Bert. In a further reference to French practice, the Report noted that rapid decompression which was used on early French contracts, resulted in fatalities. The Report, no doubt influenced by having Haldane as one of its authors, discussed how initial decompression to half absolute pressure appeared not to yield adverse symptoms. Consequently it contained recommendations for stage decompression. Although Haldane prepared the decompression tables in the report for diving use, it seems likely they were widely applied in caisson sinking also.

It is interesting that much reference was made in the report to the usefulness of experience gained from caisson sinking, which was a relatively common practice at that time. By contrast, almost 100 years on the tunnelling industry is adopting practices common in the diving industry.

It appears that some other countries were bringing in legislation to regulate compressed air working around the turn of the century. Hill (1912) made reference to Dutch Regulations of around 1906 "*Verslag van de Ambtsbezigheden van der Medisch Adviseur bij de Arbeidsinspectrie*".

2.4.2. *ICE Report 1936*

In 1935, the Institution of Civil Engineers set up a Compressed Air Committee (which was to continue in being till 1960 (Buchanan, 2005b)), representing both engineering and medical interests. Its report (ICE, 1936) set out principles for good practice and the thinking behind them, some of which are still relevant today. The report covered a range of safety and health issues including maximum shift length, plant and equipment, medical provisions and welfare. Decompression tables were included in the report.

Given his views (Japp, 1935b), it was not surprising that Japp was a member of the committee. Continuity with the 1907 Admiralty report was ensured as Haldane was a contributor to both. Experience had shown that some of the decompression times in the Admiralty report were excessive while others were too short. Additionally the threshold pressure for stage decompression of 1.25 bar (18 psi) which had been recommended by the Admiralty, could be raised to 1.50 bar (22 psi). This seems to have reflected the commercial pressures from contractor representatives to minimise decompression time.

The committee recognised that body tissue was saturated after an exposure period of around five hours and therefore further exposure would not increase the decompression requirements. Accordingly a major change in practice was recommended in that the practice of split shift working should be abandoned and a single longer shift substituted. Whereas in the past, safety had been gained by reducing exposure time, the change to single shift working halved the number of decompressions and thus enhanced safety. A further suggestion in the report related to the technique of phase decompression, which is described in Section 2.2.3 of this thesis.

2.4.3. The 1958 Regulations

The Work in Compressed Air Special Regulations (Great Britain, 1958) came into force in 1958 following almost 20 years of drafting activity by officials in the Ministry of Labour and industry experts.

A draft set of regulations for work in compressed air, to be made under the Factories Act 1937 (Gt. Britain, 1937) was sent to the ICE of comment in June 1939 but were never brought into force (Taylor, 1939). A "preliminary draft" set of regulations applying to "safety, health and welfare" in connection with "works of engineering construction" was published in 1945 (Buchanan, 2005b). Both documents contained decompression tables however the range of permitted exposures was more severe in the 1939 version. The latter text covered both diving and compressed air work.

Following a period of reduced activity during the war, in 1946 the ICE Compressed Air Committee advised the Ministry of Labour that it had re-formed (ICE, 1946). Later that year the MRC was asked to appoint a representative to sit on the ICE Committee (Paton, 1967), (Paton & Walder, 1954; Preface). By then the Ministry of Labour had started work on draft regulations covering safety, health and welfare in works of engineering construction. The regulations included requirements covering both work in compressed air and diving operations. Ministry of Labour officials appeared to have been concerned lest the ICE independently published conflicting requirements as an updated version of their 1936 Report (ICE, 1936). In their comments to the Ministry of Labour on the draft of the regulations at that time (Ministry of Labour, 1961), the ICE noted that additional information had by then become available following experience gained during the war and it would be advantageous to reconsider the requirements in the Ministry of Labour proposals. Departmental records (Ministry of Labour, 1958b) showed that ICE was already in favour of separate regulations for diving and tunnelling.

To avoid any conflict of interests a joint ICE/Ministry of Labour compressed air committee was set up in 1946. this in turn set up a Joint Medical Panel in 1947 (Buchanan, 2005b) and the committee produced their "First interim report" in 1948 (Ministry of Labour, 1961). The committee agreed to accept Haldane's stage decompression method as the basis for decompression practice but considered the decompression tables in the ICE Report (ICE, 1936) gave excessively rapid decompression.

Revised tables were drawn up by Damant and Paton around 1947- 48 (Paton & Walder, 1954) and (Paton, 1967), and published for public comment in 1951 (Ministry of Labour, 1951). Haldane had proposed a 1.05 bar (15 psi) threshold for stage decompression which he considered would have given absolute safety (Ministry of Labour, 1961). However in March 1948 the drafting committee, which was wary of the commercial implications of longer decompression times, adopted a threshold pressure of 1.25 bar (18 psi) but suggested it be reviewed within 2 – 3 years (Ministry of Labour, 1961). No record of any review was found. They also proposed that miners remained on site following decompression, for a period of 1 hour at pressures up to 2.75 bar (40 psi) and 1.5 hours over that. This period on site is sometimes referred to as the "bends watch".

Departmental records (Ministry of Labour, 1959b) showed that consultation between the Ministry of Labour, ICE and interested parties, begun in 1946, continued for a number of years. In autumn 1953 ICE and the Ministry of Labour appeared to favour separate "special" regulations for work in compressed air and diving operations (Ministry of Labour, 1959b). This was because these activities were not restricted to "works of engineering construction" - a term defined in the draft regulations (Ministry of Labour, 1951) and the Ministry recognised that delays in gaining consensus over the full package of draft regulations would unnecessarily delay the regulation of diving and work in compressed air (Ministry of Labour, 1959b).

Although the subject of a public consultation exercise in 1953 (Lamont, 1997) and again in 1955 and 1957 (Ministry of Labour, 1959b), the combined special regulations were never made. Records (Ministry of Labour 1959a) showed that there were continuing concerns over the application of the requirements for diving using standard dress to diving using self contained underwater breathing apparatus (scuba), which had by then been developed.

The fate of combined regulations for compressed air working and diving was finally resolved in a file note dated 25/3/57 (Ministry of Labour, 1959a) which gave a clear recommendation to the then Chief Inspector of Factories to proceed with special regulations for work in compressed air only. The above summary both explained the delay in making the regulations and highlighted that there were hazards common to both compressed air tunnelling and diving.

This commonality of hazard was recognised in France through a single set of regulations covering both industries (JORF, 1992). Anderson and Lamont, (1991) found no evidence of similar links in the regulation of diving and tunnelling in other countries.

Diving regulations (Great Britain, 1960), finally came into force in 1960, a year before the general construction regulations – the Construction (General Provisions) Regulations (Great Britain, 1961b) and the Construction (Working Places) Regulations (Great Britain, 1961c) in 1961.

The 1958 Regulations covered a similar but wider range of technical issues than the 1936 report as well as containing decompression tables. A general comparison between the requirements of the ICE report and the 1958 Regulations was made by Haxton (1959).

2.4.4. CIRIA 44

In 1973 CIRIA formally published a code of practice (CIRIA, 1973) covering the medical aspects of work in compressed air.

The Panel subsequently revised and updated the code on two occasions (CIRIA, 1975) (CIRIA, 1982). A further revision had been almost completed in 1988 when HSE announced it was revising the 1958 Regulations and in consequence the revision was never completed (Buchanan, 2005a). However, its draft recommendations were taken into account when the Guidance (HSE, 1996) was compiled.

The physiological basis of the 1958 Tables had been agreed around 1947 (CIRIA, 1974). In 1964 the Panel acknowledged the 11 year delay between the formulation of the 1958

Tables and their coming into use and recognised the general dissatisfaction with them particularly over the incidence of DON. Accordingly they invited Dr H. V. Hempleman, then Superintendent of the Admiralty Marine Technology Establishment - Physiological Laboratory, to calculate new decompression tables (CIRIA 1974 and Section 2.2.5). The resulting tables were trialed on a sewer contract in Blackpool in 1966, with the agreement of HM Factory Inspectorate and published by CIRIA (1973). They have become universally known as the "Blackpool" Tables. A more extensive trial was undertaken on the Dungeness "B" contract (CIRIA, 1974)

Regulation 10 of the 1958 Regulations required that decompression should be carried out in "accordance with the Rules set forth in Part II of the schedule" to the regulations. However by virtue of Regulation 10(3)(1), HM Chief Inspector of Factories of the day had power to approve alternative rules for decompression "subject to such conditions as may be specified in the certificate of approval". It became HSE policy to encourage contractors, undertaking work in compressed air at pressures above 0.95 bar (14 psi), to seek approval under this regulation for the use of the Blackpool Tables in preference to the 1958 tables. Approval Certificates were normally signed by a Deputy Chief Inspector of Factories under delegated powers. Initially contract specific Certificates of Approval to use the Blackpool Tables were issued by HSE, however a general Certificate of Approval for their use, which the author drafted, was issued in 1995. The conditions normally included requirements for ventilation of the manlock, the provision of hot drinks and for the keeping and retention of exposure records.

Evans (CIRIA, 1992) undertook a comparative assessment of the effectiveness of the Blackpool Tables and the 1958 Tables but found little difference in their performance. The Blackpool Tables departed from both the 1958 Tables and ICE 1936 Report tables in that the initial drop in pressure was to half gauge pressure rather than to half absolute pressure, followed by decompression to atmospheric pressure in a series of 0.2 bar decrements separated by stages or stops at which the pressure was held constant for a given time. A comparison of the decompression profile for an exposure of 6 hours at 2 bar pressure using the respective tables is shown in Figure 2.4.

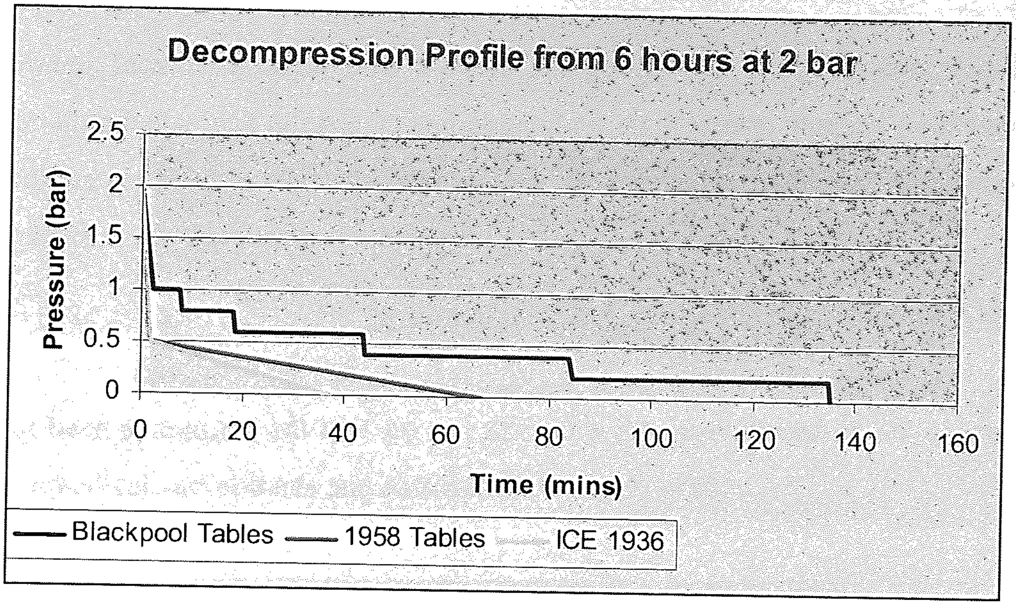


Figure 2.4 – Comparison of decompression profiles

It should be noted in passing that HM Chief Inspector of Factories also had power of exemption under Regulation 2(3), however only one recorded instance exists in HSE's files of an exemption being granted.

2.4.5. The 1996 Regulations

In 1996 the Work in Compressed Air Regulations (Great Britain, 1996) came into force. They were considerably wider in both application and extent than the 1958 Regulations. The regulations were goal setting in nature and were based on the principle of "reasonable practicability". This well-established principle relates to the balance between the reduction in risk and the cost of achieving that reduction (Ford, 2002). The Regulations were accompanied by extensive guidance on best practice in both safety and health issues (see 2.4.6).

2.4.6. Guide to the Work in Compressed Air Regulations 1996

The current guidance on compressed air working practice is contained in the HSE booklet L96 (HSE, 1996), and the addendum for oxygen decompression and the use of non-air breathing mixtures (HSE, 2001).

Considerable specialised plant and equipment, including compressors, coolers and filters along with a small number of key personnel are required to undertake work in compressed air in a safe manner.

Key personnel include a person in overall charge of the work in compressed air, compressor attendants, lock attendants and depending on pressure, medical lock attendants all of whom are required to be on site throughout compressed air working. Their duties are set out in detail in the Guidance.

2.4.7. *Health surveillance and medical fitness for work*

It has long been a requirement that no one should work in compressed air unless under appropriate medical surveillance and certified fit for such work.

Health and
Safety
Executive

Factories Act 1961
Work in Compressed Air Special Regulations 1958
(SI 1958 No. 61)
Work in Compressed Air (Amendment)
Regulations 1960 (SI 1960 No. 1307)

Compressed air health register

LAMONT, DONALD
Name

F 751
Reprinted February 1980

80p net (exclusive of tax)
ISBN 0 11 883347 2

This Register must be kept by the employer of the person named herein and handed to that person on termination of his employment. Thereafter the person should keep the Register until he is next employed in compressed air where he must hand it to his new employer before commencing work. The employer must supply a new Register when necessary.

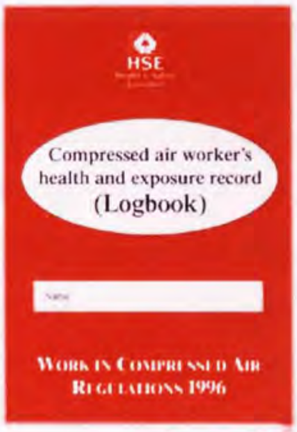
Figure 2.5 – Compressed air health register - Form 751

Under the 1958 Regulations, an employer had a duty to make arrangements for medical surveillance by an "appointed" doctor. The results of that surveillance in terms of fitness for work in compressed air, were recorded in the individual's Compressed air health register (Form 751) (see Figure 2.5) in accordance with Regulation 14(2). The regulations were prescriptive in relation to the frequency of medical examination. They required an examination every three months for exposure to low pressure (i.e. under 0.95 bar (14 psi)) and every 28 days for high pressure exposure. Under Regulation 14(4), the certification of fitness could be made conditional in terms of maximum pressure or duration of exposure at the appointed doctor's discretion. Employees had a duty under regulation 14(5) to report any ailment which could render them unfit for work in compressed air.

Regulation 9 of the 1996 Regulations requires the CMA (appointed by the CAC) to advise on "all aspects of health relevant to the work in compressed air". This innovative and important requirement gives the CMA as wide ranging a role as possible in the occupational health management on site.

Regulation 10 sets out the requirements for medical surveillance, which should be undertaken by an Appointed Doctor or CMA, there being a presumption in the Guidance (Appendix 4) that one doctor would fulfil both roles. The Guidance (Appendix 5) also includes information for the Appointed Doctor on medical standards for fitness to work in compressed air.

Regulation 16(1) places a duty on the CAC to ensure that only persons certified medically fit, work in compressed air and that anyone suffering from a condition likely to render him unfit for work in compressed air does not do so (Regulation 16(2)). In addition individual workers have a duty under Regulation 16(3) to report to the CAC and their employer, any condition which renders them unfit for work in compressed air. Reasons for unfitness include any complaint affecting the respiratory system, ears nose or throat, or pregnancy.



HSE

Compressed air worker's health and exposure record
(Logbook)

Name

WORK IN COMPRESSED AIR
REGULATIONS 1996

Figure 2.6 – Compressed air worker's health and exposure record (Logbook)

A further innovation was the conversion of the Compressed air health register (Form 751) into a "Compressed air workers health and exposure record" (see Figure 2.6) known colloquially as a logbook (Logbook, 1996). This contains medical fitness certificates and also details of training along with a man's full exposure history. It was introduced in the hope that this would encourage compressed air workers to value and retain the document.

2.4.8. Compliance with regulations

From the author's years of experience of site inspections, it is believed that in general the regulations have been complied with. This is due in part to the very small size of the industry with only one major plant and equipment supplier and the professionalism of the engineers, LAs, MLAs and CMAs within it.

Failure to report unfitness for work and the symptoms of DCI has long been considered a problem with varying estimates of under-reporting, however as a result of better education of the workforce (see Section 3.6.5) it is hoped that under-reporting will cease to be an issue of concern.

2.5. Doppler and Ultrasonic monitoring

Doppler monitoring is a physiological monitoring technique whereby sound waves are passed through body tissue and the frequency shift of the reflected echoes analysed and interpreted to detect bubbles in the circulatory system. It was described in detail by Nishi *et al* (2005). Two non-linear grading systems for bubble concentration are commonly used – the Kisman-Masurel method and the Spencer method. Both require considerable skill on the part of the operator in detecting and counting the bubbles passing the detector. Monitoring should be undertaken in accordance with carefully defined protocols to ensure consistency. The equipment is compact and readily portable. There are a number of preferred standard locations for placing the Doppler probe including over the pulmonary artery or the subclavian vein. Monitoring is done with the subject at rest or following movement. The science and physiology behind the technique is well beyond the "engineering perspective" of this study. Although the technique had been used extensively in diving research, the first use of the technique in UK compressed air tunnelling research was at Weston and Swansea contracts (Flook, 1998) as part of HSE's hyperbaric research programme (Lamont, 2002). It was later used in hyperbaric trials of oxygen decompression for tunnelling (Lamont *et al*, 2002).

Ultrasonic monitoring was also undertaken as part of HSE's tunnelling research programme but its use was discontinued due to difficulties in transporting the equipment to site and the lack of any apparent benefit compared to the use of Doppler equipment. Ultrasonic monitoring is also a physiological monitoring technique and is based on the use of ultrasonic pulses which are passed through the body with the time taken for the echo to return being measured. The technique was also described in detail by Nishi *et al* (2005). Three display modes can be used depending on the output required but the most common displays a 2-dimensional screen image. Again the science behind the technique is well beyond the "engineering perspective" of this study. Monitoring is usually of the pulmonary artery. A supposedly less complicated, non-linear grading systems is used to measure bubble concentrations.

Both techniques quantify bubble concentrations or "grades". The detection of bubbles can be used as an indicator of decompression stress and may be a more sensitive indicator than DCI incidence. Nishi et al (2005; p 522) noted that from a sample of almost 3500 (diving) exposures, bubbles were detected following decompression in 56% of them whilst only 2% gave rise to symptoms of DCI. Bubbles may also be an indicator of DCI risk however the correlation between bubble grades and DCI risk is weak. Nevertheless high bubble grades are considered to represent a greater risk of DCI.

2.6. Lessons from the UK diving industry

At the time of publication of the Admiralty Report in 1907, the diving industry was able to learn from the tunnelling industry about its experiences of working under pressure. For much of the following century, diving was associated with military applications, marine salvage and maritime civil engineering using surface supplied diving equipment. The development of self contained underwater breathing apparatus in the mid 1950s led to the popularity of recreational diving. Initially exposure depths were relatively shallow at around 30 to 50 metres maximum but the discovery of oil reserves under the North Sea changed this considerably.

The upsurge in diving activity which accompanied the start of oil exploration in the North Sea, was characterised by high levels of DCI, particularly Type 2 DCS. This prompted the Department of Energy, then responsible for enforcement of occupational health and safety legislation in the offshore industry, to undertake research into the extent of the problem. Following the report into the Piper Alpha disaster in 1988 (Cullen, 1990) enforcement responsibility passed to HSE and led to the formation of its Offshore Safety Division (OSD). Since then, OSD has continued the research into both the short term and long term health effects of hyperbaric exposure. Robertson (1996) published an initial summary of this research. Initially the research focussed on the reduction of DCI incidence, but in time the focus changed to the reduction of gas load as bubbles in the bloodstream. In many respects, this paralleled the situation in the tunnelling industry a decade or so later and which gave rise to this project. The applicability to tunnelling decompression practice of the results of that research is considered as part of this study.

Because of the range of diving techniques used in the North Sea, a wide-ranging programme of research was undertaken. The initial work was carried out by Shields and Lee (1986) and involved an analysis of all dives carried out in 1982/83 in the UK sector of the North Sea. Recommendations for restrictions on exposure, arising from this research were published as Diving Safety Memorandum (DSM) 7/86 (Department of Energy, 1986). This was followed by a similar analysis of diving activity up to 1990 (Shields *et al*, 1994). Shields *et al* examined the diving techniques and exposure patterns which resulted in the highest incidences of DCI. They determined that hyperbaric stress was the most significant factor affecting the occurrence of DCI, and proposed limits on exposure to reduce that incidence, based on the severity of the hyperbaric stress. These limits varied with the diving technique. Further limits on exposure were imposed by OSD over time (DSMs 5/88, 4/89 and 2/90, (Department of Energy 1988, 1989 and 1990)). The exposure restrictions in DSM 7/86 (Department of Energy, 1986)) were actually applied as limits on decompression time and the application of this approach to tunnelling is discussed in Section 6.1.

Duff *et al* (1996), undertook a mapping analysis of DCS for a range of diving techniques. Although in that work, Duff et al (1996) quantified the number of exposures and DCI events in a matrix of pressure/time increments, they did not calculate the incidence of DCI for each increment as in the Single Exposure Risk Factor (see Section 4.4.3).

Robertson and Simpson (1996) comprehensively reviewed OSD's research, including that relating to Bubble Growth Index (BGI) and Hempleman's Exposure Index (P√T) (Hempleman, 1993). Simpson (1999) reported the outcomes of a workshop of leading international experts who met in 1998 to discuss OSD's hyperbaric research programme.

Lambertsen *et al* (OTO 96 800, 1996) noted that most of the longer-established decompression tables were based on the Haldanian model – exponential gas exchange between blood and tissue and a tolerable level of supersaturation – resulting in the 2:1 pressure reduction ratio. They believed that with increasing severity of exposure, the Haldane ratio of 2:1 became inadequate. Lambertsen *et al* reviewed several measures of decompression stress including a number based on bubble growth and others based on supersaturation – both relatively complex physiological concepts and beyond the "engineering perspective" of this study. Of the measures studied, they concluded that P√T was a good, simple predictor of DCS.

P√T frequently occurs in the diving hyperbaric literature. However, it is a measure of the hyperbaric stress of exposure and as such indicates the potential for DCI. It is not a measure of the outcome of the decompression procedure although it could be linked to DCI incidence arising from a specific decompression regime. Robertson and Simpson (1996) deemed it inappropriate as a measure of DCI incidence. The main application for P√T is as a comparative measure of exposure severity however its validity does not extend to the full range of exposure periods, common in tunnelling. The use of P√T is considered further in Chapters 4 and 6.

Robertson and Simpson (1996) also reported on the use of Doppler monitoring but that is a monitoring technique to determine gas in blood and not a measure of DCI incidence for use in the retrospective analysis of exposure data.

Chapter 3 Data

This chapter reviews the statutory requirements for data protection and the specific requirements for recording exposure to compressed air. There is a critical description of the acquisition of data for this study, the construction from those data of a number of summary databases and spreadsheets and discussion on inconsistencies, omissions and errors in those data.

3.1. Data Protection Act 1998

The legislation relevant to the protection of data is the Data Protection Act 1998 (1998, c29).

3.1.1. Data Protection Act 1998

The management, storage, transfer and processing of personal data by electronic means is regulated by the Data Protection Act 1998. The Act applies to "personal data" which are data relating directly to an individual who can be identified from that data or who can be identified from the data along with other accessible information (Lloyd, 1998: pp 18 - 19). "Sensitive personal data", includes data such as ethnic and medical data and its use is subject to severe restriction (Lloyd, 1998: pp 19 - 20).

Application of the Act is typically to an individual's employment data; financial data; and school, health and social services records (Lloyd, 1998). Under Sections 16 and 18, persons controlling data must register certain information about themselves and their purpose in holding and processing data, with the Data Protection Commissioner.

3.1.2. Principles of Data Protection

The Act contains a number of schedules of which Schedule 1 deals with the principles of data protection. According to Schedule 1, individuals have the right to have personal data recorded only for lawful purposes and to have the right to consent to its processing except for a number of activities for which data processing can be undertaken without consent (Hammond Suddards, 1998). There is also the right to have personal data processed fairly;

only to have data recorded which is up to date, accurate, relevant and which is not excessive; to have that data held securely and only for the minimum time necessary.

3.1.3. Exemptions from the Act

There are a number of exemptions from all or parts of the Act, some of which are relevant to this study and are described below.

Consent, by the data subject, to the acquisition and processing of personal data is a major principle of the Act but the need for consent is not required where the processing of the data is in exercise of any function of a government department (Schedule 3 (7)(1)(c)).

The Act gives the data subject rights of access to the data for error correction and provides the data subject with the right to be notified about how the data is being used. However data processing for the purposes of health, safety and welfare at work is exempt from the "subject information provisions" (S 31). Provided anonymity is maintained, S 33 exempts data for research purposes from Section 7 of the Act, "Right of access to personal data".

3.1.4. Application of the Act to this study

The extent to which the Act applies to this study is debateable however the spirit of the Act will be applied where reasonably practicable to do so. All databases under HSE's control, containing personal data, including those used in this study, are registered by HSE centrally, with the Data Protection Commissioner.

For many of the individuals covered by this study, the only item of identifiable personal information held is name although for around one third, National Insurance number is also held.

The collection and analysis of compressed air exposure data and the publication of anonymised results has gone on openly within the industry since the 1950s. Although individuals were not asked to consent to information held in the statutory registers being used in an anonymised form for research, pre-employment medical questionnaires do contain a consent declaration. CAWG (2003) agreed that CMAs should in future, explicitly advise their patients that all compressed air exposure data could be subject to analysis in an anonymised form.

It was not considered to be reasonably practicable to notify the individuals whose data was used in this study as no permanent contact addresses were recorded when the data was first obtained. Tunnel miners are seldom long-term employees and frequently their employment with a particular contractor is for the duration of a contract only, although they may return to that contractor for subsequent contracts. It is doubtful if name only would have been sufficient to identify the individual although no guidance on this has been found.

Throughout the study, anonymity was maintained as, although the names of individuals were required as identifiers, they were otherwise irrelevant to the results presented. The only deviation from this was the use of two extracts from Lock Attendants' registers - one handwritten and one electronic – in Chapter 3 (Figures 3.2 and 3.3 respectively) to illustrate the sources from which raw data was obtained and one extract from the electronic transcription of a Lock Attendant's register to illustrate the poor quality of data from certain contracts (Figure A6.1). Although the extracts contained names of individuals, the information they contained was freely available to all those working in compressed air on the shifts to which the respective extracts referred. Consequently, the sensitivity of the information disclosed was considered sufficiently insignificant to allow extracts to be included as illustrative material because of their major importance to the study, without breaching confidentiality.

A similar principle was applied to CACs and CMAs however most within the industry were aware of their identities.

"Sensitive personal data", which includes data such as medical data are subject to more severe restriction (Lloyd, 1998 pp 19-20). Although occupational exposure information could be considered "sensitive", the data were not being analysed for medical purposes and hence were not covered by the requirements for confidentiality amongst health professionals contained in Principle 8 and Schedules 3, 8 and 9 of the Data Protection Act.

3.2. Statutory Requirements to make and keep records

There is a range of health and safety legislation applicable to compressed air tunnelling and record keeping has been a specific requirement for many years.

3.2.1. Health and Safety at Work etc Act 1975 – Powers of Inspectors

Under Section 20(k) of the Health and Safety at Work etc Act (HSW Act) (Great Britain, 1974), an Inspector appointed under Section 19 of the Act, is empowered to take copies of any book or document, which is required to be kept under any of the Relevant Statutory Provisions. The latter include the Work in Compressed Air Regulations, 1996. Hence this is considered to be the statutory basis for the acquisition of CAC's records.

3.2.2. Requirements in the 1958 Regulations for keeping a record of exposures

There were specific requirements in these Regulations regarding the making and keeping of records by contractors. Regulation 10(1) required the lock attendant to enter in a register, details of the pressure, time of entry to and exit from the manlock and the time for decompression to be carried out. There was no specific requirement for how long the records should be kept but there was a general requirement in Section 141 of the Factories Act (Great Britain, 1961a) that all records should be kept for two years.

One condition, which the Certificate of Approval (see Section 2.4.4) routinely imposed on contractors, was that records had to be retained for fifteen years. The author increased this requirement to thirty years.

3.2.3. Requirements in the 1996 Regulations for keeping a record of exposures

The duty to make and keep records is set out in Regulation 11(4). This regulation requires the CAC to make a record of the pressure and duration of each exposure to compressed air and maintain this record in a suitable form for at least forty years from the date of the last entry. Regulation 11(5) requires the CAC to maintain an exposure record "in respect of each person who undertakes work in compressed air", and Regulation 11(7)(b) requires the CAC to give each person exposed, a record of their exposures.

The industry still keeps records in the form of the lock attendant's register although this is often now in an electronic version. An individual's records are kept in his "Compressed air worker's health and exposure record" (see Figure 2.6) which is given to him on leaving the contract in the hope that compressed air workers will value and keep their logbooks as divers do. There is no evidence that this culture has yet been established on any widespread scale.

Regulation 11(7)(a) requires that each employer must maintain a set of records for his own employees, again for at least forty years.

The information to be kept in the records is set out in Regulation 11(6).

3.2.4. Requirements in the 1996 Regulations for keeping a record of decompressions

Under Regulation 8(1) the CAC is required to provide all plant and equipment necessary for the safe conduct of work in compressed air. The Guidance (Paragraph 104) includes "suitable recording pressure gauges" in this requirement. This is to enable the CAC to make a record of all decompressions over 1 bar. Although Regulation 11(6) requires the CAC to record "decompression details", there is no duty, other than by implication, to make a pressure/time record of each decompression (see Chapter 7). Appendix 9 of the Guidance, paragraph 5(a) requires that a functional check of the recording pressure gauge be done before decompression commences and Guidance (Paragraph 36(f)) requires the lock attendant to keep safe the "manlock decompression charts".

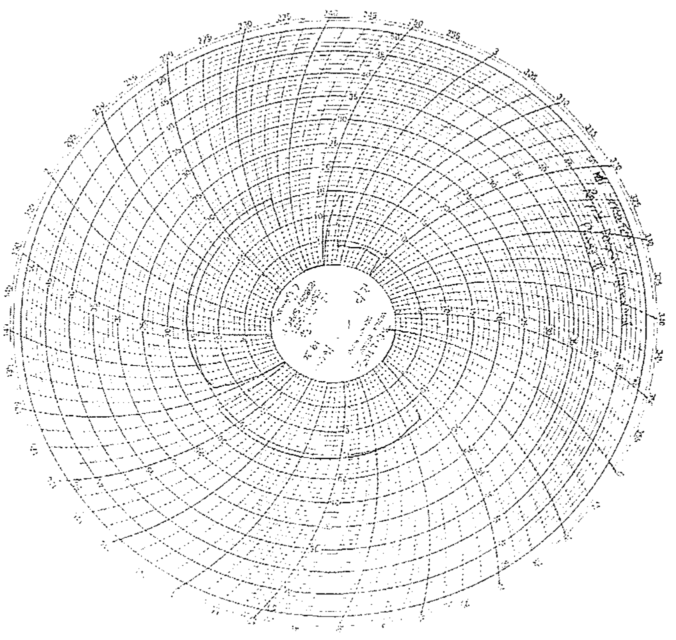


Figure 3.1 - Recording pressure gauge chart – centre zero

(approx. ¼ full size)

Prior to the coming into force of the 1996 Regulations, most recording gauges were of a circular centre zero type (Figure 3.1). However, the need for the greatest accuracy and readability of the trace is in the final stages of decompression which takes place at the lower pressures and hence towards the centre of the chart where, on the centre zero chart, the trace is most compressed. In drafting the Guidance, this problem was recognised and perimeter zero gauges specified. Zaninni (1967) noted that a similar problem had also been recognised in Italy. Longitudinal strip charts are acceptable but are rarely used in UK practice.

3.2.5. The Lock Attendant's Register

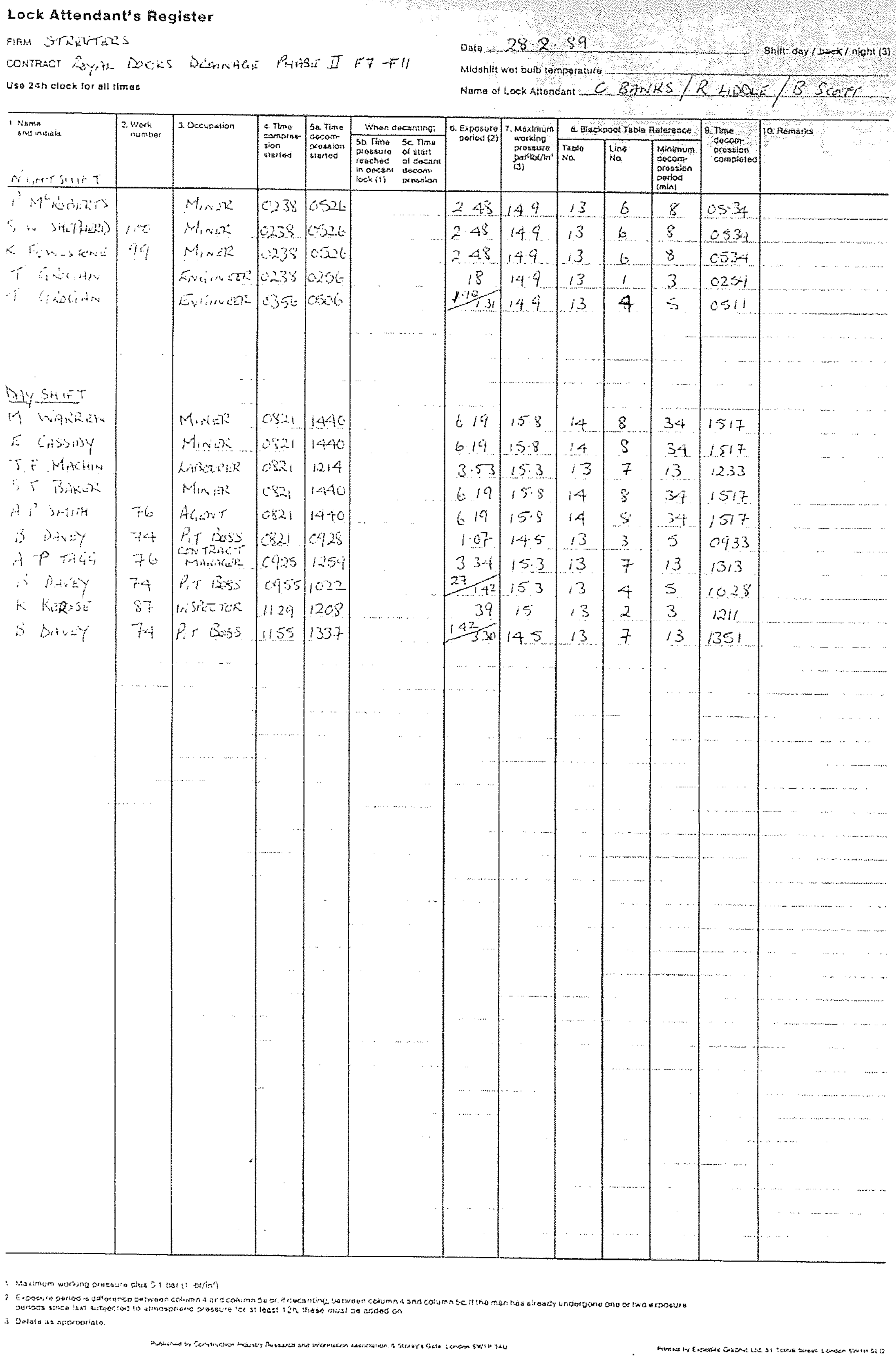
Regulation 10(1) of the 1958 Regulations required that records were kept in a Lock Attendant's Register (Form 752). Although the requirement in the 1996 Regulations is simply for an "adequate record" to be made, the term "lock attendant's register" remains the standard industry term for that document. The paper version of the lock attendant's register currently used is similar to that for 1958 Regulations. A sample of the hand-written paper version is shown in Figure 3.2. Its electronic counterpart contains similar information, apart from the columns devoted to decanting, and an extract from the register for Hull is shown in Figure 3.3. A discussion on anonymity is contained in Section 3.1.4.

Information recorded in both versions of the register falls into two categories although the terminology varies. The first, is information which is more related to the contract and includes details of the CAC, contract and Lock Attendant(s). The second category is information relating to the individual and his exposure - name, occupation and usually a works or tally number. National Insurance number is also recorded in the electronic version of the register (see Section 3.3.2). The 1996 Regulations (Regulation 11(6)) require date, time of entry, duration and maximum pressure of each exposure, and decompression details (table number and line number of Blackpool Table and remarks such as the occurrence of DCI) to be recorded.

The purpose of the information recorded is as follows:-

- **Name** – used for identifying individuals, however since the tunnelling industry does not have the ethnic diversity of the overall population, there can be a certain similarity in the names (see Section 3.6.7).
- **Works or tally number** - this is a quick and easy way to identify individuals. It is also used for accounting for personnel in the tunnel as part of the site emergency procedures.

- **NI Number** - this is a unique identifier and was introduced as it was the only identifier which could reliably be used to track men across a number of contracts (electronic version only). Its secondary purpose was to differentiate between men with similar names.
- **Occupation** - an individual's exposure pattern is a consequence of his occupation. Miners, TBM drivers and other production operatives work regular long shift patterns whereas supervisors and technical staff tend to have exposure patterns of irregular short shifts. Intuitively, regular long exposures should increase the risk of DCI. Hence occupation is a significant indirect factor in determining an individual's risk of DCI (CIRIA, 1992).
- **Date** - this enables records to be identified chronologically.
- **Time compression started (or time of entry)** - this allows the shift worked to be identified (see Section 5.1.5).
- **Time decompression started** – for calculation of exposure period.
- **Exposure period** - a key parameter in determining the decompression required. Time of entry/start of compression and exposure period are sufficient, completely to define an exposure in respect of time.
- **Maximum working pressure** – the other key parameter in determining decompression requirements. The decompression table required is determined from the maximum pressure experienced during the shift together with the exposure period. This results in a decompression, which is based on a rectangular exposure profile - maximum pressure for maximum time. Any period spent at lower pressure will reduce the need for decompression, but such theoretical reduction is ignored, ensuring that decompression practice is slightly conservative. It is similar to traditional diving practice, before the introduction of dive computers which integrate time and depth at regular short intervals to give a more accurate but less conservative exposure profile.
- **Blackpool Table and line number** – this allows a retrospective check on whether the correct decompression profile was selected.
- **Remarks** – Lock attendants should enter details of any deviation from normal practice, abnormal response by individuals to compression/decompression, DCI etc.



Lock Attendant's Register

FIRM STREVTERS

CONTRACT ROYAL DOCKS DRAINAGE PHASE II F7 - F11

Use 24h clock for all times

Date 28·2·89 Shift: day / ~~back~~ / night (3)

Midshift wet bulb temperature

Name of Lock Attendant C BANKS / R LIDDLE / B SCOTT

1. Name and initials	2. Work number	3. Occupation	4. Time compression started	5a. Time decompression started	When decanting: 5b. Time pressure reached in decant lock (1)	When decanting: 5c. Time of start of decant decompression	6. Exposure period (2)	7. Maximum working pressure bar/lbf/in² (3)	8. Blackpool Table Reference: Table No.	8. Blackpool Table Reference: Line No.	8. Blackpool Table Reference: Minimum decompression period (min)	9. Time decompression completed	10. Remarks
NIGHT SHIFT													
P McROBERTS		MINER	0238	0526			2 48	14 9	13	6	8	05·34	
S W SHEPHERD	[illegible]	MINER	0238	0526			2·48	14·9	13	6	8	0534	
K FOWLESTONE	99	MINER	0238	0526			2 48	14·9	13	6	8	0534	
T GEOGHAN		ENGINEER	0238	0256			18	14·9	13	1	3	0259	
T GEOGHAN		ENGINEER	0356	0506			1·10/1·31	14·9	13	4	5	0511	
DAY SHIFT													
M WARREN		MINER	0821	1440			6 19	15 8	14	8	34	1517	
E CASSIDY		MINER	0821	1440			6 19	15·8	14	8	34	1517	
T F MACHIN		LABOURER	0821	1214			3·53	15·3	13	7	13	1233	
S T BAKER		MINER	0821	1440			6 19	15·8	14	8	34	1517	
A P SMITH	76	AGENT	0821	1440			6 19	15·8	14	8	34	1517	
B DAVEY	74	PIT BOSS	0821	0928			1·07	14·5	13	3	5	0933	
A P TAGG	76	CONTRACT MANAGER	0925	1259			3 34	15·3	13	7	13	1313	
B DAVEY	74	PIT BOSS	0955	1022			27/1 42	15 3	13	4	5	1028	
K KEROSE	87	INSPECTOR	1129	1208			39	15	13	2	3	1211	
B DAVEY	74	PIT BOSS	1155	1337			1 42/3 30	14 5	13	7	13	1351	

1 Maximum working pressure plus 0·1 bar (1 lbf/in²)

2 Exposure period is difference between column 4 and column 5a or, if decanting, between column 4 and column 5c. If the man has already undergone one or two exposure periods since last subjected to atmospheric pressure for at least 12h, these *must* be added on.

3 Delete as appropriate.

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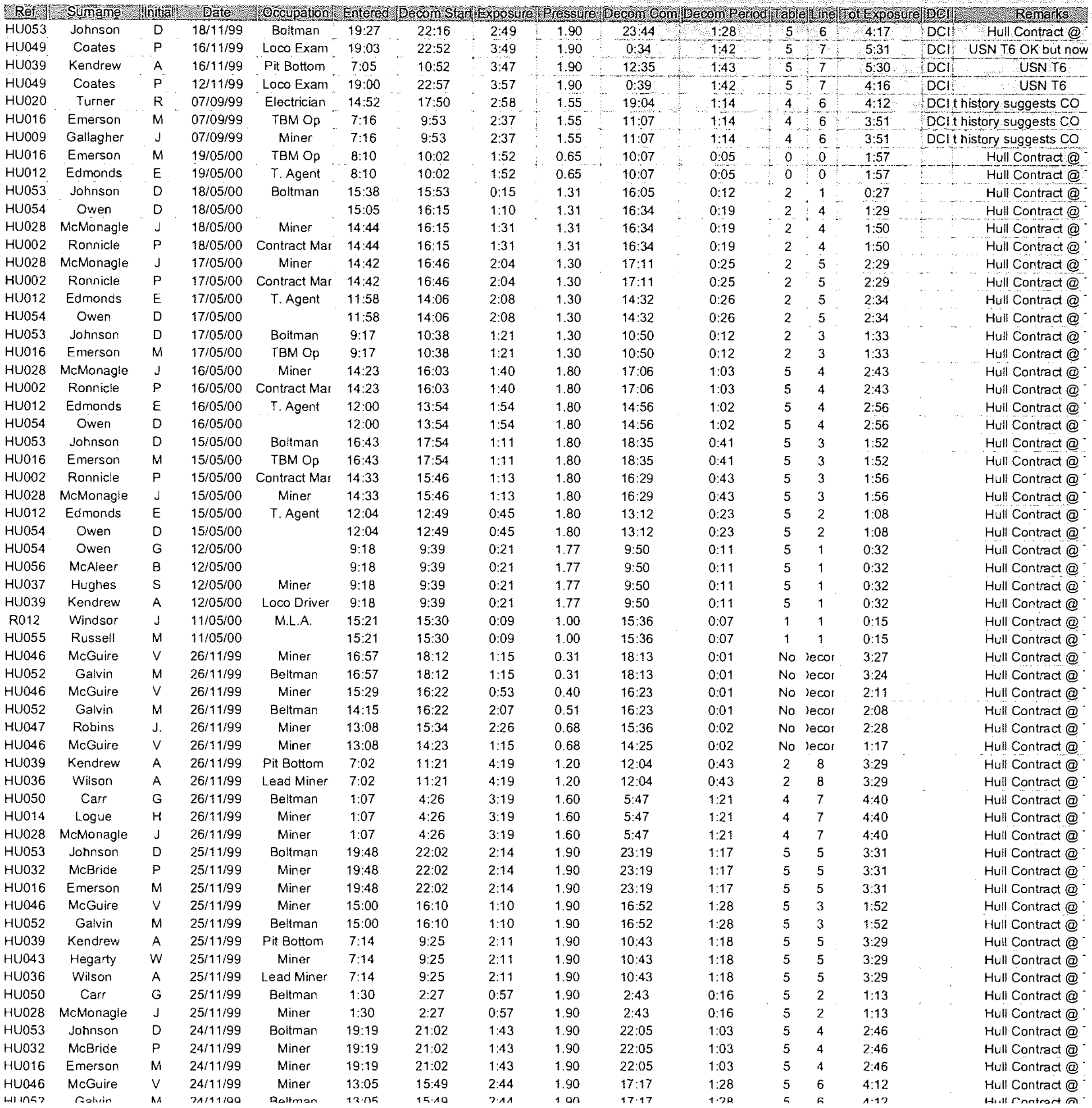
Printed by Expedite Graphic Ltd, 31 Tooks Street, London SW1H 9LG

Figure 3.2 – Extract from Lock Attendant's register for Royal Docks Phase 2

(full size – A3)



Ref	Surname	Initial	Date	Occupation	Entered	Decom Start	Exposure	Pressure	Decom Com	Decom Period	Table	Line	Tot Exposure	DCI	Remarks
HU053	Johnson	D	18/11/99	Boltman	19:27	22:16	2:49	1.90	23:44	1:28	5	6	4:17	DCI	Hull Contract @
HU049	Coates	P	16/11/99	Loco Exam	19:03	22:52	3:49	1.90	0:34	1:42	5	7	5:31	DCI	USN T6 OK but now
HU039	Kendrew	A	16/11/99	Pit Bottom	7:05	10:52	3:47	1.90	12:35	1:43	5	7	5:30	DCI	USN T6
HU049	Coates	P	12/11/99	Loco Exam	19:00	22:57	3:57	1.90	0:39	1:42	5	7	4:16	DCI	USN T6
HU020	Turner	R	07/09/99	Electrician	14:52	17:50	2:58	1.55	19:04	1:14	4	6	4:12	DCI	t history suggests CO
HU016	Emerson	M	07/09/99	TBM Op	7:16	9:53	2:37	1.55	11:07	1:14	4	6	3:51	DCI	t history suggests CO
HU009	Gallagher	J	07/09/99	Miner	7:16	9:53	2:37	1.55	11:07	1:14	4	6	3:51	DCI	t history suggests CO
HU016	Emerson	M	19/05/00	TBM Op	8:10	10:02	1:52	0.65	10:07	0:05	0	0	1:57		Hull Contract @
HU012	Edmonds	E	19/05/00	T. Agent	8:10	10:02	1:52	0.65	10:07	0:05	0	0	1:57		Hull Contract @
HU053	Johnson	D	18/05/00	Boltman	15:38	15:53	0:15	1.31	16:05	0:12	2	1	0:27		Hull Contract @
HU054	Owen	D	18/05/00		15:05	16:15	1:10	1.31	16:34	0:19	2	4	1:29		Hull Contract @
HU028	McMonagle	J	18/05/00	Miner	14:44	16:15	1:31	1.31	16:34	0:19	2	4	1:50		Hull Contract @
HU002	Ronnicle	P	18/05/00	Contract Mar	14:44	16:15	1:31	1.31	16:34	0:19	2	4	1:50		Hull Contract @
HU028	McMonagle	J	17/05/00	Miner	14:42	16:46	2:04	1.30	17:11	0:25	2	5	2:29		Hull Contract @
HU002	Ronnicle	P	17/05/00	Contract Mar	14:42	16:46	2:04	1.30	17:11	0:25	2	5	2:29		Hull Contract @
HU012	Edmonds	E	17/05/00	T. Agent	11:58	14:06	2:08	1.30	14:32	0:26	2	5	2:34		Hull Contract @
HU054	Owen	D	17/05/00		11:58	14:06	2:08	1.30	14:32	0:26	2	5	2:34		Hull Contract @
HU053	Johnson	D	17/05/00	Boltman	9:17	10:38	1:21	1.30	10:50	0:12	2	3	1:33		Hull Contract @
HU016	Emerson	M	17/05/00	TBM Op	9:17	10:38	1:21	1.30	10:50	0:12	2	3	1:33		Hull Contract @
HU028	McMonagle	J	16/05/00	Miner	14:23	16:03	1:40	1.80	17:06	1:03	5	4	2:43		Hull Contract @
HU002	Ronnicle	P	16/05/00	Contract Mar	14:23	16:03	1:40	1.80	17:06	1:03	5	4	2:43		Hull Contract @
HU012	Edmonds	E	16/05/00	T. Agent	12:00	13:54	1:54	1.80	14:56	1:02	5	4	2:56		Hull Contract @
HU054	Owen	D	16/05/00		12:00	13:54	1:54	1.80	14:56	1:02	5	4	2:56		Hull Contract @
HU053	Johnson	D	15/05/00	Boltman	16:43	17:54	1:11	1.80	18:35	0:41	5	3	1:52		Hull Contract @
HU016	Emerson	M	15/05/00	TBM Op	16:43	17:54	1:11	1.80	18:35	0:41	5	3	1:52		Hull Contract @
HU002	Ronnicle	P	15/05/00	Contract Mar	14:33	15:46	1:13	1.80	16:29	0:43	5	3	1:56		Hull Contract @
HU028	McMonagle	J	15/05/00	Miner	14:33	15:46	1:13	1.80	16:29	0:43	5	3	1:56		Hull Contract @
HU012	Edmonds	E	15/05/00	T. Agent	12:04	12:49	0:45	1.80	13:12	0:23	5	2	1:08		Hull Contract @
HU054	Owen	D	15/05/00		12:04	12:49	0:45	1.80	13:12	0:23	5	2	1:08		Hull Contract @
HU054	Owen	G	12/05/00		9:18	9:39	0:21	1.77	9:50	0:11	5	1	0:32		Hull Contract @
HU056	McAleer	B	12/05/00		9:18	9:39	0:21	1.77	9:50	0:11	5	1	0:32		Hull Contract @
HU037	Hughes	S	12/05/00	Miner	9:18	9:39	0:21	1.77	9:50	0:11	5	1	0:32		Hull Contract @
HU039	Kendrew	A	12/05/00	Loco Driver	9:18	9:39	0:21	1.77	9:50	0:11	5	1	0:32		Hull Contract @
R012	Windsor	J	11/05/00	M.L.A.	15:21	15:30	0:09	1.00	15:36	0:07	1	1	0:15		Hull Contract @
HU055	Russell	M	11/05/00		15:21	15:30	0:09	1.00	15:36	0:07	1	1	0:15		Hull Contract @
HU046	McGuire	V	26/11/99	Miner	16:57	18:12	1:15	0.31	18:13	0:01	No	)ecor	3:27		Hull Contract @
HU052	Galvin	M	26/11/99	Beltman	16:57	18:12	1:15	0.31	18:13	0:01	No	)ecor	3:24		Hull Contract @
HU046	McGuire	V	26/11/99	Miner	15:29	16:22	0:53	0.40	16:23	0:01	No	)ecor	2:11		Hull Contract @
HU052	Galvin	M	26/11/99	Beltman	14:15	16:22	2:07	0.51	16:23	0:01	No	)ecor	2:08		Hull Contract @
HU047	Robins	J.	26/11/99	Miner	13:08	15:34	2:26	0.68	15:36	0:02	No	)ecor	2:28		Hull Contract @
HU046	McGuire	V	26/11/99	Miner	13:08	14:23	1:15	0.68	14:25	0:02	No	)ecor	1:17		Hull Contract @
HU039	Kendrew	A	26/11/99	Pit Bottom	7:02	11:21	4:19	1.20	12:04	0:43	2	8	3:29		Hull Contract @
HU036	Wilson	A	26/11/99	Lead Miner	7:02	11:21	4:19	1.20	12:04	0:43	2	8	3:29		Hull Contract @
HU050	Carr	G	26/11/99	Beltman	1:07	4:26	3:19	1.60	5:47	1:21	4	7	4:40		Hull Contract @
HU014	Logue	H	26/11/99	Miner	1:07	4:26	3:19	1.60	5:47	1:21	4	7	4:40		Hull Contract @
HU028	McMonagle	J	26/11/99	Miner	1:07	4:26	3:19	1.60	5:47	1:21	4	7	4:40		Hull Contract @
HU053	Johnson	D	25/11/99	Boltman	19:48	22:02	2:14	1.90	23:19	1:17	5	5	3:31		Hull Contract @
HU032	McBride	P	25/11/99	Miner	19:48	22:02	2:14	1.90	23:19	1:17	5	5	3:31		Hull Contract @
HU016	Emerson	M	25/11/99	Miner	19:48	22:02	2:14	1.90	23:19	1:17	5	5	3:31		Hull Contract @
HU046	McGuire	V	25/11/99	Miner	15:00	16:10	1:10	1.90	16:52	1:28	5	3	1:52		Hull Contract @
HU052	Galvin	M	25/11/99	Beltman	15:00	16:10	1:10	1.90	16:52	1:28	5	3	1:52		Hull Contract @
HU039	Kendrew	A	25/11/99	Pit Bottom	7:14	9:25	2:11	1.90	10:43	1:18	5	5	3:29		Hull Contract @
HU043	Hegarty	W	25/11/99	Miner	7:14	9:25	2:11	1.90	10:43	1:18	5	5	3:29		Hull Contract @
HU036	Wilson	A	25/11/99	Lead Miner	7:14	9:25	2:11	1.90	10:43	1:18	5	5	3:29		Hull Contract @
HU050	Carr	G	25/11/99	Beltman	1:30	2:27	0:57	1.90	2:43	0:16	5	2	1:13		Hull Contract @
HU028	McMonagle	J	25/11/99	Miner	1:30	2:27	0:57	1.90	2:43	0:16	5	2	1:13		Hull Contract @
HU053	Johnson	D	24/11/99	Boltman	19:19	21:02	1:43	1.90	22:05	1:03	5	4	2:46		Hull Contract @
HU032	McBride	P	24/11/99	Miner	19:19	21:02	1:43	1.90	22:05	1:03	5	4	2:46		Hull Contract @
HU016	Emerson	M	24/11/99	Miner	19:19	21:02	1:43	1.90	22:05	1:03	5	4	2:46		Hull Contract @
HU046	McGuire	V	24/11/99	Miner	13:05	15:49	2:44	1.90	17:17	1:28	5	6	4:12		Hull Contract @
HU052	Galvin	M	24/11/99	Beltman	13:05	15:49	2:44	1.90	17:17	1:28	5	6	4:12		Hull Contract @

Figure 3.3 – Extract from electronic Lock Attendant's register for Hull

3.3. Data Acquisition

Access to data of a quality suitable for analysis formed the basis of this study and was achieved through the cooperation of the industry and CMAs and earlier work in HSE. The starting point for this study was the electronic copy of the lock attendant's register, received either directly from the CAC (see Section 3.3.2) or from W.S. Atkins (see Section 3.3.3).

3.3.1. *Newcastle Registry*

Because of emerging concerns in the mid-1960s over the incidence of DCI and more especially DON, the Panel set up a centralised system of data collection at the University of Newcastle upon Tyne in 1964. This subsequently became known as the "Newcastle Registry". It eventually accumulated data on nearly 500,000 exposures affecting some 15000 men from around 70 contracts from the period 1948 to around 1980. The Registry stopped accepting data around 1981 and closed in 1984. Analysis of the data was not undertaken until 1991 (CIRIA, 1992).

3.3.2. *HSE compressed air exposure database*

This came into existence in 1994 as a result of concerns within HSE over the incidence of DCI on two contracts – JLE 105 and Cromer. As part of the subsequent investigation, some analysis of the contract records was undertaken. To be able to make comparisons, the analysis was extended to the N Woolwich and LWRM contracts. This required the acquisition of contractors' records and with them came the realisation that little meaningful analysis could easily be done unless the paper records were converted to an electronic format.

As the 1996 Regulations were being drafted at the time they were structured to permit, if not encourage, CACs to make electronic records. This was achieved relatively easily and cost effectively by utilising the MLAs' time to input the data. MLAs are required to be present on site at all times during work in compressed air over 1 bar and for twenty four hours after the final decompression. Apart from treating DCI, making a fair copy of the lock attendant's register and (now) generally supervising the hyperbaric regime, MLAs spend much of the rest of their time on standby.

Initially a colleague Mr Nigel Thorpe C. Eng MICE, then HM Specialist Inspector - Construction Engineering, constructed a series of routines based around the Lotus 1-2-3® spreadsheet package, into which the exposure data could be directly input. The spreadsheet format was chosen only because no database software was available to HSE staff at that time.

The routines generated a daily lock attendant's register as well as providing a complete contract record. A key aspect of the routines was the use of a single identifier, initially works number or tally number, for each individual. This linked the exposure data to data on the man's name, occupation etc. without the need for duplication in data entry with its accompanying risk of error.

CACs were given a disk containing the routines onto which they input their records before returning the disks to HSE. Each exposure generated one row of data however a major limitation of the spreadsheet was that it was restricted to around 8000 rows of data. Once database software became available, Mr Thorpe converted his routines to that format.

Mr Thorpe's work formed the basis for combined exposure and health surveillance data capture software developed as a sophisticated relational database by another colleague, Mr Martin Holden, C. Eng MICE, HM Principal Specialist Inspector - Construction Engineering (Holden, 1997). The database format remains the preferred format for all data collection.

Since 1996, most CACs have utilised HSE data capture software, but the data from those who did not have been transcribed into electronic format by W. S. Atkins, Consulting Engineers, under a research contract with HSE.

3.3.3. Data from earlier contracts

Around 1996 it was realised that there was a risk of losing data from contracts dating back to 1981 when the Registry closed, unless they were collected without delay. This was because the Approval Certificates for these contracts had set a retention limit of only fifteen years.

All contractors issued with Approval Certificates back to 1981 were contacted and requested that a copy of their records be sent to Atkins. All contractors contacted agreed in principle to our request but two were subsequently unable to locate some or all of the relevant records in their company archives. Additionally one tunnelling company had succumbed to bankruptcy and one to take-over in the intervening period and as a consequence, at least part of their records had been lost. Contracts from which it would have been interesting to obtain data but for which none could be located, were the caisson sinking for Redheugh Bridge; Abbey Sewer, Leicester and the shaft sinking work at Factory Lane, Manchester. The number of exposures which these contracts represent is unknown.

Once records were obtained, the data were converted into electronic format by Atkins, and added to the HSE exposure database.

No records have been obtained from before 1984 however there appears to have been little compressed air working in the early 1980s (Lamont, 1996; CIRIA, 1978).

3.4. Contracts in study

Some background information on industry working practice may help to clarify the detail in this section.

3.4.1. High v Low pressure

It is normal industry practice to categorise contracts on the basis of exposure pressure - low or high pressure. “High” pressure is normally been taken as above the threshold pressure at which stage decompression is required. The threshold for stage decompression has varied with time (Lamont, 1997).

Under the 1958 Regulations “high” pressure was originally taken as 1.25 bar (18 psi) and over. This became 0.95 bar (14 psi) – subsequently metricated to 1.0 bar - and over, with the introduction of the Blackpool Tables. Although in September 2001, stage decompression was introduced from 0.7 bar, industry practice still seems to define “high” pressure as 1 bar and over, however this may change with time.

The significance of the stage decompression threshold is that many of the measures to mitigate risk from compressed air working take effect at that threshold. Appendix 17 of the Guidance lists these measures.

3.4.2. Shift length and pattern

The Blackpool Tables are based on a total shift time of 10 hours i.e. exposure period + decompression time is limited to 10 hours. This limit gives a 14-hour break at atmospheric pressure between exposures.

It was normally a contractual requirement in open-faced hand tunnelling that the face should be continuously manned unless timbered for support. Consequently shift lengths were nominally a sub-multiple of 24. Change-over between gangs could occur at the face or on the surface. Depending where change-over took place, exposure time for shift production workers would be slightly under the nominal shift length for surface change over and over for face change over. Exposures were always allocated to the time increment for their actual duration. For work under 1 bar, 10 and 12-hour shifts were standard practice.

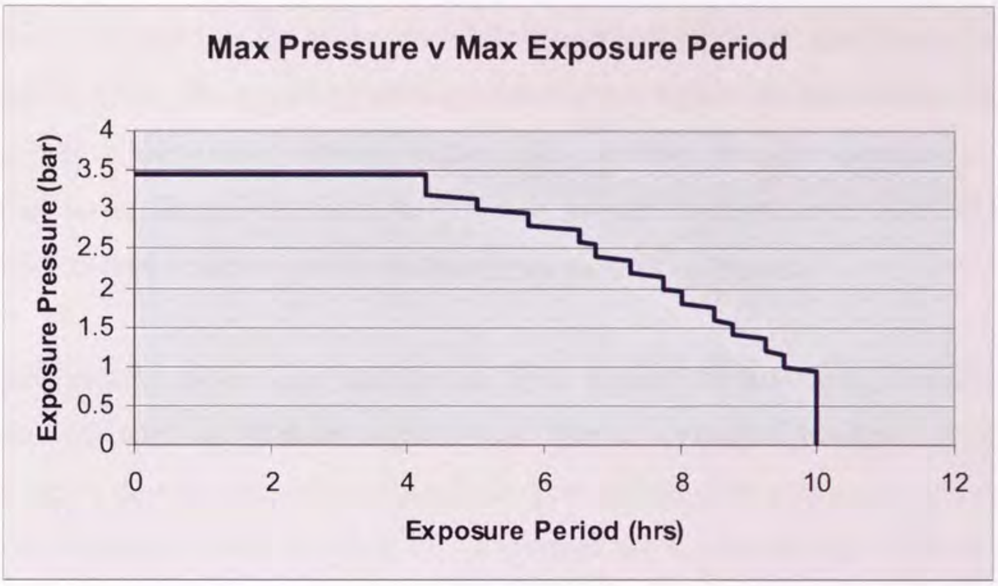


Figure 3.4 – Envelope of maximum pressure and exposure period (Blackpool Tables)

In closed face tunnelling with TBMs, shift patterns have generally been standardised at 3 x 8 hour shifts per 24-hour day with compressed air interventions lasting a sub-multiple of 24 hours. Shift length in compressed air, is unlikely now to exceed 8 hours and would be determined by the work to be done and the clinical judgement of the CMA.

Permissible exposures under the Blackpool Tables can be determined from Figure 3.4, which shows the envelope of maximum pressure and exposure period. A similar plot cannot be drawn for the 1958 Tables as they do not specify exposure periods at each pressure increment. Buchanan (2005a) suggested that the 1958 Regulations could be interpreted to imply that a maximum exposure period of 19 hours at any pressure, was permissible. It was accept that this may have been the industry interpretation of the Regulations. Shift durations used at Auckland Bridge were discussed by Rose (1962, Paragraph 4.4).

Weekly shift patterns vary with the contract. A common pattern was 5 working shifts with 2 shifts off, leaving Saturdays and Sundays for essential tunnel maintenance. More recently CACs have used a 6 days on/3 off shift pattern for continuous production with maintenance being carried out daily. Shift rotation is usually undertaken.

3.4.3. Details of Contracts in study

The contracts included in the study are briefly described below in approximately reverse chronological order. The contract names used in this text reflect the sometimes-abbreviated name by which they were entered in the HSE database and not necessarily the full contractual name. More extensive descriptions of the contracts can be found in the tunnelling literature and on websites such as www.tunnelbuilder.com.

A contract pressure profile has been shown for a number of contracts. This is a plot of maximum daily exposure pressure against date. They are presented to show how exposure pressure varied during typical compressed air contracts. In particular a comparison of the profiles for Ramsden Dock and JLE 105 illustrates the fundamentally different contract pressure profiles typical of a caisson sinking project in which the pressure increases constantly as the caisson sinks (Figure 1.12) and of a tunnel which is usually driven at roughly constant pressure (Figure 1.13).

Channel Tunnel Rail Link - Contract 320 – this was the first UK contract on which routine oxygen decompression was used (see Section 6.2).

Belfast – this was a small project and one of the first uses of compressed air in N. Ireland. As N. Ireland is outwith the jurisdiction of HSE, the data were supplied by courtesy of the Health and Safety Executive (Northern Ireland). PDSOB was used over 0.75 bar.

Portsmouth – this was a tunnel sewer project on which low-pressure compressed air was applied as a precaution following an incident which adversely affected the stability of the tunnel lining.

London Cable Tunnel - this was a TBM-driven tunnel, constructed to facilitate the upgrading of the high voltage electricity distribution network in London. There was a small amount of low-pressure compressed air working at pressures of around 0.35 bar.

Hull - this was a major TBM-driven sewer tunnel project on which a limited amount of compressed air working was initially undertaken in connection with intermittent TBM maintenance and work around shafts. Following a major collapse of the tunnel lining which occurred late in the construction phase, high-pressure compressed air was applied as a damage limitation measure because of the speed with which the equipment could be set up. Ultimately the majority of the recovery operations were undertaken using ground freezing techniques rather than compressed air to avoid the risk of DCI (T&TI, 2000c).

Great Yarmouth Power Project - this was a TBM-driven tunnel on which a planned compressed air intervention took place under the beach to facilitate access to the cutter head for maintenance purposes before the tunnel was driven out under the sea. This contract was the first in the UK to adopt the use of PDSOB (T&TI, 2000a).

Docklands Light Railway - high pressure compressed air was required on the Lewisham Extension for the construction of cross passages and sumps in twin, standard gauge light-railway tunnels under the Thames at Greenwich.

Figure 3.5 – Engineers examining site of blow-out DLR contract
(NCE, 2004)

The contract could have been the first UK contract to use routine oxygen decompression (under a 1996 Regulations Certificate of Approval). An oxygen breathing system had been installed. However shortly before compressed air working began, there was a catastrophic blow-out of the working chamber (NCE, 2004). Following recovery work, compressed air working was undertaken but using air-only decompression as following the blow out (see Figure 3.5) it was not considered prudent to be the first trial of oxygen decompression.

Hastings - this was a large diameter sewage transfer/storage tunnel project on which high-pressure compressed air was required to give access to the TBM cutterhead for maintenance purposes (T&TI, 2000b).

Bacton - extensive hand excavation was undertaken on this project, which involved the construction of a tunnel to facilitate the landfall of an offshore gas pipeline. High-pressure compressed air was applied to ensure face stability under the beach and tidal waters.

Swansea 5 and **Swansea 6** - these were two sewer tunnel contracts which were awarded some time apart to the same contractor who treated them as a single contract. Consequently there was considerable overlap of labour and resources. Men were routinely transferred between contracts to meet the contractor's programme requirements. In legal terms the contracts were separate undertakings but the amount of overlap made it logical in this study to treat the contracts as a single undertaking. Doppler and ultrasonic monitoring was undertaken on site as part of HSE's hyperbaric research programme. (Flook, 1998).

Weston super Mare - the contractor divided the construction of this hand dug sewer tunnel into a number of discrete parts, however the records have been aggregated for analysis purposes. The Doppler and ultrasonic monitoring which was undertaken on this site (Flook, 1998) was the first research contract to be let in the programme which ultimately led to the introduction of oxygen decompression (Lamont, 2002).

Swanage - this was a flood relief tunnel driven by TBM in soft rock, on which high-pressure compressed air was used to reduce water inflow. Although a relatively recent contract, the contractor chose not to use HSE software and even worked in imperial units. The paper records were transcribed by Atkins.

Fylde – this was a major sewer tunnel project on which high-pressure compressed air was used for access to the TBM cutterhead for maintenance purposes. In an attempt to reduce the incidence of DCI, the CMA decided with HSE agreement, to decompress men using profiles which were two tables greater in pressure than the actual exposure pressure. The south end of this project linked to the tunnel at which the Blackpool tables were first used.

Jubilee Line Extension Contract 105 – Compressed air was used on JLE 105 for groundwater control during the driving of the enlargements which formed the station tunnels at Bermondsey station. The enlargements were hand dug (see Figure 1.5). This contract had the largest number of exposures of any in the period from 1986 and was also notable for the number of DCI events which occurred below 1 bar.

The contract pressure profile is shown in Figure 1.13. Pressure rose over five days at the start of the compressed air working from around 0.5 bar to 1.3 bar. Thereafter it fluctuated around the 1 bar level until early April when air was taken off on completion of the first station tunnel. There was a short break whilst preparations were made for the second drive which followed an approximately similar profile but with a slight downwards trend in pressure rather than with pressure fluctuations.

This contract was also notable by being probably the first to have MLAs with a background in the offshore life support industry. Earlier contracts such as LWRM had MLAs with commercial diving backgrounds. The MLAs at JLE 105 brought a new level of hyperbaric experience and professionalism to the contract which has resulted in a lasting improvement in standards of lock attending.

Jubilee Line Extension Contract 107 - Compressed air was used on JLE 107 for two separate operations. The first was to facilitate sinking of a caisson for Canada Water station and the second was for access to the TBM cutterhead for maintenance purposes.

Jubilee Line Extension Contract 110 - High-pressure compressed air was used on JLE 110 for access to the TBM cutterhead as well as for ground support during the excavation of mid-river sumps and pumping stations where the running tunnels passed under the Thames.

Cromer - this was a TBM-driven sewer outfall tunnel in chalk containing flints. Unfortunately the flints caused catastrophic damage to the cutterhead, the repairs to which required extensive work in high-pressure compressed air.

High-pressure air was maintained for the remainder of the tunnel drive with the pressure being periodically increased to facilitate inspection and maintenance of the cutterhead.

Fluctuations in working pressure were a notable feature of this project, and could have resulted in increased DCI. The break in compressed air working over Christmas 1993 and Easter 1994 can also be seen from the contract pressure profile in Figure 3.6.

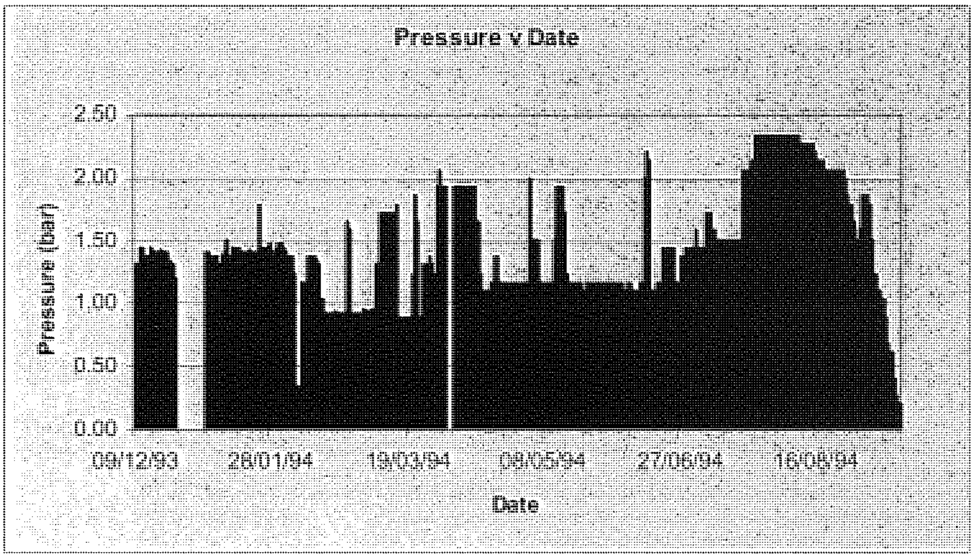


Figure 3.6 - Contract pressure profile - Cromer

Southport – this was a major sewer tunnel driven by TBM in sandy ground where compressed air was used to control groundwater inflow. HSE was advised that the contract was operating at pressures below 0.95 bar (14 psi). However, the contract was used by the Health and Safety Laboratory for field research into the behaviour of atmospheric monitoring equipment in a hyperbaric atmosphere (Dabill *et al*, 1996). Data obtained from that project and subsequent analysis of contract records showed that working pressures had routinely been around 1.00 bar (14.5 psi). This was technically a high pressure contract for which an Approval Certificate to use the Blackpool tables should have been sought although the contractor could legally have used the 1958 tables without such a certificate. Additionally an MLA would have been required for high-pressure work, which would have added significantly to the contractor's overheads.

Ennerdale - this contract was for sinking of a shaft and the hand excavation of an outlet tunnel from Ennerdale Water in a highly cohesive normally consolidated clay. Poor ground conditions led to the use of compressed air for two separate operations. The first was the completion of shaft sinking in the soft clay. It was then decided to undertake the whole tunnel drive in compressed air to ensure face stability. The separate nature of the operations can be seen in Figure 3.7

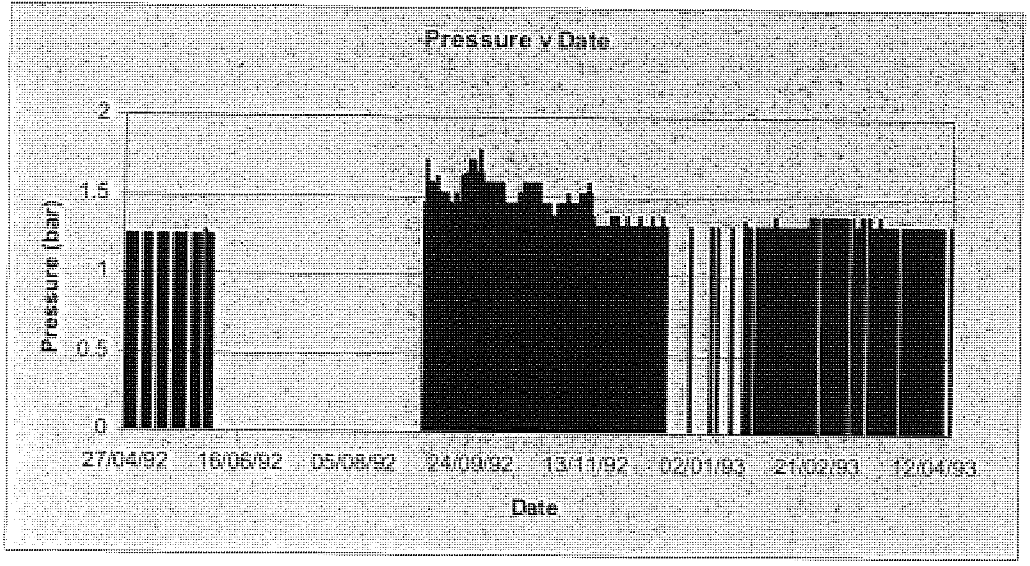


Figure 3.7 – Contract pressure profile - Ennerdale

Ramsden Dock - this was a very large caisson-sinking project (see Figure 1.1) and was interesting in a number of ways. The labour force was predominantly from a diving industry background and the work involved the use of high pressure water jets to wash sand and gravel into a sump from where it was pumped out of the caisson. Consequently the working chamber was cooler than normal and the men were thought to have been working in water to above knee level, for extended periods. The contract pressure profile for Ramsden Dock is shown in Figure 1.12.

Royal Docks Phase 9 - This was a tunnel sewer contract. A small number of exposures (378 out of 3326) ended in decanting but it is not known if there were any special reasons for this other than those in Section 2.2.7.

London Water Ring Main - this contract involved the use of high pressure compressed air for ground support after it became necessary to realign the tunnel when an unexpected obstruction was encountered in the tunnel face. The contract pressure profile shows that there was little variation in exposure pressure during the contract. There was some concern that the break over Christmas 1988 would result a second period of acclimatisation however that was not the case. The contract pressure profile is shown in Figure 5.13.

N Woolwich – (also known as Royal Docks Phase 4) - this was a major contract in which high pressure compressed air was used to control water inflow in a tunnel being driven in chalk. A small number of decant decompressions were undertaken (201 out of 7617).

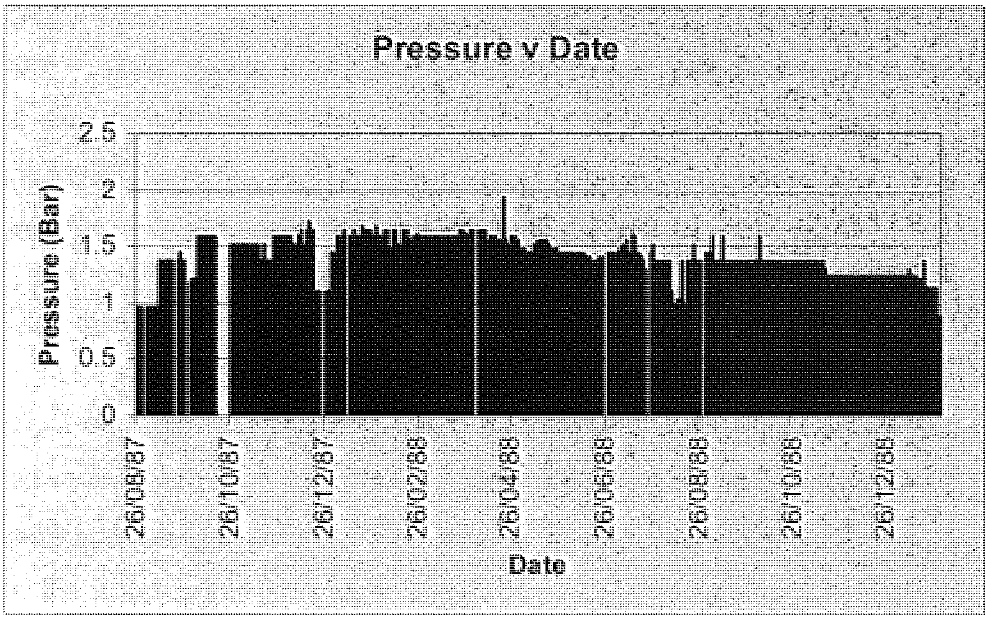


Figure 3.8 – Contract pressure profile – N. Woolwich

Rochdale – low pressure compressed air was used in two phases on this tunnel sewer contract.

Coppermills – the contractor originally intended to construct this water supply tunnel using pipejacking techniques but the method of driving had to be changed to conventional tunnelling during the construction phase.

Royal Docks Phase 2 – This was a tunnel sewer contract. This contract has been excluded from most of the analysis apart from some work using MANLIST because of doubts over DCI records. A small number of exposures (75 out of 1168) ended in decanting but no particular reasons for this outcome were known other than those in Section 2.2.7.

Lowestoft – this was a cable tunnel driven under Lowestoft Harbour.

Bideford – Compressed air was used on this contract to facilitate the sinking of caissons for bridge foundations.

In addition limited quantities of data were obtained from a number of low pressure contracts including Pepperhill, Billingham, Folkestone, and Kelvin Valley. It has not been possible to separate the exposures from 0.7 to 0.95 bar from those below 0.7 bar for these contracts.

The amount of data relating to oxygen decompression is very limited. A small amount of additional data could have been obtained from the hyperbaric trials (Lamont *et al*, 2002) however the trials were not totally representative of industry conditions so these data have been omitted.

3.5. Data manipulation and consolidation

The principal objective of this study was the analysis of data from a number of contracts, undertaken over a period of years. As the data were acquired piecemeal over a period of time, separate databases each with a similar format, were set up for each contract. Thereafter the information from each contract was aggregated and summarised to provide overall results. Two major databases DCI and MANLIST and a spreadsheet TOTAL were constructed to do this.

Standard business software packages from the Microsoft Corporation and Lotus Development Corporation were used for all data manipulation. The choice of software was dictated by HSE's somewhat restrictive policy on software provision. Initially this required the use of Lotus business software only and did not permit the use of Microsoft business software. However the policy was later relaxed to permit the use of Microsoft software and then changed again to insist on its use. Because of the flexibility and integration of applications within a modern business software suite, it was generally possible to open database files from within either a database or spreadsheet environment depending on the operation to be undertaken. Likewise some data files were translated between Microsoft and Lotus packages to facilitate analysis when necessary. Additionally MathCAD® and the Insightful Corporation's Axum® graphing package which had advanced graphing capability were available for the study.

3.5.1. Database DCI

This database drew together the records of DCI events and held information on a range of aspects of each exposure which had resulted in individual DCI events along with information on the person experiencing each DCI event. An extract from Database DCI is shown in Figure 3.9.

The fields in the database, many of which replicated the lock attendant's register, were:-

- **Reference number** - a number to identify each DCI event. The number itself was of no consequence and was inserted automatically by the software.
- **Initials/Forename & Surname** - to identify an individual worker.
- **Occupation** – to identify the nature of an individual's work and consequently his likely exposure pattern.
- **NI number** – a unique identifier between men who worked on more than one contract
- **Contract** – the contract on which an individual worked.
- **Exposure record number for contract** – the number of the exposure record in individual contract databases of an exposure leading to a DCI event and that exposure record to be located quickly if required for checking purposes.
- **Tally/works number** – the identifier preferred on site for identifying individual workers.
- **Date of DCI event** – as field name suggests.
- **Exposure pressure** - the maximum pressure experienced during the exposure.
- **Exposure time** – the time from start of compression to start of decompression (most usefully expressed in minutes).
- **Multiple exposures that day** – the number (2 or more) of compression/decompression cycles undergone in a shift.
- **Shift** – an indicator of the shift worked in a day/back/night shift rotation pattern.
- **DCI Type** - the particular manifestation of DCI experienced – barotrauma/DCS Types 1 or 2/niggles etc.
- **Site of DCI** – part of body affected by DCI.
- **Exposure number 1st, 2nd, 3rd, 4th DCI event** - the number of the exposure within an individual's exposure history resulting in DCI.
- **Total number of exposures** - an individual's total number of exposures on a contract.
- **Remarks** - narrative from lock attendant (LA)/medical lock attendant (MLA) etc on any incident affecting the exposure.

- **Decanting** - identifies if the exposure resulting in DCI was followed by a decant decompression.
- **No of DCI events on contract** – total number of DCI events an individual experienced on a single contract.
- **Exposure pressure (Bar)** – as above but in consistent units of pressure to facilitate searching/sorting.
- **Exposure time (minutes)** – as above but in consistent units of time to facilitate searching/sorting.

Two versions of this database were used, one contained records of all DCI events, the other only those events for which full records were available. The latter principally excluded DCI data for the Bideford contract.

3.5.2. Database MANLIST

This database contained information on the men who had worked in compressed air during the study period. MANLIST brought together information on the men's exposure to compressed air on each contract. There was some duplication of information with database DCI but this was for convenience in the analysis. An extract from Database MANLIST is shown in Figure 3.10.

The fields in the database were:-

- **Initials & Surname** – as database DCI.
- **NI number** – as database DCI
- **Tally number** – as database DCI.
- **Occupation** – as database DCI.
- **Contract** – as database DCI.
- **Date of first exposure** – date of a man's first exposure to compressed air on a contract.
- **Date of last exposure -** date of a man's last exposure to compressed air on a contract.
- **No of Exposures** - as "**Total number of exposures**" in database DCI.
- **DCI** – number of DCI events.
- **Notes** - for comment as appropriate.

To assist in identifying men who appeared to have worked on more than one contract, men who possibly had experienced DCI on more than one contract and the analysis of DCI incidence by occupation, three additional fields were added to MANLIST - **No of contracts on which a man worked, No of contracts on which a man experienced DCI** and **Occupational category** (see Section 4.4.5).

3.5.3. Spreadsheet TOTAL

Spreadsheet TOTAL consisted of a number of worksheets each tabulating the exposure data and calculating the DCI incidence for a single contract along with a summary worksheet which calculated overall totals for exposures and DCI events along with a range of DCI incidence data.

For each contract, TOTAL displayed the number of exposures and DCI cases in each of a number of increments of pressure and exposure time. TOTAL had 8 pressure increments and 5 time increments which were chosen to be consistent, within the limits of metrication, with those used by Evans (CIRIA, 1992). The figures were formed into a number of tables within each worksheet. Arithmetical routines were included to operate on the tables and thus quantify the incidence of DCI using the measures of DCI incidence identified in Section 4.4. The complexity of the spreadsheet, particularly the summary worksheet, grew with time as ever more extensive data analysis was undertaken. A modified version of TOTAL was constructed in which the exposures at 0.95 bar and below, were divided into pressure increments of below 0.7 bar and 0.7 bar and above. This was referred to as TOTAL795. Both spreadsheets existed in Lotus 1-2-3® and Microsoft Excel® versions to facilitate analysis. The structure and purpose of a typical contract worksheet from TOTAL795 and the summary worksheet are described below.

The worksheet for the Cromer contract from TOTAL795 was selected as being typical of individual contract worksheets and is shown in Figure 3.11 (and in more detail in Figure A2.1). For each contract, the number of exposures for an individual pressure/time cell was determined manually, from the contract database representing the lock attendant's register and entered into the appropriate cell of the worksheet (cells B7 - F15). These data were totalled by pressure and time increment for the contract (cells G7 – G15 and B16 – F16)). Similarly the number of DCI events for each pressure/time cell was determined and entered accordingly (cells B21 – F29) and totalled by pressure and time increment for the contract (cells G21 – G29 and B30 – F30). Each worksheet contained a table of long-term average data (LTA) derived from the Guidance (Table 1; p 69) which in turn, had been based on the work of Evans (CIRIA, 1992). This was tabulated in the form required to calculate the SBR (cells B35 – F50). Alternate rows within this section of the worksheet were used to calculate SERFs for current data for each pressure/time cell which allowed a direct comparison to be made between the SERF for current data and the SERF for LTA data. A further table (cells B56 – F63) was used as for the calculation of "expected DCI events" as an intermediated step within the SBR calculation. The CBR for all exposures was calculated (cell C51) along with the SBR (cell G51). Subsequently, formulae to calculate CBRs for exposures > 0.7 bar and > 1 bar were added to each contract worksheet in TOTAL795 (cells K10 and K20).

The summary worksheet from TOTAL795 is shown in Figure 3.12 (and in more detail in Figure A2.2) and its main functions described below. A list of the formulae embedded in TOTAL795 is given in Appendix 2. Colour coding was used to make it easier to identify some of the calculated values within the worksheet and has been replicated below. The summary worksheets in both TOTAL and TOTAL795 were structured on a similar layout to individual contract worksheets. The summary worksheet aggregated the numbers of exposures by pressure and time increment for all contracts (cells B3 – F11) with DCI events being similarly aggregated in cells B21 – F29, and gave overall totals in G12 and G30 respectively.

Thereafter it calculated the total number of exposures and DCI events by pressure increment (cells G3 – G11 and cells G21 – G29 respectively) and by time increment (cells B12 – F12 and B30 – F30 respectively). This was followed by the total number of exposures over 0.7 bar, by time increment (cells B13 – G13), broken down by percentage in cells B14 – F14. The number of DCI events from exposures of 0.7 bar and over in each time increment was calculated in cells B31 – F31.

A weighted average exposure period for all exposures was calculated in cell I14 and for exposures of 0.7 bar and over in cell H17. A weighted average exposure pressure for exposures of 1 bar and over was calculated in cell H18.

Totals and breakdowns by percentage, for hours worked in each time increment, based on mid increment values, were set out in cells B15 – G17 and for each pressure increment in cells I3 – I10.

SERFs were calculated for each increment of pressure and exposure period in alternate row of **cells B35 – F49**. Bends rates by exposure period increment were calculated for all exposures in **cells B51 – F51** and for exposures of 0.7 bar and over in **cells B52 – F52**. The incidence of DCI per hour worked (DCI/HW) by exposure period increment was calculated for all exposures in **cells B53 – F53** and for exposures of 0.7 bar and over in **cells B54 – F54**. The incidence of DCI by pressure increment was calculated in **cells G35 – G49** and of DCI/HW in **cells H35 – H49**.

A range of CBRs by pressure and time increments were calculated in cells G33 – H47 and B49 – F50 respectively. DCI/HW was calculated in **cells B53 – F54**. Overall CBRs and bends rates per hour worked, were calculated in **cells B55 – D56**. The SBR was displayed in **cell G53**. Long term average data for the SBR calculation was stored in alternate rows between cells B36 and F50. "Expected" DCI for the SBR calculation was calculated in cells B60 – G68.

TOTAL795 contained a further three tables which calculated the number of exposures by pressure/time increment as a percentage of all exposures (cells L3 – P11) along with a breakdown (by percentage) by pressure increment (cells Q3 – Q11), and a breakdown (by percentage) by exposure period (cells L12 – P12). The number of exposures pressure/time increment as a percentage of the number of exposures of 0.7 bar and over along with similar breakdowns was calculated in cells L18 - Q25 and the DCI/HW values and breakdowns for pressure/time increments at pressures of 0.7 bar and over in cells L30 – Q38.

The equivalences shown in Table 3.1 were used for calculating the breakdown of exposures and DCI events by pressure on contracts where imperial units had been used.

Metric – Imperial equivalences for pressure increments in TOTAL	
Metric (bar)	**Imperial (psi)**
$P < 0.7$	$P < 10$
$0.7 \leqslant P \leqslant 0.95$	$\geqslant 10$ - <14
$1.0 \leqslant P \leqslant 1.25$	$\geqslant 14$ - $\leqslant 18$
$1.3 \leqslant P \leqslant 1.55$	>18 - <23
$1.6 \leqslant P \leqslant 1.85$	>23 - <27
$1.9 \leqslant P \leqslant 2.15$	$\geqslant 27$ - $\leqslant 31$
$2.2 \leqslant P \leqslant 2.35$	>31 - $\leqslant 34$
$2.4 \leqslant P \leqslant 2.65$	>34 - <38
$2.7 \leqslant P$	$\geqslant 38$

Table 3.1 - Metric – Imperial equivalences for pressure breakdowns in TOTAL

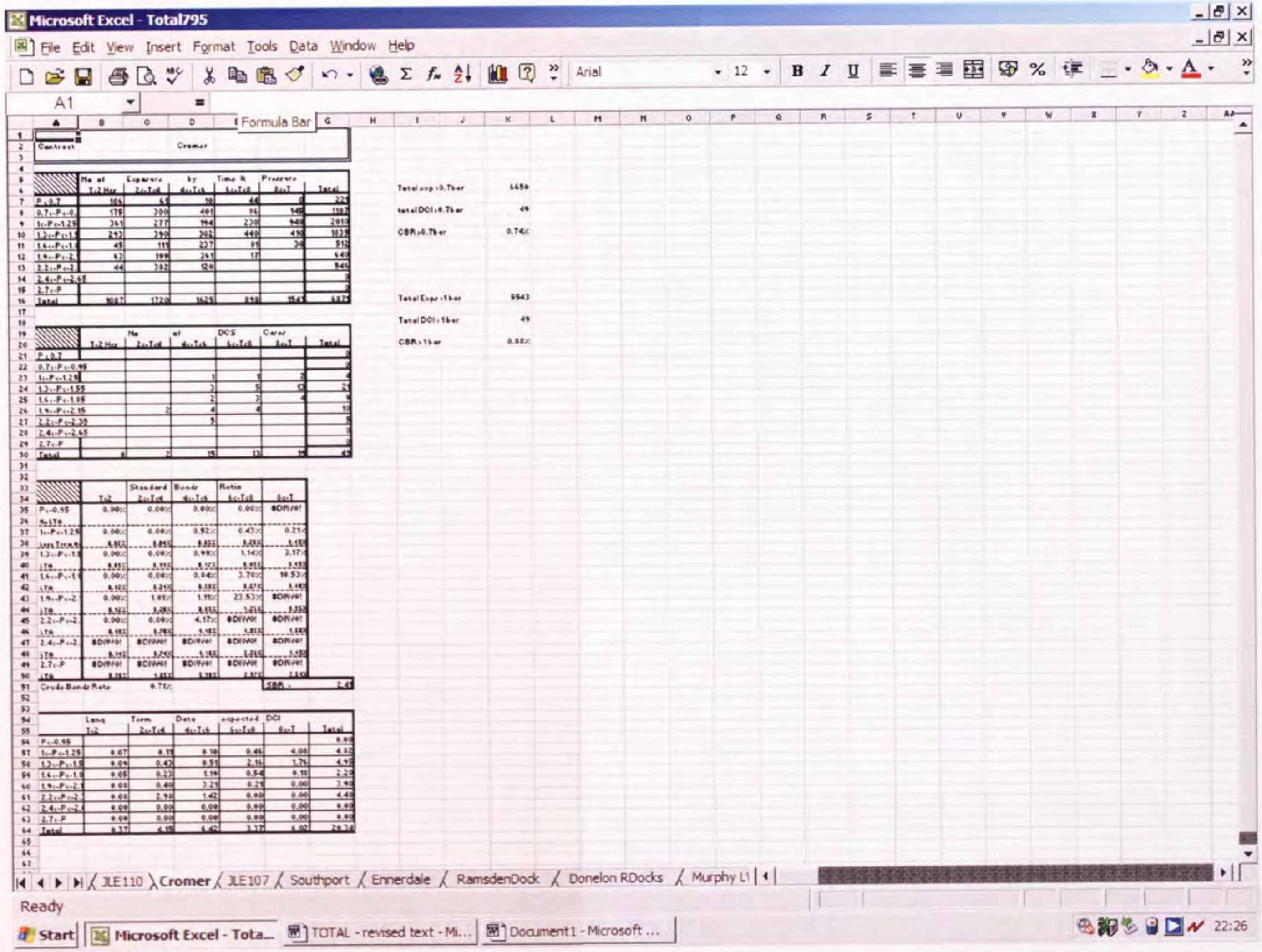


Figure 3.11 – Worksheet for Cromer (Microsoft Excel version) – shown in more detail in Figure A2.1

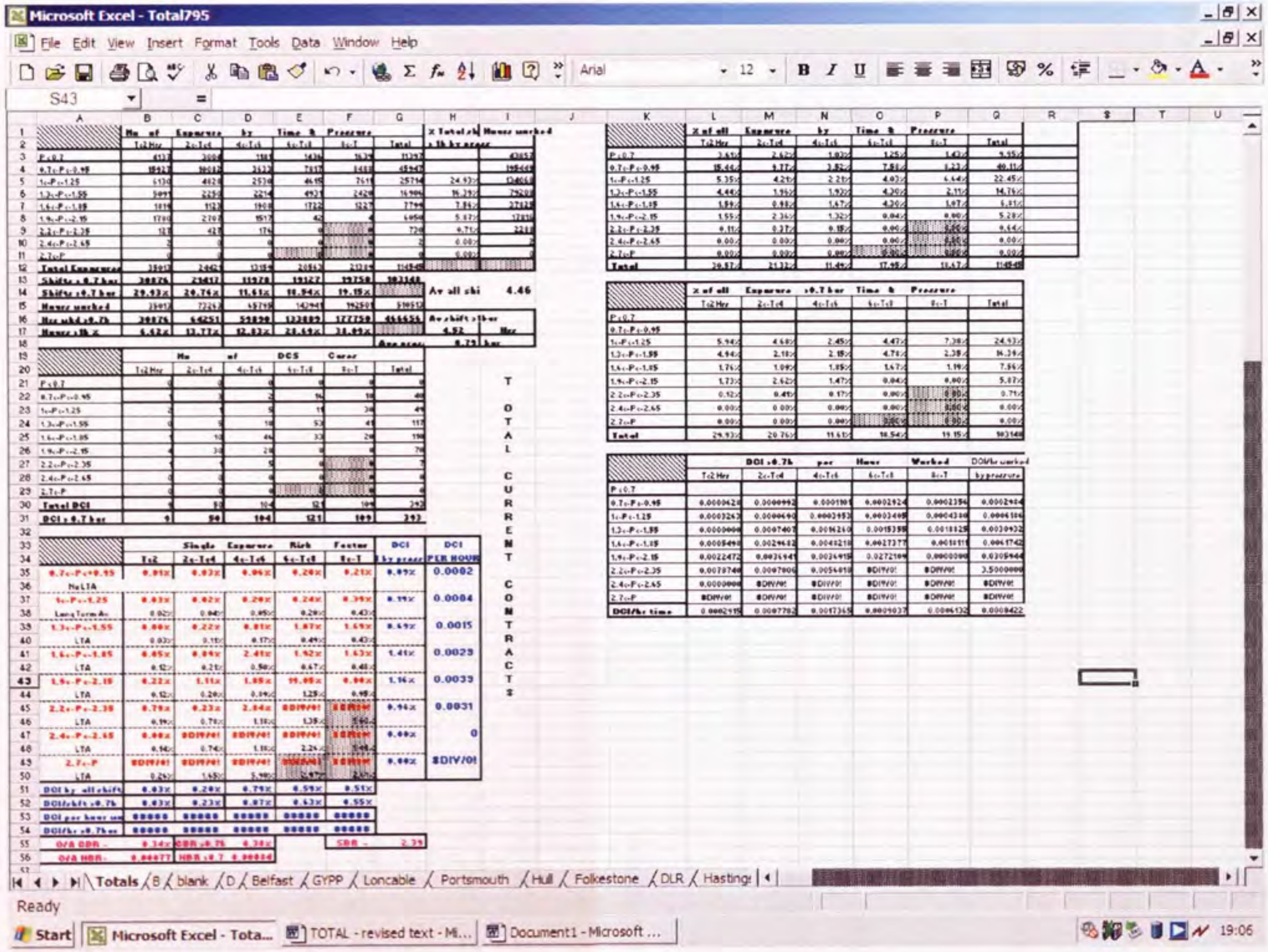


Figure 3.12 - Summary worksheet TOTAL795 (Microsoft Excel version) – shown in more detail in Figure A2.2

3.5.4. Spreadsheet TOTAL – error checks

TOTAL was checked for logical correctness and for arithmetical accuracy. Both checks were performed initially at the single contract worksheet stage and then on compilation of the full spreadsheet.

For the single contract worksheet, logical correctness was checked by scrolling over the tables in the worksheet to ensure consistency in the cell references and formulae. Arithmetical accuracy was checked by inserting double and single digit numbers in the tables of exposure and DCI data respectively. Figures were inserted in rows and columns and the totals checked for accuracy. By using a consistent ratio between the figures for exposure and the number of DCI events, the accuracy of the CBR could easily be checked. Similar principles were adopted to check the SBR calculation. The total number of exposures and DCI events calculated by the worksheet, were also checked against these numbers taken directly from the lock attendant's register. As a further check an order of magnitude check was carried out mentally on the totals.

The full spreadsheet was built up from the individual worksheets for each contract. The structure of each contract worksheet was an electronic copy of the original so no further checking was undertaken. A blank worksheet was always maintained at one end of the sequence of contract worksheets with the worksheet for Lowestoft at the other. Tables of total number of exposures and DCI events in the summary worksheet were built up by summing the respective cells in all contract worksheets between the blank and Lowestoft worksheets. As data for further contracts were added, the relevant worksheets were always inserted within the sequence. This ensured that formulae in the summary worksheet for summing total exposures and DCI always included inserted worksheets.

The structure of the summary worksheet resembled that of the contract worksheets. Total numbers of exposures and DCI events by pressure and time increments were displayed along with a number of additional rows and columns of totals and breakdowns of totals by percentage were included. Logical accuracy was again checked by scrolling over the tables in the summary worksheet to ensure consistency in the cell references and formulae. Arithmetical accuracy was checked when the spreadsheet consisted of only three contract worksheets by inserting double and single digit numbers in the tables of exposure and DCI data respectively. Figures were again inserted in rows and columns and the totals checked for accuracy. By using a consistent ratio between the figures for exposure and DCI, the accuracy of the CBR could easily be checked. As before, similar principles were adopted to check the SBR calculation and an order of magnitude check was carried out mentally. Similar but much less extensive checks were undertaken when TOTAL795 was developed.

Similar checks were applied to the additional tables which were added to the summary worksheet during the study period to calculate DCI/HW.

For the data which were input manually to TOTAL (and TOTAL795), i.e. the number of exposures for each of the 8 (9 for TOTAL795) pressure and 5 time increments, arithmetical accuracy was checked by sorting data for individual cells and calculating row and column totals. This was followed by a number of separate sorts for row and column totals as a sample check. The final check was a comparison between the numbers of exposures in a worksheet and those in the LA's register.

3.5.5. Spreadsheet LIMIT

Spreadsheet LIMIT calculated the increase (or decrease in some cases) in number of exposures, DCI and decompression time for a particular increment in the SBR matrix for a given restriction on exposure period as set out in Section 6.1.5. Implicit within LIMIT was the assumption that no additional labour would have been taken on to undertake the additional exposures but instead the contract duration would have been extended. This assumption was considered reasonable as there is an optimum number of men for any tunnelling operation, above which the deployment of additional men would not result in greater productivity partly due to lack of working space. It was considered reasonable to assume that an extended contract period would entail additional supervision requirements. The amount of additional supervision was assumed to be a function of the proportional increase in the duration of the contract period. The option of not increasing supervision was also considered in the calculation. Figure 3.13 shows the layout of spreadsheet LIMIT for the two modules representing a 4 hour nominal maximum exposure period without and with additional supervision. Jardine (1992) and Jardine *et al* (CIRIA, 1992) proposed a "sample size reduction factor" based on (number of exposures)$^{0.5}$ to account for acclimatisation and self selection on large contracts, when predicting DCI incidence. They do not define "large" but refer to " ….. relatively small projects (less than say 5,000 to 10.000 man decompressions" (CIRIA, 1992; p63). This concept has been ignored in spreadsheet LIMIT.

The calculation was based on average figures derived from the summary worksheet of spreadsheet TOTAL. The calculation was done for each pressure increment in turn.

LIMIT was essentially set up as four interdependent modules, each of which operated in a similar manner on one set of input data. Four modules were required to cover the possible combinations of 4 and 2 hour maximum exposure periods respectively and the conditions with and without an allowance for additional supervisory shifts. The benefit of working within the four modules simultaneously was that data were entered once and copied electronically into the remaining three modules, thus reducing the scope for error. For convenience, spreadsheet LIMIT was set up on the summary worksheet of spreadsheet TOTAL. Cells into which data were entered manually were coloured red for ease of identification (the same convention is adopted in the text below).

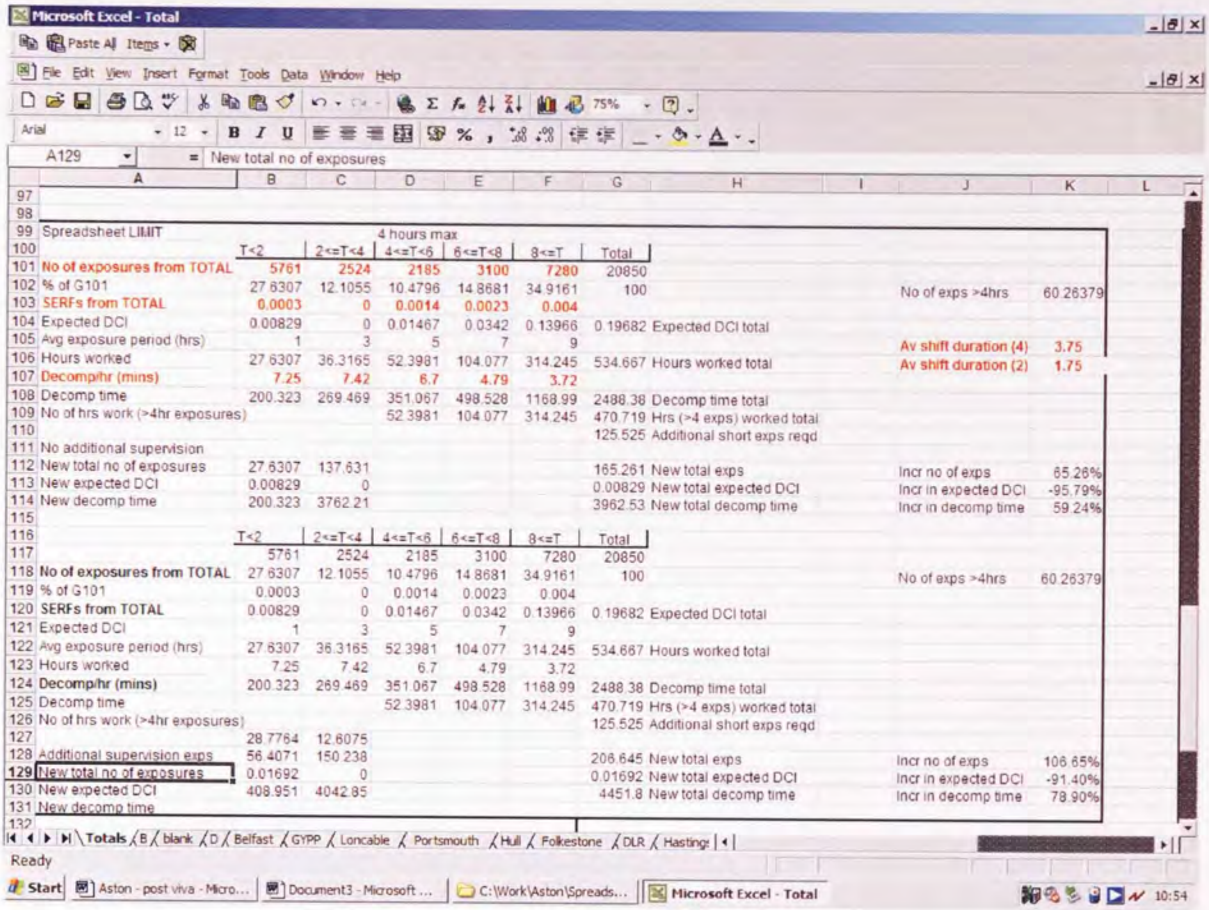
For a given pressure increment in the exposures matrix in Spreadsheet TOTAL (cells B3 – F11), the total number of exposures for each of the five time increments in that pressure increment was entered in LIMIT (cells B101 – F101) and these numbers summed over all increments in cell G101. The percentage, the number of exposures in each of the five time increments represented, of the total number of exposures for that pressure increment, was calculated in cells B102 – F102. The number of exposures of 4 hours and over was calculated in cell K102. From there on, the calculation was based on a per 100 exposures basis for simplicity.

The SERFs, calculated in cells B35 – F49 of the TOTAL summary worksheet, for each of the five time increments at that pressure increment were entered (cells B103 – F103). The expected number of DCI events based on the number of exposures and the corresponding SERF for each time increment was calculated in cells B104 – F104 and summed in cell G104. The mid-increment time for each increment was set up in cells B105 – F105. The number of hours worked in each time increment was calculated from mid-increment time and the number of exposures for the increment (cells B106 – F106) and summed over all increments in cell G106.

The decompression time (in minutes) per hour worked was calculated by a standalone routine and entered manually (cells B107 – F107). Decompression time per hour worked (DCI/HW), for a pressure time increment was taken as the arithmetical average of the decompression times for the four extreme points of the increment – max/min pressure and max/min time and divided by the mid-increment time. The time spent undergoing decompression was calculated for each increment in cells B108 – F108 and summed over all increments in cell G108. The number of hours work arising from exposures of over four hours was copied from cells D106 – F106 to D109 – F109 and summed over the relevant increments in cell G109. The nominal duration of the restricted maximum exposure period was entered manually (cell K105 for a 4 hour nominal maximum exposure period and cell K106 for a 2 hour nominal maximum exposure period). It was recognised that on site, various work-related factors could reduce the nominal period hence LIMIT had the capability of having this figure entered manually. The number of extra exposures (cell G110) was then calculated from cells G109 and K105. The notional number of exposures required with a 4 hour maximum exposure period, to complete the given amount of work was the original number of 0 – 2 hour exposures (copied from cell B106 into cell B112) and the original number of 4 hour exposures (cell C106) plus the additional nominal 4 hour exposures, from cell G110 (cell C112). These were summed in cell G112. As the calculation was initially based on 100 exposures over all time increments, the additional number of exposures required was easily calculated as a percentage (cell K112). The predicted number of DCI events was calculated from the SERFs (cells B103 – C103) and the nominal number of exposures (cells B112 – C112) and any increase/decrease given as a percentage in cell K113. The time spent undergoing decompression was calculated from the number of exposures, mid increment time and decompression time per hour worked (cells B112, B107, B105 etc) and summed in cell G114. The increase/decrease was calculated in cell K114.

Two of the modules included the facility to calculate an additional number of supervisory exposures required to cover the increased number of working exposures. It was assumed that on average, 50% of exposures of under 2 hours duration were by supervisory staff (the other 50% being visitors, short production shifts etc) and that supervision was related to the number of exposures worked not their duration. The additional number of supervisory exposures necessitated by the extended contract duration, was therefore taken as the original number of supervisory exposures increased by the ratio of the additional number of 4 hour exposures to the number of exposures they replaced. This would have been entered in cell B111 however the module described above represented the "without additional supervision" option.

The two modules for a nominal 2 hour limit were set out alongside those described above.



A129 = New total no of exposures

	A	B	C	D	E	F	G	H	I	J	K
97											
98											
99	Spreadsheet LIMIT			4 hours max							
100		T<2	2<=T<4	4<=T<6	6<=T<8	8<=T	Total				
101	**No of exposures from TOTAL**	**5761**	**2524**	**2185**	**3100**	**7280**	20850				
102	% of G101	27.6307	12.1055	10.4796	14.8681	34.9161	100			No of exps >4hrs	60.26379
103	**SERFs from TOTAL**	**0.0003**	**0**	**0.0014**	**0.0023**	**0.004**					
104	Expected DCI	0.00829	0	0.01467	0.0342	0.13966	0.19682	Expected DCI total			
105	Avg exposure period (hrs)	1	3	5	7	9				**Av shift duration (4)**	**3.75**
106	Hours worked	27.6307	36.3165	52.3981	104.077	314.245	534.667	Hours worked total		**Av shift duration (2)**	**1.75**
107	**Decomp/hr (mins)**	**7.25**	**7.42**	**6.7**	**4.79**	**3.72**					
108	Decomp time	200.323	269.469	351.067	498.528	1168.99	2488.38	Decomp time total			
109	No of hrs work (>4hr exposures)			52.3981	104.077	314.245	470.719	Hrs (>4 exps) worked total			
110							125.525	Additional short exps reqd			
111	No additional supervision										
112	New total no of exposures	27.6307	137.631				165.261	New total exps		Incr no of exps	65.26%
113	New expected DCI	0.00829	0				0.00829	New total expected DCI		Incr in expected DCI	-95.79%
114	New decomp time	200.323	3762.21				3962.53	New total decomp time		Incr in decomp time	59.24%
115											
116		T<2	2<=T<4	4<=T<6	6<=T<8	8<=T	Total				
117		5761	2524	2185	3100	7280	20850				
118	**No of exposures from TOTAL**	27.6307	12.1055	10.4796	14.8681	34.9161	100			No of exps >4hrs	60.26379
119	% of G101	0.0003	0	0.0014	0.0023	0.004					
120	**SERFs from TOTAL**	0.00829	0	0.01467	0.0342	0.13966	0.19682	Expected DCI total			
121	Expected DCI	1	3	5	7	9					
122	Avg exposure period (hrs)	27.6307	36.3165	52.3981	104.077	314.245	534.667	Hours worked total			
123	Hours worked	7.25	7.42	6.7	4.79	3.72					
124	**Decomp/hr (mins)**	200.323	269.469	351.067	498.528	1168.99	2488.38	Decomp time total			
125	Decomp time			52.3981	104.077	314.245	470.719	Hrs (>4 exps) worked total			
126	No of hrs work (>4hr exposures)						125.525	Additional short exps reqd			
127		28.7764	12.6075								
128	Additional supervision exps	56.4071	150.238				206.645	New total exps		Incr no of exps	106.65%
129	New total no of exposures	0.01692	0				0.01692	New total expected DCI		Incr in expected DCI	-91.40%
130	New expected DCI	408.951	4042.85				4451.8	New total decomp time		Incr in decomp time	78.90%
131	New decomp time										
132											

Figure 3.13 – Two modules of Spreadsheet LIMIT
(shown in more detail in Figure A3.1)

Spreadsheet LIMIT was checked for logic errors and for arithmetic errors by comparison with manual calculation.

3.5.6. Statistical analysis

Shields and Lee (1986; p 15) noted the difficulty in determining appropriate statistical techniques to use in the analysis of decompression data, as in their opinion the distribution of data did not follow the any of the simple mathematically defined distributions. In tunnelling as in diving, the work being undertaken dictates the exposure pressure, the exposure period and the duration of the project. Shields and Lee decided to present their results descriptively. Given the spread of activity represented by the data in this study and the inconsistency in them, it is considered that findings should be presented as trends rather than as definitive results.

Where statistical techniques were used, these were generally in accordance with the methods described by Kennedy and Neville (1976). A further but less rigorous description of regression analysis was provided by Rumble (1976) whilst reference was made to Hopkins (2000) for information on correlation and regression analysis.

Graphs were plotted using standard Microsoft Excel® graphing functions whilst Excel was also used to calculate the correlation coefficient "r" (Kennedy & Neville, 1976; Ch 16). The significance of regression lines was tested using the "t" value which was calculated manually in accordance with the relevant equations in Kennedy and Neville (1976; Ch 15 and Appendix E). Significance was judged against the statistical tables in Kennedy and Neville. Linear, logarithmic and other analyses were undertaken on data in Sections 5.3.4 and 5.3.7 in accordance with the recommendations of Miller (2006).

To those unfamiliar with the vagaries of compressed air working, a few data points could be considered to be outliers and consideration was given to the rejection of these outliers using techniques such as Chauvinist's criterion. However, the latter is based on the assumption that the data are normally distributed which is not necessarily the case (Shields and Lee, 1986). In addition a judgement would have had to be made on whether and to what extent to reject the exposures associated with such a DCI event.

3.6. Quality of raw data

One important aspect of a retrospective study such as this, is that the data on which the study is based were recorded before the study began. Therefore it may not be possible to acquire more data or to improve the quality of the data acquisition process. Likewise it is not possible to design the data acquisition process to meet the study objectives. In a retrospective study, the objectives and methodology must be chosen to make best use of the available data.

This contrasts poorly with diving DCI research which strives to use but does not always succeed in using high quality data. Lambertsen *et al* (1999; p10) noted that "even large numbers of exposures lose their importance" in the absence of high quality laboratory and trials data.

It may however be possible to improve the quality of the data by identifying and rectifying errors and inconsistencies but this can only be done where the researcher has detailed knowledge of the subject. At this point the observer becomes a participant – see Section 1.2.3.

This study involved three categories of data - exposures, men and DCI. The primary source of data was the HSE compressed air exposure database. Good data quality is obviously critical to the outcome of any analysis. In this case, good data quality meant that there should be no missing data, no inconsistencies in the data and the data could easily be filtered and sorted electronically. The legibility of the paper records was obviously a factor in determining the quality of the data which had been converted into electronic format. However, nothing in this study could be done to influence that. Figure 3.2 shows a legible and properly completed page from a lock attendant's register.

As will be described in detail in Section 3.6 and Appendix 4, poor data quality was found in each category of data. Because of the amount of poor quality data which was identified, a decision had to be made either to eliminate poor quality data from the study or to attempt to improve data quality. To have eliminated poor quality data, would have significantly reduced the data available for analysis and consequently the value of the study. For example, data excluded on account of their poor quality, would have included the entire Southport contract, which alone represented around 8% of all exposure records in the HSE database. It was therefore decided to attempt to improve data quality using the knowledge and experience of compressed air working practice available to the author (see Appendix 4). This became an important part of the data acquisition phase of the study. The impact of poor data quality on the accuracy of the results is discussed further in Section 4.5.

3.6.1. Exposure data - quality checks

From discussions with Atkins about their contract, there had been noticeable variations between contracts in data quality (probably more precisely, between MLAs on contracts) i.e. completeness, clarity and legibility of the paper records and this inevitably gave rise to inconsistencies. Some paper records had been patently incorrect or incomplete when studied in detail. Atkins used computerised data checking routines to identify potentially inconsistent records as a quality assurance measure within their contract, but to minimise cost, Atkins had been instructed by HSE not to correct these inconsistencies or to check the electronic version against the paper version of each record. The computer check highlighted apparent inconsistencies, some of which resulted from accepted industry practice. For example, a fitter doing a quick repair towards the end of a shift would have decompressed with the miners. The computer check would have identified his decompression time as being excessive for his exposure, but such a practice is normal in the industry to optimise the use of the manlock.

A number of checks were made on the HSE data acquisition software by its creators before it was released, to confirm its performance was satisfactory. The routines themselves were fairly straightforward and incorporated some self-checking procedures. One of these was to ensure that exposures on the night shift overrunning midnight were correctly calculated and were allocated against the date on which compression began. In industry practice, the working day is normally taken as a 24-hour period starting from 06:00 or 07:00 hours.

On the more recent contracts, the MLA(s) usually input data directly on site thus forming the master record for the contract. The opportunities for introducing inconsistencies were limited with the main source of inconsistency being from keyboard errors.

Inconsistencies in determining exposure pressure would generally have been unlikely as on most tunnel projects, the pressure changes little from day to day. The accuracy of the pressure gauges could not be checked retrospectively. However, the Guidance (Paragraph 102) sets out their expected performance standard. HSE inspection experience indicated that site calibration checks tended to be carried out in accordance with the requirements of the Guidance.

Times for entry to or exit from compressed air, were normally obtained on site from a simple clock or from a digital stopwatch. Inconsistencies were considered to be relatively uncommon due to simple nature of the recording task and the routine nature of the exposures.

The miners on a shift normally enter and leave the working chamber together. They usually work a full shift, which is of approximately equal length each day, over the contract period. This gives a consistency to recording shift length. Records for those who work part shifts such as fitters and electricians, were perhaps more likely to contain arithmetical errors.

Other checks included a comparison of the exposure period, calculated as the difference between the time of start of compression and the time of start of decompression, with that input directly; a check that exposure pressure had not been omitted and a check that the times recorded for start of compression, and start of decompression were logically correct i.e. non-zero, decompression started after compression, the numerical values were in the correct format *viz* hh:mm and numerically less than 24:00. In all these cases Atkins had been instructed that the figures were to be transcribed as written. Comment on checks relating to the decompression table used, is made in Section 3.6.6.

One of the simplest alterations to the data which was made during the early part of the project was the substitution of a colon for a semicolon, dividing the hours and minutes. This facilitated computer sifting of the data through ensuring consistency in its format. Another alteration of similar simplicity concerned short exposures of under one hour duration. Those which had been entered without leading zeros were changed accordingly i.e. 35 altered to 00:35.

Times were not always entered correctly on a 24-hour clock. This was usually obvious from a comparison of entry and exit times as well as a comparison with others on the same shift. There were a few errors of incorrect use of the twenty-four hour clock in which times in the hour following midnight were recorded as 24:xx.

An error by Atkins' in database construction had meant that, for some contracts, date and time were input to text fields and not date and time fields as would have been expected. This made sorting virtually impossible and Atkins altered these databases to store the date correctly as a date field and to express the exposure time as a number (of minutes) in a numeric field.

Some missing exposure data could be deduced from other data for a contract. For instance, pressure should be the same for all workers exposed together on a given shift which allowed reasonably accurately estimates of missing pressure data to be made. Similarly, the whole gang normally enters and leaves the working chamber together so this could be used in appropriate circumstances to estimate missing exposure times. Fitters, electricians and supervisory staff may enter the workings mid-shift but stage decompression, if required, would normally be done with the miners.

A further description of the principles used to improve data quality is given in Section 5.4.4; a detailed description of the work done to improve the data quality on the Lowestoft contract is given in Section 3.6.7 with that relating to the remainder of the contracts being set out in Appendix 4.

3.6.2. Effect of metrication on exposure data

Metric units have been used throughout the text however a significant amount of information from the literature and much of the data had originally been recorded in imperial units. Both had to be converted to metric equivalents (see Section 1.4.2). As with other aspects of the use of units of pressure, this gave rise to problems (see Section 1.4).

Evans (CIRIA, 1992) in his SBR calculation used discontinuous pressure increments usually of 0.2 bar (3 psi); 0.95 – 1.15 bar (14 – 17 psi), 1.25 – 1.45 bar (18 – 21 psi) etc. Conversion of his pressure increments in imperial units, to pressure increments in metric units introduced some inconsistency (see Table 1.1). Some LAs recorded pressures in fractions of psi, some of which fell between Evans' increment boundaries.

A further inconsistency arose in the conversion of the Blackpool tables from imperial units to metric units. The threshold pressure when the tables were introduced, was 0.95 bar (14 psi) but became 1 bar on metrication. This change introduced some anomalies over which exposures required/received stage decompression and which did not.

Taking all the above together, it is not possible to metricate data originally recorded in imperial units and be consistent with Table 1.1 and industry decompression practice. SBRs calculated by Evans are done so from imperial units and accordingly are not totally consistent with SBRs for current data.

3.6.3. Data on the men exposed

The basic search to identify individual men and their exposure history was by name or works/tally number within individual contract databases. This was supplemented by searches using the unique record/duplicate record routines within the software package. On every contract a significant number of men had fewer than five exposures each. As the data processing effort was comparable for one or one hundred exposures per man, searching was a time consuming process. Numerous inconsistencies were discovered which hindered searching and increased the time required to construct the database MANLIST.

Tunnel mining in the UK is an occupation in which the workforce tends to come from backgrounds of limited geographical and ethnic diversity and one in which extended family members occasionally work together. Consequently similar or identical names for different individuals are not uncommon and further complicated the construction of MANLIST. The use or otherwise of a middle initial, names with an apostrophe (e.g. O'Donnell), more than one man on a contract with the same surname and spelling, variations in spelling a name (Doherty and Docherty) were all added complications. It became something of a skill to identify the unique group of two to four letters in a name on which to search, to find all variations for a single man in one search. In many cases a parallel search on tally number was required for confirmation.

A very common source of data inconsistency, was the number of variants of a single name in the raw data. For example a (fictitious) William Smith could appear as William Smith, Willie Smith, W. Smith, W Smith, Bill Smith, B Smith, B. Smith, Billy Smith etc not to mention any mis-spelling of Smith. Give him a middle name and the number of combinations or variations increased. All would appear in a computer search for unique records as separate individuals, however in reality the variations were due to inconsistencies by the lock attendant in recording the name of one person. No doubt the transcription process generated some of the variants because of poor handwriting and the faint nature of the paper originals. Records in which the initials/Christian name and surname were listed in separate fields were much easier to search in that respect.

Because of the numerous inconsistencies in the data, it was not always possible to allocate all the exposures against identifiable individuals. It was therefore decided that an acceptable tolerance would be for the sum of the number of exposures for each man on a contract, to differ from the number of exposures for that contract in TOTAL, by not more than 1% or 1 exposure per man. Whilst this target was not always possible to achieve because of difficulties in identifying individuals and their exposure history, overall the sum of exposures for each of the 2387 men identified, totalled 115418 against 115740 exposures in TOTAL for the same contracts. For the data as a whole, this was well within the target of 1 exposure per man or 1% of contract exposures.

Checks by works or tally numbers were invaluable in overcoming inconsistencies in name but such numbers were not allocated on all contracts. One annoying inconsistency in the allocation of tally numbers was found on some contracts where the tally number of someone who ceased work, was reassigned to a new starter. This practice saved the CAC from having to acquire additional metal tallies.

When doubts arose if exposures were for one man or for two men with similar names, occupation was used as a further check. Checks on exposure date and time were also used to confirm whether one man or two men were involved. On one contract (LWRM), there were 5 separate initials associated with one surname and two occupations in 47 exposures. Examination of the exposure dates showed that apart from on one date, the exposures fell into a pattern of five consecutive days exposure followed by two days without exposure. This was considered to represent just one individual. Later, examination of medical data (see reference to Colvin, 2003 in Section 3.6.4) confirmed this and revealed that the same man had experienced a DCI event which had not been recorded in the LA's register.

A further characteristic which was occasionally used to identify or separate men was continuity in their employment by a particular contractor. It is a feature of the industry that recruitment is often on the basis of personal knowledge, preference or recommendation. Consequently there was a small number men who worked on more than one contract but with the same contractor e.g. Donelon or Johnston.

A very few men appeared to have had two separate series of exposures on a contract as if they had ceased work then restarted later. This was consistent with experience and in those circumstances the men were considered to have had a single but split exposure history.

Virtually all the above problems were overcome on more recent contracts, by the use of HSE software (see Section 3.3.2). The use of NI number when available, should have been a unique identifier however inconsistencies and missing data occurred with NI numbers also.

The quality of data on occupation varied between contracts. Normally it was always possible to identify if a man was a manual/skilled operative as opposed to a supervisor although his precise occupation – miner's labourer, miner or leading miner - was not always clear. On Ramsden Dock, the term "compressed air worker" covered all non-supervisory workers. The use of these data necessarily reduced the accuracy of the results in Section 4.5.5, however the section was more for interest than of major importance.

Additional data manipulation utilising MANLIST was done in the part of the study relating to the identification of men who worked on more than one contract and experienced DCI on more than one contract, and is reported in Section 5.4.5.

3.6.4. DCI data

Few inconsistencies were expected in DCI records. DCI was normally but not always, recorded in the remarks column of the LA's register and it should have been recorded in the CMA's clinical notes. Although DCI is a reportable industrial disease under RIDDOR, past experience showed that HSE could not locate the relevant reports and was therefore not a potential source of data.

No record of DCI could be found in the register for the Royal Docks Phase 2 contract, and a check with the CMA was unsuccessful in clarifying the situation as his records had been archived on his retirement and were not readily available. Additionally, discussions with industry contacts did not provide a conclusive outcome. Although it could have been assumed that no DCI had occurred, the pattern of pressure and exposure periods made this assumption unsafe, and that contract has been excluded from most aspects of the study.

Occasionally there was inconsistency over the date of the exposure which resulted in DCI. Normally this occurred following a nightshift exposure for which the resulting DCI event was treated on the day following the start of the shift.

There was one case of DCI in a Lock Attendant's register which did not appear in the CMA's records for the site and the assumption was made that the LA Register was correct.

It proved possible to identify and resolve inconsistencies in the DCI data through collaboration with Dr A. R. Colvin. As part of his research, Colvin (2003) had obtained the CMAs' clinical records of men identified in this study as experiencing DCI. From his work it was possible to confirm details of the DCI events relevant to this study. A small number of discrepancies between the LA's records and those of the CMA were identified and apart from the DCI event noted above, it was generally taken that the CMAs' records formed the more complete record. Overall this affected fewer than 1% of the DCI events but provided a useful check on the completeness of the records of DCI events. It was not an issue which significantly affected the results.

There was also a possibility of mis-diagnosis of DCI. It has long been industry belief that speed of recompression was of the essence, with the result that MLAs often diagnosed and treated DCI before the attendance of the CMA on site. It is HSE policy that if there was any doubt over whether anyone was suffering DCI, they should be treated as if they had experienced DCI. It is also HSE policy that any treatment of suspected DCI constituted a reportable DCI event.

3.6.5. Under reporting of DCI

The extent of under reporting of DCI by tunnel workers is unknown. There are, however, numerous apocryphal stories of self treatment of DCI using pain killers and alcohol to make the pain bearable until the return to pressure at the start of the following working shift gave relief. Andersen (2002) cited 4 examples of untreated DCI in a recent Danish study. In each case workers returned to compressed air on successive days in unsuccessful attempts to resolve the problem without undergoing therapeutic recompression.

Reporting levels on recent contracts were probably higher than on earlier ones due to better education of the workforce and closer supervision from more experienced lock attendants. Nevertheless it is generally accepted that not all DCI is reported. HSE has no information on the level of reporting and definitive research into this aspect of UK compressed air working has never been undertaken. Accordingly the assumption was made that all DCI was reported. For recent contracts this assumption may well be reasonable and is in line with current HSE policy.

Having thought that the problem of under reporting had largely been overcome, during the hyperbaric trials at the National Hyperbaric Centre, Aberdeen (Lamont *et al*, 2002), one case of unreported Type 1 DCS was detected by medical staff overseeing the trials.

Kindwall (1996), a long term advocate for better understanding of the extent of unreported DCI, suggested that anonymous reporting of symptoms would give a better indication of the true extent of tunnelling DCI incidence.

Shields and Lee (1986) in their offshore diving study were similarly unable to estimate the level of under reporting of DCI by divers.

3.6.6. Ad-hoc safety factors in decompression

The application of ad-hoc safety factors in decompression (see Section 2.2.6) was another issue, which could affect the results of a study of this type. The magnitude of the factor applied could vary with pressure, lock attendant and CMA. Such practices make detailed analysis of DCI incidence more difficult, however their overall effect on DCI rates may be limited (Flook, 1998). Additionally, they may influence the calculated incidence of DCI but they do not invalidate that calculation. As they represent accepted industry practice, the incidence of DCI which is thus calculated should be representative of average industry values. The considerable extent to which such factors are used can be seen from Appendix 4. The practice was identified by comparing the decompression details in the LA's register with the Blackpool Tables. Atkins undertook this check electronically for the records they transposed.

In considering the overall effect of safety factors on the study, it was concluded that it would be slight and would tend to reduce the incidence of DCI slightly. Overall it was decided to ignore safety factors except where they are specifically considered in Section 6.1.1.

3.6.7. Raw data quality

Considerable work was done on the data from many contracts to improve their quality. An account of the work done on the Lowestoft contact is set out below. Lowestoft was one of the earliest contracts in the study chronologically and was also one of the first to be subject to data quality checking and improvement.

The raw data came from the contractor's paper records and was converted to electronic format by Atkins. The contract covered 1026 exposures of which only 294 records were identified by Atkins' computer check as being free of inconsistencies. Some records had multiple inconsistencies.

679 exposure records were identified in which the recorded decompression did not match the theoretical decompression requirements for the exposures undergone. This illustrates the points made in Section 3.6.6 above. In this case, the *ad-hoc* safety factor was decompression to a table, two tables higher than required, for exposures of over 2 hours at

pressures of 1.725 bar (25 psi) and above. Only a small number of the inconsistencies appear to have been due to numerical errors in the original data.

Another practice which showed as a decompression inconsistency, was decompression following a person's 2nd or 3rd exposure for the day. In these circumstances, decompression should be based on the individual's total exposure for the shift, not on the exposure immediately preceding that decompression (see Guidance Paragraph 175).

Inconsistencies in 45 records of exposure period were identified by the computer check. On some contracts this type of inconsistency could be overcome by using the work patterns of fellow shift workers to determine the inconsistent or missing times. Here however, it was considered that the inconsistency was probably due to arithmetical error. A slight error in exposure time often does not make any difference when the analysis is based on 2-hour time increments.

15 records with missing exposure pressures were identified. By referring to the exposure pressures for others on the same shift, it was possible to determine 14 of the 15 missing pressures.

675 records were identified in which recorded exposure times were incompatible with the arithmetical difference between times of start of compression and start of decompression in the paper records. It was discovered that the incompatibility had arisen from an incorrect understanding on site, of the definition of exposure period which had wrongly (but understandably) been calculated as the period from the start of compression to the end of decant decompression. All records except for 5 for which data were missing, were corrected electronically.

Of the 1026 exposures on the contract, 649 exposures were followed by a decant decompression. The remaining 377 exposures were followed by a normal decompression when the main lock was available for the relatively short decompressions required, or the exposure did not require stage decompression. Typically the exposures not requiring decompression were of short duration, mainly under 2 hours and involved fitters, the pit boss, the RE staff, an HSE Inspector etc.

It was estimated that from having started with inconsistencies in around 71% of the exposure records, it was possible to resolve the inconsistencies in all but 5% of the records. This justified the decision to attempt to improve data quality rather than to reject inconsistent data out of hand (see Introduction to this Chapter). Whilst the computer check identified data inconsistencies, it required human intervention to determine the response to these inconsistencies.

In deriving the MANLIST data for this contract, 35 individuals were identified who had been exposed to compressed air, however a computer search had identified 75 name variations, which appeared at least twice in the contract records. Unique entries were not counted. As an indication of the difficulty in calculating the number of exposures attributable to a single man, a check on one individual who had undergone 89 exposures on the contract, showed there were 13 variations for his name in the records. Of the 13 variations, 8 appeared at least twice and 5 appeared once. With two forenames and an apostrophe in the surname, he typified the problems identified in Section 3.6.3.

Significant inconsistencies were identified in the DCI data for this contract. One case of DCI had probably been attributed to the wrong person however this was identified and rectified following a phone call to one of the persons concerned. It was subsequently discovered that a further four cases of DCI had been omitted from the lock attendant's records. This discovery was the result of the chance finding of an MLA's hand written notes, in the records of another contract being undertaken by the same firm. That MLA had been asked to carry out a retrospective review of the DCI events at Lowestoft.

3.6.8. Allowance for decanting in the analysis

Decanting appeared intermittently in the exposure records for many of the contracts in the study, undertaken prior to 1996. Evans (CIRIA, 1992) found that decanting increased the average incidence of DCI by over 50%.

However it was considered that the variation in DCI incidence for individual contracts, as measured by the CBR, was sufficiently great and the numbers of decant decompressions sufficiently small that decanting could be treated as yet another variation in industry practice similar to the use of *ad-hoc* safety factors, and consequently it was ignored in the calculation of overall average DCI incidence for the period covered by the study.

3.7. Concluding remarks

The acquisition of good quality raw data is obviously fundamental to any study. Where the researcher generates that data, the researcher can control its quality. Where the researcher is dependent for data, retrospectively on the actions of others, the researcher can work only with the data which is available and must make appropriate allowances for any shortcomings in data quality. This caveat is considered to be particularly relevant to studies of this type and topic.

Efforts were made to avoid subjective bias between low and high pressure contracts when acquiring data and it is considered that all that reasonably could have been done, was done to acquire a spread of data. Importantly, the majority of DCI events occurred over or around 1 bar and it is considered that all available data for contracts on which DCI occurred within the study period has been acquired.

Extensive information has been given on how the available data were manipulated to overcome the numerous and varied inconsistencies in them and this information provides evidence to support the decision to introduce an electronic data recording system.

Throughout this section the word "inconsistency" has deliberately been used in preference to "error" in the descriptions of the raw data. Clearly some were "errors" because of the human involvement in the record keeping process. However there was an explanation, within the norms of industry practice, for many of the deviations from strict adherence to the approved decompression regime. Although these inconsistencies hindered electronic data manipulation and were identified as errors by computer checking, most could be resolved with human intervention.

Some inconsistencies had been deliberately introduced through the use of *ad hoc* safety factors. This has been discussed also. Taken overall, the data represent current industry practice as opposed to theoretical practice. By any measure, the quality of the data used in this study is far removed from that which would arise from laboratory or hyperbaric trials. This must be borne in mind in the interpretation of the results.

Chapter 4. The incidence of DCI

Unlike exposure to other physical agents, such as noise or vibration, which give rise to occupational ill health and the exposure to which is regulated by real time monitoring against control limits, the effectiveness of the control of exposure to compressed air has traditionally been measured by retrospective studies of the incidence of acute DCI. Such studies have been undertaken for individual contracts, as for Auckland Bridge (Rose, 1962) or for a number of contracts spanning a period of time, as by Evans (CIRIA, 1992). The work reported in this Chapter falls into the latter category. The data described in Section 4.1 were used also in Chapters 5 and 6.

4.1. Data available for study

In total for air-only decompression, records of 120388 exposures were collected from 32 contracts dating from 1984. From these records, 2387 names were listed on the lock attendant's registers of whom 2331 had undergone one or more exposures to compressed air. As some men had worked on more than one contract, the number of individuals exposed to compressed air was less than this (see Section 5.4). Not all contracts provided complete records. Exposure records were not available for Bideford, DCI records could not be established for Royal Docks Phase 2 and a small proportion of the records for Fylde Coast and LWRM were missing. The records for Pepperhill, Billingham and Kelvin Valley did not list men and were not sufficiently complete to allow subdivision above and below 0.7 bar. A summary of the available records is shown in Table 4.1. The column totals in that table are for information only not calculation. The use of data from CTRL 320, which was completed in 2004 using oxygen decompression, was restricted to Section 6.2.

The numbers above represent maxima. In practice records which were partially complete had to be removed from some of the analyses however in the sections which follow, the largest possible number of records have been used in each case. A breakdown of the exposure records, excluding Bideford and Royal Docks Phase 2 contracts, aggregated by pressure and time increment is shown in Table 4.2. This table reflects what was established practice, by not dividing exposures below 1 bar into different pressure increments. However as DCI had been recorded below 1 bar, it was considered necessary to subdivide exposures below 1.0 bar into two increments *viz.* 0.7 – 0.95 bar and <0.7 bar respectively.

Contract	Total No of Exposures	No of exps (full records <1.0 bar)	Total No of DCI events	No of DCI events (full records)
Belfast	70	70	0	0
Gt. Yarmouth Power Project	150	150	4	4
London Cable Tunnel	354	354	0	0
Portsmouth	2273	2273	0	0
Hull	450	450	7	7
Folkestone	87	87	0	0
Docklands Light Railway	1813	1813	0	0
Hastings	1291	1291	4	4
Bacton	2909	2909	3	3
Pepperhill	2083	0	0	0
Billingham	481	0	0	0
Swansea 6	14969	14969	0	0
Weston super Mare	7483	7483	5	5
Swansea 5	8155	8155	28	28
Kelvin Valley	2120	0	0	0
Swanage	5305	5305	17	17
Fylde Coast (245 missing exp records)	1115	1115	12	7
Jubilee Line Extension 105	19681	19681	60	60
Jubilee Line Extension 110	2449	2449	28	28
Cromer	6871	6871	49	49
Jubilee Line Extension 107	568	568	0	0
Southport	10407	10407	8	8
Ennerdale	2844	2844	10	10
Ramsden Dock	8826	8826	43	43
Royal Docks Ph 9	3309	3309	27	27
Royal Docks Ph 2 (excluded from much of the analysis)	1159	0	no DCI data	no DCI data
London Water Ring Main (missing exposure records)	3082	3082	42	40
Rochdale	791	791	0	0
Coppermills	660	660	0	0
North Woolwich	7617	7617	35	35
Lowestoft	1016	1016	18	18
Bideford (excluded from part of the analysis)	no exposure data	no exposure data	28	0
Totals	**120388**	**114545**	**428**	**393**

Table 4.1 – Summary of air-only decompression data by contract

Pressure / Time	Exposures by Pressure and Time					
	0 - <2	**2 - <4**	**4 - <6**	**6 - <8**	**≥8 hrs**	**Total by pressure**
<= 0.95 bar	21198	13529	7705	9464	10132	62028
1.0 – 1.25	6130	4828	2530	4615	7611	25714
1.3 – 1.55	5091	2250	2214	4931	2420	16906
1.6 – 1.85	1819	1123	1908	1722	1227	7799
1.9 – 2.15	1780	2707	1517	42	4	6050
2.2 – 2.35	127	427	176	0	▨	730
2.4 – 2.7	2	0	0	0	▨	2
>2.7	0	0	0	▨	▨	0
Total by time	36147	24864	16050	20774	21394	**119229**

Table 4.2 – Breakdown of exposures by pressure and time

Table 4.3 includes this sub-division however the records for three low pressure contracts, Pepperhill, Billingham and Kelvin Valley, had to be excluded as they lacked sufficiently detailed information to allow the subdivision to be undertaken.

Pressure / Time	Exposures by Pressure and Time					
	0 – <2	**2 – <4**	**4 – <6**	**6 – <8**	**≥8 hrs**	**Total by pressure**
< 0.7 bar	4137	3004	1181	1436	1639	11397
0.7 – 0.95	15927	10082	3633	7817	8488	45947
1.0 – 1.25	6130	4828	2530	4615	7611	25714
1.3 – 1.55	5091	2250	2214	4931	2420	16906
1.6 – 1.85	1819	1123	1908	1722	1227	7799
1.9 – 2.15	1780	2707	1517	42	4	6050
2.2 – 2.35	127	427	176	0	▨	730
2.4 – 2.7	2	0	0	0	▨	2
>2.7	0	0	0	▨	▨	0
Total by time	35103	24421	13159	20563	21389	**114545**

Table 4.3 – Breakdown of exposures by pressure and time – subdivided below 1 bar

(full exposure records only)

▨ **Indicates exposures not permitted under the Blackpool Tables.**

The distribution of the number of exposures undergone per man is shown in Figure 4.1. Figure 4.1 was derived by sorting the number of exposures each man underwent into descending numerical order and graphing the result. The "Man No" is of no consequence, being merely the position in the sort of a particular number of exposures. For the 2331 men exposed, the number of exposures per man ranged from 457 to 1, with an average of 49.5 and median of 25.

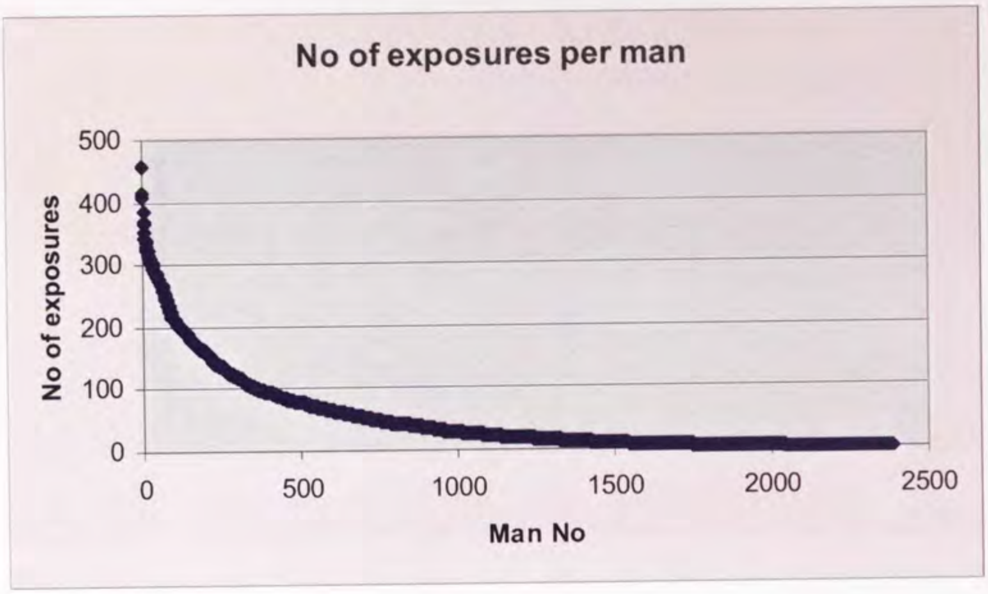


Figure 4.1 – Distribution of number of exposures per man
(see also column 6 of Table 5.1)

Pressure / Time	DCI by Pressure and Time					
	0 – <2	2 – <4	4 – <6	6 - <8	⩾8 hrs	Total by pressure
<= 0.95 bar	1	3	2	16	18	40
1.0 - 1.25	4	1	5	11	29	50
1.3 - 1.55	1	5	19	56	42	123
1.6 - 1.85	3	10	47	46	21	127
1.9 - 2.15	4	30	31	14	0	79
2.2 - 2.35	1	1	7	0	▨	9
2.4 - 2.7	0	0	0	0	▨	0
>2.7	0	0	0	▨	▨	0
Total by time	14	50	111	143	110	**428**

Table 4.4 – Breakdown of DCI events by pressure and time

Records of 428 cases of DCI were identified from all contracts including Bideford but not Royal Docks Phase 2, and their breakdown by pressure and exposure period is shown in Table 4.4. No DCI occurred below 0.7 bar. A plot of the DCI events by pressure, time and type is shown in Figure 4.2. As records of the exposures resulting in 35 of the DCI events were incomplete, in particular 28 from Bideford and a further 7 from Fylde and LWRM, these DCI events were included in Figure 4.2 but excluded from calculations of DCI incidence. The resulting breakdown of DCI events by pressure and exposure period, subdivided at 0.7 bar, is shown in Table 4.5.

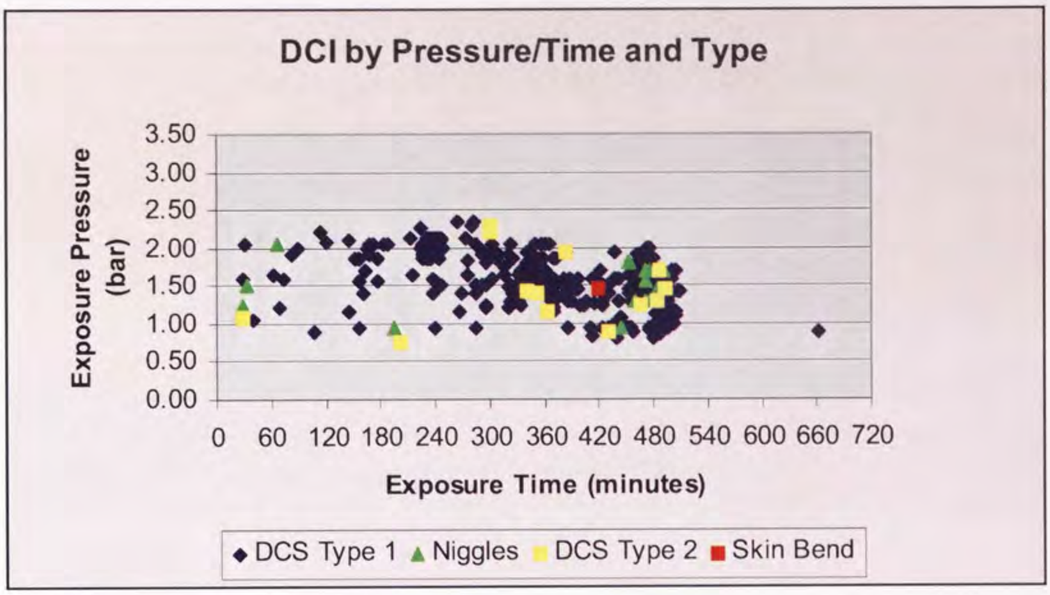


Figure 4.2 - DCI events by pressure/time and type

Pressure / Time	DCI by Pressure and Time					
	0 – <2	**2 – <4**	**4 – <6**	**6 - <8**	**≥8 hrs**	**Total by pressure**
< 0.7 bar	0	0	0	0	0	0
0.7 – 0.95	1	3	2	16	18	40
1.0 - 1.25	2	1	5	11	29	48
1.3 - 1.55	0	5	18	53	41	117
1.6 - 1.85	1	10	47	33	20	111
1.9 - 2.15	4	30	28	8	0	70
2.2 - 2.35	1	1	5	0	▨	7
2.4 - 2.7	0	0	0	0	▨	0
>2.7	0	0	0	▨	▨	0
Total by time	9	50	105	121	108	**393**

Table 4.5 – Breakdown of DCI events by pressure and time - subdivided below 1 bar

(full exposure records only)

▨ **Indicates exposures not permitted under the Blackpool Tables.**

The equivalent to Tables 4.2 and 4.4 but for Evans' data are set out as Tables 4.6 and 4.7. They do not cover decant exposures. These tables aggregate exposures followed by a normal decompression and are those chosen by HSE to form the baseline data on which SBRs are calculated (Guidance Table 1). SERFs based on these exposures are given in Table 4.18.

Pressure	**Exposures by Pressure and Time**					
Time	**0 - <2**	**2 - <4**	**4 - <6**	**6 - <8**	**⩾8 hrs**	**Total by pressure**
⩽0.95 bar	10667	3846	3924	10674	3817	32928
1.0 – 1.25	15348	4762	6408	7946	8295	42975
1.3 – 1.55	11946	5344	6499	6766	16831	47386
1.6 – 1.85	18882	12434	11330	15077	84543	142266
1.9 – 2.15	13214	7947	9407	15084	48901	94553
2.2 – 2.35	8311	2827	4835	5718	16757	38448
2.4 – 2.7	6972	1487	2792	2260	5986	19497
>2.7	1137	303	373	337	2180	4330
Total by time	86477	38950	45568	63862	187310	**422167**
Exposures ⩾1 bar	75810	35104	41644	53188	183493	**389239**

Table 4.6 – Breakdown of exposures by pressure and time – normal decompression (after Evans (CIRIA, 1992))

Pressure	**DCI by Pressure and Time**					
Time	**0 – <2**	**2 – <4**	**4 – <6**	**6 – <8**	**⩾8 hrs**	**Total by pressure**
⩽0.95 bar	3	0	0	0	1	4
1.0 – 1.25	3	2	3	16	36	60
1.3 – 1.55	3	6	11	33	73	126
1.6 – 1.85	22	26	57	101	404	610
1.9 – 2.15	16	16	84	188	464	768
2.2 – 2.35	16	22	57	77	268	440
2.4 – 2.7	10	11	33	51	89	194
>2.7	3	5	22	10	57	97
Total by time	76	88	267	476	1392	**2299**
DCI (exposures ⩾1 bar)	73	88	267	476	1391	**2295**

Table 4.7 – Breakdown of DCI by pressure and time – normal decompression (after Evans (CIRIA, 1992))

4.2. Objectives

The objectives for this chapter were to consider ways in which the incidence of acute DCI in tunnelling could be measured, to quantify its incidence using these measures, to assess the effect of poor data quality on the results, to compare the current incidence of DCI in the UK with published data on DCI incidence and to consider the respective incidence of Types 1 and 2 DCS. In all sections which follow, any reference to DCI is implicitly a reference to acute DCI.

The specific questions to be answered and issues to be addressed were:-

- what measures of DCI could be identified?
- which could best be used for compressed air tunnelling?
- what was the current incidence of DCI by these measures?
- how were the results affected by data quality?
- how did that incidence compare with other hyperbaric experience?
- what were the relative proportions of Types 1 and 2 DCS?
- what inferences or conclusions could be drawn from these results?

4.3. Methodology

Measures of DCI incidence were identified from a literature search and through personal knowledge. Their usefulness as measures of DCI incidence in tunnelling was assessed through the opinions of others, the author's own experience and the use of simple arithmetical and graphical techniques to highlight deficiencies identified in them.

Calculation of the incidence of DCI by the measures identified in Section 4.4 was done using Spreadsheet TOTAL (see Section 3.5.3) supplemented by graphical techniques from within standard Microsoft business software as appropriate, and is reported in Section 4.5.

Information on other hyperbaric experience, was obtained through a literature search and through the author's professional contacts. It fell broadly into three categories:- historic UK tunnelling data; current international tunnelling data and UK diving data. The major source of historic UK data was the Evans' study (CIRIA, 1992). Comparisons were made using measures described in Section 4.4 where appropriate, and are reported in Section 4.5.8.

The impact of poor data quality was assessed in Section 4.5. Where appropriate the study was informed by relevant practice in the UK commercial diving industry.

4.4. Measures of the incidence of DCI in tunnelling

On every contract, exposures vary in terms of pressure and time. There is a risk to the individual from each exposure undertaken but there is also an overall risk to those exposed over the duration of a contract. For a measure to be useful in compressed air tunnelling, it should take account of the pressure and time of exposure(s) and it should be clear whether that measure assesses the risk to the individual or to the population exposed. A measure, which quantified comparative risk, e.g. between contracts, but which remained sensitive to pressure and time of exposure, could also be useful.

There are three measures of DCI incidence, which are currently used in UK tunnelling. In addition, a small number of other measures have been identified from the literature including that related to diving,

Any excursion into compressed air can be considered in two parts – the working exposure and the decompression. The incidence of DCI should be independent of the hyperbaric stress generated by the working exposure and should be determined only by the effectiveness of the decompression. A decompression regime should be, but is often not consistently effective across the permissible range of exposures (see Table 4.17).

4.4.1. Crude Bends Rate

"Bends rate" is the traditional measure of DCI incidence in tunnelling. For many years it was referred to simply as the "bends rate", but more recently, possibly because of the variable basis or the unsophisticated nature of the calculation, Evans referred to it as the "crude bends rate" (CBR), (CIRIA, 1992). As a measure of DCI incidence, it is insensitive to exposure pressure or time. CBR is based on population risk e.g. risk of DCI for a single contract, and not on individual risk. No inference is drawn between CBR and the contractor's compliance with current good practice (see Section 2.4.8).

CBR is calculated as the number of DCI events on a contract divided by the number of exposures, and is expressed as a percentage. Generally the calculation of CBR is based on the number of exposures above the threshold for stage decompression (Rose, 1962). The underlying assumption appears to be that as no DCI should occur below that pressure, only exposures capable of causing DCI should be used in the calculation. Otherwise the result could be artificially lowered by including low pressure exposures unlikely to cause DCI. Rose (1962), in his analysis of DCI at Auckland Bridge, excluded exposures below the then threshold pressure of 1.25 bar (18 psi).

The basis on which a CBR has been calculated is often not clear and consistent. Kell and Ridley (1966) quoted a bends rate of 1.13% at the 2nd Blackwall Tunnel but only included exposures of over 4 hours. Griffiths at the 1965 Workshop (see Section 2.1.5), found it necessary to question the basis of the calculation (Walder, 1967; p 69). CIRIA (1974; p 15) commented that the overall DCI rate could be very misleading for reasons including the variability of working pressure and duration of exposures. Walder (1967; p 66) summed it up, "It therefore becomes obvious that the overall bends rate for a contract is not of great value".

The decompression threshold has successively been reduced over the years from 1.50 bar (22 psi) in 1936 (ICE, 1936) to 0.7 bar in current UK practice (Lamont, 2002), as DCI has been recorded at ever-lower pressures. It is unclear however if this has always been reflected in CBR calculations. Unless restrictions on the exposures used in the calculation are stated, there may be a hidden inconsistency in the CBRs quoted in the literature.

Rose (1962) noted that at Dartford, DCI had occurred down to 1.10 bar (16 psi) although none was recorded below 1.25 bar (18 psi) at Auckland. By comparison, on JLE 105, 21 (35%) of the 60 DCI events on that contract occurred at exposure pressures below 1 bar.

A further slight inconsistency in calculating the bends rate can arise depending whether or not cases of DCS and barotrauma are aggregated for the purposes of the calculation. Barotrauma can be both a compression illness and a decompression illness.

Despite these failings, the widespread use of CBR and its regular appearance in the literature has made it the *de facto* standard measure of decompression performance on and between contracts.

In theory, a bends rate can be calculated for any group of exposures. Variations in its use have occurred, such as in the acclimatisation work by Paton & Walder (1954) in which they calculated a "daily" bends rate.

There is considerable discussion in the literature over what CBR value should be considered acceptable. The ICE Report (1936) proposed that a bends rate of 2% per week was acceptable. Rose (1962, p 34) supported that figure, as did Paton and Walder (1954). Throughout the 1990s, a CBR of 0.5 – 1.0% was considered acceptable within the parts of HSE dealing with construction. Andrews (1998) quoted a bends rate of 3 – 4% being acceptable in military diving.

Bennett and George (2002), in describing an Australian project, used the reciprocal of CBR as a measure of DCI incidence. They referred to it as the "number needed to compress" (NNC) i.e. the average number of compressions required to produce one DCI event. An NNC of 100 = CBR of 1%. The use of this measure has not been encountered in the UK. NNC has all the disadvantages of CBR.

4.4.2. Standardised Bends Ratio

In his study of data in the Newcastle Registry (CIRIA, 1992), Evans proposed a new measure which he called the "standardised bends ratio" (SBR), for use in comparing the incidence of DCI against reference data. Sources of reference data could be long term historical data (HSE, 1996; Table 1) or data from another contract.

In calculating the SBR for a series of exposures, Evans totalled the number of these exposures in each cell of a predefined matrix of pressure/time increments. The average or "expected" bends rate for each pressure/time increment of the matrix was derived from the reference data. Using the actual number of exposures in each cell and the "expected" bends rate for that cell, the corresponding number of DCI events for each pressure/time increment could be calculated and then totalled to give the "expected" number of DCI events for that series of exposures. He defined the SBR as the ratio between the actual number of DCI events and the "expected" number.

The SBR takes account of differences in pressure and time between the exposures in two datasets. For convenience in calculation, pressure increments are generally in 0.3 bar steps with time increments of 2 hours duration. The sensitivity of the calculation can be refined by reducing the size of increments. Although the SBR was devised as a comparator between datasets for exposed populations, it could in theory be used to compare an individual's exposure history or an occupational group's exposure experience with that of a reference population.

As originally derived, the SBR calculation was restricted to exposures over 1 bar. However, in view of the occurrence of DCI below 1 bar, the calculation has also been done for all exposures above 0.7 bar (see Table 4.5).

4.4.3. *Single Exposure Risk Factor*

In the mid 1990s, during the discussions within HSE leading to the decision to change to oxygen decompression, the Single Exposure Risk Factor (SERF) was introduced for regulatory purposes. SERF is defined as the risk of DCI following a single exposure of a given pressure/time combination. It was required as a measure of DCI incidence which reflected the risk to the individual rather than to the population and which was sensitive to exposure pressure and time. SERFs were derived to show how the risk of DCI varied across the range of exposures on a contract and to quantify more accurately the risk of DCI for shift workers such as miners, than was achieved by CBR.

SERFs are a by-product of the calculation for SBR so for convenience, have been calculated using the same pressure/time increments as used in the SBR calculation (see Section 4.5.2). Providing sufficient data are available, greater selectivity in the calculation of SERFs can be achieved by increasing the number of pressure/time increments. As long as there are at least 1000 exposures in a pressure/time increment, a change of one in the number of DCI events for that increment will change the SERF by not more than 0.1%. A change in the number of DCI events of this magnitude due to under reporting or variations in men's tolerance of DCI is reasonably foreseeable. Ideally there should be at least 10000 exposures in an increment to reduce the error further but this cannot be achieved in a reasonable timescale with current levels of compressed air tunnelling activity and such numbers are unlikely to be achieved in the future. Because each increment represents a range of values, errors in recording pressure or times have no effect on the calculation of SERF provided the exposure or DCI event is still allocated to the same cell in the pressure time matrix as if the error had not occurred.

SERF is now routinely regarded by HSE as the preferred measure of DCI incidence in tunnelling and is used by research contractors working for HSE. Support for this measure was provided by Sterk (2003), "I agree with you completely and welcome your SERF".

4.4.4. *DCI per hour worked*

The measures identified above are all calculated on a "per exposure" basis. However to a contractor, it is the productive working time i.e. the length of the exposure period which is important. This governs the number of shifts required per day. To a CAC, decompression time is an unproductive overhead and is disruptive to the production cycle. Consequently

DCI/HW should be an important measure to the CAC to allow him to maximise the amount of productive work but minimise the overall amount of DCI expected on a contract. It is not however an industry standard measure. Shields and Lee (1986; p 50) suggested a similar concept for diving, proposing that the incidence of DCI could be measured in terms of "time in the water". They did not develop the measure further.

It is reasonable to assume that a certain amount of productive work is required to construct a tunnel irrespective of the exposure period adopted. Therefore the longer the exposure period, the fewer the number of exposures which are required to give the same amount of productive time. This results in reduced contract overheads and labour costs.

It is possible to calculate the DCI/HW for different lengths of exposure period. As a measure of DCI incidence, it is sensitive to exposure pressure and time as, given sufficient data, it can be calculated for any pressure/time increment in the SBR matrix. It could therefore be used to predict the optimum shift length to minimise the total amount of DCI on a contract. However, its usefulness is limited by the general view that shorter exposures are to be preferred to limit SERFs.

4.4.5. Distribution of DCI within occupational groups

For a given exposure pressure, the severity of exposure is closely linked to an individual's occupation. Work patterns have changed with increasing mechanisation over the study period. In hand excavated tunnels, miners were the most severely exposed as they normally worked full shifts on 5 or 6 consecutive days. Fitters, electricians and supervisors tended to be exposed for shorter shifts but equally frequently. On TBM drives, for which interventions are only required for maintenance and face inspection purposes, exposure tends to be intermittent and more varied in frequency. In addition, there is usually a considerable number of individuals who make a few infrequent visits into compressed air. CBR gives an overall average measure of DCI incidence but it is incorrect to assume that a CBR of (say) 1% implies that a similar proportion i.e. 1%, of the number of individuals exposed to compressed air on that contract experiences DCI (see Section 4.4.5).

Walder (1967, p 67) noted that most men working at pressures above 1.05 bar (15 psi), if questioned closely enough, would admit to having experienced DCI at some time. In the light of the above comment, it seemed reasonable to consider the distribution of DCI within the workforce. The proportion of a given occupational group experiencing DCI is a crude but simple measure of DCI incidence. It is insensitive to exposure pressure and time. It may however be dependent on the nature of the contract and duration of a contract. The measure is not suitable for rigorous analytical purposes but nevertheless is an indicator of disproportional risk to a particular occupational group.

When the database DCI was originally set up it contained a number of occupational descriptors. This was limited to 15 to simplify the analysis. However as contract records were sent to HSE by CACs, an increasing number of occupational descriptors appeared. A search using the "find distinct records" function in Lotus Approach™ indicated 217 separate occupational descriptors in database MANLIST.

It was decided that reducing this to 4 core occupational groups adequately represented the main categories of worker, typically exposed to compressed air. The groups were - **regular supervisory** (20 exposures or more) which included non-manual workers such as shift engineers, foremen etc; **intermittent supervisory** which included all casual visitors, management representatives and engineers, MLAs and CMAs, HSE inspectors; **shift skilled** which included electricians, fitters, carpenters and welders etc and **shift production workers** which included manual workers such as miners, labourers, loco drivers, pit boss etc. The threshold of 20 exposures after which a supervisor was deemed to be "regular" was arbitrary. This threshold excluded all supervisory staff on short duration contracts such as GYPP. As this measure was intended to be more illustrative than quantitative, it was decided not to examine the sensitivity of the threshold.

The supervisory categories included all non-manual entrants to the tunnel whilst manual workers were covered by the other two categories. Some skilled workers such as electricians and fitters occasionally work long shifts in compressed air but overall their exposure was likely to be more varied. Production workers were the most likely to undergo repetitive long shifts on a regular basis. A fifth group - **occupation unspecified** - covered those for whom it was not possible to determine an occupation.

Colvin (2003) considered there to be only three occupational groups as he did not subdivide the supervisory category. In this study, it was considered that their range of exposures and work patterns varied so much that subdivision was required.

4.4.6. Diving industry measures

Of the measures discussed by Robertson and Simpson (1996), the Exposure Index (P√T) put forward by Hempleman (1993, 2003, 2004) best met the "engineering perspective" in that it could easily be calculated from exposure data. However it is strictly a measure of hyperbaric stress of exposure and not of decompression stress. BGI (see Section 2.6) may be a predictor of DCI incidence but it is not a measure of it. Accordingly no measures were identified which were not already in use in tunnelling and which could be considered to be within the "engineering perspective".

4.4.7. Concluding remarks

Of the measures identified, SERF was favoured as the most useful measure of DCI incidence and by implication, the risk of decompression illness to a worker in the industry. It was sensitive to pressure and time and this sensitivity could be varied by the size of the pressure and/or time increment in the calculation matrix. Conversely, CBR was the least favoured measure not only because of its insensitivity to pressure and time but also because of the uncertainties around the pressure range involved. Although the measure DCI/HW was available, it has never been used by industry.

It was not possible to identify any measure of DCI incidence used by the diving industry, which came within the "engineering perspective" of the study, and which was not already used in tunnelling. The bends rate was a direct comparison with CBR, the mapping analysis had similarities with SBR/SERF. P√T was a measure of hyperbaric stress but not of DCI incidence.

It is suggested that within the "engineering perspective", there are a number of measures of DCI incidence which the engineer could easily calculate. Some of these in the industry's view have served it well for many years. In essence however they are all based on numbers of exposures and numbers of DCI events. They differ only in the arithmetic which is used.

However, the complexity of the physiological mechanisms surrounding decompression and DCI raises the question that whilst certain simple measures based on exposure data, will continue to be of interest to the engineer, they will be of little value when compared with the increasingly sophisticated physiological and medical techniques which are now available and which are used in diving related hyperbaric research,

4.5. The current incidence of DCI

The results given in this section were derived from spreadsheets TOTAL and TOTAL795 (see Section 3.5.3).

4.5.1. Crude Bends Rate

The CBR for all exposures of 1 bar and over, was calculated in spreadsheet TOTAL as 0.62%. The sample size (57201 exposures, 353 DCI events) was sufficiently large for data quality only to have affected the second significant figure. By comparison, the equivalent CBR for data in the Newcastle Registry after Evans (CIRIA, 1992) was 0.59% (389239 exposures, 2295 DCI events). On the basis of CBR, there was virtually no difference in DCI incidence between current data and Evans' data.

In Section 4.4.1, it was noted that the CBR should be calculated for all exposures above the decompression threshold. Section 6.1.1 describes how the decompression threshold was voluntarily reduced to 0.8 bar on a number of contracts. This reduction was formalised in 2001 when it was further reduced to 0.7 bar (Lamont, 2002). It was therefore appropriate to consider the CBR for all exposures of 0.7 bar and over. This was calculated in TOTAL795 as 0.38% (103148 exposures, 393 DCI events). Comparing the respective CBRs for exposures of 1 bar and over and 0.7 bar and over, clearly demonstrates how CBR was reduced by including additional low-pressure exposures.

To further illustrate the inappropriateness of CBR as a measure of DCI incidence because it does not consider pressure and time, the distribution of exposures by pressure in the current data and in Evans' data, has been set out in Table 4.8 and illustrated in Figures 4.3 – 4.4. The equivalent distribution of exposures by time in the current data and in Evans' data, has been set out in Table 4.9 and illustrated in Figures 4.5 – 4.6. In both cases the calculations were undertaken within the summary worksheet of TOTAL795.

The values for "Average pressure" given in Table 4.8 were calculated on the basis of mid increment values weighted by the number of exposures in that increment (see Section 4.5.4).

Pressure (bar)	% of all exposures current data	% of exposures ⩾1 bar current data	% of all exposures Evans' data	% of exposures ⩾1 bar Evans' data
⩽0.95	52.02	-	7.80	-
1 – 1.25	21.57	44.95	10.13	10.99
1.3 – 1.55	14.18	29.56	11.22	12.17
1.6 - 1.85	6.54	13.63	33.70	36.55
1.9 - 2.15	5.07	10.58	22.40	24.29
2.2 - 2.35	0.61	1.28	9.11	9.88
2.4 - 2.7	No data	No data	4.62	5.01
>2.7	No data	No data	1.03	1.11
(Average Pressure)		(1.43 bar)		(1.83 bar)

Table 4.8 – Summary of distribution of exposures by pressure (%)

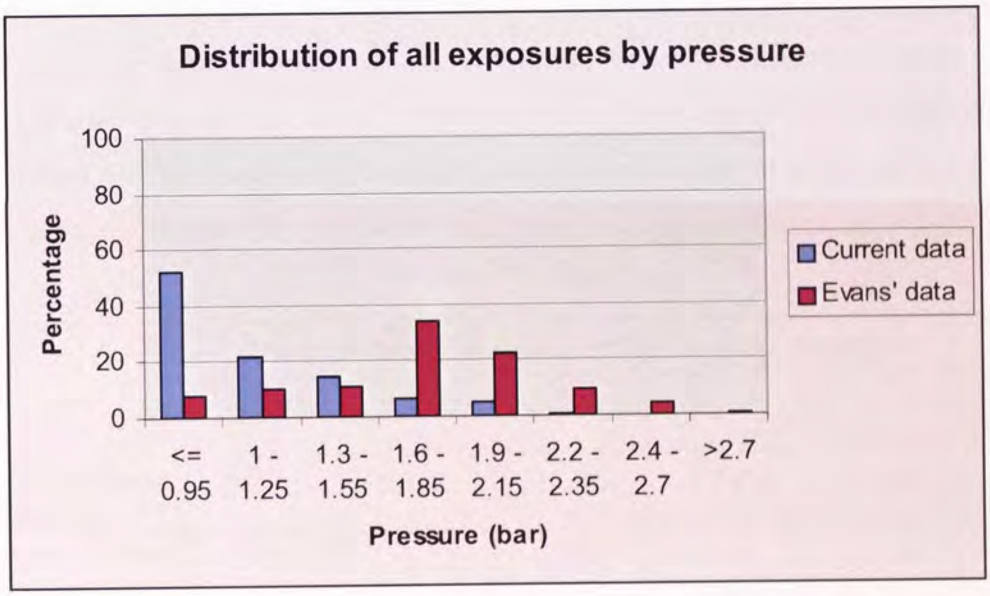


Figure 4.3 - Distribution of all exposures by pressure (%)

Table 4.8 and Figures 4.3 and 4.4 show that in the current data, there has been a noticeable trend towards lower exposure pressures. As pressure is a function of ground water level, this reduction in pressure is partly a function of the location of tunnels being driven. However, some of the reduction has been due to the increased awareness by contractors of the health risk from DCI, leading them to use partial dewatering to enable them to operate at as low pressures as reasonably practical.

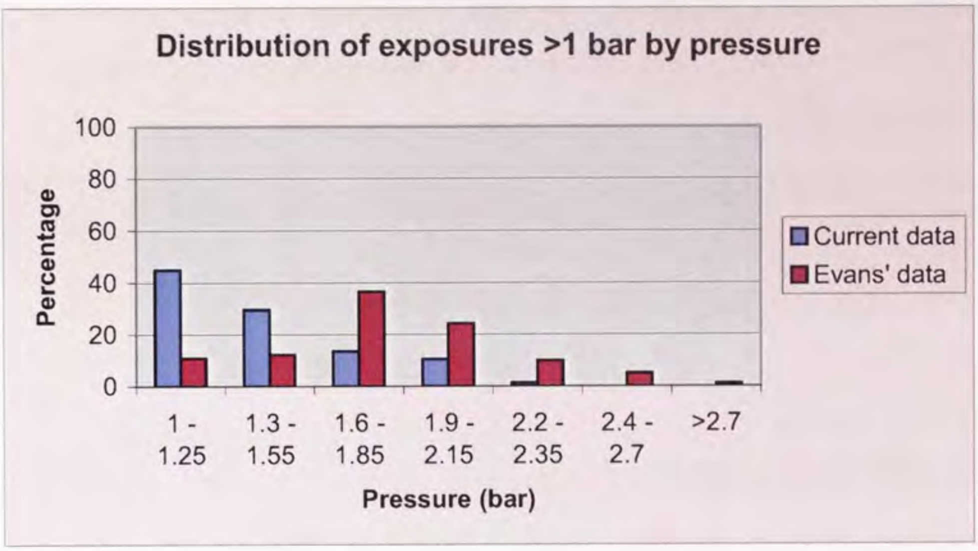


Figure 4.4 - Distribution of exposures at 1 bar and over by pressure (%)

The figures based on "all exposures" in these tables, provide a slightly less accurate comparison since they were influenced by the number of low pressure contracts which were selected (see Section 4.1 for criteria), whereas Evans' data were based on contracts selected because they were nominally being driven at 1 bar and over. Although both have been included for completeness, it is the figures for exposures at 1 bar and over (Figure 4.4) on which any comparison should be made to be consistent with earlier reports.

	Distribution of Exposures (%) by time (hours)					
	0 – 2	**2 – 4**	**4 – 6**	**6 – 8**	**8+**	**Average (Hours)**
All exposures current data	30.32	20.85	13.46	17.42	17.94	4.44
Exposures ⩾1 bar current data	26.13	19.82	14.59	19.77	19.69	4.74
All exposures Evans' data	20.48	9.23	10.79	15.13	44.37	6.07
Exposures ⩾1 bar Evan's data	19.48	9.02	10.70	13.66	47.14	6.20

Table 4.9 – Summary of distribution of exposures by time (%)

It can be seen from Table 4.9 and Figures 4.5 and 4.6, that there has been a noticeable trend towards shorter exposures. This was mainly the result of a direct response by CMAs and contractors to the occurrence of DCI, in an attempt to reduce its incidence. Limits on exposure time by the CMA, in response to high DCI incidence, were first introduced on LWRM contract on which compressed air was used from 1988 - 1989.

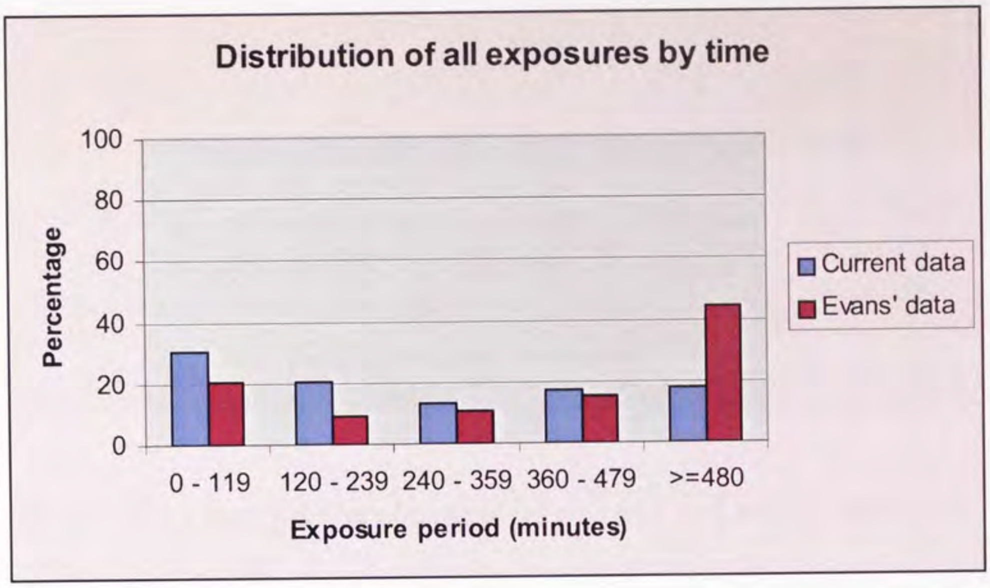


Figure 4.5 - Distribution of all exposures by time (%)

The figures based on all exposures, were influenced by the number of low pressure exposures included in the calculation as on many contracts there was no reported DCI occurring below 1 bar. For these contracts any differences in the CBR for exposures of 1 bar and over and 0.7 bar and over, were due solely to the different numbers of exposures used in the calculation. Once more it is the figures based on exposures at 1 bar and over (Figure 4.6) on which any comparison should be made.

Average exposure periods were calculated within spreadsheet TOTAL again based on mid-increment values weighted by the number of exposures in each increment. As above, these should be considered to be indicative only.

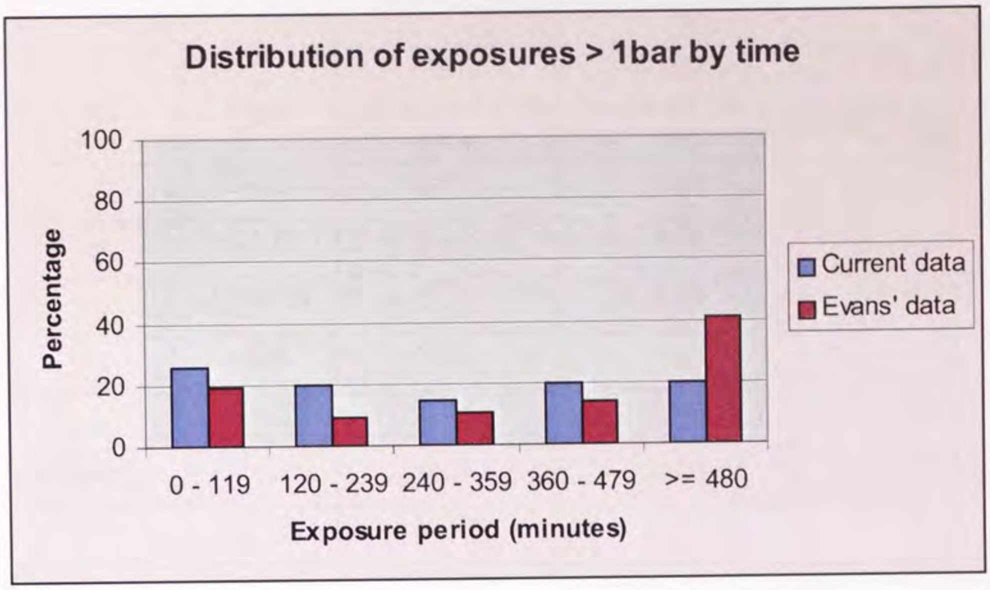


Figure 4.6 - Distribution of exposures at 1 bar and over by time (%)

Contracts on which DCI did not occur are listed in Table 4.10. Table 4.11 presents the CBRs for individual contracts on which DCI occurred. From this table it can be seen that there was considerable variation between contracts. This variation is greater when it is considered that DCI did not occur on every contract.

Contract - Date		
Belfast - 2002	DLR - 1998	Kelvin Valley
London Cable Tunnel 2000	Pepperhill	JLE 107 - 1995
Portsmouth - 2000	Billingham	Rochdale - 1987/88
Folkestone - 1999	Swansea 6 - 1997/98	Coppermills - 1987/88

Table 4.10 – Contracts (with dates) on which DCI did not occur

Contract	**Date**	**CBR (all exposures) (%)**	**CBR (exps ⩾1 bar) (%)**	**CBR (exps ⩾0.7 bar) (%)**
GYPP	2000	2.67	3.08	3.03
Hull	1999	1.56	3.08	2.29
Hastings	1998/99	0.31	0.36	0.33
Bacton	1998	0.10	0.07	0.11
Weston	1996/97	0.07	0.00	0.08
TSJV Swansea 5	1996/97	0.34	0.50	0.34
Swanage	1996	0.32	0.44	0.32
Fylde Coast	1995/96	0.63	0.66	0.64
JLE 105	1995/96	0.30	0.37	0.31
JLE 110	1995	1.14	1.23	1.18
Cromer	1993/94	0.71	0.88	0.74
Southport	1993	0.08	0.00	0.09
Ennerdale	1992	0.35	0.36	0.35
Ramsden Dock	1991	0.49	1.24	0.66
Royal Docks Ph 9	1989	0.82	0.82	0.82
LWRM	1988/89	1.30	1.34	1.31
N Woolwich	1987/88	0.46	0.47	0.46
Lowestoft	1986	1.77	1.81	1.78

Table 4.11 - CBRs on contracts where DCI occurred

The relationship, if any, between the CBR and the number of exposures on a contract is considered in Section 5.3.6.

Bends rates could also be calculated for all exposures within a given pressure or time increment. Table 4.12 shows the bends rate, by pressure increment, for data taken from Table 4.3. As might have been expected, the bends rate increased with increasing pressure however it peaked at the 1.6 - 1.85 bar increment. To peak below maximum pressure (3.5 bar) appeared to be counter intuitive as it would have been reasonable to have expected the bends rate to have continued to increase with increasing pressure over the full pressure range, reflecting the increasing severity of the hyperbaric stress of exposure. However the Blackpool Tables restrict the exposure period as the pressure increases and increase the decompression time. Consequently, this apparent anomaly may be due to the complexity of the relationship between exposure pressure, hyperbaric stress of exposure and effectiveness of decompression. There could also be physiological reasons associated with time to saturation of various tissues in comparison with exposure period, both of which are outwith the "engineering perspective", which could give rise to such a result.

Bends Rate (by pressure increment)		
Pressure increment (bar)	**Number of exposures**	**Bends rate (%)**
< 0.7	11397	0.00
0.7 – 0.95	45947	0.09
1.0 – 1.25	25714	0.19
1.3 – 1.55	16906	0.69
1.6 – 1.85	7799	1.41
1.9 – 2.15	6050	1.16
2.2 – 2.35	730	0.96
2.4 - 2.7	2	0.00
>2.7	0	No data

Table 4.12 - Bends Rate (by pressure increment)

		Bends Rate (by time increment in hours)				
		0 - < 2	**2 - < 4**	**4 - < 6**	**6 - < 8**	**>=8**
All exposures	**Bends rate**	0.03%	0.20%	0.79%	0.59%	0.51%
Exposures ≥ 1 bar	**Bends rate**	0.05%	0.41%	1.22%	0.93%	0.81%
Exposures ≥0.7 bar	**Bends rate**	0.03%	0.23%	0.87%	0.63%	0.55%
No of exposures		35013	24421	13159	20563	21389

Table 4.13 - Bends Rate (by time increment)

Table 4.13 shows the bends rate by time increment. Again as might have been expected, the bends rate increased with increasing time however it peaked at the 4 - <6 hours increment. To peak below maximum exposure time was again slightly counter intuitive as it would have been reasonable to have expected the bends rate to have continued to increase over the full range of permitted exposure times, reflecting the apparent increasing severity in exposure stress. However the exposure time becomes reduced as pressure increases. Again this apparent anomaly may be due to the complexity of the physiological relationships involved which are outwith the “engineering perspective”. In addition the counter intuitive result may have been due to the small number of exposures over 1.9 bar pressure and 6 hours exposure which might have been expected to result in considerable DCI.

Evans (CIRIA, 1992) reported a similar trend in the data which he analysed. He suggested this might be due to men pacing themselves by not working so strenuously over a longer shift. Buchanan (2005a) suggested that the peak in bends rate at increments below maximum pressure or exposure period was due to an element of self selection in the workforce in that the more arduous exposures in terms of pressure or duration tended to be undertaken by those who considered themselves to be relatively unsusceptible to DCI. No simple explanation based on working practice can be offered.

Examples of CBRs from other tunnelling hyperbaric experience are set out in Table 4.14. Walder (1967; p 65) noted that the 1958 Tables “might result in bends rates up to two percent”.

The current CBR of 0.62% is within the range of CBRs quoted in Table 4.14. Given the criticisms of the insensitivity of CBR as a measure, it would have been surprising if it were not. The reported bends rates cover a variety of contracts with normal and decant decompressions, all exposures and exposures at 1 bar and over. Court (1992) reporting on a contract in Cairo, and Campbell and Gutteridge (1992) on a contract in Hong Kong, quoted CBRs for workers in a multi-racial workforce. They questioned whether ethnicity gave rise to differences in bends rate however on these contracts there was probably a correlation between occupation and ethnic background, consequently any differences in bends rate might not have been due to ethnicity alone.

Information on the acceptable incidence of DCI from commercial diving experience included that quoted for the N Sea by Shields and Lee (1986). They considered an overall incidence of DCI of <0.5% to be good. In their opinion, some Type 1 DCS could be tolerated, as unlike DON, Type 1 DCS did no long-term damage. However they considered

Type 2 DCS unacceptable because of possible long-term neurological damage hence the only acceptable incidence of Type 2 DCS was zero. Further examples of DCI incidence in diving are shown in Table 4.15.

Contract	No of exposures	Max pressure	Bends Rate
East River (Levy, 1922)	1361461	3.5 bar (50 psi)	0.05%
Auckland (Rose, 1962; p 35)	Shift workers – 7635	3.375 bar (49 psi)	3.3%
	Non-shift – 2391		0.5%
	Total exposures 10026		2.6%
Auckland (Rose, 1962; p 99)		> 3.125 bar (>45 psi)	4.6%
Tyne Pedestrian 1948/49 (Rose p 35)		2.575 bar (37 psi)	0.87
Thames (Rose p 36)		2.425 bar (35 psi)	4.2%
Dartford 1957/59 (Rose p 36)	Normal Decompressions	1.45 bar (21 psi)	0.93%
	Decants 2400		0.33%
Clyde 1958/63 (Walder, 1967; p 68)	161000		0.29%
2nd Blackwall (Kell and Ridley, 1966)	63670	2.50 bar (36 psi)	1.13%
Evans (CIRIA, 1992)	389239	-	0.59%
Cairo 1984/85 (Vincent and Rowley, 1992)	14400	2.38 bar	0.46%
	54811	2.34 bar	0.56%
	41764 (over 1 bar)	2.34 bar	0.74%
Hong Kong (1975) (Campbell and Gutteridge, 1992)	226554	2.45 bar	0.68%
	79676	2.3 bar	0.40%
	28255	1.8 bar	0.074%
Singapore (1984 – 1987) (How *et al*, 1992)	188538	2.35 bar	0.087%
	64959 >1 bar	2.35 bar	0.26%
Lamont (2000)	119229	2.4 bar	0.62%
Storebaelt (Andersen, 2002)	9018	2.95 bar	0.14% as an overall rate using French tables

Table 4.14 – CBRs from other tunnelling hyperbaric experience

Diving	No of exposures	Bends rate
Robertson & Simpson (1996)	162042 dives – North Sea	0.31% in 1983 0.07% in 1990. Authors give average = 0.23%
Recreational diving 1998 – 2002 (Vann *et al*, 2004)	46494	0.01% to 0.28% (depending on dive location)

Table 4.15 – CBRs from diving hyperbaric experience

4.5.2. *Standardised Bends Ratio*

To calculate an SBR, a reference dataset must be chosen. HSE recommends the use of the data in Table 1 of the Guidance (p 69) as the reference dataset (see Table 4.18). This data was first published in imperial units by Evans' (CIRIA, 1992).

Overall and individual contract SBRs were calculated by spreadsheet TOTAL/TOTAL795 as described in Sections 3.5.3 and 4.4.2. With the data from Table 1 of the Guidance as reference dataset and considering only exposures of 1 bar and over, the overall SBR for current data was 2.39 i.e. the current incidence of DCI was 2.39 times that which would have been "expected" had the DCI outcome of current exposures replicated that in the reference data. Sensitivity analysis undertaken on TOTAL795 showed that poor data quality would have affected the result at the second decimal place only. It was considered that quoting SBR to three significant figures perhaps implied a precision which was not meaningful within the "engineering perspective" of the study. Consequently the error due to poor quality of the data could be ignored.

In Durban, Lamont (2000) presented the then current SBR as "approximately 2". However as part of this study the conversion of the data from imperial units into metric units on which the Durban paper were based was reassessed. This has had the effect of moving some exposures and DCI events into a lower pressure band resulting in an increased SBR.

A possible explanation for such a high SBR is that the nature of the contracts was different in this study from those studied by Evans (CIRIA, 1992). Evans data was from large contracts where hand excavation was carried out by teams of miners over long periods. In the 1980s compressed air was mainly used on hand dug small diameter tunnels but in the

1990s it was used on both hand dug and machine excavated tunnels. More recently compressed air has been used mainly to facilitate maintenance of TBMs with exposures being undertaken on an irregular basis. This would have reduced or removed any effects of acclimatisation or self-selection (see Section 5.3). Another explanation could be that reporting of DCI was more extensive in recent years, as training of the workforce in the risks of compressed air working became more rigorous. Certainly since the mid 1990s, a culture had been created in the workforce in which reporting of symptoms was encouraged to a much greater extent than ever before.

Contract	**No of exposures ⩾1 bar (⩾0.7 bar)**	**SBR**
GYPP	130	18.24
Hull	227	21.02
Hastings	832	3.75
Bacton	1464 (2805)	0.48 (0.94)
Weston	0 (6595)	(1.17)
TSJV Swansea 5	5381 (8153)	3.12 (2.62)
Swanage	3863	2.05
Fylde Coast	1064	2.66
JLE 105	10575 (19600)	1.45 (1.23)
JLE 110	2283	2.99
Cromer	5543	2.41
Southport	4558 (9235)	0.00 (0.83)
Ennerdale	2806	1.61
Ramsden Dock	3319	3.63
Royal Docks Ph 9	3283	3.27
LWRM	2983	4.19
N Woolwich	7400	1.42
Lowestoft	993	4.74

Table 4.16 - SBRs on contracts where DCI occurred

((figure in brackets) = when exposures ⩾0.7 bar are included)

Table 4.16 shows the SBRs for each contract on which DCI occurred. The original SBR calculation was based on DCI events at or over 1 bar. However this study showed that a significant number of DCI events occurred below this pressure. Accordingly an estimate of the SBR when exposures and DCI events at and above 0.7 bar are taken into account has been made and is given in brackets in columns 2 and 3 of Table 4.16.

The SBRs for GYPP and Hull contracts were particularly high. Similarly, both contracts had high CBRs although proportionally not so high when compared to overall figures. Both involved small numbers of exposures and pressures above 1.5 bar. Whilst undoubtedly these were two contracts on which more DCI than expected had occurred and that more DCI had occurred disproportionately at lower pressures than expected, the relatively small number of exposures ⩾1 bar (GYPP 130, Hull 227) may have influenced the figures. Jardine et al (CIRIA, 1992; p61) reported SBRs (referenced against the same data as used in this study) up to 3.81 for staged decompressions and up to 5.2 for decompressions following decanting.

Some simple analysis could have been done to discover if there were any differences between the SBR for hand dug tunnels and that for machine dug tunnels. However from consideration of the contracts concerned, it would have been difficult (and meaningless) to have made a distinction between the two methods of excavation, as the work done in air did not necessarily reflect the way in which the remainder of the tunnel was driven.

4.5.3. Single Exposure Risk Factor

The SERFs calculated by TOTAL795 for the data given in Tables 4.3 and 4.5 are set out in Table 4.17 and those calculated for Evans data (CIRIA, 1992) are set out in Table 4.18.

It should be noted that in the current study, virtually no data were available for pressures above 2.35 bar whereas Evans had a wider spread of exposure data. The SERFs for current data were higher than for Evans' data. This is fully in accordance with the SBR results.

It can be seen from Table 4.17 that there is a considerable band of exposures towards the higher pressure and longer duration corner of the table for which the risk of DCI is in the range 1 - 3%. The longer duration shifts in particular were mainly worked by miners. This illustrates the use of SERF to determine the risk from individual exposures. It also shows the discrimination available by using SERF compared with CBR as a measure of DCI incidence.

Pressure Time	**Single Exposure Risk Factors %**				
	0 - < 2	**2 - < 4**	**4 - < 6**	**6 - < 8**	**⩾8**
< 0.7	0.00	0.00	0.00	0.00	0.00
0.7 – 0.95	0.01	0.03	0.06	0.20	0.21
1.0 – 1.25	0.03	0.02	0.20	0.24	0.39
1.3 – 1.55	0.00	0.22	0.81	1.07	1.69
1.6 – 1.85	0.05	0.89	2.41	1.92	1.63
1.9 – 2.15	0.22	1.11	1.85	19.05**	0.00**
2.2 – 2.35	0.79*	0.23*	2.84*	No data	▨
2.4 – 2.7	0.00**	No data	No data	No data	▨
>2.7	No data	No data	No data	▨	▨

Table 4.17 – Single Exposure Risk Factors

** - very small sample - <100 exposures

* - small sample - <1000 exposures

▨ Exposure not allowed under Blackpool Tables

Pressure Time	**Single Exposure Risk Factors %**				
	0 - < 2	**2 - < 4**	**4 - < 6**	**6 - < 8**	**⩾8**
<= 0.95	0.03	0.00	0.00	0.00	0.03
1.0 – 1.25	0.02	0.04	0.05	0.22	0.43
1.3 – 1.55	0.03	0.11	0.17	0.49	0.43
1.6 – 1.85	0.12	0.21	0.50	0.67	0.48
1.9 – 2.15	0.12	0.20	0.89	1.25	0.95
2.2 – 2.35	0.19	0.78	1.18	1.35	1.60
2.4 – 2.7	0.14	0.74	1.18	2.26	1.49
>2.7	0.26	1.65	5.90	2.97	2.61

Table 4.18 – Single Exposure Risk Factors from the Guidance

(Guidance, Table 1 after Evans (CIRIA, 1992))

4.5.4. DCI per hour worked

DCI/HW was calculated within TOTAL795 from data in Tables 4.3 and 4.5 and is presented in Table 4.19. The figures in Table 4.19 were calculated using average mid-increment times as opposed to actual exposure times as was done by Evans (CIRIA, 1992).

Pressure / Time	**DCI per Hour Worked (events/hr)**				
	0 - < 2	**2 - < 4**	**4 - < 6**	**6 - < 8**	**⩾8**
< 0.7	0.000000	0.000000	0.000000	0.000000	0.000000
0.7 – 0.95	0.000063	0.000099	0.000110	0.000292	0.000236
1.0 – 1.25	0.000326	0.000069	0.000395	0.000340	0.000438
1.3 – 1.55	0.000000	0.000741	0.001626	0.001535	0.001882
1.6 – 1.85	0.000550	0.002968	0.004822	0.002738	0.001811
1.9 – 2.15	0.002247	0.003694	0.003691	0.027211**	0.000000**
2.2 – 2.35	0.007874*	0.0007816*	0.005682*	No data	▨
2.4 – 2.7	0.000000**	No data	No data	No data	▨
>2.7	No data	No data	No data	▨	▨

Table 4.19 – DCI per Hour Worked

** - very small sample - <100 exposures

* - small sample - <1000 exposures

▨ Exposure not allowed under Blackpool Tables

The validity of this assumption was checked (Figure 4.7 and Tables 4.20 and 4.21) and considered reasonable. However to date DCI/HW has not been used by industry as a measure of DCI incidence.

Table 4.20 shows the duration of the average exposure in each increment of exposure period for Cromer. This contract was chosen because it had a wide spread of exposures pressures – up to 2.35 bar. The distribution of exposure times is shown in Figure 4.7. That distribution was approximately linear at least up to 540 minutes (linear regression gives r = 0.99). There was good agreement between the duration of the average exposure as calculated from actual exposure data and the mid increment value used in the DCI/HW calculation.

Duration of average exposures – Cromer					
	0 – <2 hrs	**2 – <4 hrs**	**4 – <6 hrs**	**6 – <8 hrs**	**⩾ 8 hrs**
No of exposures	1253	1403	1776	898	1541
Total duration (mins)	89215	255091	518022	379468	812491
Duration of average exposure (mins)	71	182	292	423	527
Mid-increment value (mins)	60	180	300	420	540

Table 4.20 - Duration of average exposures – Cromer

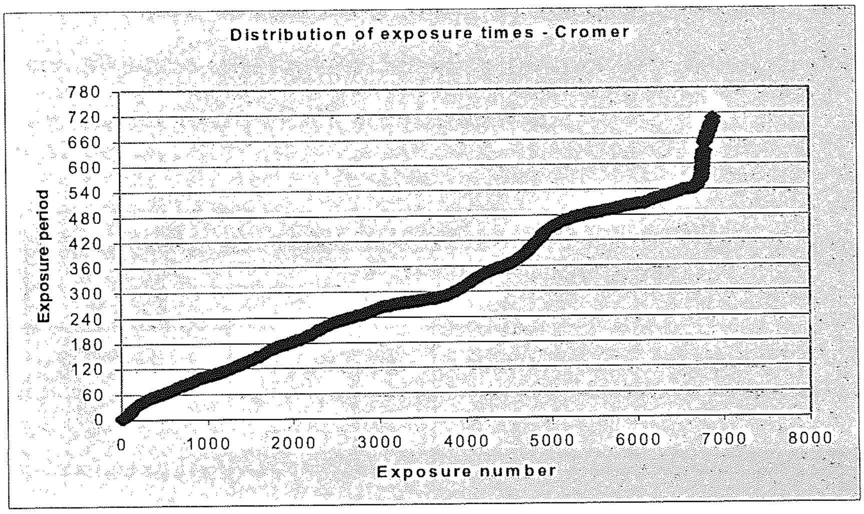


Figure 4.7 – Distribution of exposure times - Cromer

Duration of average exposures – 4 contract check					
	0 - <2	**2 - <4**	**4 - <6**	**6 - <8**	**⩾ 8**
No of exposures	5477	5277	5040	5370	5242
Total duration (mins)	315267	987314	1511847	2312435	2653064
Duration of average exposure (mins)	58 (range 44 – 71)	187 (range 173 – 210)	300 (range 290 – 313)	431 (range 369 – 448)	506 (range 493 – 527)
Mid-increment value (mins)	60	180	300	420	540

Table 4.21 - Duration of average exposures – 4 contract check

Three other contracts (LWRM, Ramsden, N Woolwich), chosen to reflect the wider spread of pressures found in the database, were checked in addition to Cromer and the aggregated figures are shown in Table 4.21. There was some variability between contracts in each time increment average which is reflected in Table 4.21. This was considered to be due to the dominant effect of large numbers of exposures just below or above an increment boundary, reflecting industry practice (see Section 3.4.2). However because the value of DCI/HW as a measure of DCI incidence has not yet been recognised by industry (see Section 4.4.4) and the hyperbaric community, it was considered reasonable not to make further refinements in the calculation of mid-increment time.

DCI/HW averaged over the pressure ranges indicated and for the normal 2-hour increments of exposure period, are shown in Table 4.22. As with the calculation of CBR, it is probably more relevant to calculate this measure only for exposures capable of causing DCI. However for completeness, the figures for all exposures are included. For comparison, figures for Evans' data (CIRIA, 1992), are also shown.

DCI per Hour Worked (events per hour)					
Data source	**Exposure period (hours)**				
	0 - <2	**2 - <4**	**4 – <6**	**6 – <8**	**⩾8**
Current data ⩾0.7 bar	0.0002915	0.0007782	0.0017365	0.0009037	0.0006132
Current data ⩾1 bar	0.0005352	0.0013821	0.0024446	0.0013263	0.0008978
Evans' data ⩾1 bar	0.0009629	0.0008356	0.0012823	0.0012785	0.0008423
Current data all exp	0.0002490	0.0006703	0.0012960	0.0008321	0.0005661
Evans' data all exp	0.0008788	0.0007531	0.0011719	0.0010648	0.0008257

Table 4.22 - Comparison of DCI per Hour Worked for different data sources (all pressures by time increment)

It can be seen from Table 4.22 that for current data the DCI/HW increased with increasing exposure period till it peaked at 4 – ⩽6 hour exposures, then decreased for 6 – ⩽8 hour exposures and decreased further for >8 hour exposures. DCI/HW as calculated, is a function of the bends rate for the increment and the mid increment time. This finding was numerically consistent with the findings in Table 4.13 (see Section 4.5.1). Intuitively the incidence of DCI could be expected to continue to increase with increasing and hence more severe, exposure period. However as shown by Table 4.13, this was not the case. The increase in DCI/HW over the three time increments to 6 hours exposure may to some extent reflect both the lengthening exposure period and the change in occupational category of those undergoing longer exposures (see Section 4.5.5) with the attendant changes in physical activity, from supervisory to shift production worker. Apart from reflecting numerical trends in increment bends rates (see Section 4.5.1), the decrease in DCI/HW for exposures of 6 hours and over may reflect an element of self selection by the workers concerned or non-uniformity of effectiveness in the decompression tables. There may also be physiological reasons for this finding relating to the time for saturation to occur but beyond the "engineering perspective".

On the assumption that a certain amount of work has to be done in compressed air to construct the works, the number of exposures required is inversely proportional to their duration. The total work to be done can therefore be achieved by fewer longer exposures or more shorter exposures. The results in Table 4.22 indicated that the total number of DCI events on a contract would appear to be minimised by working either short or long exposure periods. Exposures of 4 – ⩽6 hours would appear to generate more DCI in the population exposed. Evans (CIRIA, 1992) found a similar pattern but with a peak at 6 – ⩽8 hour exposure. He was similarly unable to account definitively for the result.

4.5.5. Distribution of DCI within occupational groups

The extent to which DCI affects the workforce tends to get lost through the over use of CBR as the measure of DCI incidence. Walder (1967, p 66) reported that at Dartford, 20% of men experienced DCI rising to 50% at Tyne Pedestrian Tunnel. When compared with a CBR of 0.5% it is clear that once the number of exposures is taken into account, considerably more than 0.5% of the workforce experiences one or more DCI events. This could be considered unacceptable in today's risk averse climate.

Of the 2387 individuals in database MANLIST, 194 initially lacked an occupational descriptor. No occupational descriptors were recorded in the LA's register for the Southport contract and the majority of the workers at Ramsden Dock were generically described as "compressed air workers". DCI data for Royal Docks Phase 2 were missing and these men were excluded from this analysis, as were the men from Bideford for which exposure data was missing. Five records were completed by comparison with data from other analyses in this study such as those used in Section 5.4. Nevertheless sufficient data were available for the results to be representative of the industry. After data quality improvements had been undertaken, there were sufficiently complete records to allow 2346 men representing a total of 114270 exposures, to be allocated to an occupational category, of whom 285 experienced a total of 400 DCI events.

Table 4.23 gives a breakdown by occupational category, of the workforce and of the men experiencing DCI. The breakdown of the workforce is done in terms of number of men in each occupational category and the proportion each category represents of the total workforce. The breakdown of the men experiencing DCI is done in terms of the number of men in each occupational category who experienced DCI, that number as a proportion of the total number of men in the occupational category and also that number as a proportion of the number of men experiencing DCI.

Occupational category	**Workforce**		**Men experiencing DCI**		
	Number in category	**Proportion of total workforce**	**Number in category**	**Proportion of total men in category**	**Proportion of men experiencing DCI**
Regular supervisory	228	9.7%	16	7.0%	5.6%
Intermittent supervisory	448	19.1%	8	2.8%	2.8%
Shift skilled	346	14.7%	43	12.4%	15.1%
Shift production workers	1135	48.4%	211	18.6%	74.0%
Occupation unspecified	189	8.1%	7	3.7%	2.5%
Totals	**2346**	-	**285**	**12.2%**	-

Table 4.23 – Breakdown of workforce and those experiencing DCI - by occupational category

Table 4.23 shows that 19.1% of those entering compressed air were in the intermittent supervisory category. Shift production workers accounted for 48.4% of those entering in compressed air. The table also shows that only 2.8% of intermittent supervisory personnel experienced DCI compared to 18.6% of shift production workers. However, shift production workers accounted for 74% of all the men experiencing DCI. This disproportional risk to shift production workers – mainly the miners - was further highlighted when the figures for individual contracts were examined from which it was found that on the higher pressure contracts such as LWRM and Cromer, 45% and 52% respectively, of the shift production workers on these contracts experienced DCI.

Table 4.24 gives a breakdown of DCI events by occupational category and by the number of DCI events experienced. From this table it can be seen that the majority of DCI events and in particular the multiple events were experienced by shift production workers.

Occupational category	No of men experiencing repetitive DCI				Total no of men with DCI	Total no of DCI events
	DCI x 1	DCI x 2	DCI x 3	DCI x 4		
Regular supervisory	13	1	2		16	21
Intermittent supervisory	7	1			8	9
Shift skilled	30	12	1		43	57
Shift prod'n workers	140	52	15	4	211	305
Occupation unspecified	6	1			7	8
Totals	**196**	**67**	**18**	**4**	**285**	**400**

Table 4.24 – Breakdown of DCI events by occupational category

Table 4.25 shows that the shift skilled and shift production categories combined accounted for 90.5% of DCI events. This equates to 145 DCI events per 100 shift production workers compared with only 113 per 100 intermittent supervisory personnel. By all these findings, DCI is predominantly a disease of the shift worker.

Occupational category	Total no of men	Total no of DCI events	% of total DCI events	DCI events per man
Regular supervisory	16	21	5.25%	1.31
Intermittent supervisory	8	9	2.25%	1.13
Shift skilled	43	57	14.25%	1.33
Shift prod'n workers	211	305	76.25%	1.45
Occupation unspecified	7	8	2.00%	1.14
Total	**285**	**400**		**1.40**

Table 4.25 - DCI events per man by occupational category

Table 4.26 gives a breakdown of the number of exposures undergone by occupational category. Some might find it surprising that the number of exposures per man was significantly greater for regular supervisory personnel than for shift production workers. This difference may be due to two factors – regular supervisory personnel are more likely to undergo multiple exposures in a single shift than production workers. They are also likely to have greater continuity of employment by being on the staff of the CAC, engineer or client. Table 4.26 also justifies the decision to split the supervisory category into two as it demonstrates the difference in exposure history between regular and intermittent supervisory personnel.

Occupational category	No of exposures	% of total exposures	Exposures per man
Regular supervisory	20935	18.3%	92
Intermittent supervisory	3063	2.7%	7
Shift skilled	13186	11.5%	38
Shift prod'n workers	65799	57.6%	58
Occupation unspecified	11287	9.9%	60
Totals	**114270**	-	-

Table 4.26 – Breakdown of exposures by occupational category

Table 4.23 showed that approximately 19% of the workforce were in the intermittent supervisory category whilst shift production workers accounted for around 48% of the workforce. However Table 4.26 shows that the intermittent supervisory category accounted for only 2.7% of exposures against 57.6% for shift production workers. Whilst there is nothing revolutionary in this, it is nevertheless a clear indication of the relative number of intermittent supervisory personnel entering compressed air workings and their impact on the number of exposures undergone.

The findings in this section are not new (see Walder; 1967). The results emphasise both the extent to which DCI is a disease of the shift worker and the high - unacceptably high perhaps - proportion of shift workers who experience DCI. Obviously a contract is an indeterminate but finite period of time and a different series of contracts could have given different results however what is set out in this section reflects average industry experience during the study period.

4.5.6. Diving Industry Measures

No directly relevant measures of DCI incidence from the diving industry, were identified in Section 4.4.6.

Robertson & Simpson (1996) and Shields *et al* (1994) compared the occurrence of DCI with the severity of exposure. Similar comparisons can be made in tunnelling and tunnelling experience can be compared with diving experience, however the differences in the respective working environments and decompression regimes must be borne in mind when considering any results.

P√T, the exposure index (see Section 2.2.5), relates to the hyperbaric stress of an exposure and is not in itself an indicator of decompression stress. However for any decompression table, exposure severity can be an indicator of overall risk (Robertson & Simpson, 1996; p28). For the diving exposures they examined, Robertson & Simpson noted (p 29) that P√T = 20 approximated to a lower bound on exposure severity which resulted in DCI. Robertson and Simpson (p 26) suggested limits on the validity of P√T. Quoting pressures as depths of water, Robertson and Simpson suggested validity limits of 15m (50ft) to 52m (170ft) depth and up to 130 minutes exposure time. This equates to approximately 1.5 – 5.2 bar pressure and is slightly more restrictive than the limits put forward by Hempleman (see Section 2.2.5). Shields *et al* (1994; Table 5) examined the decompression outcome from a range of diving techniques, most of which bore little resemblance to compressed air working practice, but for in-water decompression, the diving technique which most closely represents compressed air practice, they recorded DCI at P√T values as low as 16.6.

The exposure indices for all DCI events in database DCI were calculated and a plot of the P√T values for all DCI events in database DCI is shown in Figure 4.8. From this plot it can be seen that because of the long exposures in tunnelling, P√T values were typically between 40 and 60. However the figure shows that a number of DCI events occurred at P√T values between 10 and 20.

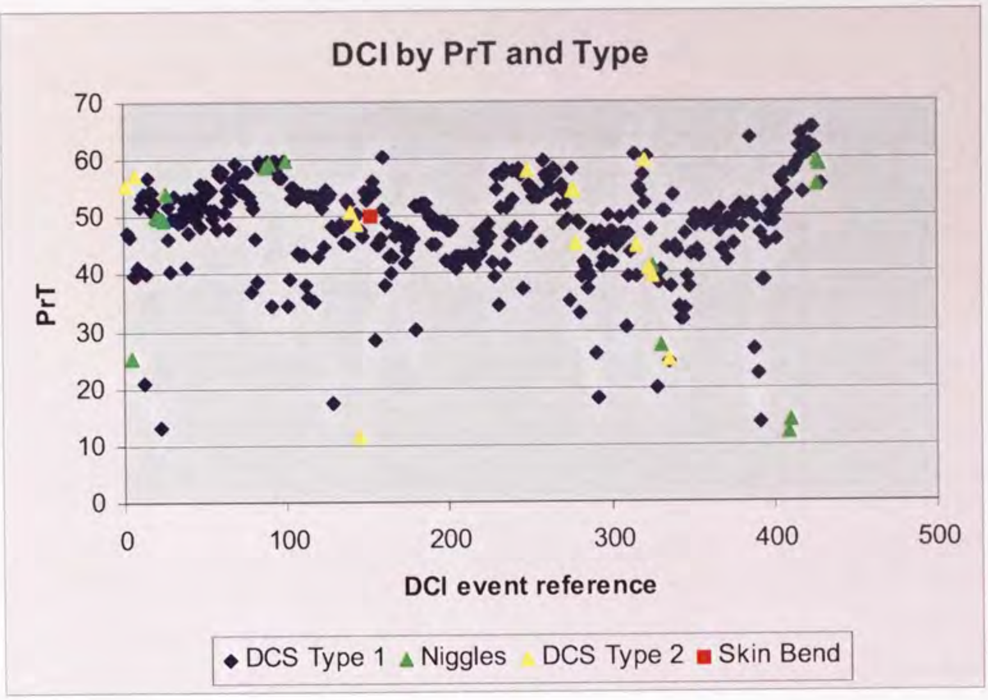


Figure 4.8 - DCI by P√T and Type

Details of the exposures which resulted in DCI and which occurred at P√T values below 30 are set out in Table 4.27 along with the type of DCI. Those with the lowest P√T values fell within the limits of validity for P√T given by Hempleman but not within the limits suggested by Robertson & Simpson. Table 4.27 also contains details of other exposures leading to DCI for which the exposure period exceeded 120 minutes and consequently were strictly outwith the Hempleman limit for P√T (exposures exceeding the 120 minute limit are shown in red in Table 4.27). Nevertheless because the formula uses √T as opposed to T, for exposures of up to ~200 minutes the numerical difference between √120 and √200 is small, the use of P√T as a comparator of exposure stress is considered to be valid for the conclusion to be drawn that in tunnelling, DCI arose from exposures of at least as low exposure stress as in diving.

This is a factor of the effectiveness of the decompression tables used and different decompression tables would have resulted in a different outcome. The finding obviously depends also on the accuracy of diagnosis of DCI however it is highly unlikely that all 17 cases were misdiagnosed. Conversely a number of untreated cases of DCI may have occurred but were not reported because the person concerned had undergone a low stress exposure and did not associate the symptoms with DCI. The occurrence of two Type 2 DCS cases at such a low P√T values was however a matter of concern.

Exposure pressure (bar g)	Exposure period (mins)	P√T	DCI Type
1.08	30	11.39	DCS Type 2
1.25	29	12.12	Niggles
1.05	41	13.13	DCS Type 1
1.60	29	14.00	DCS Type 1
1.50	33	14.36	Niggles
2.05	32	17.25	DCS Type 1
1.20	69	18.27	DCS Type 1
0.90	108	19.75	DCS Type 1
1.65	63	21.03	DCS Type 1
1.60	74	22.37	DCS Type 1
0.95	158	24.51	DCS Type 1
0.76	201	24.95	DCS Type 2
2.04	68	25.07	Niggles
1.15	146	25.98	DCS Type 1
1.92	84	26.76	DCS Type 1
0.95	195	27.23	Niggles
2.00	89	28.30	DCS Type 1

Table 4.27 – DCI events with P√T < 30 and T < 120 minutes

(DCI events with P√T < 30 and T > 120 minutes)

4.5.7. Categories of DCI

The different manifestations of DCI were described in Chapter 2. Most DCI in tunnelling is reported as Type 1 DCS or niggles/skin bends. A small proportion is diagnosed as Type 2 DCS. Type 2 DCS is of considerable concern as it is potentially life threatening. The breakdown of DCI by Type is set out in Table 4.28. The relatively small proportion of Type 2 DCS is consistent with Evans' findings (CIRIA, 1992) (see Table 4.29).

Type of DCI event	No of events	% of total DCI
Type 1 DCS	395	92.5%
Type 2 DCS	14	3.3%
Niggles	17	4.0%
Skin Bend	1	0.2%
Total	427*	100.0%

Table 4.28 - Breakdown of DCI by Type

(* 1 DCI event at LWRM not categorised)

Data source	Type 1 DCS	Type 2 DCS	Other DCI
Tunnelling – 1984 – 2002	92.5%	3.3%	4.2%
Tunnelling – from 1948 **Evans (CIRIA 1992; p 46)**	96.0%	4%	0.0%
Diving - N Sea data 1982 – 1990 **(Robertson & Simpson)**	63.8%	37.2%	0.0%

Table 4.29 - Breakdown of DCS by Type: tunnelling v diving

The occurrence of different types of DCI is shown graphically in Figure 4.9. It can be noted from the figure, that the distribution of Type 2 DCS is reasonably spread across the full range of DCI events. DCS Type 2 is more often associated with fast tissue problems and therefore the distribution of Type 2 DCS could have been expected to have been biased more to the shorter exposures. To confirm that the distribution of Types 1 and 2 DCS was similar, average P√T values were calculated for exposures resulting in Type 1 DCS and Type 2 DCS. The values were 48.60 and 46.06 respectively. As many of the exposures resulting in DCS were of long exposure time, this use of P√T could not wholly be justified but no more-suitable comparator existed. As the same decompression table was applied throughout the study, albeit of non-uniform effectiveness and with local modifications, this was the nearest to a valid comparison in the respective distributions which could be made.

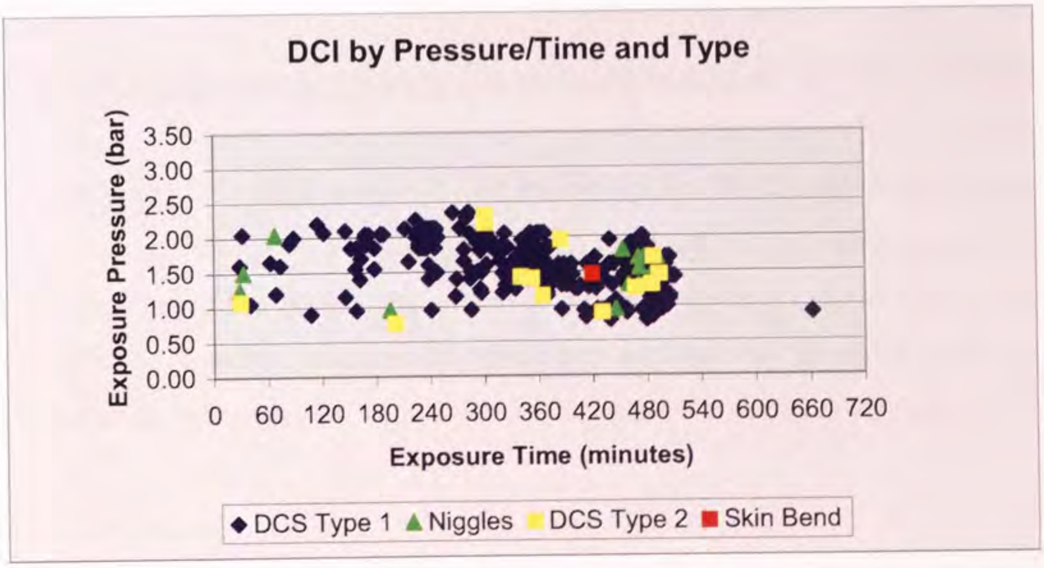


Figure 4.9 – Distribution of DCI by Type

Type 2 DCS is proportionally more prevalent in diving (see Table 4.29), which may reflect a tendency towards short high-pressure exposures in non-saturation air diving.

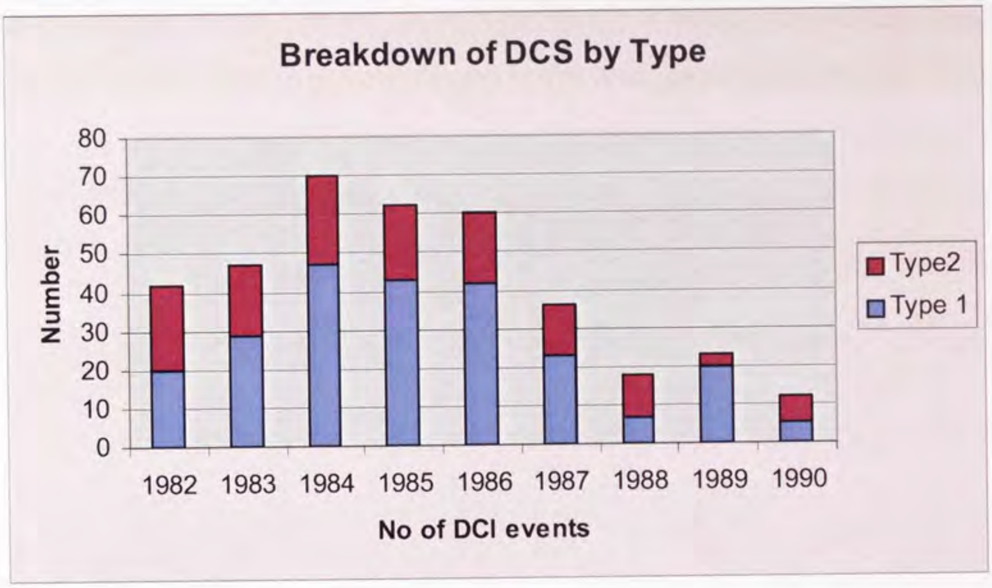


Figure 4.10 – Breakdown of DCS in diving 1982 – 1990 by Type

(after Robertson and Simpson, 1996)

The breakdown between DCS Types 1 and 2 in diving for the same period is shown in Figure 4.10. It shows that for diving, whilst the annual total of DCI events reduced the proportion of these DCI events which were Type 2 DCS increased over the period.

4.5.8. Comparisons with DCI incidence in the diving industry

Of the measures of DCI incidence described in Section 4.4, bends rate is the only measure for which data is readily available. The data from Duff *et al* (1996) was for diving exposures, the range of pressures and exposure periods of which did not match tunnelling practice particularly well. Consequently, bends rate was the only measure which could be used for comparison between DCI incidence in the respective industry sectors.

Robertson and Simpson (1996) gave the incidence of DCS (as a bends rate), in the N Sea as 0.39% in 1983 – reducing to 0.07% in 1990, and quoted an average of 0.23% (see Table 4.15). Figure 4.11 shows the consistently downward trend over that period.

From Figure 4.11, it is clear that over a ten-year period, the bends rate in diving was reduced from the same order of magnitude as tunnelling to around an order of magnitude less. The current incidence of DCI in UK commercial diving is around 0.01% (Sherman, 2005). Even without taking into account the different exposure patterns and criticisms of CBR as a measure of DCI incidence, there is no reason to pursue this comparison further. The risk of DCI from diving exposure is much lower than from tunnelling exposure!

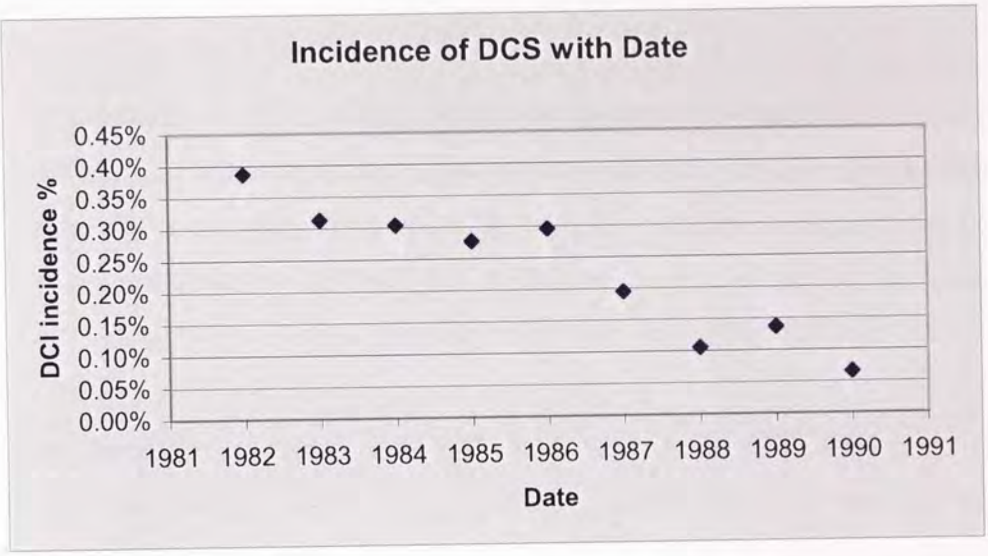


Figure 4.11 – Incidence of DCS in diving 1982 - 1990

(after Robertson and Simpson, 1996)

Further comparisons between the effectiveness of decompression in diving and tunnelling could be made if the study extended into Doppler monitoring as some Doppler data following tunnelling decompression are available from HSE research (Flook, 1998; Lamont *et al*, 2002). However such techniques are beyond the "engineering perspective".

4.6. Concluding remarks

It can be seen from Figure 4.9 that there was no recorded DCI below 0.7 bar. Similarly there was no DCI above 2.5 bar. However whilst there were exposures below 0.7 bar there were only two recorded exposures in the pressure band 2.4 – 2.7 bar and none above.

There was a cluster of DCI events across the pressure range at exposure times of around 450 – 500 minutes. This reflected the large number of shifts of around 8-hours duration worked to achieve production and confirmed that hyperbaric tunnelling was characterised by long duration exposures at pressures which were considered high by the industry but which were relatively low when compared with commercial diving. Additionally there was a cluster of DCI events around 2.0 bar and 4 hours exposure. They arose from a number of contracts where 4-hour exposures were worked. Otherwise the DCI events were reasonably spread over the range of pressures and times worked. There was one outlier representing a DCI event following a long shift at low pressure. Such exposures were not uncommon during the earlier part of the study period however CMAs would now advise against such long exposures.

A number of measures of DCI incidence were identified and subsequently those incidences were quantified. The advantages and disadvantages of each measure were considered. Because of the extent to which it was possible to remove inconsistencies in the raw data, data quality has not adversely affected the overall results in this section, to a significant extent.

Numerically, there was apparently little difference between the CBR for current data and that for Evans' data (CIRIA, 1992). At around 0.6%, both CBRs were well below the 2% considered acceptable in the past. However the breakdown of exposures by pressure and time, the considerable change in exposure patterns, which has occurred in tunnelling since around 1980 showed the unsatisfactory nature of CBR.

The matrix used in determining SBR, for calculating the number of exposures in each pressure and time increment was not subject to statistical averaging whereas Evans used a statistical rounding technique to compensate for the highly skewed distribution of exposures within his dataset. The results are considered not to have been affected by this.

The SBR was calculated and considered to be a useful comparator when used in conjunction with large numbers (>10000) of exposures. Because of the variation in exposure numbers, the SBRs for individual contracts were not considered to be as significant as the difference in their numerical values might suggest. The SBR accounts for differences in exposure pressure and time but does not take contractual variation into account. Some of the high SBRs were for contracts of short and/or intermittent duration and this could have been a factor in the variability. Whether site management was also a factor could not be determined. The one outcome from the calculation of SBR which was important, was that overall, the current incidence of DCI was more than twice that which would have been expected from long term average data (CIRIA, 1992). Those data were dominated by the big hand-dug road tunnels and the trend is now very much to short interventions as part of mechanised tunnelling. Human factors such as changing eating/exercise patterns affecting fitness and weight, better training and awareness of risk, the compensation culture, changing social attitudes and expectations about work could all affect the occurrence and reporting of DCI, as could tolerance of the discomforts of DCI.

Perhaps the reasons for the increased incidence of DCI do not matter in this study. DCI events occurred and had to be treated. The author has regularly reviewed cases of DCI with CMAs and together found reasons from industry folklore to excuse DCI occurring – "he was cold", "he fell asleep with his arm against the airlock wall", "he was susceptible". However in the end, the conclusion was always reached that the manner in which the work in compressed air had been undertaken reflected the industry norms. Therefore to be effective, the decompression regime with all its inadequacies, must include an allowance for these industry norms.

SERF which has been introduced for regulatory purposes, is sensitive to pressure and time but more importantly it highlights the increasing risk to the individual with increasing hyperbaric stress. Today's tunnelling industry operates in a risk-based environment and SERF is compatible with this approach. The SERFs from current data tend to be higher than those published in the Guidance (HSE, 1996). This is consistent with an SBR of around 2.4.

The DCI/HW results confirmed the finding by Evans (CIRIA, 1992) that long shifts apparently presented a lower risk to the workforce compared to shifts of shorter duration. This arose through the combination of higher SERFs for long exposures, and hence a greater risk of DCI from individual exposures, coupled with a correspondingly much greater reduction in the number of long shifts required to achieve the same amount of productive work. A balance between the risk from an individual exposure and the overall number of DCI events arising from a given amount of productive work is required. At present that balance favours reducing the risk from an individual exposure.

The proportion of shift workers (shift production and shift skilled) experiencing DCI and the proportion of all DCI they experience, was a salutary reminder of the extent to which shift workers were the real victims of DCI whatever the CBR.

The extent of the occurrence of DCI after low exposure stress exposures was surprising and reflected badly on the effectiveness of the decompression regime undertaken in tunnelling.

Although Type 1 DCS remained the dominant form of DCI in tunnelling and engineers are not professionally competent to comment on its long term detrimental effects on health, its resolution still required the man to undergo treatment for what was work-related ill-health. The results demonstrated an incidence affecting shift-workers which could be considered unacceptable. Fortunately the occurrence of Type 2 DCS was very low. The link between DCS Type 1 and DON also justified steps to reduce the DCI incidence.

The extent to which comparisons were made with other hyperbaric experience was limited as it was found that little was to be gained from the exercise. Although the results from this study were within the range from elsewhere, the limited validity of the measures used, and the massive difference in DCI incidence between tunnelling and diving, rendered the exercise somewhat valueless.

By whatever measure DCI incidence was calculated, the extent of the ill-health experienced by shift workers in the period covered by the study, was unacceptable and justified the decision by HSE to introduce an improved decompression regime.

Chapter 5 - Human response to DCI

There is a range of physiological and behavioural response from those undergoing hyperbaric exposure in tunnelling and experiencing DCI, including susceptibility to DCI - Section 5.1, tolerance of DCI – Section 5.2, and possibly acclimatisation to compressed air – Section 5.3. The caveat "within the bounds of normal compressed air practice" should be applied to any trends identified in this chapter.

5.1. Susceptibility to DCI

A decompression table is a balance between the risk of DCI and commercial expediency. For commercially available tables, a small but finite percentage of exposures will result in DCI. When they were introduced, the 1958 Tables were predicted to result in a CBR of 2% (Walder, 1967; p 65). With longer decompression, a smaller percentage of exposures would have resulted in DCI but the unproductive costs would have been greater. What, if anything, within the "engineering perspective" marked out those who were susceptible to DCI?

Susceptibility to DCI following hyperbaric exposure varies with the individual. Both inter and intra-individual susceptibility can be demonstrated. There is inter-individual susceptibility in that only a percentage of a shift will experience DCI on a given day and intra-individual susceptibility in that someone undergoing a similar exposure on consecutive days will only occasionally suffer DCI after exposure. Some individuals could be considered particularly susceptible or "bends prone" in that they experience repetitive or multiple DCI events.

Decompression, as shown by Table 4.17, is the primary factor in susceptibility to DCI. Various other factors thought to influence susceptibility to DCI have been put forward over the years but there is a lack of evidence to support them. Those which arose during the development of knowledge about compressed air working, were discussed at length in Chapter 2. Amongst recent authors whose work is relevant to this issue were Evans (CIRIA, 1992) who discussed the relative influence on susceptibility of a range of factors associated with a man's exposure history and Colvin (2003) who found no statistically significant factor, from a range of personal characteristics and physiological factors, predisposing someone to repetitive DCI. Both studies are important in that they make use of UK data. No other country is thought to have as extensive a collection of exposure data on which to undertake research, as the UK.

From the earliest reports of compressed air working, authors have speculated that obesity was a predisposing factor. It was not found to be statistically significant in Colvin's study but as a further check, HSE is undertaking a project involving the analysis of a CMA's records, in which one of the objectives is to reassess the role of obesity in susceptibility to DCI.

5.1.1. Questions to be answered

What if any, were the differences in exposure history and DCI experience between men who experienced a single DCI event on a contract and those who experienced multiple events? Could these differences be used to identify men who were particularly susceptible to DCI?

Likewise the differences in exposure history between men who experienced DCI and those who did not could have been considered, however a difficulty with this was to devise a way of selecting the exposures for men not experiencing DCI with which to make comparisons. One approach would have been to select the "controls" whom Colvin identified for his case control study (Colvin, 2003) and this would have given a list of men with many similarities in occupation and exposure to those experiencing DCI. However it would not have resolved the question of which of their exposures to use for comparison. To have made the assumption that they would have experienced DCI had they each undergone one more exposure than they actually did would have generated an exposure history. It would not have given exposure pressure and period. Perhaps that could have been taken as the exposure with the same exposure number as that which caused DCI in their matching case. In the event such assumptions were considered to be too contrived to make the resulting analysis meaningful.

5.1.2. Methodology

The methodology adopted was to use simple graphical and arithmetical techniques to compare a number of aspects of the DCI experience and exposure history of those experiencing DCI and identify any trends or differences arising.

5.1.3. Number of exposures before first DCI event

From a simple examination of database DCI, it could be seen that there was considerable variation in the number of exposures undergone by the individual before the first DCI event occurred. For some, their first exposure resulted in DCI whilst others underwent around 200 exposures before experiencing DCI. Figure 5.1 is a cumulative plot, by percentile, of the number of exposures to a person's first DCI event for those experiencing both single and multiple DCI events. It was compiled from the DCI events for the 282 men for whom the man's full exposure history existed. Figure 5.1 can be interpreted to imply that if an individual was going to experience DCI, his first DCI event was most likely to occur during the early part of his exposure history. In fact, 50% of those experiencing DCI had their first DCI event within their first 14 exposures. Jardine *et al* (CIRIA, 1992; p 63) quoted an equivalent figure of 50 days but for large contracts of much longer duration. The current finding should be qualified by an examination of the distribution of total numbers of exposures undergone (Table 5.1) which showed that around 20% of men underwent no more than 14 exposures in any case.

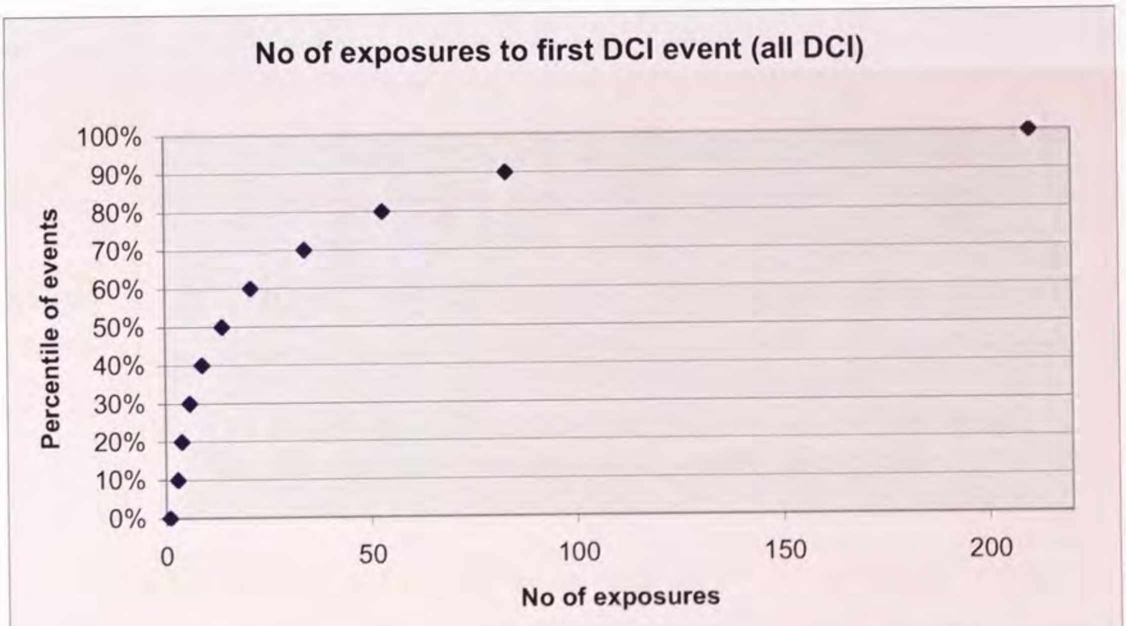


Figure 5.1 - No of exposures to first DCI event

Figure 5.1 also shows that around 10% of individuals experiencing DCI, underwent 100 – 200 exposures before experiencing DCI. To some extent the data were selected in that the number of exposures undergone by a man was limited either by the duration of work on a contract or by the man's decision to cease work in compressed air. The former restricted the number of exposures undergone for reasons outwith the man's control.

It is possible that if work in compressed air had been undertaken for longer on each contract, a small number of men would have experienced DCI after even greater numbers of exposures than shown in Figure 5.1. Similarly the difference between at least some "bends free" and "bends prone" men may only be in the number of exposures undergone.

Distribution of number of exposures to first DCI event and distribution of number of exposures undergone					
	No of exposures to first DCI event		**Number of exposures undergone**		
Percentile of men	**Men experiencing more than 1 DCI events**	**Men experiencing 1 DCI event**	**Men experiencing more than 1 DCI events**	**Men experiencing 1 DCI event**	**All men (see Fig 4.1)**
10	3	3	8	5	1
20	3	5	18	16	3
30	5	7	23	25	7
40	7	10	42	36	12
50	10	16	60	49	20
60	16	25	72	61	33
70	22	39	97	77	53
80	41	66	139	101	82
90	57	88	159	144	140
100	129	210	275	296	457
see Fig 5.2	■	◆	×	▲	
Average **(Range)** **No of men**	21.9 (1 – 129) 89	33.5 (1 - 210) 196	74.2 (3 – 275) 89	63.7 (1 – 296) 196	49.5 (1 - 457) 2331

Table 5.1 - Distribution of number of exposures to first DCI event and distribution of number of exposures undergone

Table 5.1 which except for the final column, is based on the 285 men experiencing DCI for whom full exposure histories were available, gives a comparison in terms of exposure history between men experiencing one DCI event and those experiencing more than one event. Figure 5.2 illustrates this comparison. In terms of the number of exposures to their first DCI event, Figure 5.2 illustrates that men experiencing more than one DCI event on a contract (■) consistently experienced their first event after fewer exposures than men experiencing one DCI event only (◆). In terms of the number of exposures undergone, Figure 5.2 also illustrates that men experiencing more than one DCI event (×) generally underwent more exposures than men experiencing one DCI event only (▲). Thus men experiencing more than one DCI event had their first DCI event earlier and undertook more exposures than men experiencing one DCI event only. This may explain why they experienced more DCI. The second group may have gone on to experience more DCI had they undergone more exposures.

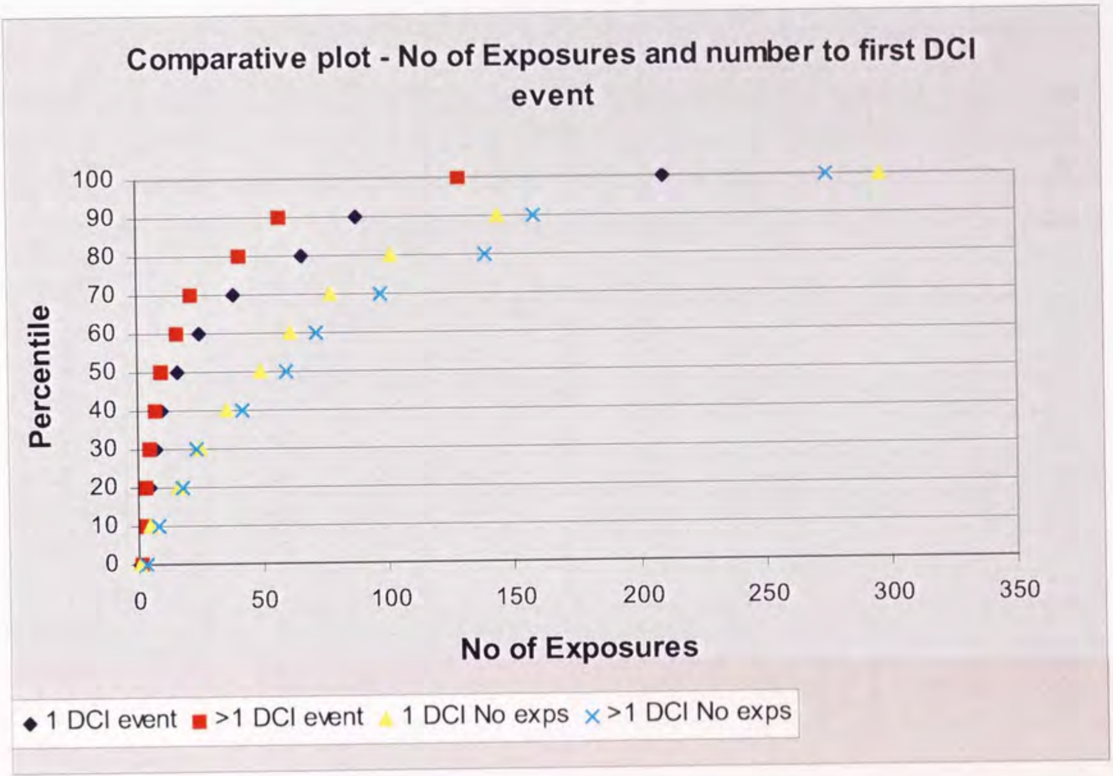


Figure 5.2 – Comparative plot – total number of exposures and number of exposures to first DCI event (see text for details)

Figures 5.1 and 5.2 were based on the number of the exposure resulting in DCI, in a man's exposure history as opposed to the number of days from the start of his exposure history. In compiling these plots it was recognised that all men did not start on the same day and thus a man's exposure history was based on exposure number rather than on date to eliminate some of the differences due to variations in start date. The not unreasonable assumption was also made that their exposure history followed a consistent pattern and could thus be expressed by exposure number rather than by date. Factors such as irregular exposure pattern or incorrect decompression could have triggered a DCI event but were ignored as they all went to make up typical industry practice.

The two curves showing number of exposures to first DCI event are clearly separate. Nothing could be found in this difference on which an individual's susceptibility to DCI could be assessed.

5.1.4. Repetitive DCI

Contract	**No of men with multiple DCI Events**				**Total DCI**	**Total men**
	DCI x 1	**DCI x 2**	**DCI x 3**	**DCI x 4**		
Bacton	3				3	**3**
Bideford	10	6	2		28	**18**
Cromer	17	8	4	1	49	**30**
Ennerdale	6	2			10	**8**
Fylde	10	1			12	**11**
GYPP	4				4	**4**
Hastings	4				4	**4**
Hull	5	1			7	**6**
JLE 105	31	10	3		60	**44**
JLE 110	11	5	1	1	28	**18**
Lowestoft	6	1	2	1	18	**10**
LWRM	18	12			42	**30**
N Woolwich	13	3	4	1	35	**21**
Ramsden Dock	28	6	1		43	**35**
Royal Docks 9	12	6	1		27	**19**
Southport	6	1			8	**7**
Swanage	4	5	1		17	**10**
Swansea 5	13	6	1		28	**20**
Weston	5				5	**5**
Total no of men	**206**	**73**	**20**	**4**		**303**
Men % of total	**67.99%**	**24.09%**	**6.60%**	**1.32%**		
%Men 1 DCI						**67.99%**
%Men >1 DCI						**32.01%**
Total DCI	**206**	**146**	**60**	**16**	**428**	
DCI % of total	**48.13%**	**34.11%**	**14.02%**	**3.74%**		
1x DCI as %					**48.13%**	
> 1x DCI as %					**51.87%**	
Avg DCI/Man						**1.41**

Table 5.2 – Breakdown of single and multiple DCI events by contract

(for contracts on which DCI occurred)

For a considerable time it has been recognised that a relatively few men are particularly susceptible to DCI and contribute disproportionately to its occurrence on a contract (see Section 4.5.5). The distribution of such men in the contracts within the current study can be seen from Table 5.2.

Table 5.2 was compiled from the 428 DCI events in Database DCI and gives a breakdown by contract of the number of DCI events experienced by individuals along with some summary information. The maximum number of DCI events experienced by an individual in the current study was four, however other studies have recorded men experiencing considerably more e.g. Robinson (1967) reported up to nine DCI events for each of two men at Vancouver. A total of 303 men were identified who had experienced DCI over the contracts in the study. Some men experienced DCI on more than one contract, so the number of individuals was somewhat less (see Section 5.4). As all contracts except Swansea 5 and Swansea 6 (see Section 3.4.3) were stand alone contracts, the double-counting of these men was considered to be appropriate.

Table 5.2 shows that for men experiencing DCI, each averaged 1.41 DCI events and that 32% of those men accounted for 52% the DCI events recorded i.e. a third of the men accounted for a half of the DCI. This disproportional DCI experience is illustrated in Figures 5.3 and 5.4 and its consequences are considered further in Section 6.1.4.

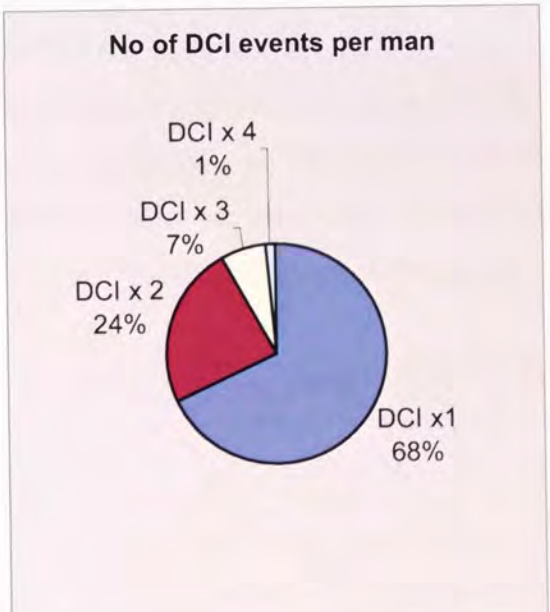


Figure 5.3 – No of DCI events per man

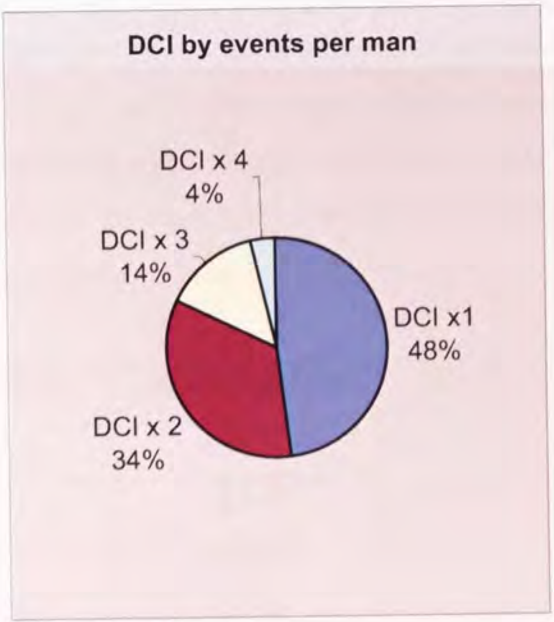


Figure 5.4 - DCI by events per man

In Figure 5.3, the number of men experiencing DCI is broken down by the number of DCI events experienced per man e.g. the **◖-coloured** sector indicates that 24% of men experiencing DCI experienced 2 DCI events. In Figure 5.4, the total number of DCI events accounted for by these men, is similarly broken down using the same colour scheme e.g.

the **◖-coloured** sector indicates that 34% of the total number of DCI events recorded was accounted for by men experiencing 2 DCI events. The disproportionate effect of men experiencing multiple DCI events can be seen when the information presented in Figures 5.3 and 5.4 is compared e.g. 24% of men experiencing DCI experienced 2 DCI events but these men accounted for 34% of the total number of DCI events recorded.

5.1.5. *Influence of Shift*

Evans (CIRIA, 1992) found that the occurrence of DCI differed with the shift worked. According to him the incidence of DCI was greatest on back shift (CIRIA, 1992; p 22).

Shift data were not directly available for many exposures. A brief analysis was made of the respective incidence of DCI on each of the three working shifts per 24 hours (see Table 5.3). There was no record of shift for 2 DCI events and the records for a further two noted "evening" shift. Table 5.3 shows that the number of DCI events was highest on the night shift, followed by the back shift. As a first approximation, it could be assumed that the number of exposures would have been approximately the same on each shift. Although the data were not available, it is assumed that the greatest number of exposures was on day shift as day shift working only was undertaken on some contracts. In addition there would have been numerous short exposures by intermittent supervisory personnel (see Section 4.5.5). Such visits would rarely have been undertaken at night. Had the data been available, an alternative for comparing the incidence of DCI on each shift would have been to compare the SBRs for each shift using the full dataset for reference.

Shift	No of DCI	% of total DCI
Day	119	28.07%
Back	136	32.08%
Night	169	39.86%
Total	424	100%

Table 5.3 – Occurrence of DCI events by shift

In the past, such variation may allegedly have been due to a desire by the back shift to decompress quickly and get to the pub or to poor lock-keeping practice during the night when supervision was lax. There is nothing in normal working practice which makes back shift or night shift different from day shift, therefore no explanation within the "engineering perspective" other than differences in supervision levels can be given for this result. The findings were more of curiosity as to why the incidence of DCI continues to be greater on a particular shift, than of importance in influencing working or decompression practice.

5.1.6. Concluding remarks

The main findings were that as a group, men experiencing multiple DCI events, had their first DCI event after fewer exposures than the group of men experiencing one DCI event only. Additionally they underwent more exposures than the latter group. The greater number of exposures and having the first DCI event earlier in their exposure history may account for this difference. The differences in DCI experience over time were not sufficiently marked to provide a means of identifying men likely to experience multiple DCI events.

In addition, those experiencing multiple DCI events accounted for a disproportionately large number of all DCI events recorded. This was not new information but it formed the basis for one approach to reducing DCI whilst retaining air-only decompression (see Section 6.1.4).

The most likely time for DCI to occur was the night shift, followed by back shift. This varied slightly from Evans' comments (CIRIA; 1992) that back shift was the most common time of occurrence.

5.2. Tolerance of DCI

Whilst compiling database DCI, it was apparent that a proportion of those suffering DCI did not wish to repeat the experience and immediately ceased working in compressed air. The majority appeared to do so voluntarily as it was only in a very small number cases that the records noted the man ceased work on medical advice.

Men voluntarily ceasing work after a DCI event, would have resulted in an element of self-selection in the workforce. Even with replacement – with an average 1 in 8 chance per replacement man of DCI (see Table 4.23) - the long term working population would have been made up of those who were disproportionately "healthy" i.e. not susceptible to, less susceptible to or tolerant of DCI. This would have had the effect of slightly reducing the incidence of DCI in the long term.

5.2.1. Questions to be answered

What were the differences in exposure history and in what way could they have influenced some men to cease working in compressed air immediately after a DCI event whilst others continued working?

As a DCI event appeared to be the trigger for some men to cease working in compressed air, was it the experience of DCI or something about the exposure itself, which brought about the decision to cease work?

5.2.2. Methodology

The most reliable way to answer this would have been to ask the men concerned but that was not possible retrospectively. Also, their reasons could have been subjective. An objective assessment was desired.

The methodology adopted was to use simple graphical and arithmetical techniques to compare a number of aspects of the exposure history of those experiencing DCI to identify trends or differences.

Obviously a large number of men ceased working in compressed air on completion of a contract and without ever having experienced DCI. It was possible that in a very few cases, a man experienced DCI on his final exposure at the end of a contract. This was checked by comparing the date of final exposure with the contract end date. Because of the shift pattern not all men would have finished on the same day but the shift exposure pattern would have been clear. On Fylde contract two men experienced DCI on their final exposure and within five days of the end of the contract but as neither was a shift production worker with a regular exposure pattern, their precise status could not be confirmed. Otherwise all men who left work voluntarily did so before the end of a contract.

5.2.3. DCI experience

Of 303 men who experienced DCI, exposure histories were available for 285 of them. These data were taken from database DCI. Those excluded were from the Bideford contract for whom DCI data but not exposure data were available. Of these 285 men, 67 (23.5%) ceased work in compressed air immediately following a DCI event (see Table 5.4). A further 17 (5.9%) did so within 2 exposures of a DCI event but were not included in the analysis below.

Contract	**No of men experiencing DCI**	**No of men ceasing work following a DCI event**
Great Yarmouth Power Project	4	0
Hull	6	2
Hastings	4	0
Bacton	3	1
Weston super Mare	5	0
Swansea 5	20	5
Swanage	10	1
Fylde Coast	11	7
Jubilee Line Extension 105	44	11
Jubilee Line Extension 110	18	7
Cromer	30	6
Southport	7	0
Ennerdale	8	2
Ramsden Dock	35	13
Royal Docks Ph 9	19	1
London Water Ring Main	30	4
North Woolwich	21	7
Lowestoft	10	0
Totals	285	67

Table 5.4 – Number of men experiencing DCI - by contract

The effect that experiencing multiple DCI events had on a man's decision to cease work in compressed air was examined. Table 5.5 shows that the more DCI events a man experienced, the more likely he was to cease work in compressed air immediately following a DCI event. This outcome was not unexpected as each DCI event presumably highlighted to the individual affected, the health risks associated with such work.

No of DCI events experienced "X"	Men experiencing "X" DCI events		Men ceasing work in compressed air after "Xth" DCI event	
X	Number	% of Total	Number	% (of men experiencing X DCI events)
1	196	68.8	41	20.9
2	67	23.5	16	23.9
3	18	6.3	8	44.4
4	4	1.4	2	50.0
Total	**285**		**67**	**23.3**

Table 5.5 – Work outcome following DCI event

Those who experienced DCI were divided into two groups – men who ceased work after a DCI event and men who did not. The percentages of each group experiencing 1, 2, 3, or 4 DCI events respectively and the average number of DCI events per man (expressed as DCI events per hundred men (since no one can experience part of a DCI event)) are shown in Table 5.6. The group of men who ceased work had experienced slightly more DCI than those continuing work. This was a logical outcome.

No of DCI events "X"	Following their "Xth" DCI event			
	Men who ceased working in compressed air		Men who continued working in compressed air	
X	Number	% of group	Number	% of group
1	41	61.2	155	71.1
2	16	23.9	51	23.4
3	8	11.9	10	4.6
4	2	3.0	2	0.9
Totals	**67**	**100.0**	**218**	**100.0**
No of DCI events per hundred men		**157**		**135**

Table 5.6 – Effect of number of DCI events on decision to cease work

The nature of the DCI event could also influence the decision to cease working. A DCS Type 2 event would obviously be more serious than a DCS Type 1 or similar event such as niggles and could be more likely to lead to medical unfitness. Table 5.7 (which excluded one case of niggles considered to be neither DCS Type 1 or 2) confirmed that a man experiencing a DCS Type 2 event was much more likely to cease work than a man experiencing a DCS Type 1 or similar event. This was not unexpected.

No of DCS Type 1 (or similar) events	386
No of men ceasing work after DCS Type 1	59
% of DCS Type 1 events after which men ceased work	15.3%
No of DCS Type 2 events	14
No of men ceasing work after DCS Type 2	8
% of DCS Type 2 events after which men ceased work	57.1%

Table 5.7– Effect of type of DCI event on decision to cease work

5.2.4. Exposure history

The exposure history prior to experiencing DCI was examined to determine if there were obvious differences in the number and severity of the exposures after which a man ceased working in compressed air. Severity was judged by visual examination of figures 5.5 and 5.6 below along with an assessment of average P√T values in Table 5.8.

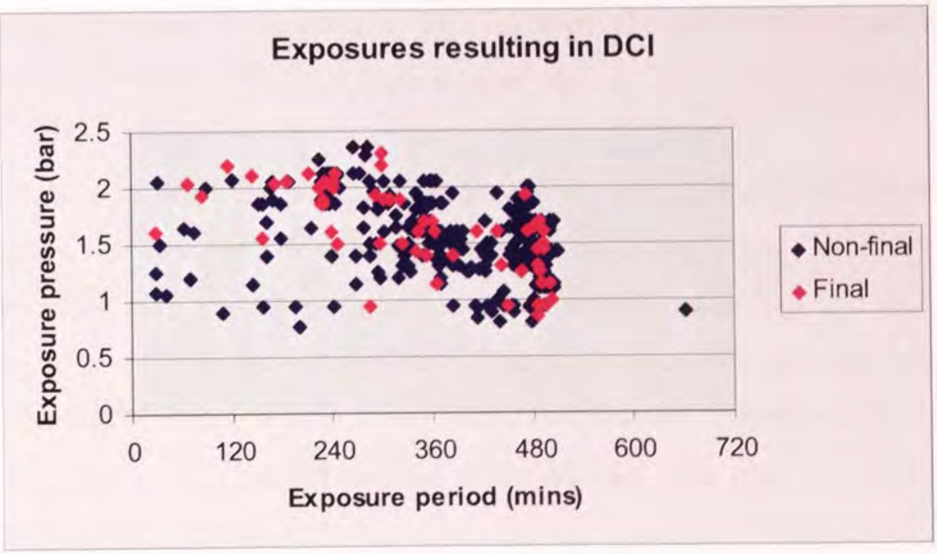


Figure 5.5 – Exposures resulting in DCI for all men

Figure 5.5 shows all the exposures resulting in DCI for men who continued working (◆) and for those who ceased working in compressed air (◆) following a DCI event. On purely visual examination of the spread of data points by pressure and exposure period, there was little obvious difference in the spread of exposures experienced by both groups except that relatively low pressure short exposures (<1.5 bar for 4 hours) resulted in DCI but not in anyone ceasing to work in compressed air. It was assumed that the proportion and working patterns of those who continued working to those who ceased working were sufficiently similar on each contract, that they could be averaged over all contracts without inducing unacceptable error (see Table 5.4). Consequently no obvious difference between the distribution of the exposures undergone by each group would have been expected.

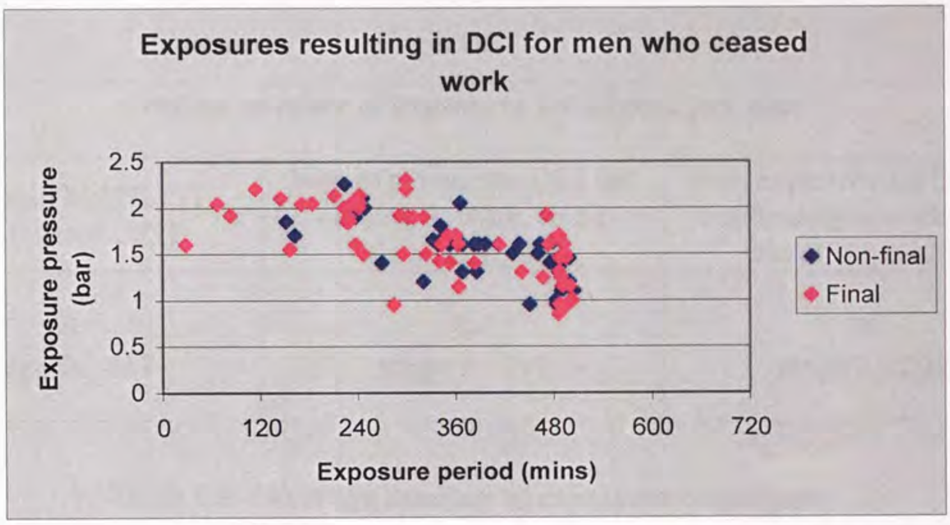


Figure 5.6 – Exposures resulting in DCI for men who ultimately ceased work in compressed air

Figure 5.6 relates to men who ultimately ceased work in compressed air following a DCI event and shows all exposures resulting in DCI for that group. Some exposures resulted in DCI but not in the man ceasing work (◆); some exposures resulted in DCI after which the man ceased work (◆). Some men did not cease work until after having experienced as many as four DCI events. Again from visual examination it appeared the severity of exposure, in terms of exposure pressure and period, had little impact on the decision to cease work. This was not unexpected.

P√T was used as an approximate measure in comparing the severity of exposure of the two groups, to confirm the visual assessments. The conclusion from visual comparison is supported by simple numerical averaging as shown in Table 5.8. The limitations in the use of P√T were discussed in Section 4.5.6.

Group	P√T - Non-final exposure	P√T - Final exposure
Men who ceased work in compressed air following DCI (n = 67)	48.05 (n = 33; range = 35.14 – 55.95)	46.00 (n = 67; range = 14.00 – 63.44)
Men who continued work in compressed air following DCI (n = 218)	48.37 (n = 334; range = 11.39 - 60.61)	Not applicable

Table 5.8 – Approximate numerical comparison of exposure severity

Average number of exposures undergone per man		
All men in MANLIST No of men = 2331	Men experiencing DCI but ceasing to work in air No of men = 67	Men experiencing DCI but continuing to work in air No of men = 218
49 range 1 – 457	30 range 1 - 147	76 range 2 - 296

Table 5.9 - Average number of exposures undergone

Table 5.9 shows that for those for whom full records were available, the 67 men who experienced DCI and ceased work immediately thereafter, on average worked fewer than half the number of shifts than the 218 men who experienced DCI and did not cease work immediately thereafter. As the average exposure history for all men in MANLIST was 49 exposures, men ceasing work also worked fewer shifts than the overall average. This was consistent with the decision to cease work following a DCI event and was not unexpected.

The final aspect of exposure history which was examined, was the number of exposures to each DCI event for the two groups of men.

It can be seen from Table 5.10 that men who ultimately ceased work in compressed air experienced their DCI events earlier in their exposure history than men who did not cease work. This result was consistent with the findings in Table 5.9 regarding numbers of exposures worked by the respective groups. As severity of exposure resulting in DCI had been similar for the two groups (see Table 5.8) more similarity in the number of exposures to each DCI event might have been expected.

Group	Avg no of exposures to 1st DCI event	Avg no of exposures to 2nd DCI event	Avg no of exposures to 3rd DCI event
Men who eventually ceased work	20.06 (n = 67; range 1 – 103)	28.15 (n = 26; range = 3 - 103)	61.40 (n = 10; range = 20 - 105)
Men who continued work despite DCI	32.42 (n = 218; range = 1 - 210)	52.54 (n = 63; range 4 - 147)	73.58 (n = 12; range 11 - 166)

Table 5.10 – No of exposures to 1st, 2nd and 3rd DCI events

5.2.5. Concluding remarks

The main findings were that 23.5% of men experiencing DCI ceased work in compressed air immediately after a DCI event and had as a group, experienced proportionately more DCI events and at an earlier stage in their exposure history than those who continued working. Men who ceased work immediately after experiencing a DCI event undertook on average fewer than half as many exposures as men experiencing DCI and continuing work. However as a group, the exposures which led to their final DCI event were of approximately similar severity in terms of exposure pressure and period as well as $P\sqrt{T}$, to the exposures leading to DCI for those who continued working. Additionally their final exposure was no more severe than previous exposures they had undergone and which had resulted in DCI but after which they had continued working in compressed air.

The main triggers for a man ceasing to work in compressed air after a DCI event therefore seemed to have been the number and frequency of previous DCI events experienced and the severity of the final DCI event (in terms of Types 1 or 2 DCS). This outcome was consistent with normal human behaviour. Unlike a diver who always works under pressure, a tunnel worker has the option of seeking employment on contracts where compressed air is not being used. Tunnel workers therefore have the luxury of being able to tolerate DCI until they decide that “enough is enough”. However that tolerance is clearly finite.

5.3. Acclimatisation

The existence or otherwise of acclimatisation to compressed air – the phenomenon whereby exposure to compressed air apparently creates some form of resistance to whatever causes DCI – has been a topic of debate for some time. The Guidance extended the acclimatisation procedure from a single half shift on first exposure to a work-up period of up to four shifts (Paragraphs 165 - 171). Not all authors agree that acclimatisation exists. Le Péchon (1995) for one, has long been critical of the UK's approach to acclimatisation.

5.3.1. Background

The study which first identified acclimatisation in compressed air workers is considered to be that by Paton and Walder (1954) at the Tyne Tunnel in 1948 – 50 (Walder, 1968). They concluded that acclimatisation or "adaptation" occurred in compressed air workers and was of sufficient importance that some form of gradual induction to compressed air should be introduced to counteract the initially high incidence of DCI. This was not taken forward in the 1958 Regulations but a requirement that a first exposure should be for a half shift only, was included in CIRIA Report 44 (1973; p 9). They also concluded that acclimatisation could be lost following an increase in pressure or following a number of days of non-exposure. Other studies such as at Auckland Harbour Bridge (Rose, 1962) and at Dartford (Walder, 1968) supported these findings. Because the tunnelling industry cannot provide continuity of employment, miners seek alternative work possibly within the construction industry, or opt not to work, between contracts. Accordingly at the start of a contract they may be less physically fit than they were at the end of their previous contract.

Paton and Walder and later authors have never definitively described the mechanism behind the phenomenon. CIRIA Report 44 (1982; p 35) specifically noted "It is a fact, so far unexplained that man can become acclimatised to working in compressed air". Possible explanations offered included the suggestion that an individual had a reservoir of available bubble nuclei which was depleted during the first few exposures to compressed air; or that bubble nuclei were generated by the rupture of muscle fibre due to an individual being unaccustomed to hard physical work or that successive exposures resulted in nerve endings becoming fatigued and no longer sensitive. Rose (1962) likened it to getting fit for exercise. Eckenhoff and Hughes (1984) in a diving study, suggested possible mechanisms for acclimatisation were a reduction in nuclei and body evolved gas load or a change in the body's response to bubbles. Lambertsen *et al* (1999) agreed that the sources of nuclei remained to be established.

The studies by Paton and Walder and Rose were carried out on groups of workers engaged in hand tunnelling techniques on individual sites over relatively long periods. At Tyne, Paton and Walder's acclimatisation study covered combinations of men and exposure, from 120 men over 10 exposures up to 30 men with over 300 exposures each.

There was no opportunity with current working patterns, to study so many men for so long on a single contract. To avoid problems with small data samples, the current study of acclimatisation was based on data from a number of contracts, only some of which involved extensive hand excavation at relatively high pressures. Similarly with working patterns tending towards short intermittent periods of exposure, acclimatisation if it existed, might no longer be achieved. The results in this section should be viewed in the light of these caveats. Whereas Paton and Walder studied acclimatisation in a group of men, an objective of the current study was to consider if the phenomenon could also be demonstrated in individuals.

5.3.2. Questions to be answered

Could acclimatisation in the workforce, defined as a decrease in DCI incidence with time (but not necessarily its elimination), be demonstrated from current data? Could acclimatisation in the individual, defined as an increased number of exposures between successive DCI events, also be demonstrated? Was acclimatisation a population or individual phenomenon and were there limits to when or for how long into a man's exposure history it occurred?

5.3.3. Methodology

The approach taken to address these questions involved the use of arithmetical, statistical and graphical techniques (see Section 3.5.6).

Paton and Walder calculated the daily bends rate over a given number of days for their group of men, each of whom had experienced one or more DCI events. They showed that within the group, there was a trend towards decreasing daily bends rate with time. Apparent acclimatisation through the self-selection of susceptibles out of the group was avoided as all in the group experienced the same number of exposures. Paton and Walder allowed for changes in the demand for labour during the contract, by basing each man's exposure history on his first day in compressed air rather than on a calendar date. This meant that each man in the group did not experience precisely the same pattern of exposures however Paton and Walder considered this an acceptable approach.

Paton and Walder's approach was followed in Section 5.3.4 of this study to the fullest extent possible by selecting the records of men experiencing DCI and undergoing 20 or more exposures, from the current data.

Section 5.3.5 explores another approach, graphically based, to demonstrate if acclimatisation occurred over the period of a contract. This was a method which the author had used in the past to demonstrate the concept of acclimatisation to colleagues. The cumulative number of DCI events was plotted against date on the reasonable assumption for many contracts, that daily exposure numbers were roughly constant. The curve should have given a plateau shape if acclimatisation had occurred. As a check the exposure pressure was plotted against date, to show any major changes in pressure which could have influenced the DCI outcome. One failing of this approach was that whilst the number of exposures per day could be shown to remain roughly constant, no allowance was made for new workers starting during a contract to replace susceptible individuals who had self-selected out of the workforce, thus enhancing any trend towards acclimatisation.

Section 5.3.6 examines the variation in CBR and SBR with the number of exposures on a contract to discover any discernible patterns. The analysis involved the reasonable assumption that the number of men on a contract, and hence the number of exposures, was roughly dependent on the duration of the work to a much greater extent than on the tunnel diameter. In addition it ignored the fact that some exposures had arisen from shaft sinking.

In respect of individual response, it was considered that acclimatisation in bends-susceptible individuals would be demonstrated if for individual men, there was a trend of increasing numbers of exposures between successive DCI events. The assumption was made that each man's exposure had been on a sensibly regular basis and that increased exposure severity was not the trigger for a DCI event. Additionally there was the possibility that acclimatisation, if it existed, only occurred over the initial few exposures of individuals' exposure histories. This required some analyses to be undertaken for specific numbers of exposures.

Men who experienced two and three DCI events respectively, were selected from the group of men known to have experienced DCI and the relationships between the number of exposures to their first DCI event and then between subsequent DCI events were examined and reported in Sections 5.3.7 and 5.3.8.

5.3.4. Acclimatisation in the workforce

Following a similar approach to that of Paton and Walder (1954), a group of 218 men, each of whom had undergone at least 20 exposures to compressed air and had experienced DCI, was identified from database DCI. The daily bends rate was calculated for this group and is given (as a decimal fraction) in Table 5.11 with a plot of the data in Figure 5.7.

Day Number	Bends Rate (as decimal fraction)	Day Number	Bends Rate (as decimal fraction)
1	Omitted	11	0.0367
2	0.0367	12	0.0229
3	0.0505	13	0.0229
4	0.0183	14	0.0459
5	0.0550	15	0.0092
6	0.0321	16	0.0321
7	0.0321	17	0.0275
8	0.0183	18	0.0092
9	0.0505	19	0.0092
10	0.0229	20	0.0229

Table 5.11 – Daily bends rate

The data point for Day 1 was omitted from the analysis as a man's first exposure should have been restricted to the second half of the shift in accordance with the requirements of CIRIA 44 (1973; p 9), and hence not representative of subsequent exposures. Linear regression analysis as used by Paton and Walder, showed that a relationship of the equation $y = -0.0013x + 0.0436$ ($r^2 = 0.2734$) fitted the data. The relationship was significant at the 5% level. In line with the recommendations of Miller (2006) for Figure 5.8 below, a similar non-linear relationship was tested for Figure 5.7 but gave a marginally less good fit ($y = -0.0103\ln(x) + 0.0523$, ($r^2 = 0.2337$)) than the linear relationship for the 20-day period in question although over a longer period it would have been a better fit.

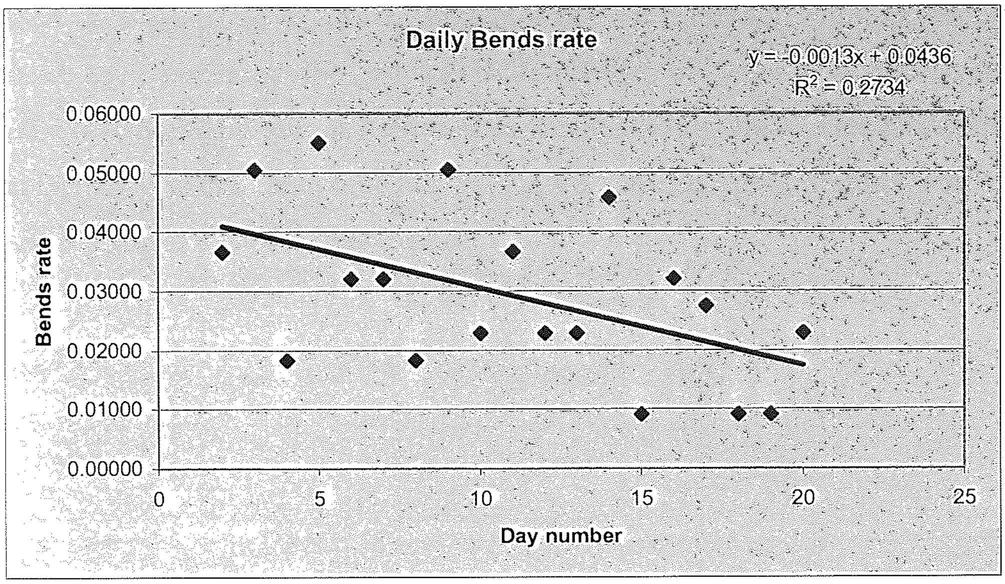


Figure 5.7 – Daily bends rate

The analysis illustrated in Figure 5.7 was restricted to a cohort of men, each of whom had undergone 20 or more exposures and experienced DCI within their first 20 exposures.

An acclimatisation trend was also demonstrated when the whole workforce was considered (Figure 5.8). The analysis illustrated in Figure 5.8 was of the daily bends rate over each of up to the first 50 days of a man's exposure history. To calculate the daily bends rate for Figure 4.8 again as a decimal fraction, the number of exposures for day one was taken as the number of men undergoing one or more exposures; for day two the number of men undergoing two or more exposures and so on up to day 50. The respective daily number of exposures was then reduced by a factor of 0.9005 to take account of the 9.95% of all exposures in spreadsheet TOTAL795 which occurred at pressures below 0.7 bar and hence did not result in DCI. The number of DCI events per day was obtained from Database DCI. Figure 5.8 shows that the daily bends rate decreased with time in what, by observation, was a non-linear manner. Miller (2006) suggested that a single non-linear relationship was appropriate for this analysis as a linear relationship when extrapolated, gave a negative bends rate which was illogical. Regression analysis showed that the equation $y = -0.003\ln(x) + 0.0137$ ($r = 0.711$) provided a good fit.

Part of any acclimatisation trend in the whole workforce could be accounted for by the self-selection out of compressed air working by those particularly susceptible to DCI. Against that, increases in working pressure were likely over the first few days of compressed air working as exposure pressure was built up to full working pressure and these could have increased the risk of DCI. Neither of these two effects could be quantified. Nevertheless Figure 5.7 showed an acclimatisation trend over 20 days for men experiencing DCI within that time whilst Figure 5.8 showed a similar trend for the workforce as a whole over a 50 day period.

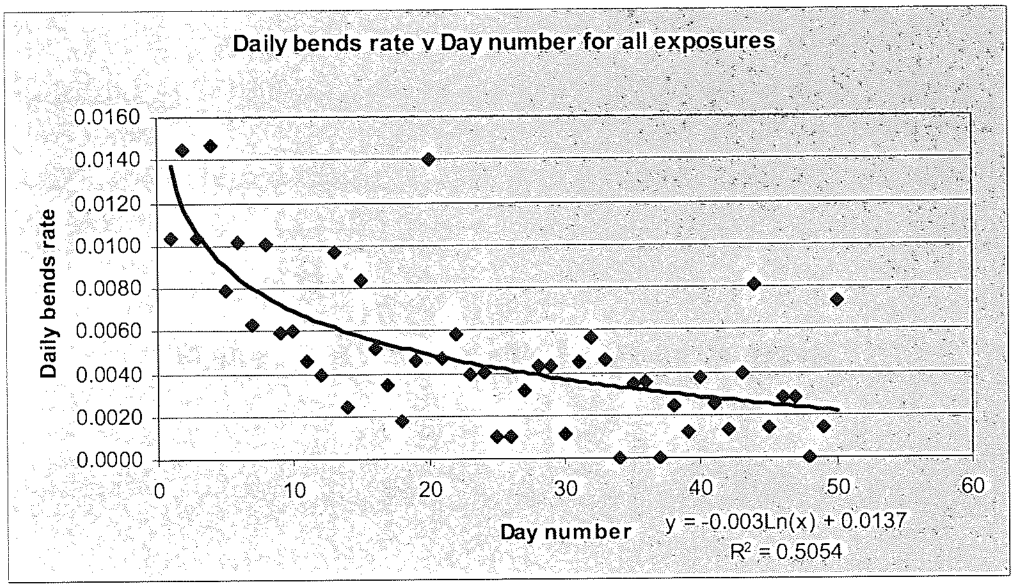


Figure 5.8 - Variation in daily bends rate with increasing numbers of exposures.

Because DCI is an all or nothing event, this analysis did nothing to indicate whether those not experiencing DCI - the majority of those exposed – became more or less likely to experience DCI. In this respect the "engineering perspective" is not particularly appropriate as an indicator of acclimatisation and some physiological measure may be more appropriate.

5.3.5. Cumulative DCI plots

Section 5.3.4 demonstrated a statistically significant acclimatisation trend in the overall workforce. A graphical method of demonstrating an apparent acclimatisation effect on individual contracts was to plot the cumulative number of DCI events on a contract against date. Such plots are shown for Ennerdale in Figure 5.9 and for LWRM in Figure 5.12 with their respective pressure profiles in Figures 5.10 and 5.13.

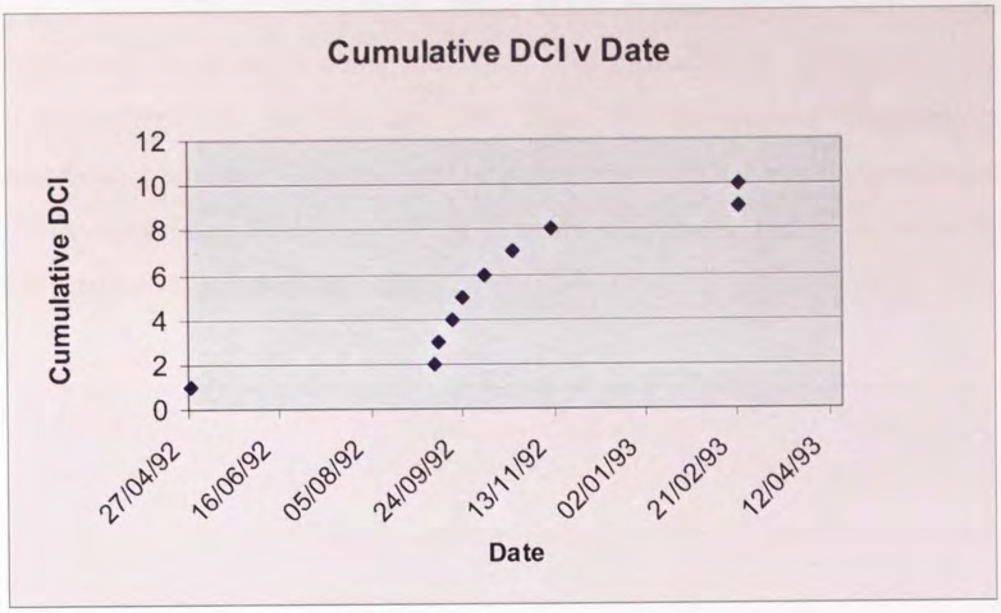


Figure 5.9 - Cumulative DCI v Date - Ennerdale

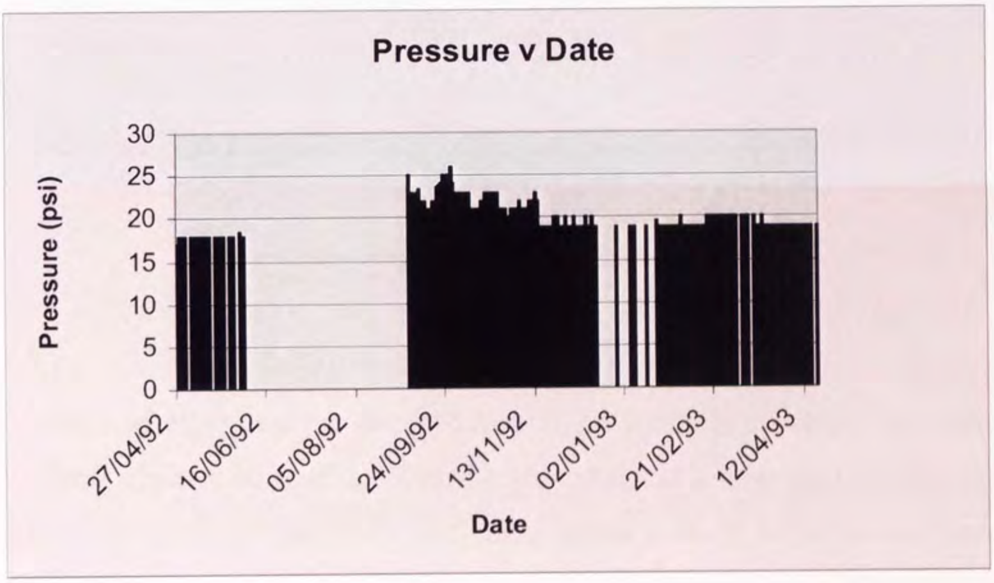


Figure 5.10 - Pressure v Date – Ennerdale

Figure 5.10 gives a profile of the Ennerdale contract in terms of working pressure against date. The author knew from his personal involvement in the contract that compressed air at around 1.25 bar (18 psi) had been used at Ennerdale to complete shaft sinking between April and June 1992. Following a set-up period of about three months, tunnelling under compressed air began at about 1.50 bar (22 psi) and continued until April 1993. In total 10 DCI events occurred on the contract. Figure 5.9 shows the cumulative distribution of DCI events with date. The rate of increase in the cumulative number of DCI events during tunnelling, as would be indicated by the slope of a curve joining the points, reduced with time which could be taken as some indication of acclimatisation. The curve “plateau’d” between November 1992 and February 1993, when the pressure was effectively constant. Acclimatisation is not taken as meaning the elimination of DCI merely a reduction in the frequency of occurrence, hence the two DCI events which occurred towards the end of the Ennerdale contract were not unexpected.

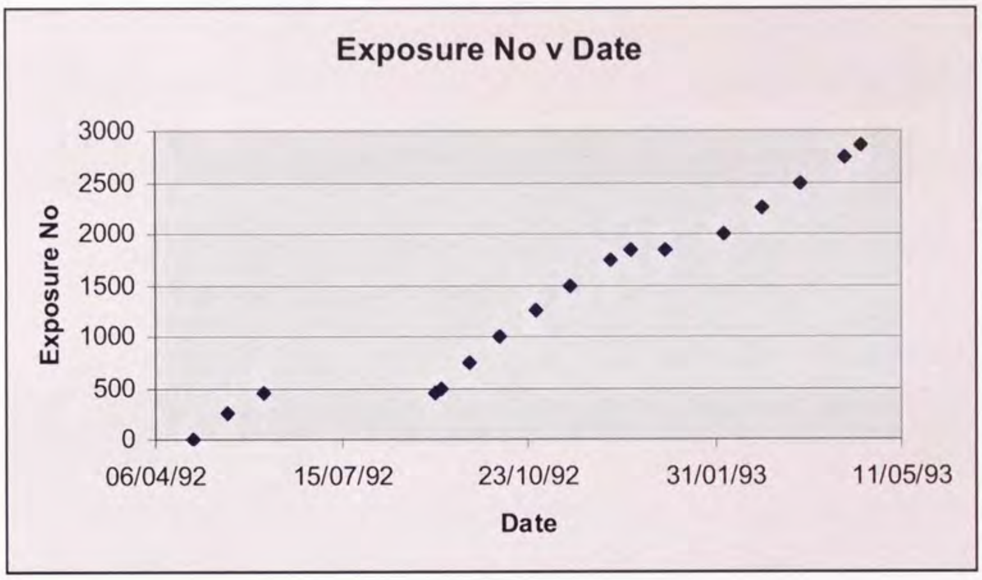


Figure 5.11 – Exposure No v Date – Ennerdale

Figure 5.9 shows an apparent acclimatisation trend however it was based on the premise that the number of exposures per day had been approximately constant. The accuracy of this assumption appears acceptable from the almost linear distribution of data points (at 250 exposure intervals) in Figure 5.11, excluding breaks in work shown as zero pressure in Figure 5.10.

In a similar exercise for the LWRM contract, Figure 5.12 shows that the cumulative number of DCI events rose sharply during the first month of compressed air working but that the rate of increase reduced considerably thereafter. Although Figure 5.13 shows that exposure pressure increased slightly during the initial few weeks of compressed air working, an apparent acclimatisation effect in the contract workforce was demonstrated by Figure 5.12.

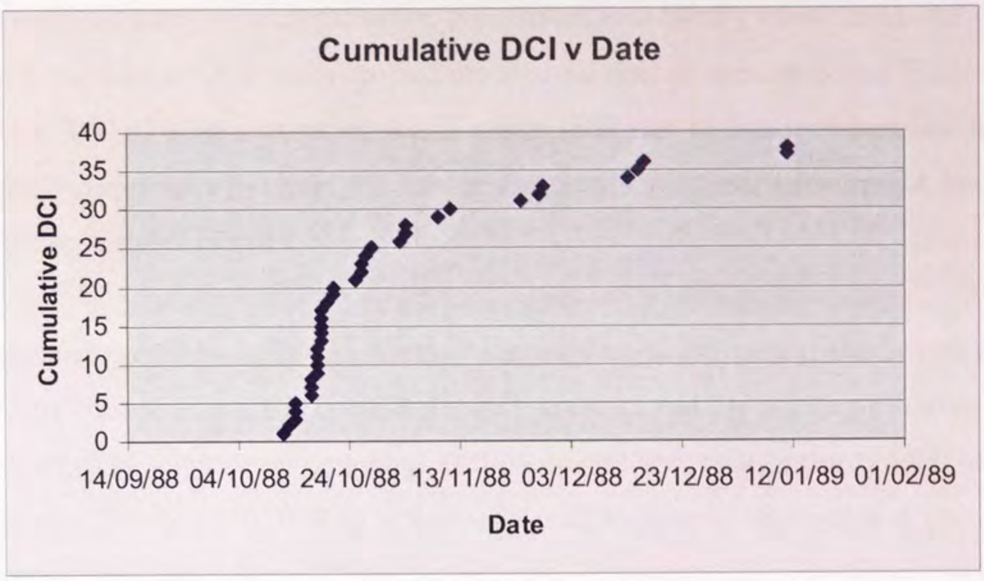


Figure 5.12 – Cumulative DCI v Date – LWRM

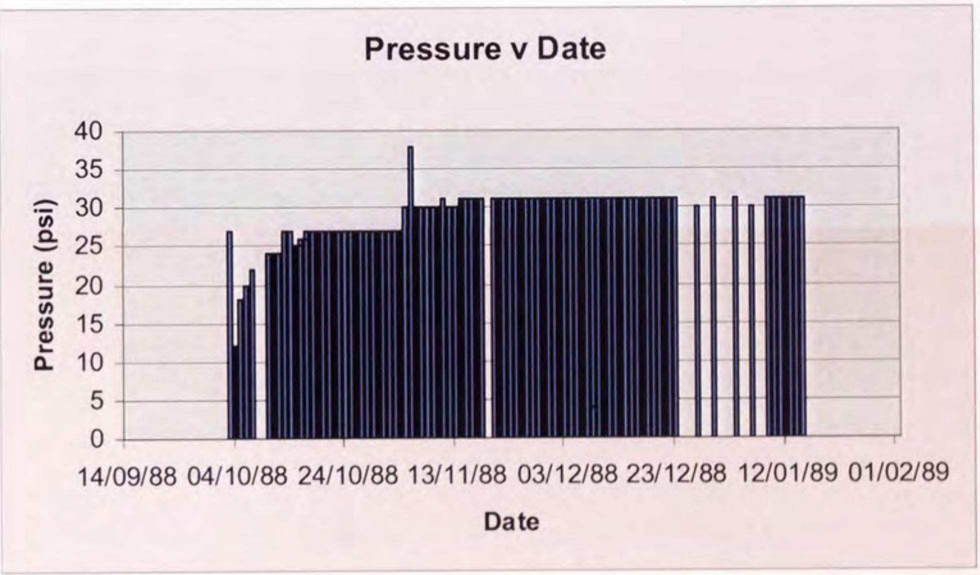


Figure 5.13 - Pressure v Date – LWRM

Figures 5.9 and 5.12 are similar to Figure 5.8 in that they do not allow for self selection out of the workforce by those susceptible to DCI and are thus taken as being indicative only.

5.3.6. CBR/SBR and numbers of exposures on contracts

The possibility of a statistically significant relationship between the number of exposures on each contract and the CBR (see Table 4.11) or SBR (see Table 4.16) for that contact which would indicate an acclimatisation-type trend was briefly considered. As CBR or SBR was a measure of DCI incidence and the total number of exposures (see Table 4.1 and spreadsheet TOTAL) on a contract was a crude indicator of contract duration with the greater the number of exposures the longer the contract period, there might have been some value in such an exercise.

The multipanel graphing facility in Axum® was used to quickly test if there were obvious relationships between the CBR or SBR for each contract and the number of exposures on that contract. The multipanel graphing facility meant the relationship could be tested simultaneously for the CBR/SBR as calculated for all exposures, exposures at and above 1 bar and exposures at and above 0.7 bar respectively. No statistically significant relationship was detected between any of the variables tested. However, some indications of the existence of an upper bound to DCI incidence as measured by CBR, were observed and are discussed briefly below.

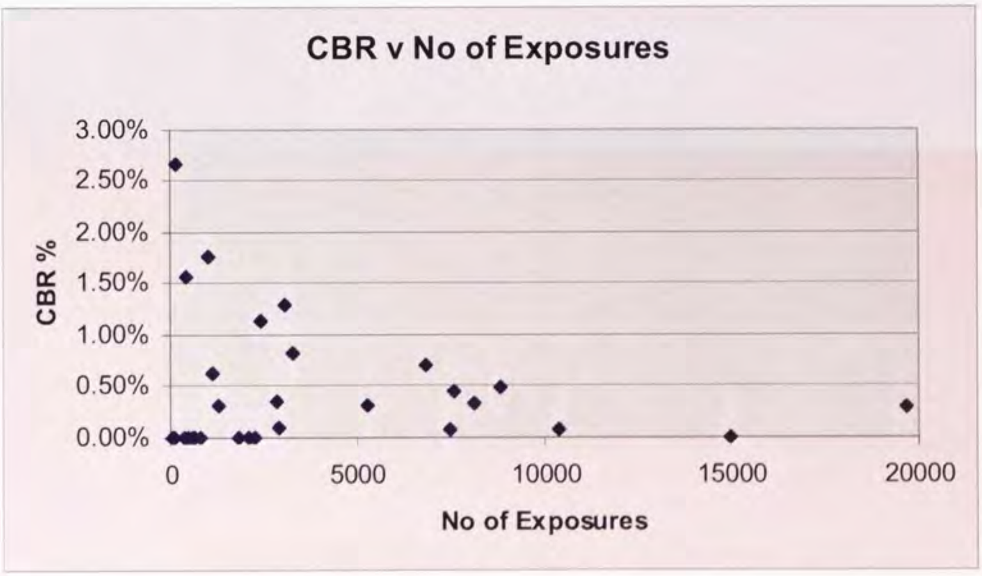


Figure 5.14 – CBR v Number of exposures (all exposures)

Figure 5.14 shows the relationship between the CBR ("all exposure pressures" in Table 4.3) and the total number of exposures on a contract. There was considerable scatter in the data points and the only trend which was apparent was a reduction in CBR with increasing numbers of exposures to the extent that an asymptotic curve reaching a CBR of around 0.2 – 0.4% for contracts with 10000 exposures and above, formed an upper bound on the graph. Apart from the unsatisfactory nature of CBR as a measure of DCI incidence, the contracts with the greatest numbers of exposures were Swansea and JLE 105, both of which were undertaken at pressures around 1 bar – pressures at which the incidence of DCI would have been expected to be low in any case.

Given that SBR had been identified as an appropriate comparative measure of DCI incidence, it was considered whether a similar upper bound existed in a plot of SBR against the number of exposures. Figure 5.15 is the plot of SBR against number of exposures. The data for GYPP and Hull were omitted because these SBRs were so high; however they could have been included using a log scale had the analysis been considered sufficiently important. Again the only apparent trend which could be determined was perhaps a relatively loose upper bound to the SBR with increasing number of exposures.

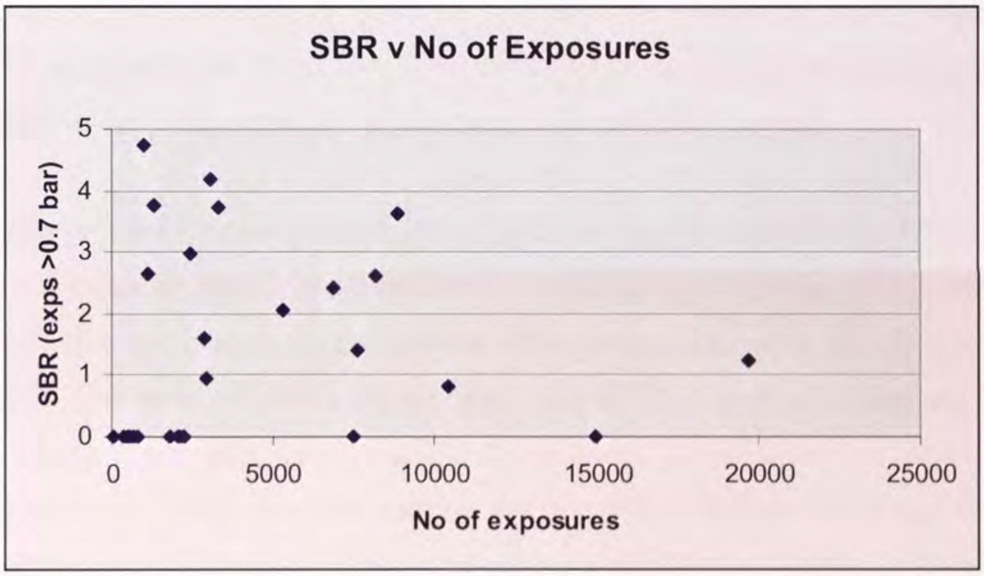


Figure 5.15 – SBR v Number of exposures
(SBR based on exposures >0.7 bar)

The conclusion was that an upper bound to CBR/SBR might exist which would reduce with increasing numbers of exposures on a contract, however any relationship was highly tenuous.

5.3.7. *Acclimatisation in the individual*

In this section it was considered if an acclimatisation trend could be demonstrated between a man's first and second DCI events.

The approach adopted in Section 5.3.4 was to examine changes in daily bends rates for a group and consequently it related to the workforce rather than to the individual. If acclimatisation arose from a physiological characteristic, then the phenomenon should have been demonstrable in both the workforce as a group and in individuals. It was not possible to identify any factor related to the tunnelling process or within the "engineering perspective" in relation to individual characteristics which could give rise to acclimatisation. Techniques required to identify acclimatisation if it existed, may therefore be outwith the "engineering perspective". Nevertheless attempts were made to determine if an acclimatisation trend could be demonstrated in the individual from the "engineering perspective" and are discussed in this and the following Section.

Using the Paton and Walder approach in Section 5.3.4, acclimatisation was demonstrated by a decreasing DCI incidence, in which the number of DCI events per day - "bends rate" - within the group reduced. At an individual level this equated to an increasing number of exposures between DCI events, given the group size remained constant.

To examine if there was an acclimatisation trend between an individual's first two DCI events, their exposure history was considered. For all men experiencing two or more DCI events, the relationship between the number of exposures to a man's first DCI event and the number of exposures between his first and second DCI events was examined but was found not to be statistically significant. The data initially analysed extended to a first DCI event on the man's 130^{th} exposure whereas the group data in Figures 5.7 and the group acclimatisation trend in Figure 5.8 extended only to a man's first DCI event within 20 and 50 exposures respectively. Consequently the relationship between the number of exposures to a first DCI event and the number of exposures between first and second DCI events was examined for men experiencing their first DCI event within their first 25 exposures only. Again no statistically significant acclimatisation trend was demonstrated.

That relationship was similarly examined when the first DCI event occurred during a man's first 15, 16th – 30th, 31st – 45th; and 46th – 60th exposures respectively. Apart from the first group, the limits resulted in fairly small samples (5 – 10 data points). Following a recommendation from Miller (2006) the linear relationship between the variables and between $\log_{10}$ of the variables was examined but in no case was a statistically significant relationship found.

Paton and Walder had demonstrated an acclimatisation trend in a group of men on the basis of a decreasing daily bends rate for only a limited number of days following first exposure. An analysis similar to that described earlier in this section was therefore repeated for groups of men in their data, selected by the number of exposures to their first DCI event.

The groups examined were those experiencing their first DCI event within their first 15, 25 and 50 exposures respectively. No group showed a statistically significant trend. Although there appeared to be an acclimatisation trend for men experiencing their first DCI event within their first 25 exposures (Figure 5.16) and such a trend could have been expected from Paton and Walder's findings on acclimatisation in the group, closer examination of Figure 5.16 shows that effectively there is a cluster of scattered data points without any relationship along with a single outlying data point which consequently has had an exaggerated effect on determining the position of the regression line.

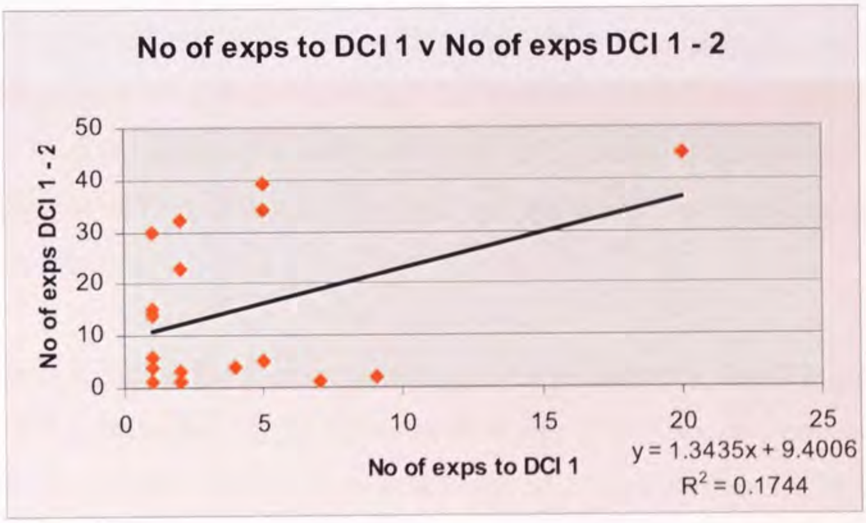


Figure 5.16 – No of exposures to 1st DCI v No of exposures 1st – 2nd DCI

(Paton and Walder data – DCI 1 in first 25 exposures; 19 data points r = 0.418, t = 1.895)

5.3.8. Individual acclimatisation over multiple DCI events

This section extended the examination of acclimatisation from two DCI events to three. In Section 5.3.7 it was shown that an acclimatisation trend could not be demonstrated in individual men experiencing two DCI events but as a check the analyses were extended to the first three DCI events in a man's history to determine whether similar results were obtained.

If acclimatisation arose from a characteristic specific to the individual, and could be shown to extend over the initial 20 exposures or thereabouts, any acclimatisation trend should not be limited to the first and second DCI events but should extend to further DCI events provided they occurred early enough in a man's exposure history.

To assess this, the records for the 22 men in database DCI, each of whom, had experienced three or more DCI events were examined. In particular the exposure history of the 9 men who experienced their first DCI event within their first 10 exposures was examined but no statistically significant relationship was found between the number of exposures separating their first, second and third DCI events respectively.

The exposure history of men experiencing their second DCI event within 10 exposures of their first was examined for an acclimatisation effect following their second DCI event. There were 13 men in this category, some of whom had also been in the group of those who experienced their first DCI event within their first 10 exposures. No statistically significant relationship was found between the number of exposures between first and second DCI events or between second and third DCI events. Likewise no statistically significant relationship was found in the same group, when their first and second DCI events were considered.

The analysis was repeated for men experiencing DCI within their first 22 exposures and their second DCI event within 22 exposures of their first (a 20 exposure criterion gave too few additional data points). This resulted in samples of 15 and 16 respectively but in both cases no statistically significant relationship was found between the number of exposures separating the respective DCI events.

On the basis of these findings, it was concluded that no statistically significant acclimatisation trend could be demonstrated in individuals.

The Paton and Walder data was again examined and similar analyses undertaken for men in their data, experiencing 3 or more DCI events and having their first DCI event within their first 20 exposures. As 18 of the 23 men in their data who experienced 3 or more DCI events, experienced their first DCI event within their first 20 exposures, that restriction was barely relevant.

Although an acclimatisation trend was detected, it was only significant at the 10% level, and consequently it was concluded that the relationship between the number of exposures up to first and between first and second DCI events could be discounted. Likewise no statistically significant trend was identified between the second and third DCI events.

Brief consideration was given to whether there was any relationship between acclimatisation and repetitive DCI. Table 5.12 was based on men experiencing their first DCI event within their first 10 exposures. The acclimatisation ratio was defined as the ratio of the number of exposures between first and second DCI events to the number of exposures to first DCI event.

Men with DCI in first 10 exposures and "x" DCI events overall	Average no of exposures to DCI 1	Average no of exposures between DCI 1 and 2	Acclimatisation ratio	Average total number of exposures
3 or more DCI events n = 9	4.4 range = 2 - 9	15.8 range = 1 – 61	3.6	70.6 range = 19 – 143
Only 2 DCI events n = 35	4.8 range = 2 - 10	20.9 range = 1 – 138	4.4	38.4 range = 3 – 238

Table 5.12 - Change in acclimatisation trend with number of DCI events

Table 5.12 shows that men experiencing three or more DCI events displayed less of an acclimatisation trend than those experiencing only two DCI events. This was logical, however as a check, the average number of exposures each group underwent was also calculated. As can be seen from Table 5.12, the group of men experiencing only two DCI events underwent considerably fewer exposures on average, albeit with a greater range, than the other group, which could explain why they did not experience more DCI. No conclusions were therefore drawn about acclimatisation trends from this.

To examine this further, it would have been necessary to consider individuals' exposure histories and DCI experiences across more than one contract. This is discussed in Section 5.4.

In view of the requirements for a longer acclimatisation period which came into effect through the Guidance in 1996, it was considered if there were enough data to undertake an analysis of contracts operating under the pre-1996 and post-1996 requirements. As only 69 DCI events would have been available, it was concluded there were insufficient data from post-1996 contracts to make such an exercise valid.

5.3.9. Discussion

Paton and Walder (1954) showed a decreasing daily bends rate for a group of men during their first 20 exposures, who were hand-excavating a tunnel which reworking of their data confirmed. They also showed a decreasing weekly bends rate over the duration of the contract (Paton and Walder, 1954; Fig. 3a). These trends were for the group as a whole and did not consider individuals' exposure history. However, the occurrence of acclimatisation in compressed air workers is not universally accepted. The current data were for a range of contracts, on some of which hand excavation was undertaken, with TBM interventions on others. The data covered a range of exposure pressures and thus could be considered more representative of compressed air working in general than those of Paton and Walder which were from a single contract. It could be however, that acclimatisation is less pronounced at lower pressures or in the absence of strenuous physical activity. In that case the current data, having been aggregated over a range of pressures and work patterns, would have been less indicative of an acclimatisation trend than contract-specific data from a single high pressure contract. However it was considered that there were insufficient DCI events arising on any one contract to make contract-specific analysis meaningful.

By following Paton and Walder's approach it was possible to demonstrate a decreasing daily bends rate in a group of men in the current data (Figures 5.7 and 5.8 along with Table 5.11). However an examination of the relationship between the numbers of exposures up to first and between first and second DCI events for individual men did not show a statistically significant acclimatisation trend even over the first 15 exposures. Likewise it was not possible to demonstrate a statistically significant trend between the number of exposures separating first, second and third DCI events for individuals. It was therefore concluded that acclimatisation could not be demonstrated at an individual level. In any case, no explanation seems yet to have been accepted by the hyperbaric community to explain possible physiological factors which could give rise to such a trend. Furthermore, when similar analyses were applied to Paton and Walder's data, the same results were found. These results cast doubt on whether it is acclimatisation or some other phenomenon which is being demonstrated. No reason can be advanced from the "engineering perspective" as to why an apparent acclimatisation trend should be demonstrable in a group and not at an individual level.

It was possible to confirm by other, less mathematically rigorous approaches and ignoring self selection, that an acclimatisation trend appeared to occur in the workforce over the period of individual contracts. Additionally whilst no statistically significant relationship existed between CBR/SBR and the number of exposures on contract, it was tenuously suggested that an upper bound existed to such relationships.

Because of the uncertainty over acclimatisation it could be questioned whether any benefits had arisen from the more onerous requirements for acclimatisation procedures in the 1996 Regulations. It was considered that any analysis undertaken to examine this it would have been of doubtful statistical validity as insufficient DCI events were available for analysis.

In all this work the implicit assumption has been made that external factors such as pressure changes, poor decompression practice and intermittent exposure were not the trigger for DCI. With the power of today's computers, it has become very easy to generate statistics, trend lines and graphs, which may be meaningless in physiological terms.

As part of the hyperbaric trials which HSE funded before introducing oxygen decompression (Lamont *et al*, 2002), regular Doppler monitoring of the trials subjects was undertaken. Analysis of the results did not show any evidence of a reduction of Doppler bubble score with exposure time. This was consistent with the findings of Eckenhoff & Hughes (1984) from a diving study which failed to show any statistically significant reduction in Doppler scores over 12 days of diving trials. The extent to which Eckenhoff and Hughes' findings were due to inadequacies in Doppler technology at the time, or reflected a valid finding are unknown. Likewise the extent to which reductions in Doppler bubble grades could be taken to infer an acclimatisation effect manifested as a decreasing incidence of DCI is also unknown. It is suggested that more extensive examination of the use of Doppler monitoring in situations such as this could be undertaken to examine this issue further.

It is also recommended that acclimatisation should be subject to further research from a fundamentally different aspect than the "engineering perspective" of exposure and DCI history. In view of the limited amount of compressed air working anticipated to occur in the UK in the foreseeable future it is unlikely that this will be feasible. In 2003, the author tried unsuccessfully, to persuade contacts in a non-UK Labour Inspectorate to undertake large scale Doppler monitoring to determine if any time-related changes in bubble count could be detected.

5.3.10. Concluding remarks

The author believes that DCI is not an all or nothing event, merely the manifestation that an individual has gone beyond some trigger threshold after which physical symptoms have manifested themselves. This threshold may vary from day to day. Consequently individuals may be close to the DCI trigger but not beyond it and hence do not have DCI. A similar view was recently expressed by Doolette (2003). Examination of the number of exposures between DCI events was an attempt from the "engineering perspective" to discover if an acclimatisation trend existed. In this respect, it is suggested that it would be necessary to go beyond the "engineering perspective" into some form of physiological monitoring of men for a period immediately following decompression, to confirm whether or not an acclimatisation trend exists. The question of which physiological parameters to measure would have to be addressed.

5.4. Susceptibility/Acclimatisation across contracts

Within the group of men exposed to compressed air on a contract, some individuals are more susceptible to DCI than others (see Section 5.1) with some of the group experiencing multiple DCI events (see Section 5.1.4). To what extent is this, a function of the contract or the individual?

Similarly, some of those exposed on a contract may demonstrate an acclimatisation effect (see Section 5.3), but do they display similar effects on other contracts?

5.4.1. Background

The tunnelling industry comprises a relatively small number of firms with a workload which is somewhat intermittent in nature. The workforce has traditionally been peripatetic because of the lack of continuity of employment. Many have worked abroad in places such as Cairo, Singapore and Hong Kong. No evidence was found of any information which has been published on patterns of employment in the UK industry. It is known within the industry (and demonstrated to some extent by the data analysed for this Chapter) that miners, tunnel fitters and tunnel electricians regularly move between tunnelling contracts and contractors but most contracts do not involve work in compressed air.

It would be reasonable to assume that men who were susceptible to DCI on one contract would be equally susceptible on others.

5.4.2. Questions

There were a number of questions to be answered. To what extent did men work across a number of contracts and experience multiple DCI events on more than one contract? To what extent did men show similar response to compressed air exposure over contracts and did acclimatisation occur to a similar extent in men who worked on more than one contract?

5.4.3. Methodology

The proposed methodology was to identify all the men in database MANLIST who had worked on more than one contract and also those who had experienced DCI on more than one contract from database DCI. Then, using graphical and arithmetical methods, it was intended to compare their exposure and DCI histories across all the contracts on which they worked to answer the questions in Section 5.4.2.

Two conditions had to be met for this to be achieved. A sufficiently large group of men who had worked on more than one contract had to be identified and a sufficiently large proportion of these men had to have experienced DCI. Differences in exposure pressure and time had to be addressed to make valid comparisons. It had been considered this would be difficult as $P\sqrt{T}$ (see Section 4.5.6) was not a particularly valid comparator. SBR could have been used (see Section 4.4.2) to compare overall DCI experienced but the number of exposures could have been too small to give a meaningful comparison. The approaches set out elsewhere in this chapter could also have been used

5.4.4. Data quality and manipulation

Although the quality of data in databases DCI and MANLIST was good, both databases had been constructed from the raw data described in Section 3.6 and were subject to all the inconsistencies in it. Nevertheless no better data existed elsewhere.

Database MANLIST was searched electronically for duplicate surnames. 598 records from MANLIST were identified using the "find duplicate records" facility in Lotus Approach®. Those who had worked on more than one contract were separated from those with the same surname on a single contract. Had NI numbers been available for all men, this operation would have been straightforward, however only 236 records contained a NI number. For the remainder it was necessary to resort to other means to allocate men to the appropriate group.

Access to the data used by Colvin (2003) was available and HSE happened to have on file, details of those medically examined by a certain CMA from the 1990s. Colvin's data indicated those within a cohort of individuals who had undergone previous work in compressed air and those from that group who had experienced DCI. The CMA's data covered JLE 105 and Southport contracts amongst others and comprised names and some NI numbers along with brief histories of some individuals' previous exposure.

When there was no NI number, knowledge of the industry and its working practices was used to identify the remainder of the men who had worked on more than one contract. When a duplicate name check involved JLE 105 or Southport, a decision was made on the basis of other information before the existence of an NI number or previous exposure history in the CMA's data was checked. This allowed the accuracy of the technique to be tested. The procedure was found to be correct in the majority of cases. Eventually it proved possible to resolve around 90% of the records.

The information on which these techniques depended included the author's knowledge of individuals' work history, which allowed him to determine which name variations referred to a particular individual, or to confirm that identical names on a number of contracts referred to one individual. This applied particularly to supervisory personnel with whom the author had had a professional relationship.

Another procedure which was used related to similarity in name along with association of name and occupation. Where records had name variations associated with certain well defined occupations such as TBM operator, it was assumed that all referred to only one individual. For example, a man with an uncommon surname which recurred across a number of contracts, was referred to as "caulker 'X'" on one contract and given the occupation "caulker" on another. For others there was a group of occupations which indicated career progression in tunnelling – miner becoming leading miner, becoming pit boss.

Even where NI numbers were given, a few inconsistencies occurred. In all cases these could be reconciled as transcription errors e.g. "77" instead of "YY". With some records, diminutives of names could be recognised in the records e.g. B (Bob) = R (Robert).

For other records, a pattern of continuity of employment with a single employer could be determined - Ennerdale, Rochdale and Royal Docks 9 were all undertaken by the same contractor over a period of time. For JLE 107 and Ramsden Dock contracts, the link was through the same German JV partner. For other records the link was in the number of men all moving from one particular contract to another being undertaken around the same time period. Dates of first and last exposure were then used as a further check. In each of these situations, it was considered reasonable to assume that where a similar name arose on more than one contract, they referred to one individual.

Yet another link was between multiple records for a single name but for which only some had identical NI numbers. This was assumed to indicate a history of compressed air work involving only one man.

The main reason for being unable to resolve duplicate surnames was the lack of NI number along with the predominance of relatively few surnames of predominantly Irish origin amongst the miners. Their spread of Christian names was similarly limited.

A similar analysis of database DCI, was undertaken for those experiencing DCI. This resulted in 13 individuals being identified who potentially met both criteria in Section 5.4.3, from the 303 individuals identified in the study as experiencing DCI. This was a much lower figure than had been expected when drafting the study objectives.

The 13 men had each experienced DCI on two contracts. However, as before, further information was needed to confirm if the duplicate surname referred to one or two individuals. NI number would have been the most reliable identifier however this information was missing from most of the records. Attempts were made over a nine month period to obtain NI numbers directly from the CMAs however it proved impossible to obtain this information as they either could or would not respond within the required timescale. The same procedures were used for processing similar names from database DCI as for MANLIST. As a result it was concluded that 4 men had experienced DCI over more than one contract with a further 6 who had possibly done so.

5.4.5. Patterns of multiple exposure and DCI

From the analysis of database MANLIST it was possible to identify with reasonable certainty, 220 men who had worked on two or more contracts. Table 5.13 shows a breakdown by occupational group and by the number of contracts on which they had worked.

No of contracts	**Occupational category**					**Total**
	Occupation unspecified	**Regular supervisory**	**Intermittent supervisory**	**Shift skilled**	**Shift production workers**	
13			1			1
7			1			1
6			2		1	3
5			2			2
4			1	2	7	10
3	1	5	10	17	12	45
2	4	19	34	25	76	158
Total	5	24	51	44	96	220
Breakdown	2.3%	10.9%	23.2%	20.0%	43.6%	100%
Breakdown of workforce by occupational category (Table 4.23)	8.1%	9.7%	19.1%	14.7%	48.4%	100%

Table 5.13 - Men identified as having worked on two or more contracts (by occupational category)

A further 25 men had possibly worked on multiple contracts but there was insufficient information in their records – non-availability of NI numbers - to be certain. Table 5.14 provides information on these men who were predominantly shift production workers. The author was the person having "worked" on 13 contracts and MLAs made up the majority of the men working on 5, 6 and 7 contracts respectively. In total these men experienced an insignificant number of exposures but over numerous contracts. Typically in the author's case it was one exposure per contract.

It can be seen from Table 5.13 that the majority of shift workers who worked on multiple contracts did so on two contracts with only a few working on three or more.

Occupational category	**No of men**
Occupation unspecified	1
Regular supervisory	1
Intermittent supervisory	2
Shift skilled	0
Shift production workers	21
Total	25

Table 5.14 - Men identified as possibly having worked on two or more contracts (by occupational category)

The distribution of occupational categories for men working on more than one contract (Table 5.13) was compared to that for the overall workforce from database MANLIST (Table 4.23) using a χ^2 test ($\chi^2 = 7.57$; 4 degrees of freedom). This result which was based on total numbers in the groups, corresponded to a 20% probability level. There was therefore no evidence the groups were drawn from different populations. In practice the differences could be explained in that regular supervisory staff would be more likely to have a career structure within a company and hence transfer between contracts. Shift skilled workers in tunnelling such as fitters and electricians work with plant and equipment which is not commonly found elsewhere in the construction industry and hence are in demand specifically for tunnelling work. There were fewer "occupation unspecified" as over a number of contracts there was a greater availability of information on occupation. Had it been possible to resolve all the queries over identity for those in Table 5.14, the proportion of shift production workers would have more closely reflected that in Table 4.23.

It was concluded that those working on a number of contracts were a statistically significant representative sample of compressed air workers by occupational category. The assumption was therefore made that that they should have experienced DCI over the range of contracts on which they worked in proportion to the average for their respective occupational category in Table 4.23 which would have reflected the spread of pressure and exposure periods across contracts.

The 220 men with confirmed multiple contract experience accounted for 539 or 22.6% of the entries in MANLIST. It was possible to identify with certainty only four men who had experienced DCI over more than one contract. Each of them had experienced three DCI events over two contracts, one having worked on a further contract without experiencing DCI (Table 5.15). On the assumption that the 220 men could have been expected to have experienced DCI with the average incidence of their occupational groups (Table 4.25), this means that (in whole numbers) 37 DCI events would have been expected affecting 27 men (Table 5.16).

Man number	Occupational category	No of Contracts worked	No of contracts on which DCI experienced	Total no of DCI events experienced
Positively identified				
1	Shift prod'n	2	2	3
2	Shift prod'n	2	2	3
3	Shift skilled	3	2	3
4	Reg supervis	2	2	3
Total no of DCI events for positively identified men				12
Possible				
1	Shift prod'n	2	2	2
2	Shift prod'n	2	2	2
3	Shift prod'n	2	2	4
4	Shift prod'n	2	2	2
5	Shift prod'n	3	3	4
6	Shift prod'n	2	2	5
Total no of DCI events for "possible" men				19

Table 5.15 - Details of men experiencing Multiple DCI across contracts

A further six men had possibly experienced DCI over multiple contracts (Table 5.15) and it was thought worthwhile to include them in the analysis (Table 5.17). The pool of compressed air workers was sufficiently small that despite the lack of NI numbers the information available indicated there was a reasonable chance they had worked on multiple contracts. In any case their inclusion gave a limiting case. Accordingly (in whole numbers) the expected number of DCI events rose to 43 with the expected number of men experiencing DCI rising to 31 (see Table 5.17).

Occupational category	**No of men working multiple contracts**	**% of Occ category experiencing DCI (from Table 4.23)**	**Expected no of men experiencing DCI**	**Average DCI per man (from Table 4.25)**	**Expected DCI events**
Occ unspec	5	3.7	0.2	1.14	0.2
Reg sup	24	7.0	1.7	1.31	2.2
Int sup	51	2.8	1.4	1.13	1.6
Shift skilled	44	12.4	5.5	1.33	7.3
Shift prod'n	96	18.6	17.9	1.45	25.9
Total	**220**		**26.7**		**37.2**

Table 5.16 – Expected number of DCI events

Table 5.16 summarises the results of the analyses.

Excluding "possibles"				**Including "possibles"**			
Total number of men = 220				**Total number of men = 245**			
No of Men experiencing DCI		**No of DCI events**		**No of Men experiencing DCI**		**No of DCI events**	
Expected	Actual	Expected	Actual	Expected	Actual	Expected	Actual
26.7	**4**	**37.2**	**12**	**30.7**	**10**	**43.0**	**31**

Table 5.17 – Summary of multiple contract data

From Table 5.17 it is clear that when "possibles" were excluded, considerably fewer men than expected experienced DCI (by a factor of around 6.5). Additionally the number of DCI events they experienced was clearly less than expected (by a factor of around 3). When "possibles" were included similar results were obtained however the factors were of a smaller magnitude. This outcome was considered to be due to men working on more than one contract, self selecting on the basis of their relative lack of susceptibility to DCI which could have been attributable either to their personal physiological characteristics or their occupational category. This was logical given the other employment opportunities within the tunnelling industry for which exposure to compressed air was not required.

5.4.6. Concluding remarks

The results from this section of the study were surprising but not illogical. It would appear that men self-selected out of compressed air working and this was not appreciated when the study objectives were being drafted. Along with availability of work, susceptibility to DCI would appear to be a factor in determining on which contracts tunnellers work. The hypothesis that men would be equally susceptible to DCI across contracts has neither been proved or disproved and the problems of differentiating between and comparing exposures of varying hyperbaric stress have not had to be resolved.

The sample of men who experienced DCI on more than one contract seemed to be too small to make further analysis meaningful. It is believed that a sample, at least one order of magnitude greater than that available would have been required before the variations in working practice would cease to have affected the outcome.

Given how few men worked on more than one contract and the outcome Section 5.3, there was absolutely no point in considering the issue of acclimatisation across contracts.

This study covered a snapshot in time, during which the amount of compressed air working diminished compared to the previous two decades. A similar analysis of an earlier period which included exposure of expatriate workers in Cairo, Singapore and Hong Kong might have resulted in a much larger proportion of men working on multiple contacts.

Chapter 6 - Reducing the incidence of DCI

In Chapter 4, it was demonstrated that the incidence of DCI for the period 1986 – 2001 was more than twice that for the period up to the early 1980s. Additionally, the incidence of DCI was one to two orders of magnitude higher than in commercial diving. In the mid 1990s the author was able to persuade colleagues in HSE that the incidence of DCI in tunnelling was unacceptably high and should be reduced "significantly". In this context, "significant" was defined as around one order of magnitude (HSE, 1999). Strategies for achieving that "significant" reduction were required.

One strategy involved the use of oxygen as an alternative breathing gas during decompression. However a number of influential individuals within HSE preferred the imposition of restrictions on exposure whilst retaining air-only decompression. The author believed that the use of oxygen would not in principle, curtail the use of compressed air as a working technique, however the restrictions necessary to retain air-only decompression would do so and would not address the fundamental issue of a less than adequate air-only decompression regime.

The author's proposal that HSE should adopt the use of oxygen decompression was eventually accepted but one of HSE's objectives in sponsoring this study was to determine whether the retention of air-only decompression would have been a reasonably practicable way of reducing the incidence of DCI.

To be consistent with HSE policy on hyperbaric safety in diving (Robertson and Simpson, 1996), any strategy to reduce the incidence of DCI in tunnelling, should not only aim to reduce the incidence of DCS Type 1 but to eliminate all cases of DCS Type 2.

6.1. Reduction in DCI whilst retaining an air-only decompression regime

DCI incidence is a measure of risk. When considering ways to reduce the incidence of DCI, the risk to the individual and the risk to the population exposed, should both be considered. A reduction in one would not necessarily result in a reduction in the other.

In practice the risk to the individual is a function of severity of exposure but more importantly, the effectiveness of the decompression tables. Severity of exposure is a function of exposure pressure and time. The severity of exposure can therefore be reduced by placing some restriction on it. As pressure is normally determined by ground/groundwater conditions, the ability to vary it is limited within the compressed air operation and therefore the severity of exposure can normally be reduced only by restricting the time of exposure. Decompression tables are not uniformly effective, as indicated by the variation in SERFs with pressure and time for the Blackpool Tables (see Table 4.17). The risk from decompression can therefore be reduced by prohibiting exposures within the parts of the tables deemed insufficiently effective.

It is a reasonable assumption on any contract, that the amount of work to be done is independent of the length of the exposures being undertaken. There is therefore an inverse relationship between the number of exposures and their duration within any contract.

The risk to the population is a function of the number of people being exposed, the number of exposures each person undertakes and the risk from each exposure undertaken. In practice for a particular contract, the only factor which can be varied is the risk per exposure i.e. SERF. In some circumstances it would only be possible to achieve a small reduction in SERF despite significantly reducing the exposure time. Consequently the total number of DCI events for the contract could increase if the increase in the number of exposures was disproportionately greater than the reduction in SERF.

In considering the case for a reduction in DCI incidence, the results in Section 4.5.5 relating to the distribution of DCI in the different occupational groups should also be considered. Any occupational disease affecting around 50% of a particular occupational group (shift production workers at LWRM and Cromer – see Section 4.5.5) must surely be unacceptable.

A range of restrictions were considered which reflected a number of possible ways of reducing the risk of DCI.

6.1.1. Interventions by the CMA

Prior to the commencement of this study, there were a number of attempts by CMAs to reduce DCI incidence, whilst retaining air-only decompression. In some cases the CMA imposed a restriction on exposure time whilst in others, men were decompressed as if they function of exposure pressure and time. The severity of exposure can therefore be reduced by placing some restriction on it. As pressure is normally determined by ground/groundwater conditions, the ability to vary it is limited within the compressed air operation and therefore the severity of exposure can normally be reduced only by restricting the time of exposure. Decompression tables are not uniformly effective, as indicated by the variation in SERFs with pressure and time for the Blackpool Tables (see Table 4.17). The risk from decompression can therefore be reduced by prohibiting exposures within the parts of the tables deemed insufficiently effective.

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Concern had grown during the 1990s over the apparently high incidence of DCI being experienced following a small number of fairly severe exposures on the LWRM and Cromer contracts and after low pressure exposures on the JLE 105 contract. On LWRM and Cromer, the CMA responded to that concern by restricting exposure periods to less than the maximum permitted under the Blackpool Tables.

Exposures at pressures of around 2 bar, were restricted from 6 hours to 4 hours although a maximum of 7.75 hours was permitted under the Blackpool Tables. For 6 – 8 hour exposures at 1.9 – 2.15 bar, the SERF was ~19% (8 DCI events in 42 exposures from Tables 3.3, 3.5 and 4.8). SERF peaked at ~23.5% on Cromer (4 DCI events in 17 exposures).

Apart from the work on DON by Evans (CIRIA, 1992), there was no specific evidence to suggest that an incidence of DCI – specifically DCS Type 1 - represented by SERFs of around 20% was harmful however such a high incidence of any occupational illness should in itself be a reason for action to reduce it. Such a high SERF, when compared to others for adjacent cells in the pressure-time matrix, was obviously a cause for considerable concern and one which forced the CMAs into imposing immediate restrictions on exposure time. At best to have continued without introducing a restriction on exposure, would have required a large number of exposures, none of which resulted in DCI, to have reduced the individual contract SERFs to single figure values. At worst these exposures would have resulted in considerable numbers of men unnecessarily experiencing DCI events. Whilst the restriction in exposure time addressed an acute problem arising in a very small sample, it had little potential, significantly to reduce the overall incidence of DCI in tunnelling.

On the Fylde contract, the CMA advised that decompression profiles, two tables greater in pressure than consistent with the exposure, should be used. Lamont (2002; p 14) noted some time ago, "This did not appear to significantly reduce the incidence of DCI but will be subject to further analysis in due course".

When that statement was made it was not known that a search of the contract records would show that a number of exposure records for the Fylde contract could not be located.

Exposure records for 245 of the 1360 exposures known to have been undertaken on the contract, have never been obtained from the contractor, despite a formal request from HSE for them. Critically, the missing exposure records covered 5 of the 12 DCI events which occurred on the contract. For the records which were available, the SBR was 2.66, which approximates to the average SBR for all contracts in this study. It was considered if there was any way in which allowance could be made for the missing data, but it was concluded that it could not. As the missing records accounted for only ~18% of exposures but for ~42% of DCI, their inclusion in the calculations would have would have resulted in an increased SBR and SERFs.

From the complete records available, it was concluded that no significant reduction in DCI incidence had been achieved by the use of a decompression profile two increments of pressure greater than that which was consistent with the pressure of the exposure undergone.

Following experience from JLE 105, before which it had been generally accepted that DCI was not a problem below 1 bar, it became accepted practice for CMAs to advise that stage decompression to Blackpool table 1, be undertaken from 0.85 bar upwards rather then from 1 bar as required by the Tables. Although this could have been taken as being contrary to the advice of Flook, (see Section 2.2.6), it was probably justified in this instance because of the effects of metrication (see Section 1.4.2).

When oxygen decompression was introduced, the risk of DCI from an exposure at just over 1 bar would have been less than from an exposure of the same duration at just under 1 bar for which staged decompression would not have been required. Such an anomaly would have been illogical. Accordingly staged decompression from exposures of 0.7 to 1 bar became mandatory in 2001 (HSE, 2001).

6.1.2. Maximum permissible SERF

The risk of DCI to an individual, could have been reduced by placing an upper limit on SERF (tabulated in Table 4.17). The effect of this would have been to restrict the range of pressure/time combinations which could have been worked. The restriction would have limited the severity of exposure but would have done nothing to improve the effectiveness of the decompression regime. The exposures undertaken in tunnelling are less severe both in terms of pressure and duration than the extremes of those undertaken in commercial diving using air breathing. Consequently neither the maximum pressure nor exposure period permitted by the Blackpool tables can be inherently unsafe, thus the greater levels of DCI incidence in tunnelling must be due to a less adequate decompression regime than in diving. This restriction therefore did not address this cause of the DCI problem.

Initially two limits on SERF were considered – 1% and 0.5%. Subsequently it was proposed that as there was general industry acceptance of a CBR of 1.0 - 0.5%, the upper limit on SERF should be no higher than 0.5% if any reduction in DCI incidence was to be achieved (Lamont, 1999). Table 6.1 shows the exposures which would have been allowed for a maximum permissible SERF of 1%. A limit on SERF of 1% was not strictly adhered to, but discretion was exercised when constructing Table 6.1 from the SERFs in Table 4.17 to simplify the table and comply with industry practice for exposure periods at the same time. In cells marked "?" it was considered there was some doubt as to whether sample sizes were sufficiently large to allow a conclusion about the application of the limit to be made. The broad thrust of this limit would have been to restrict work in compressed air to exposures of less than 4 hours except for exposures at pressures less than 1.25 bar.

Pressure	**Permitted exposures - Restriction SERF ⩽1.0%**				
Time	**0 - < 2**	**2 - < 4**	**4 - < 6**	**6 - < 8**	**⩾8 hrs**
< 0.7 bar	✓	✓	✓	✓	✓
0.7 – 0.95	✓	✓	✓	✓	✓
1.0 - 1.25	✓	✓	✓	✓	✓
1.3 - 1.55	✓	✓	✓	░	░
1.6 - 1.85	✓	✓	░	░	░
1.9 - 2.15	✓	?	░	░	░
2.2 - 2.35	✓	✓	░	░	▓
2.4 - 2.7	✓	?	░	░	▓
>2.7	?	?	░	▓	▓

Table 6.1 – Restriction on SERF of 1%

Key	Exposures not permitted by 1% SERF limit	░
	Exposures not permitted by Blackpool Tables	▓
	Only certain exposures permitted in this cell	?

The effect of imposing this restriction on the current set of DCI events would have been to eliminate 235 of the 428 DCI events including 8 of the 14 DCS Type 2 events. The exposures no longer permitted would have been those above and to the right of the white line in Figure 6.1.

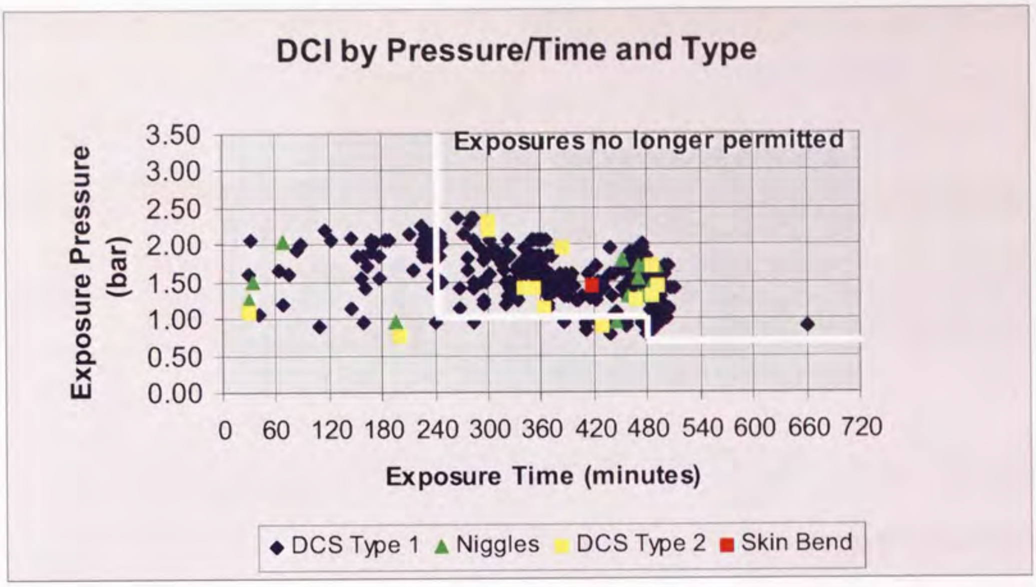

Figure 6.1 - Effect on DCI events of restriction on SERF of 1%

The economic consequences on compressed air working, of this restriction would have been to increase costs because of the increased number of exposures required to complete the work.

The further restriction on exposure, which would have arisen as a result of limiting SERF to 0.5%, can be seen in Table 6.2.

The broad thrust of this would have been to restrict the maximum exposure pressure to 2.15 bar, to restrict exposure times to 4 hours for pressures up to 1.55 bar but still to permit longer exposures at pressures below 1.25 bar. Such restrictions would have severely curtailed the use of compressed air as a working technique.

There was no medical reason why exposure *per se*, should be restricted to 2.15 bar and consequently this approach would have imposed an unreasonable restriction on the pressure range for compressed air working.

Pressure / Time	Permitted exposures - Restriction SERF ⩽0.5%				
	0 - < 2	**2 - < 4**	**4 - < 6**	**6 - < 8**	**⩾8 hrs**
< 0.7 bar	✓	✓	✓	✓	✓
0.7 – 0.95	✓	✓	✓	✓	✓
1.0 - 1.25	✓	✓	✓	✓	✓
1.3 - 1.55	✓	✓	🟥	▒	▒
1.6 - 1.85	✓	🟥	▒	▒	▒
1.9 - 2.15	✓	🟥	▒	▒	▒
2.2 - 2.35	🟥	🟥	▒	▒	⬛
2.4 - 2.7	🟥	🟥	▒	▒	⬛
>2.7	🟥	🟥	▒	⬛	⬛

Table 6.2 – Restriction on SERF of 0.5%

Key:-		
	Additional Exposures not permitted by 0.5% SERF limit	🟥
	Exposures not permitted by 1% SERF limit	▒
	Exposures not permitted by Blackpool Tables	⬛

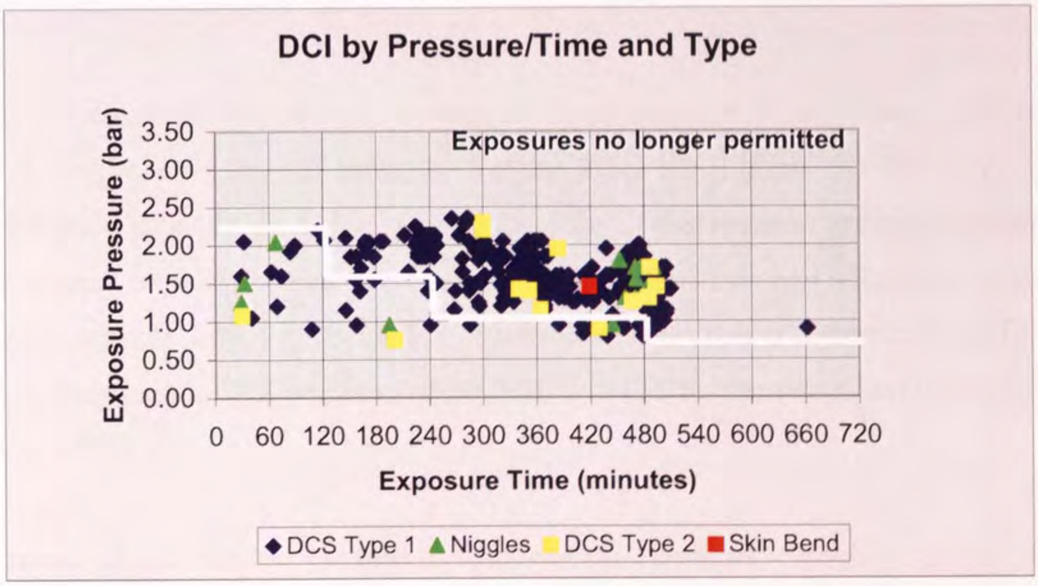

Figure 6.2 - Effect on DCI events of restriction on SERF of 0.5%

The effect of imposing this restriction on the current set of DCI events would have been to eliminate 300 of the 428 DCI events including 10 of the 14 DCS Type 2 events and is illustrated in Figure 6.2. This would have represented the elimination of a further 65 DCI events, 2 of which would have been Type 2 DCS.

Allowance would have had to have been made in assessing the effectiveness of the respective limits for the increased number of short shifts required to complete the work and these could have resulted in some additional DCI.

These restrictions in exposure times would mostly have benefited miners and other shift workers through a reduction in their risk of DCI. It is questionable whether there would have been sufficient miners in the industry to make up the additional shifts required for 24/7 working.

6.1.3. Limit on decompression time - DP Index

The retrospective study of North Sea diving activity for 1992 – 93 concluded that the incidence of DCI, particularly Type 2 DCS, was unacceptably high and should be reduced (Shields and Lee, 1986). The outcome of the study was the introduction of restrictions on exposure pressure and/or time and hence the hyperbaric stress which a diver could experience in the course of a dive.

Initially the restriction was defined in terms of "Decompression Penalty Index" (DP Index) – the decompression time in minutes, for the dive, taken from the US Navy tables (Whistler and Larne, 1984). The assumption was that if exposures of varying pressure and time required similar decompression times, these exposures had all been of similar hyperbaric severity. Initially a DP Index of around 30 was applied (Department of Energy, 1986). A reduction in DCI incidence from 0.31% to 0.07% was achieved (Robertson and Simpson, 1996).

As a result of a challenge to these restrictions on operating capability by the diving industry, which is not relevant to this study, the North Sea study was continued until 1990 (Shields *et al*, 1994). As the restriction was linked to hyperbaric stress, it was subsequently redefined as a $P\sqrt{T}$ value (see Section 2.2.5), initially $P\sqrt{T} = 29$ (Shields *et al*, 1994).

P√T as a measure of decompression stress, is not strictly applicable over the full range of tunnelling exposures because of their longer duration, so the concept of DP Index being defined in terms of decompression time was retained. Additionally Shields *et al* had defined a precise non-linear limiting envelope, by interpolation between depth and time increments in the tables. This approach might have been appropriate in diving but was inappropriate in tunnelling where exposures were required to be sub-multiples of 24 (see Section 3.4.2). Accordingly, a stepped limiting envelope was adopted.

Pressure / Time	**Permitted exposures - Restriction on DP Index of 60**				
	0 - < 2	**2 - < 4**	**4 - < 6**	**6 - < 8**	**≥8 hrs**
< 0.7 bar	✓	✓	✓	✓	✓
0.7 – 0.95	✓	✓	✓	✓	✓
1.0 - 1.25	✓	✓	✓	✓	░
1.3 - 1.55	✓	✓	░	░	░
1.6 - 1.85	✓	░	░	░	░
1.9 - 2.15	✓	░	░	░	░
2.2 - 2.35	✓	░	░	░	▓
2.4 - 2.7	✓	░	░	░	▓
>2.7	?	░	░	▓	▓

Table 6.3 – Restriction on DP Index of 60

Key:- Exposures no longer permitted by DP Index = 60 ░
Exposures not permitted by Blackpool Tables ▓
Only certain exposures permitted within this cell ?

In order to test the effect of a similar restriction in tunnelling, the same pressure/time matrix as in Section 6.1.2 was used. The DP index for each cell was calculated as the arithmetical average of the decompression time for the four combinations of minimum/maximum pressure ; minimum/maximum exposure time for that cell.

In determining what value of DP Index to set as the restriction, the objective as before was to reduce the incidence of DCI by around an order of magnitude and to eliminate Type 2 DCS.

It was considered reasonable to investigate the restrictions represented by a DP Index of 60 and 30 respectively – the latter being the restriction initially proposed by Shields and Lee (1986). The same pressure/time matrix as in the SBR calculation was used(see Table 4.2).

The exposures which would have been permissible with a maximum DP Index of 60 can be seen in Table 6.3.

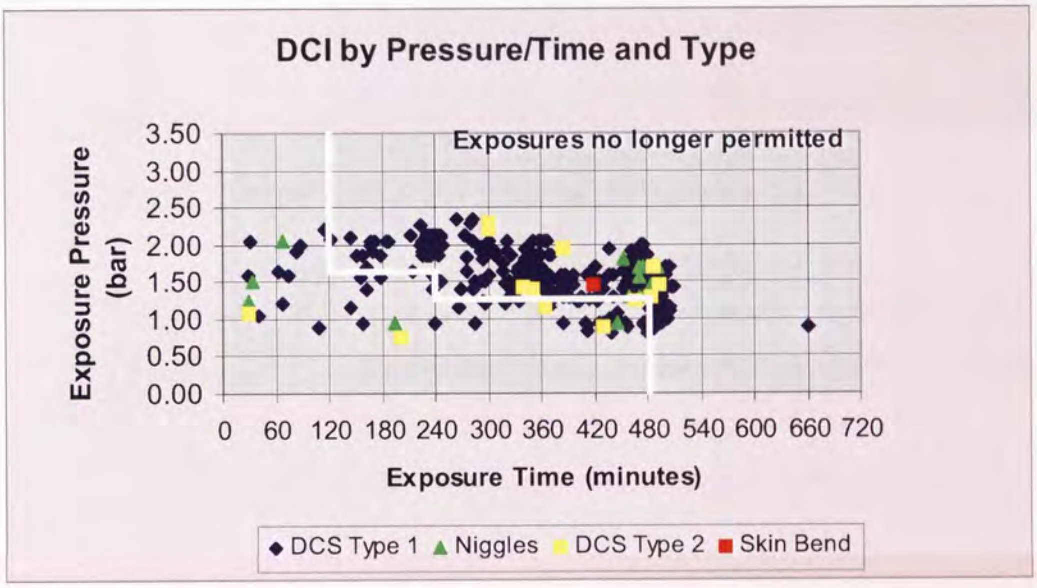

Figure 6.3 - Effect on DCI events of restriction on DP Index of 60

A restriction of DP Index = 60, would have prohibited virtually all exposures over 2 hours duration and above 1.25 bar pressure and set a maximum exposure time of 8 hours.

The effect of imposing this restriction on the current set of DCI events would have been to eliminate 372 of the 428 DCI events including 9 of the 14 DCS Type 2 events and is illustrated in Figure 6.3. This would have been a significant reduction in Type 1 DCS but would not have eliminated the Type 2 DCS . The exposures which would have been permissible, restricted to DP Index of 30, can be seen in Table 6.4.

Pressure / Time	**Permitted exposures – Restriction on DP Index of 30**				
	0 - < 2	**2 - < 4**	**4 - < 6**	**6 - < 8**	**≥8 hrs**
1.0 - 1.25	✓	?	■	■	□
1.3 - 1.55	✓	■	□	□	□
1.6 - 1.85	✓	□	□	□	□
1.9 - 2.15	✓	□	□	□	□
2.2 - 2.35	✓	□	□	□	▨
2.4 - 2.7	✓	□	□	□	▨
>2.7	?	□	□	▨	▨

Table 6.4 – Restriction on DP Index of 30

Key:-		
	Additional exposures no longer permitted by DP Index = 30	■
	Exposures no longer permitted by DP Index = 60	□
	Exposures not permitted by Blackpool Tables	▨
	Only certain exposures permitted within this cell	?

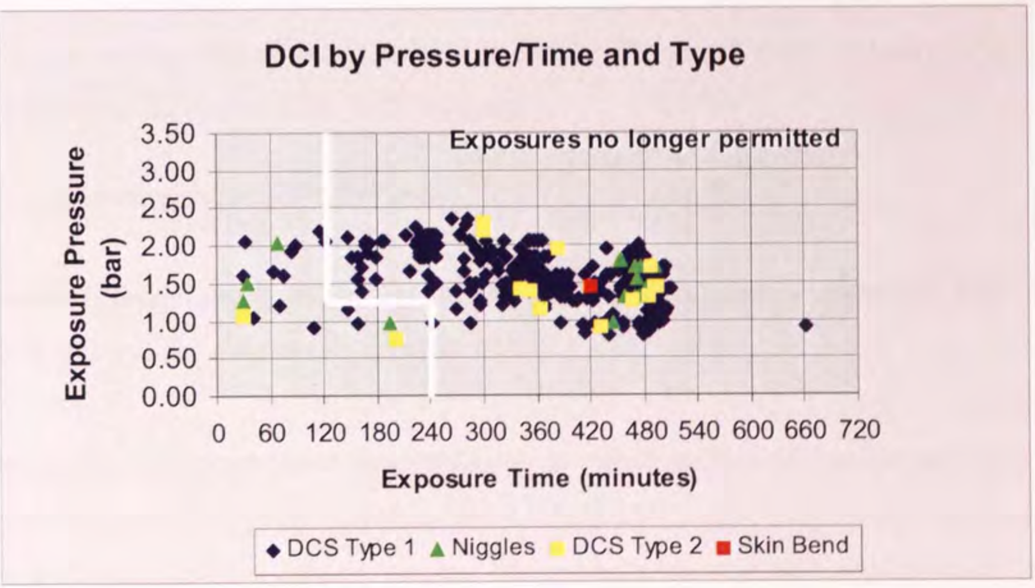

Figure 6.4 - Effect on DCI events of restriction on DP Index of 30

A restriction of DP Index = 30 would have prohibited all exposures of more than 2 hours duration apart from exposures below 1.25 bar for which an exposure time of up to 4 hours would have been permitted.

The effect of imposing this restriction on the current set of DCI events would have been to eliminate 410 of the 428 DCI events including 12 of the 14 DCS Type 2 events and is illustrated in Fig 6.2. This would have eliminated a further 38 DCI events including 1 Type 2 DCS event.

Again, allowance would have had to be made for the increased number of short shifts required to complete the work and depending on their SERFs, these could have resulted in some additional DCI.

In terms of eliminating exposures which resulted in DCI, this restriction would have achieved a significant reduction in Type 1 DCS but would not have eliminated all the Type 2 DCS events. By comparing Figure 6.4 with data from Shields and Lee (1983), its effectiveness in eliminating DCI in tunnelling would in theory have been of a similar order of magnitude to its effectiveness in the diving industry.

As with a limit on SERF, the restriction on DP Index would have severely restricted the use of compressed air as a working technique. Again these restrictions would mostly have benefited miners and other shift workers through reduction in their risk of DCI. Again it is questionable whether there would have been sufficient miners in the industry to make up the additional shifts required for 24/7 working.

6.1.4. Limit on number of DCI events

The disproportional susceptibility to DCI of certain individuals – repetitive DCI - was discussed in 5.1.4 and illustrated in Table 5.1.

Because of this disproportional susceptibility, a reduction in DCI incidence could have been achieved if an individual experiencing a single DCI event, had been prohibited from further exposure to compressed air on the expectation that his replacement in the workforce would have been less likely to suffer DCI.

This expectation could be shown to be reasonable from an examination of MANLIST which contained records of over of 2300 individuals, around 12% of whom experienced DCI. As a crude approximation therefore, the replacement for the person with DCI would have an 88% probability of not suffering DCI.

From the data collected, 303 men experienced 428 DCI events which gave an average of 1.41 DCI events per man. In this study, the maximum number of DCI events experienced by any one man was four. Other studies which covered exposure over longer contract periods, have recorded men experiencing up to 9 events each (Robinson, 1967).

The overall benefit in reducing DCI would not have been great and fewer than half the DCS Type 2 events would have been eliminated. However there was one overwhelming objection to this proposal which justified its rejection without further consideration. Reporting and treatment of DCI would automatically lead to certification of unfitness for further work in compressed air on that contract. This would have had a significant effect on earnings and for shift workers, their continuing employment on that site. It was therefore considered whether it would have been likely to lead to widespread under-reporting (and consequently under-treatment) of DCI. This would have been contrary to what had been achieved through better education of the workforce about DCI and in promoting a culture where the reporting of symptoms, no matter how slight, was encouraged. In addition there was no medical evidence to support the proposition.

A more extreme example of the benefit of limiting the number of DCI events per man could be seen from the work by Robinson (1967). He reported on a contract in Canada on which a few men experienced up to nine DCI events each. Robinson suggested that a limit of three DCI events per man before declaring them unfit on medical grounds, would have reduced the number of DCI events by around 60% and a limit of two events per man would have reduced it by around 75%.

6.1.5. Arbitrary limit on exposure period

In Section 6.1.1, the effect of restrictions on exposure period which had been made on the recommendation of CMAs were considered and found to be ineffective in significantly reducing the incidence of DCI. Influenced by this reduction strategy but without knowledge of its outcome, some colleagues in HSE believed that a significant reduction in DCI incidence could be achieved by placing more severe restrictions on exposure period.

In acknowledgement of this, the effect of a blanket restriction on exposure period, to 2 hours or 4 hours respectively was considered. The effect of these restrictions on the number of exposures required to do a notional amount of work, on the risk of DCI to the individual and to the overall workforce and on the unproductive time spent undergoing decompression was considered. The results are reported in Table 6.5. A 3 hour exposure period, which would have fitted within normal 24-hour working practice, could also have been considered, however 2 and 4 hour restrictions gave upper and lower bounds in testing its effectiveness and were sufficient for an initial assessment.

Although this restriction was a direct limit on exposure time, its effect was similar to restriction by DP Index (see Section 6.1.3), but those suggesting it would not necessarily have appreciated this.

The effectiveness of this restriction was assessed through the use of a very simple mathematical model - LIMIT. Input data for LIMIT was taken from spreadsheet TOTAL795 so that it reflected a wide range of exposure conditions. Given the variation in DCI incidence and exposure patterns between contracts, the model could have been run for individual contracts. However, it was preferred to use data from TOTAL795 to reflect the overall variations in normal industry practice.

A certain amount of work is required to complete a tunnelling operation and any reduction in exposure period results in an increase in the number of exposures required. Increasing output by increasing the number of men on a shift would not necessarily lead to greater output. In a mechanised drive, output is governed by excavation and lining erection rates whereas in a hand-excavated tunnel, there would normally be no room for extra men to be present at the face. Any reduction in exposure period therefore would result in an increase in the number of exposures required to complete the tunnel.

On each shift under normal circumstances, a certain amount of supervision, survey control and routine maintenance is required. This results in numerous short duration exposures by front line supervisors, engineers, fitters and electricians. There are also visitors to the tunnel – not least HSE inspectors - who also undertake short exposures. Short duration exposures are generally unaffected by restrictions on exposure period. The number of exposures arising from these supervisory and maintenance activities would be proportional to the number of production shifts undertaken. Therefore additional short supervisory exposures were included in the calculations to reflect the increase in the number of production shifts. The capability to include a variable number of such shifts was incorporated in LIMIT. Buchanan (2005a) suggested that their number had been underestimated.

A further allowance was made to reflect that miners do not always work a full shift irrespective of its length. This could be for a variety of reasons. For example, there is often an obscure but complex relationship between target productivity and pay which influences the shift length actually worked – only a certain length of tunnel would be built per shift depending on the bonus payment system in force. Logistical problems can affect shift length. Likewise there are points in the tunnelling cycle at which it would be preferable, for safety reasons, to halt operations prior to shift change, rather then continue work till the end of the shift. It therefore was necessary to introduce some flexibility to make further slight adjustments in maximum exposure period in LIMIT to reflect these factors. Table 6.6 illustrates the sensitivity of the figures in Table 6.5 to these adjustments. As shift length is reduced, decompression time, which would be a contractor's overhead, becomes a proportionally greater part of the working day and this was considered also.

Restriction of Maximum Exposure Period							
		Restriction:- maximum exposure period - 2 hours			**Restriction:- maximum exposure period - 4 hours**		
Pressure increment (bar)	Allowance made for supervision etc.	Effect on no. of exps %	Effect on DCI %	Effect on total decomp time %	Effect on no. of exps %	Effect on DCI %	Effect on total decomp time %
1.0 – 1.25	no	+208	-50	+50	+60	-81	+54
	yes	+252	-43	+63	+104	-75	+78
1.3 – 1.55	no	+181	-100	+43	+50	-62	+51
	yes	+235	-100	+60	+90	-58	+71
1.6 – 1.85	no	+187	-90	+75	+49	-20	+55
	yes	+227	-88	+89	+83	-12	+75
1.9 – 2.15	no	+81	-66	+30	+9	-18	+12
	yes	+112	-60	+30	+59	-15	+55
2.2 – 2.35	no	+87	+54	+33	+8	-64	+9
	yes	+104	+69	+41	+59	-45	+54

Table 6.5 – Effect of restriction on maximum exposure period

Table 6.5 was derived on the assumption that with an exposure period restricted to 2 or 4 hours maximum, the average maximum exposure periods achievable would be 1.75 and 3.75 hours respectively. The latter figures represented the adjustments described above and could be varied in the model. The "Effect on DCI" was calculated as the change from the predicted number of DCI events which would have occurred had the distribution of exposure periods for a given pressure increment been as in Table 4.3 and not restricted. Table 6.5 shows the increase in the number of exposures required to compensate for a restriction on exposure time. The increase would be greater at around 1 bar than at high pressure because exposure period is already restricted by the decompression tables at higher pressures.

In general a restriction on exposure period of 2 hours would have at least doubled the number of exposures required to complete a contract. At around 1.1 bar where currently 100 shifts of 8 hours duration would notionally have had to be worked on a contract, a restricted exposure period of 2 hours would have required over 200 additional exposures to give the same productive time including allowances for supervision and maintenance. Similarly, at 2.3 bar pressure, around 100 additional exposures would have been required.

The predicted effect on DCI was interesting and was very sensitive to SERF. At around 1.1 bar, the 2 hour exposure period restriction would have resulted in almost a 50% decrease in the expected number of DCI events because the SERFs in this range were low. However, at around 2.2 bar the same restriction would have resulted in an increase of around 50% in the expected number of DCI events because the reduction in SERFs at these pressures would have been small in proportion to the increase in the number of exposures required to complete the work. This illustrated that a reduction in risk from an individual exposure could result in a increase in overall risk to the population exposed. A choice between risk per exposure and population risk would therefore have had to have been made had these restrictions been introduced.

The predicted effect on time spent in decompression would have been to increase it by between 30 – 90% which would have introduced a considerable overhead to the CAC's costs.

The equivalent 4 hour restriction would have increased the number of exposures by 50 – 100% at pressures of around 1.1 bar but by only around 10%, excluding supervision etc, at around 2.3 bar. At 2.3 bar, exposures were already limited to 6 hours by the decompression tables.

Again, the predicted effect on DCI was interesting. At around 1.1 bar the 4 hour restriction would have resulted in approximately an 80% decrease in the expected number of DCI events, but would have resulted in a predicted increase of around 15% in the expected number of DCI events at around 2.2 bar. This again illustrated that a reduction in risk to the individual might not have resulted in a reduction in risk to the population exposed.

As far as can be ascertained, previous authors who have used this approach of restriction in exposure period e.g. Evans (CIRIA, 1992) have not made any allowance for the additional supervision and maintenance shifts required. The effect of these additional shifts can be seen in Table 6.5. It becomes less marked with increasing pressure as shift length would already have been restricted by the decompression tables. Overall, making an allowance for additional supervisory shifts renders the imposition of a blanket restriction an even less attractive proposition.

Sensitivity to variations in average exposure period							
		Restriction:- maximum exposure period - 2 hour			Restriction:- maximum exposure period - 4 hour		
Pressure increment (bar) / Exp Period	Allowance made for supervision etc.	Effect on no of exps %	Effect on contract DCI %	Effect on total decomp time %	Effect on no of exps %	Effect on contract DCI %	Effect on total decomp time %
1.0 – 1.25 (bar)							
1.75/3.75 (hrs)	no	+208	-50	+50	+60	-81	+54
	yes	+252	-43	+63	+104	-75	+78
1.5/3.5 (hrs)	no	+255	-43	+50	+69	-81	+54
	yes	+307	-34	+65	+115	-74	+80
2.2 – 2.35 (bar)							
2.0/4.0 (hrs)	no	+65	+37	+33	+6	-64	+9
	yes	+81	+50	+40	+53	-46	+51
1.75/3.75 (hrs)	no	+87	+54	+33	+8	-64	+9
	yes	+104	+69	+41	+59	-45	+54
1.5/3.5 (hrs)	no	+115	+77	+33	+10	-63	+9
	yes	+136	+95	+42	+65	-43	+57

Table 6.6 – Sensitivity of results in Table 6.5 to variations in average exposure period

It was noted earlier in this section that the actual average shift length would be less than the nominal restricted shift length for a range of practical reasons. Table 6.6 illustrates the sensitivity of some of the results in Table 6.5 to variations in average shift length. This is greatest for pressures nearest 1 bar for which the suggested restriction on exposure period represents the greatest departure from normal practice.

As a further caveat it should be noted that some SERFs, particularly at the lower pressures and for the shorter exposure periods were zero or close to zero. They were based on very small numbers of DCI events and consequently highly sensitive to that number. Any change in the number of DCI events from which that SERF was calculated by only 1 or 2 cases, would have changed predicted reductions in DCI incidence to increases.

In addition to consideration of the effectiveness of any suggested restrictions on DCI incidence, some recognition should be given to their effect on the costs of tunnel construction to satisfy the test for reasonable practicability.

When 8 hour shifts are being worked, three shifts of men would normally be required to cover 24 hour operation over a 5 or 6 day week. This would increase to 4 shifts for continuous 7 day working. Reducing shift length to 4 hours would double the number of men required. Likewise for 2 hour shifts, an four-fold increase in men would be required. All would expect a full day's pay irrespective of the productive hours worked. Miners are amongst the highest paid operatives in construction and normally command a compressed air supplement for such work. It was considered highly unlikely that there would be sufficient men in the industry to support such increases in the demand for labour. The issue of pay would impact hugely on the economics of compressed air working and would make it uneconomic. The additional number of working shifts required would lead to longer contract periods with their attendant cost overheads.

6.1.6. Increase in decompression time

This proposal was studied briefly. Physiological modelling techniques showed that decompression times had to be increased by a factor of between three and five in order to achieve the same effect as oxygen breathing. This is most easily illustrated by comparing the decompression times in the oxygenated Blackpool Tables (HSE 2001) for exposures at 0.95 bar. The tables give oxygen and air-only alternative decompression profiles and an extract is shown in Table 6.7. The increase in decompression time would result in productivity delays as manlocks would be tied up by men undergoing decompression and restrict the passage of works trains in small diameter tunnels lacking separate materials and man locks.

	Max working pressure (bar)	**Exp period (hrs)**	**Time (minutes) at Stage Pressure of:**										**Total decomp period (min)**
				1.8	**1.6**	**1.4**	**1.2**	**1.0**	**0.8**	**0.6**	**0.4**	**0.2**	
With O^2	**0.95**	**0.0 – 3.0**											**2**
		3.0 – 8.5									**10**	**10**	**22**
Air only	**0.95**	**0.0 – 3.0**											**2**
		3.0 – 8.5									**40**	**60**	**102**

Table 6.7 – Comparison of times for oxygen and air decompression

(adapted from HSE, 2001)

6.1.7. Post Decompression Surface Oxygen Breathing

This technique was described in Section 2.2.8. It was used in the UK on 82 exposures out of 150 on the GYPP contract mainly at pressures around 2 bar. The SBR on GYPP was 18.24. It was also used at Belfast where no DCI was recorded in 70 exposures at up to 1.23 bar.

PDSOB gives some of the benefits of oxygen breathing without some of the attendant risks. However from experience of its use in the UK, the author has been openly critical of it (Slocombe *et al*, 2003: p 113). Flook (Slocombe *et al*, 2003: p 113) was similarly critical of PDSOB and commented that its use offered little benefit for UK practice.

6.1.8. Concluding remarks

When considering ways to reduce the incidence of DCI, the risk to the individual and the risk to the population exposed should both be considered. It has been shown that a reduction in one may not result in a commensurate reduction in the other. If so which should take priority?

The *ad hoc* restrictions laid down by the CMAs (Section 6.1.1) were always intended to be an interim measure. As such they possibly reduced the amount of DCI at higher pressures.

All five proposals for restriction on exposure (Sections 6.1.2 – 6.1.6) were rightly rejected following internal HSE discussions without further recourse to consultation with industry. Whilst each would have resulted in a sometimes significant reduction in DCI risk for the individual, they would not necessarily have resulted in an overall reduction in the number of DCI events on a contract. The reduction in DCI incidence would not necessarily have excluded all Type 2 DCS events. However the cost implications would have made work in compressed air so expensive as to be no longer commercially viable for use on site. This would not have been acceptable to industry and was not HSE's intention when the restrictions were envisaged.

It is worth noting that the restriction on SERF (Section 6.1.2) would have resulted in a general reduction in maximum permissible working pressure whereas the DP Index restriction (Section 6.1.3) would have resulted in a marked reduction in exposure period. A compromise restriction combining the permissible exposures from both could have been derived but would still not have overcome foreseeable industry objections.

It should also be noted that were it not counter intuitive, CACs would have been advised to use as long shifts as possible in recognition that the incidence of DCI per hour worked generally was at its lowest with shift lengths of 4 – 6 hours (see Section 4.5.4).

It is not surprising that none of the proposed restrictions was found to be worthwhile. The premise behind them was fundamentally flawed in basic physiological principles. An excursion into compressed air involves three phases – compression; exposure to raised ambient pressure; decompression. Provided compression is done within the bounds of accepted practice there is no evidence it is harmful. Experience from diving shows that the exposure pressures and times used in tunnelling are not inherently harmful. Decompression need not give rise to the incidence of DCI described in Chapter 4 as experience from diving shows that it is possible to decompress safely from exposures of significantly greater hyperbaric stress than are experienced in tunnelling. DCI in tunnelling arises from inadequate decompression not from excessive exposure. Restricting exposure does not address the cause of high DCI incidence. It is the decompression regime which must be altered.

Based on the limited UK experience available, it is not believed the results of PDSOB could be considered to have proved the effectiveness of the technique. It does however have certain cost attractions for a CAC and can be used as a first aid procedure.

6.2. Reduction in DCI through the use of oxygen decompression

The introduction of oxygen decompression was described in Section 2.2.9 and by Lamont (2002). When this study began, a major objective and one which was very important for HSE, was to assess the benefits (if any) from the introduction of oxygen decompression.

It was assumed that considerable exposure data would become available from the construction of the Channel Tunnel Rail Link Phase 2 from Fawkham Junction to London St Pancras and possibly from other tunnel contracts elsewhere in Britain. When this study was being planned, it was understood that tunnels on CTRL Phase 2 were to be constructed using earth pressure balance or slurry TBMs (see section 1.5.2). These machines would have required the use of compressed air or other ground stabilisation process (see Section 1.6.3) for head access. Compressed air might also have been required for cross passage construction.

In the event, a major area-wide dewatering project was undertaken to lower groundwater levels which virtually eliminated the need for compressed air working on the London Tunnels – Ripple Lane Portal to St Pancras. Although some compressed air working was undertaken on London Tunnels Contracts 220 and 250, this was insignificant in terms of the number of exposures undertaken, all of which were at pressures under 1 bar.

6.2.1. Objectives and methodology

The objective of this section was to assess whether the introduction of oxygen decompression had led to a significant reduction in the incidence of DCI. The methodology intended was to analyse the available exposure data using the measures of DCI incidence identified in Section 4.4, and to make comparisons with DCI incidence arising from air-only decompression, to determine if the incidence of DCI had been reduced significantly (defined at the start of Chapter 6 as "around one order of magnitude").

6.2.2. Use of oxygen decompression in the UK to date

Oxygen decompression was used on CTRL Contract 320 – Thames Tunnels – see Figure 6.5. Contract 320 consisted of twin tunnels under the Thames at Swanscombe and was completed in late 2003. The exposures for which it was used were undertaken for tunnel face inspection and TBM maintenance purposes.

The engineering aspects of the CTRL tunnels have been described in a number of specialist publications such as New Civil Engineer (NCE, 2002) and Tunnels and Tunnelling International (T&TI, 2003).

Figure 6.5 – Location of contract CTRL 320
(NCE, 2002)

An unusual aspect of the contract was that although HSE had approved a decompression regime based on the Blackpool Table profiles, the CAC, an Anglo-German Joint-Venture, sought and was granted approval, to use German tables (Bundesgesetzblatt Jahrgang, 1997). The case for seeking the approval was set out by Colvin (2002) whilst HSE was reassured by the work of Flook (Flook, 2003; Lamont & Flook, 2004) that the German tables were likely to give an incidence of DCI similar to that from the approved oxygenated Blackpool Table regime.

In 2003 an assessment of UK experience with oxygen decompression was presented (Lamont, 2003) in which the author concluded that some reduction in the incidence of DCI had been achieved but it was difficult to quantify that benefit.

6.2.3. Oxygen decompression data

The contract yielded records of 360 exposures only, at pressures of up to 3.1 bar – see Table 6.8. Of these, 348 exposures potentially required decompression using oxygen. Three treatments for DCI were given however the number of DCI events was later confirmed as two following detailed retrospective medical diagnosis. 87 of the exposures were for lock tests. Data quality was good.

The results from this contract presented two issues of principle. In collecting and analysing the data for air-only decompression, it had been normal practice to include lock-test exposures with other short exposures. On many of the contracts concerned, lock tests represented a very small percentage of the total number of exposures and were of no significance to the results. On CTRL 320, 24% of the exposures were lock tests, most of which were at 3.0 bar pressure. This detracted from the value of the data as most lock tests were of 15 – 20 minutes duration only.

Pressure / Time	**Number of Exposures** **(Number of DCI events)**				
	0 - < 2	**2 - < 4**	**4 - < 6**	**6 - < 8**	**Total**
< 0.7	12	0	0		12
0.7 – 0.95	19	3	22		44
1.0 - 1.25	59	7	62		128
1.3 - 1.55	7	0	0		7
1.6 - 1.85	20	0	0		20
1.9 - 2.15	22	3	0		25
2.2 - 2.35	4	5	2		11
2.4 - 2.65	7	27 **(2)**			34 **(2)**
2.7 – 2.95	10	4 **(1)***		▨	14 **(1)***
3.0 – 3.25	65			▨	65
⩾3.3				▨	0
Total	225	49 **(3)**			360 **(3)**

Table 6.8 - No of exposures and DCI events for CTRL 320

(* injury - treated as DCI but subsequently diagnosed not to be DCI)

Exposures not permitted in German Tables (see Section 6.2.2)	▨

The second issue of principle concerned the definition of what constituted DCI (see Section 2.3.6). Policy within HSE had been to consider that DCI had occurred when a therapeutic treatment was given ("treated" cases). CMAs were aware of this policy and did not object to it (HSE, 1999). It was accepted that this was a conservative approach as a small number of persons treated may have suffered physical injury not Type 1 DCS. On CTRL 320 one of the three persons given therapeutic treatment (treated cases) was subsequently diagnosed as not having suffered DCI. Because of the very small sample size, the inclusion or otherwise of this DCI event made a very significant difference to the DCI incidence. This can be seen below.

6.2.4. Incidence of DCI using oxygen decompression

The incidence of DCI was calculated in accordance with the principles identified in Section 4.4.

Range of exposures	**All records**		**Excluding lock tests**	
	Treated cases	Diagnosed cases	Treated cases	Diagnosed cases
Exposure to all pressures	0.83%	0.56%	1.10%	0.73%
Exposure pressure ⩾0.7 bar	0.86%	0.57%	1.11%	0.74%
Exposure pressure ⩾1.0 bar	0.99%	0.66%	1.29%	0.86%

Table 6.9 – Crude Bends Rate – oxygen decompression

The CBR was calculated for a number of conditions and their effect on the numerical value of the CBR can be seen in Table 6.9. Some of the differences in figures were attributable to the inclusion or otherwise of short duration lock tests (see Section 6.2.3). By excluding the treated case which was subsequently diagnosed not to be DCI, the CBR was reduced by a third as a consequence of the small sample size. In Section 4.4.1 the CBR was criticised as being a meaningless measure of DCI incidence because it did not take pressure and time into account. Table 6.9 shows the effect that sample size had on the result.

The SBR was also calculated. This presented additional problems. The SBR calculation for air-only decompression was based on Evans' data (CIRIA, 1992) which was relatively old and not wholly representative of the work involved in TBM interventions. Evans' calculation of SBR did not include exposures below 1 bar but in this study the SBR has been reworked to take account of exposures down to 0.7 bar.

Intuitively the current air-only decompression data from this study should have been used as the reference data against which a comparison of oxygen decompression using SBR was made. However there was both insufficient data in totals and an insufficiently small spread of data for the resulting figure to have been meaningful. Evans' calculation of SBR used a single pressure increment above 2.7 bar again due to lack of data. Although Evans' data covered a wider range of exposure pressures and times than the HSE database, neither was fully representative of the high pressures experienced at Contract 320.

One approach considered was to calculate the SBR directly using current data as reference (see Section 4.4.2). Because current data covered a lower range of pressure/time combinations than Evans, this approach would have required even more extrapolation. Another approach considered was to calculate the SBR using Evans' data as reference and factor it appropriately to reflect the SBR for current air only data referenced to Evans' data (CIRIA, 1992). This would not have been totally satisfactory but would have been the better option. The second approach was favoured.

Pressure / Time	**Single Exposure Risk Factors**				
	0 - < 2	**2 - < 4**	**4 - < 6**	**6 - < 8**	**⩾8**
< 0.7	0.00	no data	no data	no data	no data
0.7 – 0.95	0.00	0.00	0.00	no data	no data
1.0 – 1.25	0.00	0.00	0.00	no data	no data
1.3 – 1.55	0.00	no data	no data	no data	no data
1.6 – 1.85	0.00	no data	no data	no data	no data
1.9 – 2.15	0.00	0.00	no data	no data	no data
2.2 – 2.35	0.00	0.00	0.00	no data	no data
2.4 – 2.65	0.00	7.41%	no data	no data	no data
2.7 – 2.95	0.00	0.00 (25.0%)*	no data	no data	no data
3.0 – 3.25	0.00	no data	no data	no data	no data
⩾3.3	no data	no data	no data	no data	no data

Table 6.10 – Single Exposure Risk Factors – oxygen decompression

(* injury treated as DCI until subsequently diagnosed not to be DCI)

The SBR for exposures utilising oxygen decompression and diagnosed DCI events was 1.7 when referenced to current air-only decompression data and 4.1 when referenced to Evans' data. The very small samples significantly affected the result and reduced its validity.

The SERFs for decompressions utilising oxygen decompression are shown in Table 6.10. Because of the small number of exposure records available and the limited spread of data, no meaningful SERFs could be calculated. Ideally there should be sufficient data for the error in SERF to be less than 0.1%, however being in that position is not foreseen for many years at current data acquisition rates!

6.2.5. *German experience of oxygen decompression*

As the decompression regime at CTRL 320 was based on German decompression tables, it was considered relevant to this study to review them. Amongst the reported information in English, on the effectiveness of oxygen decompression utilising German decompression tables, Förster and Meyer (1994), reported a CBR of 0.85% for exposures at up to 2.5 bar using the now discontinued, 1972 German tables (Druckluftverordnung, 1972).

Förster and Elfinger (1998) reported a CBR of 0.18% for exposures at up to 3.1 bar using the 1997 German tables (Bundesgesetzblatt Jahrgang, 1997), and later Förster and Angerer (2002) reported a CBR of 0.098% from over 15000 exposures at pressures between 0.65 and 1.4 bar using the same tables. They concluded that oxygen decompression in accordance with the 1997 German Tables had considerably reduced, but not totally eliminated DCI.

Faesecke (2002a), in discussions with HSE, reported a SERF of 2.9% for 303 exposures between 2.7 and 3.5 bar at the Wesertunnel South. He also reported that for the 4th Elbe Tunnel, work at 3.0 – 3.6 bar, gave SERFs of between 1.33 and 3% (Faesecke, 2002b).

6.2.6. *Review of UK experience with oxygen decompression*

To date, the use of oxygen decompression appears not to have brought about a reduction in the incidence of DCI far less eliminate it completely. However very few exposure have been recorded to date.

It is worthwhile noting that both the confirmed DCI events reported in Table 6.8 occurred after approximately 3 hours 20 minutes exposure at 2.5 bar. Such a duration of exposure is very close to the upper limit of the German tables for that pressure. The DCI incidence for exposures above 2.5 bar quoted in Section 6.2.5 were higher than would have been expected for oxygen decompression, but were not as high as experienced at Contract 320.

Predictions of gas forced into bubbles, for the nearest comparable exposure in the comparative study of international tables by Flook (2003), - 2 hours at 2.4 bar, are shown in Table 6.11. It can be seen from this table that the German tables were predicted to be almost the least effective of those studied, for this pressure/time combination. They gave a predicted 50% more gas in bubbles than the oxygenated Blackpool Tables. This may account for the two DCI events which occurred. In fact, the UK tables were shown by Flook, to be more effective than the German tables for all exposures above 1.5 bar for 4 hours although both were considered acceptable for use in the UK.

Table	Pulmonary Arterial gas ml/ml
UK	0.00220
Dutch	0.00256
French	0.00280
Swiss	0.00322
German	0.00340
USA	0.00414

Table 6.11 – Comparison of predicted effectiveness of Decompression Tables

(Flook, 2003; Table 4-j)

In addition to the normal recording of exposure data on this contract, Doppler monitoring was undertaken by the CAC, as a condition of the approval to use German Tables. Unfortunately the unpredictable and intermittent use of compressed air working on CTRL 320, made the logistics of Doppler monitoring somewhat challenging and it was only undertaken after exposures of 6 hours at 1.1 bar and not at pressures of around 3 bar which would have been more informative. For such exposures, Flook's model predicted median Kisman-Masurel scores of grade 2 bubbling (see Section 2.5) for which she predicted a 5% risk of DCI. This compared favourably with the predicted median bubble score of 3 for the same exposure using the Blackpool Tables with oxygen. Actual bubble scores were measured as median grade 2 which corresponded well with predictions (Hochtief Murphy, 2003). No DCI was reported following these exposures but in her report on the monitoring, Flook recommended that exposure times be cut to 4 hours at that pressure (Hochtief Murphy, 2003).

6.2.7. Concluding remarks

No evidence was found to show that oxygen decompression had significantly reduced the incidence of DCI. If anything, the incidence of DCI was higher for oxygen decompression than for air-only decompression. However that comparison is qualified by a caveat highlighting the lack of appropriate data.

Experience at CTRL 320 again highlighted a problem with an analysis based on the occurrence of an all or nothing event - DCI. Without full Doppler monitoring, there appears from the "engineering perspective" to be no way of knowing how close to DCI others were or how much more effective decompression would have had to have been to have eliminated the two DCI events which occurred.

Another means of reducing DCI would be the use of saturation techniques. Saturation working is common in diving, being mandatory in UK waters at pressures over 5 bar, however to date they have only once been used in tunnelling (Grimm, 2002; Sterk *et al*, 2002). Saturation working requires men to live under pressure in a hyperbaric living complex for days at a time at what is often referred to as "storage" pressure, undertaking excursions often involving transfer under pressure, to work at higher pressure. A single decompression is undertaken after a number of days exposure. In 1989 a CAWG subcommittee considered the costs associated with saturation working to be excessively high (Buchanan, 2005a). They also drew attention to the social problems which miners would experience.

The technical challenges in undertaking saturation working in tunnelling are considerable as are the social and medical challenges. Discussions with a research contractor have taken pace with a view to commissioning HSE sponsored research into the technical, physiological and social problems associated with the use of saturation techniques in tunnelling. To date no project specification has been agreed. However it is recommended that HSE should address the problems involved in saturation working and to this end appropriate recommendations have been made in Section 7.6 and Appendix 5.

Chapter 7 - General discussion and conclusions

Engineers have taken considerable interest in the consequences of their work in compressed air, since the technique was first used in the mid-19th century. They have actively observed and discussed the effects on the workforce of exposure to pressure and decompression and have worked alone and in conjunction with medical colleagues in devising procedures to reduce its adverse effects.

7.1. General discussion

For many decades the measure of the effectiveness of decompression tables from the "engineering perspective" has been DCI incidence, based on the analysis of site exposure records. It has a number of serious drawbacks. For engineers, the effectiveness of the tables has always been measured by an all or nothing event – DCI. There is no standard for determining the onset of DCI – it is left to the medically inexperienced individual to declare the existence of symptoms. There is no gradation in the seriousness of the DCI event other than a somewhat arbitrary division into Types 1 and 2 DCS. Even when medical expertise is available, the accuracy with which the diagnosis is made would appear to be questionable (Sundal *et al*, 2004). The data on which any retrospective study depends, has been gathered by relatively untrained lock attendants who are unlikely to have any real appreciation of the data quality required. It is little wonder that Flook (2004) recently likened this approach to using the incidence of hangovers as a measure of the damage caused by alcohol consumption in heavy drinkers.

In the light of the comments above, it is clear that the findings of retrospective studies of DCI need to be treated with great caution. Nevertheless, when they are based on relatively large samples, they have the confidence of the industry and their findings have been used to influence industry practice and regulation for many decades. The results of this study are presented against this background.

7.2. Chapters 1 and 2

7.2.1. Discussion

These formed an introduction to the study and set out the aims, objectives and scope. With hindsight, the objective to examine the susceptibility of men across multiple contracts, which had been seen as a major aspect of the study when it was conceived, turned out not to be achievable to the extent to which it had been hoped. This was due to a factor which had not initially been considered - namely that relatively few men worked on multiple contracts and of those who did, most were in occupations which did not give rise to high hyperbaric stress exposures and hence to the occurrence of DCI.

The review of the development of compressed air working techniques and tunnelling decompression practice along with a wider review of literature relating to hyperbaric practice including some which was diving specific, highlighted a number of points.

The use of compressed air working techniques developed rapidly in the late mid 19th century to the extent that within two decades of its first use in the UK, engineers were exposing men to pressures which would possibly be considered unacceptably high under today's regulations. This was being done long before the medical community had discovered the causes and cures for DCI.

By the start of the 20th century the diving industry was still learning from the tunnelling industry about work under pressure, as exemplified by the Admiralty Report (1907). However if Haldane were to visit a tunnelling site at the start of the 21st century, he would not notice much change in the practices surrounding the compressed air working techniques other than in the sophistication of the machinery in the modern tunnelling environment.

In the intervening period engineers generally found that compressed air working techniques met their requirements and although there were changes to the decompression regime (ICE, 1936; Gt. Britain, 1958; CIRIA, 1973 etc) there was no industry-wide initiative for radical change. Unfortunately this also meant that research into means of reducing DCI incidence was not undertaken. On a more positive note, engineers still supported the 2002 "Engineering and Health in Compressed Air Work" conference (Slocombe *et al*, 2004) but that support was not uniformly spread across the industry.

Whilst other techniques for ground stabilisation exist (see Section 1.6.3) none is without safety risk. Recent experience on a sewer contract in north London following a potentially life-threatening collapse, showed that the application of low pressure compressed air, which HSE had supported, could rapidly be undertaken and allowed the contractor much greater flexibility in the subsequent recovery operations than the dewatering and grouting which had been undertaken prior to the application of compressed air (Remnant, 2004).

It was very noticeable that changes in regulation and guidance have been infrequent. Instead of leading good practice, these have tended to follow good practice and to have been industry led (Buchanan, 2005a). It took around 12 years for the 1958 Regulations to be introduced. No sooner had they come into force than changes were being made to the decompression regime. The 1996 Regulations built on proposed changes to the CIRIA Report (1982). It is perhaps only with the introduction of oxygen decompression that the regulator has at last taken the lead in moving forward industry practice.

The wider literature review highlighted the contrast with diving. One measure of this contrast which was recently noted, was the in list of abstracts for the 2004 Undersea Hyperbaric Medical Society Conference (UHMS, 2004). Of around 200 abstracts listed, only one related to an underground environment and even then it was in the context of unintentional exposure to pressure as a result of accidental inundation of a mine, following ground collapse. All others related to diving or hyperbaric medicine. Research into the hyperbaric problems of diving has long been supported by the relevant sectors of industry, the regulatory authorities and the military. The results of this investment can be seen in the range of diving capability available and the low incidence of DCI in diving (see Section 4.5.8). With the current reluctance of tunnelling contractors to use compressed air because of its perceived health risks, this perception will never be reversed given the total lack of relevant research.

7.2.2. Conclusions

From the review of the development of compressed air working techniques, it was concluded that after rapid initial development, their subsequent development had not kept pace with advances in hyperbaric knowledge such as in diving and hyperbaric medicine. This has been very much to the detriment of those exposed to compressed air in tunnelling.

7.3. Chapter 3

7.3.1. Discussion

In this chapter, the statutory requirements for data protection and data generation on site were described, along with an account of the collection and manipulation of data into a manageable format. As acquired, the data were of variable quality and an extensive part of this study was devoted to removing inconsistencies in those data before generating the spreadsheets and databases required for analysis.

The wider review of the literature had demonstrated the importance of good data quality. Retrospective studies are always hampered by having to make do with the data available. The quality and rigour of the data must be in doubt when the lack of scientific precision in the control of the decompression is considered along with the occasional use of decanting and the widespread use of *ad-hoc* safety factors. Similarly, data quality must be in doubt when allowance is made for any lack of appreciation by the lock attendant of the need for completeness and accuracy in the registers. In addition the absence of an objective standard for when a man experiences DCI other than his subjective desire for treatment also affects data quality. This must be recognised in the extent to which reliance is placed on the results of any subsequent analysis and the confidence of the industry in the findings.

Although some numerical allowance for poor data quality was made in this study, this was in respect of inconsistencies in the recording of data only. Nothing was done to determine what allowance should have been made for errors in the actual decompression undertaken, for the use of safety factors and for subjectivity in reporting DCI other than to consider that they all fell within normal industry practice.

The decision to persuade CACs to adopt electronic data acquisition was certainly justified by the resulting improvement in data quality although that only addressed one of the problems with data.

Although an objective standard for determining the onset of DCI would be desirable, this would have to be linked to an objective monitoring system. Whether this could be based on a physiological monitoring such as Doppler or ultrasonic monitoring is well beyond the "engineering perspective".

7.3.2. Conclusions

It was concluded that it was possible to identify and collect exposure data and records of DCI arising from compressed air tunnelling in the UK since the mid 1980s and to make these data and records suitable for subsequent analysis.

A further conclusion was that the change to electronic data acquisition in the mid 1990s had significantly improved the quality of data acquired and greatly facilitated subsequent analysis.

7.4. Chapters 4 - 6

7.4.1. Discussion - Chapter 4

In Chapter 4 the data available for analysis were presented and the incidence of DCI associated with air-only decompression examined. Such a decompression regime has now been superseded by oxygen decompression.

Measures of the incidence of DCI were identified and their advantages and disadvantages were comprehensively discussed and demonstrated. The incidence of DCI arising from air-only decompression, was quantified. Of the measures identified, it was recognised that CBR was the *de facto* international standard measure of DCI incidence from the "engineering perspective". However from the growing acceptance of it by HSE and others, SERF may be the most useful and potentially most sensitive measure available to the engineer.

After taking account of all the caveats, the numerical values of DCI incidence which were calculated for current data, were higher than in previous studies of earlier data such as that by Evans (CIRIA, 1992). In addition the extent to which the distribution of DCI events within the workforce was heavily biased towards shift production workers was shown.

The extent to which this increase was due to changes in working patterns, greater reporting by a more informed workforce or another factor such as physiological changes in the workforce has not been researched. From the HSE perspective, the higher incidence of DCI, irrespective of how it arose, was a matter of concern which had to be addressed (Lamont, 2002).

From the "engineering perspective" the range of possible measures of DCI incidence has been exhausted. From the wider perspective the question must be asked as to what parameters could be measured to give a measure of the effectiveness of a decompression regime which did not depend on an all or nothing event. It is suggested that the answer may be in some form of physiological monitoring such as Doppler or ultrasonic monitoring of free gas in blood.

The incidence of DON has not been researched in this study due to lack of data. Nevertheless a link between DCI and DON was found by Evans (CIRIA, 1992) and this should be remembered when the incidence of DCI and its disproportional distribution within the workforce are being considered.

The numerical comparisons with diving were informative. This study has indicated that the difference in CBR between the respective industries is greater than one order of magnitude. It should be remembered that diving exposures tend to be of a different pressure/time pattern from tunnelling and part of the exposure takes place whilst submersed in water with the attendant effects of buoyancy. Nevertheless, the hazard to which men in both industries are exposed is the same – raised ambient pressure. The author was aware of no physiological reason to justify the acceptance of such marked differences in the incidence of DCI or other health outcome between the two industries.

7.4.2. Discussion - Chapter 5

In this chapter a number of responses to hyperbaric exposure including susceptibility to DCI, tolerance of DCI and acclimatisation to compressed air exposure were examined.

Within the group of men studied, it was apparent from the analysis of susceptibility and tolerance that there were variations across the group. However, in comparing variations in men's susceptibility or tolerance, it must be remembered that DCI occurred after a variety of pressure/time combinations of exposure, and therefore some factor to account for this variation should perhaps have been included in the analysis. The scientific approach would of course have been to have studied men who had each undergone identical exposures but such an approach was difficult to achieve in a retrospective study. Hyperbaric trials to study it would have been expensive.

Similarly there could have been men who either were very close to experiencing DCI but did not, or men who failed to report symptoms of DCI and undergo treatment. Additionally, those who did not experience DCI may simply not have undergone sufficient exposures for it to have occurred.

In this study as in other retrospective studies, men experiencing multiple or repetitive DCI have been categorised by the number of DCI events experienced. This ignored the possibility that many men could have experienced greater numbers of DCI events if their exposure history had continued for longer. In this study, men experiencing DCI and continuing to work in compressed air did so for an average of 36 exposures (range 1 - 221) following their final DCI event. Perhaps their DCI history would have been more accurately reflected, if they had been categorised in a system based on the number of exposures between DCI events. Again however, such a system would have had to have been dependent on exposure severity to be truly representative.

The study found that susceptibility to DCI could not be used as a means of identifying men who should be excluded from work in compressed air. Likewise it was considered unreasonable to exclude men from work in compressed air after they had experienced a single DCI event. However as many of those who experienced a DCI event subsequently experienced others, anyone experiencing DCI should perhaps thereafter be routinely monitored by physiological methods such as Doppler or ultrasonic techniques to check their bubble levels. Were it possible that high bubble levels could be correlated more accurately with a significant risk of DCI than at present, a man could be offered prophylactic treatment such as PDSOB or therapeutic recompression where appropriate.

It is wasteful for a contractor to lose men from the workforce after having trained them and got them experienced. DCI was obviously a trigger in a man's decision to cease work in compressed air. Some research into the human aspects behind their decisions might allow the CAC to take steps to address this problem.

Evidence from the literature suggested that acclimatisation was a factor which influenced the incidence of DCI during a man's initial exposure to compressed air. If an acclimatisation trend could be demonstrated in a group of men then logically it should be possible to demonstrate acclimatisation in individual men. This study found that whilst an acclimatisation trend could be demonstrated in the group, it could not be demonstrated in the individual in a statistically meaningful manner. This contradiction calls into question the nature of the phenomenon which is occurring and the effectiveness of the methods used for analysis. One possible explanation could be that the initial exposure to pressure triggers a sequence of adverse responses – manifested as DCI events - which occur with varying frequency in the man's subsequent exposure history. It is believed that as wide a range of analyses as possible from the "engineering perspective" has been utilised without satisfactorily proving the existence of an acclimatisation trend in individual workers.

It is possible that acclimatisation does not exist or that the proof of its existence or otherwise, may not be possible from the type of approach undertaken here. From the hyperbaric trials, which were commissioned by HSE (Lamont *et al*, 2002), and other published work such as that by Eckenhoff and Hughes (1984), Doppler monitoring has to date produced no evidence of acclimatisation as demonstrated by a reduction in bubble formation with time. This may be because there is no such phenomenon as acclimatisation in the individual; because acclimatisation is not a function of bubble scores or the studies done were simply unsuccessful in detecting trends in bubble scores. Nevertheless it is suggested that should an opportunity arise for a large scale trial of Doppler or ultrasonic monitoring, attempts should be made to gather as much monitoring data as possible.

7.4.3. Discussion - Chapter 6

Chapter 6, focussed on the reduction in DCI incidence and in particular on two issues, which were of direct interest to HSE.

Firstly, a range of hypothetical restrictions on exposure followed by air-only decompression, were examined. In some but not all cases, these could have resulted in a reduction in DCI incidence (as Type 1 DCS). They would not have resulted in the elimination of Type 2 DCS. These restrictions were considered as an alternative to oxygen decompression. In the event none was introduced by HSE. This was perhaps fortunate as the approach was fundamentally flawed. It failed to recognise that DCI is the result of inadequate decompression following a given exposure. It also failed to recognise that it is the exposure which is commercially important and therefore the decompression should be matched to it. In principle, restrictions on exposure should only be introduced where the exposure pressure or exposure period are inherently harmful. Where the decompression is inadequate, it should be modified. Apart from restrictions in exposure introduced by CMAs, the restrictions considered were so severe that working in compressed air would no longer have been reasonably practicable and an otherwise valuable method of ground stabilisation would have been lost.

The second concerned the considerably greater potential to reduce the DCI incidence through the use of oxygen decompression (Lamont, 2002). Included /within that issue was the assessment of existing UK data on DCI incidence following oxygen decompression. That work, reported by Lamont *et al* (2002), clearly showed that oxygen decompression gave the potential for significant reductions in DCI incidence. In addition it showed some value in the use of Doppler as a monitoring tool.

Unfortunately there were insufficient exposure records of oxygen decompression available for this to be reliably demonstrated in a quantitative study. However this author's impression was that DCI incidence had been reduced. There is clearly a need for further data acquisition and research into this issue.

7.4.4. Conclusions - Chapters 4 – 6

It was concluded that there was a number of measures for the risk or incidence of decompression illness. Of these it was concluded that CBR, although universally accepted, was an unsatisfactory measure of DCI incidence; SBR was suitable as a comparative measure of DCI incidence; SERF was the measure of choice for quantifying DCI risk. It was also concluded that other less rigorous measures, highlighted the disproportionate risk of DCI to certain occupational groups within the industry.

It was concluded that the incidence of DCI was higher in data collected for this study, than in historical data (CIRIA, 1992). Although CBRs were similar, the severity of exposure was less than in historical data. When compared with other hyperbaric experience as a bends rate, it was concluded that whilst the risk of DCI in UK tunnelling was of a similar order of magnitude as in other countries, it was more than an order of magnitude greater that in diving. More relevantly, the incidence of DCI was calculated as being around 2% or over for around 20% of the exposures commonly undertaken by shift workers in tunnelling (those at or over 1 bar pressure for 4 hours or more duration). Such a level of risk was unacceptable when reviewed against the wider hyperbaric literature. Using less mathematically-rigorous measures of DCI incidence, it was concluded that on some contracts up to 50% of shift production workers experienced DCI, a situation which was considered to be wholly unacceptable.

No analysis of the incidence of DON was undertaken, however it was concluded that in view of the link between DCI and DON, established by Evans (CIRIA, 1992) the likelihood of DON in the workforce, arising from the unacceptably high incidence of DCI, should be highlighted.

It was concluded that in respect of the susceptibility of individuals to DCI, the group of men experiencing multiple DCI events had their first DCI event after fewer exposures than the group of men experiencing one DCI event only. It was also concluded that nothing arose from this finding, which would allow it to be used for the identification of men particularly susceptible to DCI.

In respect of the occurrence of DCI, it was concluded that the most likely time for it to occur was the night shift, followed by back shift. This varied slightly from earlier findings (CIRIA, 1992).

It was concluded that many men were intolerant of DCI to the extent that 22% of men experiencing DCI ceased work in compressed air immediately thereafter. It was also concluded they had on average, experienced more DCI and at an earlier stage in their exposure history than those who continued working but that the exposures which led to their final DCI event, were of approximately similar severity to the exposures leading to DCI for those who continued working. For those ceasing work, their final exposure was no more severe than previous exposures they had undergone and which had resulted in DCI but after which they had continued working in compressed air.

It was concluded that the main triggers for a man ceasing to work in compressed air after a DCI event were the number and frequency of previous DCI events experienced and the severity of the final DCI event in terms of the type of DCS experienced.

In respect of acclimatisation, it was concluded that whilst it could be demonstrated that a trend towards decreasing DCI incidence over time in the population existed which could be taken as acclimatisation, a similar trend could not be demonstrated in the individual. This raised the question of whether or not the trend was acclimatisation or if exposure to compressed air acted as a trigger for DCI. The question as to whether acclimatisation existed was further raised as there was evidence from the literature that Doppler studies, including one with which the author was involved, had failed to detect a decreasing trend in bubble counts. This assumes that DCI incidence and bubble counts were linked. It was concluded that it would be necessary to go beyond the "engineering perspective" into physiological monitoring of men for a period immediately following decompression, for this to be confirmed.

In respect of men's susceptibility to DCI across contracts, it was concluded that insufficient information existed to enable a conclusion to be made on whether men were equally susceptible to DCI across multiple contracts. The reason for this was that in the period studied too few men had been exposed on multiple contracts with even fewer experiencing DCI, for meaningful analysis to be undertaken. This possibility had not been considered at the outset of the study.

In respect of the potential to make a significant reduction in the incidence of decompression illness arising from air-only decompression by restricting exposure, it was concluded that such an approach was fundamentally flawed in principle. In detail, some restrictions would not have led to any reduction in DCI incidence and there was no restriction, from those considered, which could reasonably practicably have been used to achieve a significant reduction in DCI incidence.

Finally, it was concluded that it was not possible to demonstrate that the incidence of DCI had been reduced by the introduction of oxygen decompression due to insufficient data and an insufficiently large spread of data being available. Indeed, had similar exposures been undertaken followed by air-only decompression, an SBR calculation indicated that no more than one DCI event would have occurred. However because of limited reference data that calculation might not have fully reflected the severity of the exposures undertaken.

7.5. Lessons from Diving

In respect of being informed by experience from the diving industry, it was concluded that there were few, but important, lessons to be learned within the "engineering perspective". The main conclusion was that the effectiveness of the decompression regime in tunnelling was very significantly poorer than that in diving and that this was due only to the outmoded approach to tunnelling decompression and the associated lack of research. The introduction of oxygen decompression in tunnelling hopefully goes some way to address this.

When the hyperbaric stress of the exposure preceding decompression was considered using P√T, it was concluded that there were a number of DCI events in tunnelling which had occurred at low levels of hyperbaric stress which were as low as if not lower than those recorded in diving. It was concluded that this was a further indication of the ineffectiveness of air-only decompression as practised in tunnelling.

7.6. Lessons for HSE

As HSE was sponsoring this study, consideration was given to the conclusions which were particularly relevant to it.

The main conclusions of importance to HSE were those relating to the incidence of DCI arising from air-only decompression and those relating to the reduction of DCI incidence. It was concluded from the study that there was much to be learned in the tunnelling industry from the sophisticated hyperbaric techniques backed by extensive research which were commonplace in diving.

It was also concluded that the likely value from future retrospective studies would be limited as such an approach failed to provide information in real time and was based on highly subjective data, including all or nothing events. Dependence on such studies did not recognise advances in hyperbaric knowledge and consequently should be discontinued in the longer term.

Chapter 8 - Recommendations

A limited number of recommendations arise from this study. They have been divided into two categories – those regarding changes to enforcement policy, legislation and guidance which are directed towards HSE and those which relate to current and future research (and which by default are also directed towards HSE, as the primary funder of hyperbaric research in tunnelling).

The author was fortunate in having access to research funding and other resources within HSE and has taken opportunities to promote research as the ideas arose. The number of recommendations for further research is consequently limited, as several relevant projects are already underway.

8.1. General Recommendations for HSE

Several recommendations are directed towards HSE

8.1.1. Enforcement policy

It is strongly recommend that as soon as possible, consideration is given to establishing an alternative method of assessing the effectiveness of decompression regimes in tunnelling, given the inherently unsatisfactory nature of retrospective studies. Such a method should have the capability to respond in real time and should be based on objective monitoring of individual human response to exposure and decompression.

One possible approach may be the use of Doppler or ultrasonic monitoring techniques which are extensively used in hyperbaric research and which were used by Flook as part of the research programme leading to the introduction of oxygen decompression (Flook, 1998) (Lamont, 2002; Lamont *et al*, 2002).

With this in mind, an opportunity for HSE funding arose in mid 2004, and a project has already begun to consider the "Evaluation of Doppler Monitoring for the Regulation of Hyperbaric Exposure in Tunnelling" – see Section 8.3.2.

8.1.2. Collection of exposure data

From experience of collecting and analysing compressed air exposure data for this study, there is one issue which in other circumstances would have been recommended as the subject of future change.

Given the poor quality of many of the exposure records, the development of an electronic record keeping system would have been an appropriate issue for consideration by HSE, however that has already been done and its value proved. Consequently it is recommended that the acquisition of exposure records in electronic format is continued until the recommendations in Section 8.1.1 have been implemented. In particular it is recommend that the software "COMPAIR" (Holden, 1997) be used for data acquisition purposes.

8.1.3. Effectiveness of oxygen decompression

It is recommended that the collection of exposure data arising from oxygen decompression continues and those data are evaluated using the appropriate measures identified in Section 4.4, until superseded by more effective methods for determining the effectiveness of decompression regimes.

8.1.4. Use of diving-related hyperbaric techniques

It is recommended that diving-related hyperbaric techniques should be applied in tunnelling where appropriate. Those which fall within the "engineering perspective" would include the routine breathing of non-air mixtures and saturation techniques.

The Addendum (HSE, 2001) already makes provision for the use of non-air breathing mixtures and the use of saturation techniques is the subject of a planned research project (see Section 8.3.3).

8.1.5. Legislation and guidance

Possible changes to legislation and the Guidance arising from this study are reviewed in Appendix 5.

8.2. Recommendations for further research

There are two recommendations for further research.

8.2.1. Issues arising from Chapters 4 - 6

Chapters 4 and 5 and Section 6.1 dealt with DCI associated with air-only decompression. As air-only decompression was replaced by oxygen decompression during the course of the study, specific recommendations for further research relating to air-only decompression are not relevant.

It is recommended that a survey should be undertaken to determine the views of the workforce on their experiences of and tolerance towards DCI.

It is recommended that a study should be done on the effectiveness of $P\sqrt{T}$ as a comparator between severity of exposures along with further research to identify if any other measures for comparing severity of exposure can be identified. Such a comparator, should it exist, would facilitate comparisons between contracts and differing exposure histories.

8.3. Current research

As noted above, a number of research projects arising from or relevant to this study are currently underway or are in the planning stage.

8.3.1. Analysis of Contract Medical Adviser's records

This project for the analysis of a CMA's records of principal examinations made under the 1958 and 1996 Regulations, arose indirectly as an outcome of this research. Analysis of exposure records in an attempt to study DCI was being undertaken, and obviously no one was aware that a considerable amount of related information was currently languishing within a CMA's clinical records of statutory medical exanimations.

The specification for this project set a number of objectives, all of which were aimed at analysing the information collected by a CMA in the course of routine medical examinations of compressed air workers. The aim was to further knowledge about the physical characteristics of a man, his physiological profile and his response to hyperbaric exposure. Some objectives were aimed at achieving this directly, some through using the information available to enable the mathematical model to be run with parameter values which more closely reflect the average miner (Flook, 1989).

It was hoped this work would be completed within 2005 but delays have occurred due to illness. The objectives were to:

- create a single database containing records of all principal medical examinations undertaken from 1973 to 2003;
- determine from that data, the physical characteristics of the "average" tunnel worker;
- determine from that data, significant changes, if any, in physical characteristics of tunnel workers since 1973;
- provide data on physical characteristics of tunnel workers for input to the mathematical model used by HSE for decompression profile modelling;
- determine if changes in selection techniques for fit workers, have been introduced as a result of changes in tunnelling technology;
- undertake studies of lung function from the available data.
- examine audiometry records;
- examine haematology/biochemistry records – basic parameters;
- determine the physical characteristics of those experiencing decompression illness – particularly if a correlation exists between body fat and susceptibility to DCI;
- examine long bone and joint x-rays for signs of osteonecrosis.

8.3.2. Evaluation of Doppler Monitoring for the Regulation of Hyperbaric Exposure

Exposure to physical hazards other than pressure, can be monitored in real time against exposure limits and not retrospectively as a statistical exercise as is the case with exposure to compressed air in tunnelling.

The study, which got underway in Autumn 2004, will evaluate the practicability of the use of Doppler monitoring for the real time regulation of hyperbaric exposure in tunnelling, and make recommendations for its use if appropriate. The project will tie in with the physiological modelling research which has already been done by Flook for HSE.

Current techniques rely on actual acute or chronic physical damage being caused, whereas Doppler monitoring may allow potential for physical damage to be determined. The objectives which were set for the project, were to evaluate the use of Doppler monitoring as a means of regulating hyperbaric exposure in tunnelling and develop guidelines for its use through the:

- review of literature to describe the strengths and weaknesses of Doppler monitoring in the assessment of decompression stress, and risks of decompression illness in individuals and in exposed groups;
- collation of practical experience and data (published and unpublished) on the use of the Doppler technique during Diving, Hyperbaric and Aviation Medicine and the diving and compressed air industries;
- determination of whether Doppler monitoring is appropriate as a regulatory technique;
- formulation of recommendations on its usefulness and practicability in compressed air work in UK, including a suggested protocol for its use.

8.3.3. Saturation working

A number of means of reducing the incidence of DCI were considered in Chapter 6. One common means of reducing the incidence of DCI in commercial diving is to reduce the number of decompressions through the use of saturation techniques. Although very common in commercial diving, saturation techniques have been used on only one tunnel project in Europe to date. Partly this has been due to the lack of tunnels at sufficiently high pressures to warrant such techniques and partly this has been due to the technical difficulties of undertaking saturation working in tunnelling.

Whilst there has not yet been a request from the UK tunnelling industry to use the technique and it is unlikely that any request will be forthcoming in the foreseeable future, at higher pressures (say 2.5 - 3 bar and over) the incidence of DCI would be reduced with saturation working.

Accordingly, for some time discussions have been taking place with a leading diving research contractor to study and report on the hyperbaric, engineering and social problems of saturation working in tunnelling. This project has yet to get under way.

8.3.4. Dysbaric Osteonecrosis

It is recommended that despite the current lack of data, a study of the current incidence of DON be undertaken. Currently the only research relating to DON is that which is part of the CMA's records study - see Section 8.3.1.

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Appendix 1 - O_2 in '02 (Lamont, 2002)

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Appendix 2 - Spreadsheet TOTAL

This spreadsheet was written in Lotus 1-2-3® but was later duplicated in Microsoft Excel®. It comprised a worksheet for each contract in the study and a summary worksheet from which the outputs described in Section 3.5.3 were calculated and for which the error checks described in Section 3.5.4 were undertaken .

The worksheet for a typical contract (Cromer) is shown in Figure A2.1. Within the worksheet there were 2 matrices, each of 8 x pressure and 5 x time increments. The number of exposures for each pressure/time cell was taken from the lock attendant's register and entered manually into one matrix and the corresponding number of DCI events into the other. Each worksheet contained long-term average data (HSE, 1996; Table 1) required to calculate the SBR.

A modified Microsoft Excel® version of the spreadsheet was subsequently set up (TOTAL795), in which the time interval below 1 bar was subdivided into two ranges, <0.7 bar and 0.7 – 0.95 bar respectively, giving a 9 x 5 matrix. The summary worksheet is shown in Figure A2.2

A list of the formulae in the summary worksheet of TOTAL795 is given in Table A2.1. Because of limitations within the Excel® package this could only be obtained as a printed list by opening the Microsoft Excel® version of TOTAL795 using Lotus 1-2-3®.

The LTAs in Figures A2.1 and A2.2 were taken from Table 1 of the Guidance. Colour was used to make results more conspicuous but has no other significance e.g. SERFs were shown in red.

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Figure A2.1 – Extract from Worksheet for TOTAL795 (Contract – Cromer)

Appendix 3 - Spreadsheet LIMIT

This spreadsheet was written in Lotus 1-2-3® and was later translatred into Microsoft Excel®. For convenience LIMIT was set up on the summary worksheet of TOTAL/TOTAL795 as it utilised data from it. The outputs from LIMIT were described in Section 3.5.5 along with the error checks which were undertaken.

A list of the formulae in Spreadsheet LIMIT is given in Table A3.1. Again because of limitations within the Excel® package a printed list could only be obtained by opening the Microsoft version of TOTAL795 using Lotus 1-2-3®.

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Table A3.1 – Formulae in Spreadsheet LIMIT

Appendix 4 – Data quality by contract

Lowestoft – see Section 3.6.7

North Woolwich – the contract comprised 7617 exposures. Atkins' computer data check identified no inconsistencies in 6737 exposure records. The remaining records each contained one or more inconsistencies.

696 records were identified as having inconsistencies associated with the selection of decompression profile. Of these, 202 records were for exposures below 0.95 bar (14 psi) where some stage decompression had been undertaken although strictly not required. In around 50 records, data entry errors were identified. The reminder were for exposures at 0.95 bar (14 psi), where for no obvious reason, the incorrect decompression table number (0 instead of 1) had been entered in the LA's register. This was of no consequence in this analysis.

The data check identified inconsistencies in 76 records of exposure period, which were either arithmetical errors in calculation or inconsistencies in recording clock times. As with the records for Lowestoft, it was considered that such errors did not necessarily affect the analysis when 2-hour time increments were considered.

In 10 records, missing data on exposure pressure were identified but could not rectified as they lacked sufficient information for this to be done.

An inconsistency peculiar to this contract and which was attributed to an idiosyncrasy of the lock attendant was identified in 370 records. In these, times occurring between midnight and 00:59 hours were recorded without the leading zeros. This did not affect the analysis as exposure times were converted to minutes before being analysed.

The percentage of inconsistent records for this contract was reduced from 12% to under 2%.

In deriving information for MANLIST, it was found that 79 men had been exposed to compressed air. A computer check showed 292 name variations occurring twice or more. Records of only 77 separate tally numbers having been used could be found. Of these some had been allocated to more than one man. On this contract, searching by tally number proved to be the most successful way of determining the number of exposures per man. However due to known inconsistencies in tally number allocation, these data had to be cross checked by a search on each man's name. This was undertaken by selecting and searching on a small group of letters from each name. These letters were chosen to be the most unlikely to have been mis-spelt. The process was made more time consuming by two men with 79 and 420 exposures respectively, each having the same surname but different initials.

One peculiar anomaly affected some 72 exposure records. The records referred to one surname but two initials, two tally numbers and possibly two occupations were linked to that surname. It would normally have been concluded that the records covered two men however on closer inspection, both men apparently had identical exposures on many days. Further more on at least one day on which they apparently had different exposures, the times of entry and exit were exactly 12 hours different - 2:45 and 14:45 till 4:07 and 16:07 respectively. It ultimately proved impossible to resolve whether one or two men were involved and they were entered in MANLIST as two individuals however suspicions remained that these may have been duplicate entries.

Some of the inconsistencies with this contract, may have arisen due to poor handwriting in the original paper records.

Royal Docks Phase 2 - this contract gave rise to 1168 exposures of which 684 were free of inconsistencies when checked by Atkins after transcription of the paper records to computer.

457 inconsistencies in the decompression table used and that which was theoretically required, all related to stage decompression following exposures to pressures below 1 bar. 11 records with missing data on exposure pressure were identified and all the missing pressures were deduced from other data.

124 inconsistencies relating to exposure time were identified. With all but 4 records, it was able to resolve the inconsistencies. These had arisen because the exposure times were under one hour and had been recorded as a number of minutes only and not in the only

format which the computer recognised of hours:minutes. The remaining 4 records had simple arithmetic errors.

With 8 exposures there was insufficient information to identify the person to whom the records referred and the final inconsistency rate for this contract was estimated to be less than 1%.

75 exposures were followed by decant decompressions. These occurred over a period of six weeks at the end of the contract.

A major problem with this contract was that it was not possible to find any DCI data nor could any evidence be found to the contrary. Accordingly this contract was excluded from much of the analysis.

Rochdale – these exposures were all at pressures below 1 bar. Atkins' computer check revealed few inconsistencies in the data, apart from some missing figures.

There were noticeably few spelling variations in the raw data. However one idiosyncrasy affecting the derivation of data for MANLIST was the LA's informal style. It never proved possible to confirm the identity of "C", "Roger" or "Roger's mate" although it was suspected the latter two may have been engineers.

LWRM – paper records of 3084 exposures were obtained, and transcribed by Atkins. Of these 2723 were identified as being free from inconsistencies.

Inconsistencies relating to exposure pressure were found in 27 records of which all but on were resolved. Similarly, inconsistencies in the selection of the appropriate line from the decompression table were noted in 172 records. On closer examination some appeared to have been due to the deliberate application of a safety factor, 78 related to exposures below 1 bar for which no stage decompression was required whilst the remainder could have been due to people with different exposures being decompressed together. None of these inconsistent records was altered, as the inconsistencies were not relevant to the analysis.

Inconsistencies in exposure time arose in 176 records, of which 31 were due to missing data, 28 were due to inconsistency between the recorded exposure time and the recorded clock times for start of compression and decompression with the remainder being the result of very minor arithmetical errors in the calculation of exposure time.

From an initial inconsistency rate of around 12%, it is estimated that it was again possible to reduce this to around 2%.

This was also a difficult contract for which to compile data for MANLIST, as no tally number system had been used. The method adopted was to run a computer search for duplicate names and then derive manually, a list of unique names using intuition to eliminate spelling variations. A search on three or occasionally four letters for each name was then used to identify the exposures for that name.

On cross-checking against DCI data from Colvin (2002), it was discovered that a small but indeterminate number of records were missing. There were no means of obtaining these.

Royal Docks Phase 9 - 3326 exposure records were transcribed from paper records by Atkins. Of these, 3195 were identified as consistent.

It was possible to resolve 13 out of 17 inconsistencies in exposure pressure which mainly resulted from missing data. 175 records were identified by computer check as having inconsistencies associated with the selection of decompression table and line. Of these, 143 records were identified relating to decompression with others who had undergone more severe exposure with 32 due to missing data.

378 decompressions were decants with the exposure periods for them being calculated as the time from start of compression to the start of the decant decompression. This marginally increased the exposure period used in the selection of the decompression profile and gave a slight safety factor. The decant decompressions seem to have been well distributed throughout the period of compressed air working so were possibly linked to the availability of the manlock.

The raw data for this contract had relatively few spelling variations for names however there were numerous inconsistencies in the tally numbers. When compiling MANLIST, a search was made by both name and tally number. Some inconsistencies remained even after this search process had been done twice.

Ramsden Dock - 8927 exposures were recorded on this contract. Around 1700 out of approximately 2100 exposures at pressures of 1.5 bar and over had a safety factor of one or two tables added when assessing decompression requirements. Atkins' computer check classed these as inconsistencies in table selection although in practice they were the result of a deliberate decision to introduce a safety factor.

Inconsistencies in exposure pressure were identified in 110 records. Many were due to missing data but unusually the same records also lacked data on exposure times and had comments on "stones". It was known that during the sinking of this caisson, large boulders were occasionally found in the base of the working chamber which occasionally required the use of explosives to them break up. The working chamber would have been evacuated during shot firing and there may have been some correlation – not yet discovered - between the comment "stones" and the missing data.

In 272 records, there were inconsistencies in exposure time of which many were due to the inconsistent use of the 12-hour clock in place of the 24-hour clock normally used and were thus readily resolved. The remainder were inconsistencies between recorded clock times and the calculated exposure times which could not be resolved.

Data for this contract was obtained relatively late in the study period. By then, the compilation of MANLIST had begun and so Atkins were requested as part of their data processing activities to produce a list of men exposed. This was computer generated but had some manual checking done on it. Those doing the work were not experienced in interpreting lock attendants' registers and in identifying the idiosyncrasies and inconsistencies in them. From a study of the records, it appeared that some names were duplicated due to transcription errors possibly arising from indistinct handwriting.

In addition to the 261 names identified by Atkins of those exposed to compressed air, there were at least a further 134 spelling variations of these names. Initially, the total number of exposures obtained by summing each individual's number of exposures was 9045 against only 8927 exposures in the dataset. After a closer study, only 233 individual names could be confirmed as having been exposed. This inconsistency was due to the duplication of names and tally numbers for no apparent reason.

As part of the data acquisition process for this contract, the CMA's records had been checked through and as a result, one case of DCI had been identified which had not been recorded in the Lock Attendant's register.

Ennerdale – of the 2854 exposures for the contract, 2704 were identified by Atkins as being free of inconsistencies. 9 records were identified with inconsistencies in both exposure pressure and time, with a further 5 records having inconsistencies in exposure time only. Inconsistencies associated with decompression table selection numbered 48, nearly all of which were for stage decompression following exposure at pressures below 1 bar. Arithmetical errors were identified in 21 exposure records.

There were numerous inconsistencies between names and tally numbers. A computer check yielded 113 name variants with more than one exposure. From a closer examination, It was concluded that only 63 individuals had been exposed to compressed air on this contract. One complication was that four surnames were duplicated within the workforce and additional searches on both tally number and occupation were required to separate these individuals. Ultimately only 1% of exposures could not reliably be allocated against individual names.

Southport - the very poor quality of the raw data was a notable feature of this contract. A fundamental misunderstanding of the definition of exposure time, taken as start of compression to end of decompression, meant that an incorrect exposure time had been recorded for all 10583 exposure records on this contract. Although it was contrary to the principle that the paper records were always taken to be correct, it was decided to substitute the correct exposure times, calculated electronically from the times of entry to and exit from the working chamber. This resulted in 9013 records subsequently being identified by Atkins' computer check, as free of inconsistencies.

The poor quality of the original record keeping also caused major problems in collating data for MANLIST. A computer check revealed 803 name variants, 306 of which occurred twice or more. Some variants could be correlated to individual lock attendants and gave some consistency in the mis-spellings used. On closer examination, it could be seen that with poor pronunciation, some of the variants bore a phonetic similarity to the correct name. The familial link between workers was illustrated by the use of the suffixes "snr" and "jnr" for one surname . However no such differentiation had been used before the second person started and it was therefore not possible to identify to whom the early records referred.

After extensive data manipulation, the original 803 name variants were eventually reduced to just 93 individuals. This process was not helped by the lack of tally numbers on this contract.

In two cases of DCI there were inconsistencies between the CMA's records and the LA's register which were resolved by a further check of the CMA's records.

For reasons which could not be ascertained, some exposures at pressures as low as 0.65 bar (9 psi) were followed by decompressions of up to 20 minutes.

To be consistent with the metric equivalencies in Table 3.5, and current requirements that exposures at pressures over 0.95 bar be treated as being at 1 bar, exposures at pressures over 0.95 bar (14 psi) should have been entered in the 1.0 – 1.25 pressure band in spreadsheet TOTAL. However as stage decompression after such exposures was not done in accordance with the Blackpool Tables (see Section 3.4.3), such exposures have been included within the <0.95 bar category.

JLE 107 – this contract yielded good quality data. This was attributable partly to the use of HSE software and partly to the professionalism of the LA. No unnecessary decompressions were carried out below 1 bar and for exposures above 1 bar, the Blackpool Tables were strictly adhered to. There were no inconsistencies between name and tally number, which facilitated the compilation of MANLIST data.

Cromer – this contract yielded 6911 records of exposures. Of these 6402 were identified by Atkins as being free of any inconsistencies. Inconsistencies in exposure pressure were identified in 18 records however in each case the compression had been aborted prematurely, as someone had been unable to relieve ear pain during compression. In 367 records, inconsistencies in decompression table selection were identified, however on closer examination they all referred to exposures below 0.95 bar (14 psi) which did not require stage decompression. All 403 records in which arithmetical errors were identified relating to the calculation of exposure time were corrected.

There were doubts over one DCI event however this and a number of other inconsistencies were resolved through reference to Colvin's medical data.

JLE 110 - the use of HSE software meant that no inconsistencies were identified.

JLE 105 – this contract yielded good quality data partly because of the use of HSE software and partly because it was staffed by LAs with backgrounds as offshore life support staff (see Section 3.4.3). No obvious inconsistencies in data were identified. However, there was considerable variation in the application of safety factors to decompression table selection. Safety factors were routinely applied during the first part of the contract period, suspended on the instructions of the CMA, then applied again towards the end of the contract period.

The correlation between name and tally number data was excellent and made compilation of MANLIST data extremely straightforward to the extent that 19679 out of 19681 exposures were allocated by a computer search, against 337 men at the first (and only) attempt.

Fylde – superficially, the data quality on Fylde was good with no obvious inconsistencies. However around 130 exposure records could not be obtained and which the CAC appeared to have lost. The missing exposure records included at least one exposure, which resulted in a DCI event. Additionally, three cases of DCI were identified in which there were inconsistencies between the LA's and CMA's records.

On this contract there was a deliberate policy, supported by HSE, to decompress using profiles for exposures 2 tables higher in pressure than actually experienced (see Section 3.7.7).

Swanage - although this was a relatively recent contract, the CAC opted work in imperial units and not to use HSE software. The data was transcribed into electronic format by Atkins who also derived a list of men exposed.

5308 exposure records were identified of which 3839 were free of inconsistencies. On this contract there was a deliberate decision by the CMA and with the support of HSE, to attempt to reduce DCI incidence (see Sections 2.2.6; 3.7.7 and 6.1.1) by undertaking stage decompression at pressures below 1 bar. Consequently 1435 exposures showed up on the computer check as having inconsistencies in decompression table selection.

A further 51 errors in exposure time were identified but could not be resolved giving a final inconsistency rate of less than 1%.

Swansea 5 – Although HSE software was used on this contract, data quality was considerably poorer than expected. Only 7920 records from a total of 8156 were free of inconsistencies. 228 records showed inconsistencies related to exposure time, which could not be resolved.

Swansea 6 – all 14969 exposure records from this contract were generated using HSE software. The HSE relational database software (see Section 3.3.2) used NI number as the primary key between tables. At the start of this contract, NI numbers were not known so temporary numbers were allocated. Subsequently the contractor substituted actual NI numbers without realising that this action would corrupt the data files. Fortunately Atkins were able to restore the data electronically.

Additionally there were inconsistencies in how the CAC defined exposure time, which again were eliminated electronically.

The records contained no information on decompression tables used.

Weston - there were two compressed air operations on this contract, which were before using the data. 5980 exposures were recorded at Shaft 1 of which 5879 were free of inconsistencies. Although this contract post-dated the issue of the HSE software, the CAC – the same one as at Swanage – again chose not to use it. Pressures should have been recorded to the nearest 0.5 bar above the actual, however the degree of accuracy claimed by the lock attendant, of 0.01 bar is probably not achievable. As the exposure pressure was under 1 bar, stage decompression was not strictly required however following experience on low-pressure contracts elsewhere, decompression was introduced on the advice of the CMA.

Inconsistencies in exposure time were identified on 76 records of which some were due to arithmetical errors. A novel problem affected 23 of these records. The LA got confused with the 24 hour clock so that times after 23:59 became 24:00 and over instead of reverting to 00:00 and over. These inconsistencies were easily resolved.

Shaft 4 yielded a further 1503 exposure records. 1454 were free of inconsistencies however 22 records had missing pressures, 21 exposure records contained arithmetical errors and 7 records had missing times.

There was considerable interchange of men between the two operations, but unfortunately men had separate works numbers for each operation. Additionally there were numerous spelling variants and inconsistencies in recording works number. After extensive analysis all but 46 exposures could be attributed to names. Why 6 exposures should appear to be recorded against "welding gear " is not known.

Bacton - 2909 exposures were recorded electronically for this contract. Despite the use of HSE software, a small number of inconsistencies were identified and resolved. Of these, 5 related to name and tally number. 105 records of exposures between 1.0 - 1.1 bar gave no indication of stage decompression but were assumed to be due to missing data.

There was apparently no stage decompression below 1 bar but a general safety factor of 2 tables higher pressure than required seems to have been applied above 1 bar.

Hastings - 1291 exposures recorded using HSE software, which yielded good quality data. Exposures below 1 bar were almost all decompressed to Blackpool table 1 irrespective of pressure. Above 1 bar, no general safety factor appears to have been introduced except at the upper limit of each pressure range.

Docklands Light Railway – this contract also yielded good quality data due to the use of HSE software. Stage decompression to table 1 was applied to exposures from 0.85 bar to 1 bar with strict adherence to the Blackpool Tables above that. The correlation between name and tally number data was good which made derivation of MANLIST data straightforward.

Hull – again the use of HSE software resulted in good quality data. Table 1 decompression was applied to exposures from 0.65 bar upwards with strict adherence to the Blackpool Tables above 1 bar.

There was some doubt over the diagnosis of three of the cases of DCI, which were reported by the CMA. Although they were treated as DCI when they occurred, with hindsight some doubt remains as to whether they were in fact DCI or physical injury. Nevertheless the CMA chose to adhere to the HSE policy that any case treated was counted as DCI.

GYPP – good quality data was obtained as HSE database software was used.
London Cable Tunnel - good quality data was obtained as HSE database software was used.

Portsmouth - good quality data was obtained as HSE database software was used.

Coppermills – it was originally decided to omit this contract from the study as most of the exposures were below 1 bar and it could not be determined whether the DCI information was missing or that none had occurred. Eventually confirmation was received that no DCI had occurred (King, 2003), at which time the raw data was prepared for analysis. Because much of the exposure data was of noticeably poor quality, the challenges faced in doing this are described below (see Figure A6.1).

The data from this contract contained a challenging selection of omissions, improvisations and inconsistencies. Paper records were transcribed to electronic format by Atkins.

Nominally there were at least 729 exposures on this contract however after extensive manipulation, only 660 useable records were confirmed. The data quality problems were considered to be simply the result of bad practice and carelessness by the LAs. Surprisingly, given the other variations from good recording practice, there were very few variations in the spelling of names.

12 date inconsistencies were identified which appeared to be due to bad handwriting resulting in 1986 being mistaken for 1988 during transcription. After sorting an individual's exposures by date and establishing the probable shift pattern, it was possible to identify the dates for which exposures appeared to be missing. It was then confirmed that there were exposures for others on these days but in 1986. A further 15 exposures were incorrectly recorded as 1987 instead of 1986. All 27 records were corrected for date. This problem was associated with two particular lock attendants.

Other omissions, improvisations and inconsistencies which were discovered and which made computer sorting of data somewhat difficult included those associated with time records. These included the recording of some exposures as hours:minutes and some in minutes only, the arbitrary use of 24-hr and 12-hr clocks in which 14:30 and 2:30 were interchanged randomly and the incorrect use of the 24 hour clock whereby 00:30 was recorded as 24:30. Exposure times recorded to one decimal place appeared to mean hours.minutes i.e. 1.1 hours appeared to mean 01hour:10 minutes.

To derive the missing pressure data, a complex sort on date and lock entry time had to be done, working on the assumption that all men on the same shift experienced the same exposure pressure. This was a valid assumption and as the exposures were below 1 bar, the only critical information was whether the exposure pressure was less than 0.7 bar or not. The exact pressure did not influence the analysis in TOTAL.

Missing exposure periods could not be directly calculated as the times recorded were for start of compression and end of decompression. Fortunately most exposures were below 1 bar and the decompression was limited to 5 – 10 minutes. It was decided to ignore this erroneous definition of exposure period except when the exposure time was close to a time increment boundary i.e. 2, 4, 6 hours when the appropriate correction was made.

Calculation of the missing exposure period was made more challenging when the start of compression or end of decompression time was missing. This was exacerbated by men undergoing multiple exposures in a single shift, the individual exposures for which, were not always listed in chronological order. For each man on each day a complex simultaneous sort routine of "date" (ascending), "name" (ascending) and "lock entry time" (ascending) occasionally supplemented with "shift" (ascending) was used, based on the logic that for multiple exposures, a man must compress then decompress before his next compression. In this way the pattern of multiple exposures for that shift could be determined. Attempts were made to identify the make up of gangs so that a check could be made on exposure patterns between gang members. Unfortunately occupation, which would have provided a further useful check, did not appear in the records.

In total, 20 out of 729 "lock entry times" i.e. start of compression, were missing along with 427 "lock re-entry times" i.e. start of decompression. Of the latter, in 69 records the time of end of decompression was also missing. Additionally the exposure period given was not always consistent with that calculated. A number of exposure periods were given as "12" which was meaningless or as "0.8" which seemed to be an exposure pressure not an exposure period.

One column of the LA's register was headed "Time/press" which seemed to be an *ad-hoc* mix of both parameters having entries going from 0.3 to 23.46. In that column, around 120 entries seemed to be times and 380 entries appeared to indicate pressure. Another column with some 200, seemingly random entries, was headed "pressure/pressure2".

An example of the poor quality data from the Coppermills Contract is shown in Figure A6.1 (see Section 3.1.4 regarding anonymity). Examples in Figure A6.1 of the problems described above are as follows:-

Line 376 has the "lock entry time" in the format hours:minutes on a 24 hour clock but the "lock exit time" i.e. end of compression is in the format hours.minutes on a 12 hour clock; "Expos mins" i.e. exposure minutes is assumed to be correct. The "Decomp end" is also given in the format hours.minutes. As "Decomp time" i.e. decompression time is missing but is assumed to be 0 by default, the exposure time of 465 minutes i.e. 19:00 – 2.45 is correct.

Line 21 has a change of format from hours:minutes to hours.minutes.

Lines 45 and 56; 196 and 201 represent multiple exposures for the same man.

Bideford – it was only possible to acquire DCI data, for this contract as the CAC could not locate exposure data in their archives. The quality of the data obtained was good. Bideford data is only used to a limited extent in the study due to the unavailability of the exposure records.

CTRL Contract 320 – The small amount of data from this contract was of good quality and was acquired through use of the HSE database software.

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Figure A6.1 – Poor quality raw data – extract from Coppermills contract database

Appendix 5 – Review of the Regulation of Work in Compressed Air

The development of compressed air working techniques was extensively reviewed in Chapter 2 along with the evolution of UK legislation and guidance. The current legislation (Great Britain, 1996) has been in force for less than a decade with oxygen decompression only being mandatory since September 2001.

One of the objectives of this study was to review the regulations and guidance relating to compressed air working in the light of the findings on the current incidence of DCI and to make recommendations for change where appropriate. This review of regulation and guidance was one of the factors which prompted HSE's sponsorship of this research, as undertakings to conduct such a review had been given within HSE, as part of the process of approving oxygen decompression.

A5.1 - Questions to be answered

Does this study show that the 1996 Regulations and guidance relating to decompression practice, as reflected in the incidence of DCI determined herein, are flawed or are so inadequate as to require amendment?

Having regard to the development of compressed air working practice and regulation, what changes should be made to the 1996 Regulations and the Guidance, more effectively to mitigate the risks of work in compressed air so far as is reasonably practicable?

A5.2 - Adequacy of existing legislation and guidance

Anderson and Lamont (1991) reviewed the requirements of compressed air legislation in around 20 countries worldwide. This review was used extensively during the drafting of the 1996 Regulations and ensured the Regulations took account of all the topics addressed by these authors. The 1996 Regulations are goal setting in nature and consequently can easily accommodate changes in best working practice without the need to revise the regulations themselves. This is done through changes in the Guidance to keep up with industry best practice. HSE has received no complaints to date about the 1996 Regulations or suggestions for the amendment of the Guidance. It was considered an endorsement of the 1996 Regulations and Guidance when the Northern Ireland authorities (Northern

Ireland, 2004) recently adopted them verbatim, to regulate work in compressed air. The main criticism of the 1996 Regulations and guidance is that they do not deal as effectively with the geotechnical aspects of the compressed air installation as they could have done. This was highlighted following the blow-out at DLR (NCE, 2004). However through chairmanship of BSI committee B/513/2, the opportunity arose to rectify the problem by including appropriate text in BS 6164:2001 (BSI, 2001). Muir Wood (2004) in his 2004 Harding Lecture criticised some aspects of that text but the BSI committee have rejected his criticism (BSI, 2005).

It is believed that two minor corrections to the Guidance are required – one to require the making of recording pressure gauge recordings in Appendix 9 and a change of title for paragraph 186 from "Keeping of decompression records" to "Arrangements for record keeping".

Oxygen decompression was introduced, by administrative action without the need for any changes to the legislation. This was planned during the drafting of the Regulations (Lamont, 2003).

One of the main thrusts of this study has been towards determining the incidence of DCI. In Chapter 4, it was concluded that the incidence of DCI using air-only decompression varied with the severity of exposure. Opinion was given that the incidence of DCI was unacceptably high for high-stress exposures. The use of oxygen decompression was intended to reduce the incidence of DCI but it has proved difficult to show such a reduction due to the lack of exposure data (Chapter 6). Since the introduction of oxygen decompression as a means of mitigating the risk of DCI remains largely unproved, it is believed that the 1996 Regulations should not be revised at present, until considerably more experience of oxygen decompression has been gained.

A5.3 - Suggested changes to existing legislation arising from this study

Although it is believed that the regulations require no revision at present, consideration has been given to possible future changes to the 1996 Regulations and the Guidance to make them more reasonably practicable.

The 1996 Regulations cover both the safety and occupational health aspects of work in compressed air. The incidence of DCI is not affected by many of the safety-related duties placed on CACs by the 1996 Regulations. Hence this study did not set out to provide direct evidence for proposals to change the regulations covering safety-related issues. Nevertheless a very few issues on which safety-related recommendations could usefully be made, have come to light during the study period.

It is believed that the regulations relating to safe systems of work which encompasses the personnel required on site, the plant and equipment, compression and decompression procedures and the provision of therapeutic chambers are worthy of further consideration.

Regulation 7 – Safe system of work

Regulation 7(2) sets out the competent persons required to be on site whenever work in compressed air is being undertaken. These comprise the person in charge, compressor attendant, lock attendant and medical lock attendant.

Person in charge - the requirement for a person in charge arose from the 1958 Regulations and the current duties of that person are set out in the Guidance (Paragraph 30). They were extended to cover oxygen decompression by the Addendum. No evidence has been found of a need to change the role or duties of the person in charge.

Compressor attendant - there is no mention of a compressor attendant in the 1936 ICE Report, however the 1958 Regulations required a person to be in immediate charge of the air supply plant. This person continues to be known colloquially as the "compressor attendant" and his current duties are set out in the Guidance (Paragraph 33). His duties were extended to assisting the lock attendant with the operation of the oxygen supply system, by the Addendum. As the 1958 Regulations for which drafting began in 1946 (see Section 2.4.3), referred to "air supply plant" rather than just compressors, it is assumed that this role arose from experience with the use of steam powered compressors. These would have had boilers which would have required a full-time attendant to maintain steam pressure and also undertake the frequent lubrication the compressors required to keep running (see Section 2.1.2). Buchanan (2005a) suggested that it was the unreliability of the electricity supply and the need for manual changeover to diesel powered standby compressors which prompted this requirement.

The Guidance now recommends the use of electric powered compressors (Paragraph 54) with adequate back up compressors and duplicate power supplies, although diesel powered compressors can also be used. Modern compressors are much more reliable than their steam powered predecessors and require little attention apart from occasional re-fuelling. Replacement rather than on-site repair is readily available through the use of hired plant. Having an attendant constantly available seems an unnecessary cost. The attendant could be replaced by appropriate control, monitoring and alarm systems. In these cases, the reliability of the compressors and as a consequence the capacity of back up compressors and power supplies would have to be determined on the basis of risk assessment. The duties in respect of assisting with the oxygen supply still would have to be undertaken however.

Lock attendant - the lock attendant was first required by the ICE Report (1936; p 11) and the current duties are set out in the Guidance (Paragraph 35). These were extended to operating the oxygen breathing system by the Addendum. The introduction of oxygen for decompression purposes has added considerably to the responsibility placed on the lock attendant and the level of competence demanded of him. The incidence of DCI is not directly relevant to these duties. The more intermittent working patterns, which are now common (see Section 1.6.5), mean that lock attendants are not required continuously throughout the period of tunnel excavation.

From the mid 1990s onwards – Fylde and JLE Contract 105 in particular, there has been an increasing trend for lock attendants to be from an offshore diving or life support background. This has introduced a much greater level of competence and hyperbaric experience to tunnel lock keeping and has assisted in the acceptance of oxygen decompression by the industry.

Medical lock attendant - The duties of the medical lock attendant are set out in the Guidance (Paragraphs 41 – 43) and were extended through the Addendum to the supervision of the day to day operation of all hyperbaric procedures on site including the storage and supply of gas and liaison with the person in charge and the CMA on matters affecting hyperbaric operations. Oxygen for therapeutic recompression was introduced in the 1996 Regulations.

Although the introduction of oxygen decompression added little to the technical competence required, the medical lock attendant is now also responsible for the day to day running of the oxygen decompression procedures.

Recommendations - reconsidering the roles and duties of these people in the light of this study, there is no doubt that the person in charge is still required along with the LA and MLA. However with the much greater reliability of modern compressors and the electricity supply, it is questionable if there is a the need for the compressor attendant in his traditional role. He could be replaced by an appropriate control system and the money saved put to better use

With compressed air working now being undertaken in a more intermittent way, the persons listed above may not necessarily be required continuously throughout the contract but may only be required to be available periodically. This could lead to further cost savings without jeopardising health and safety.

With oxygen decompression now mandatory and the possibility in the future of the routine use of non-air breathing mixture, it is recommended that a new role be considered to match the growing complexity of work in compressed air. That role would be the Hyperbaric Supervisor (HS). This proposal arises from the inspection of inshore commercial diving under the Diving Operations at Work Regulations (Great Britain, 1981), under which the diving supervisor had responsibility for the successful implementation of the dive plan.

Hyperbaric supervisor - although it is one of the duties of the person in charge to develop and implement the relevant parts of the health and safety plan required under the Construction (Design and Management) Regulations (Great Britain, 1996), the HS would be responsible to the person in charge for the day to day implementation of the parts of the health and safety plan relating to the hyperbaric aspects of work in compressed air i.e. those aspects covered by the 1996 Regulations, Guidance and Addendum. This role would have strong parallels with the role of the diving supervisor. The HS would be responsible for ensuring that all necessary plant and equipment was available and that sufficient competent people were available to undertake the work. The HS would be advised by the CMA on the decompression and treatment regimes to be implemented and could undertake the role of LA or MLA to the extent that his implementation/supervisory role was not compromised. In conjunction with the person in charge, the HS would determine the extent to which a compressor attendant was required and how that person would assist with the provision of air and oxygen supplies. It is suggested that the role of the HS could normally be undertaken in combination with that of the MLA. This would be a cost effective use of an already under-used resource on site and should make the proposal not only reasonably practicable but cost neutral.

Regulation 8 - Plant and equipment

The introduction to the tunnel environment of oxygen for decompression purposes, increased the range of plant and equipment required to undertake work in compressed air. Nothing has arisen from this study however to alter the requirements for plant and equipment from those in the Guidance and the Addendum.

Regulation 11 – Compression and decompression procedures

The fundamental requirement under Regulation 11(1) is for the CAC to ensure that compression and decompression is undertaken in accordance with a regime approved by HSE. In considering whether the decompression regime currently approved is adequate in maintaining a sufficiently low incidence of DCI, and having considered the information in Chapter 4 and Section 6.2. it is suggested that the incidence of DCI under air-only decompression as quantified by SERFs and other measures was unacceptably high. Whether the incidence of DCI using oxygen decompression will be reduced to an acceptable level remains to be seen (see Section 6.2). Based on the evidence from this study, it is suggested that most of the strategies for reducing DCI incidence whilst retaining air-only decompression in Section 6.1 would not have been effective and none would have been reasonably practicable.

A major long-standing difference in the UK's regulation of decompression practice in compressed air tunnelling compared to diving, has been that in tunnelling, the decompression regime has always been prescribed in detail in the regulations whereas in diving, the diving contractor has had discretion to use any appropriate decompression tables. It could be argued that the justification for the different approaches to decompression arose because in diving there were the US Navy tables with which all divers were familiar along with the in-house tables developed by major diving companies such as Comex. Thus the diving industry attained a level of familiarity with decompression tables which was lacked by tunnelling contractors, who undertook compressed air work on an intermittent basis. Whereas the UK has traditionally adopted a somewhat insular approach to decompression tables, a number of countries around the world have adopted UK decompression practice (Anderson and Lamont, 1991). The study by Flook (2003) of a number of commonly used decompression tables from around the world and the use of German tables on CTRL Contract 320 which arose from that work (Colvin, 2002 and Section 6.2) showed that the traditional UK approach had been unnecessarily restrictive.

There is a reluctance to recommend that HSE should drop its prescriptive approach to decompression tables but instead would encourage greater cooperation between Regulatory authorities in Europe in sharing decompression experience with a view to establishing the effectiveness in use of their respective tables. There were calls at the 2nd International Conference on Engineering and Health in Compressed Air, for the establishment of a pan-European exposure database under the auspices of the European Health and Safety Agency. Unfortunately, following an approach from CAWG, the Agency declined to undertake such a role.

The provisions for acclimatisation in the Guidance were inserted in response to concerns over high DCI incidence on two contracts. This followed limited consultation and was done without research into their scientific validity. In view of doubts over the existence of acclimatisation and recommendations for further research into the topic, it is recommended that paragraphs 165 – 171 of the Guidance be reviewed in the light of future research into acclimatisation.

Although the statutory pressure limit of 3.5 bar in Regulation 11(2) was not exceeded on any contract in the current data, there is probably now sufficient experience of oxygen decompression that it should be possible to work at pressures above 3.5 bar through the use of non-air breathing mixtures by line-fed masks in the working chamber and oxygen for decompression, without giving rise to excessive DCI. Such exposure would require the use of European decompression tables such as those used in German or France which contain tables for such pressures. Such a relaxation would most likely be for tunnelling in the London area and it is unlikely to be required in the foreseeable future. It is not suggested that the regulations should be revised to raise the limit but that administrative procedures in Guidance paragraph 179 be made less onerous.

Regulation 11(4) deals with record keeping. The overwhelming benefits for research from the availability of computerised records are patently obvious from this study (see Chapter 3). It is recommended that the Guidance be amended to require CACs to undertake such record keeping in the future.

Regulation 12 - Medical treatment

One potential benefit from oxygen decompression could have been the elimination of DCI below 1 bar. This would have allowed consideration to be given to raising the threshold at which a medical lock was required. In the event, it is considered that there is insufficient experience of stage decompression between 0.7 bar and 1.0 bar for such a change to be made on the basis of this study.

A5.4 - Concluding remarks

The 1996 Regulations cover both the safety and health aspects of work in compressed air. This study focussed on DCI which is obviously a major health outcome from work in compressed air, but constitutes only part of the scope of the Regulations and Guidance. As a result it is suggested that it was always unlikely that this study would produce evidence of a need for change in the safety-related parts of the regulations and guidance.

This study has not established a need for revision of the 1996 Regulations but has resulted in recommendations for changes in the guidance accompanying the regulations. The study has highlighted some changes which could be made and which would recognise the changes in compressed air working practice which have occurred since the 1996 Regulations came into force. Adoption of these would require only a re-drafting of parts of the Guidance. The most important of these relates to the introduction of a hyperbaric supervisor which is not only considered to be reasonably practicable but to be cost neutral also.

And finally …………

" ……. the experience of an investigator recapitulates knowledge accumulated by his predecessors."

(Behnke, 1969)

With the experience gained as a result of undertaking this study, I agree wholeheartedly with this statement.