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A comparison of oxygen decompression tables for use in compressed air work

Prepared by **Unimed Scientific Limited**
for the Health and Safety Executive 2003

RESEARCH REPORT 126

A comparison of oxygen decompression tables for use in compressed air work

Valerie Flook PhD, CPhys, MInstP
Unimed Scientific Limited
123 Ashgrove Road West
Aberdeen
AB16 5FA
United Kingdom

This study was commissioned to compare a number of tables used for oxygen decompression in compressed air tunneling work. The means of making the comparisons was mathematical simulations of decompression using a model previously validated for decompression studies. Tables from Brazil, France, Germany, Holland, Switzerland and USA are included together with the UK tables which are the Blackpool Tables using oxygen from 0.6 bar.

There are two main conclusions from this study:

that the Blackpool Tables are predicted to have a volume of gas carried in bubbles which is within the range of that for the other tables studied.

that the other tables studied could all be considered acceptable for use in UK.

The predictions are that the bubble numbers in the central venous blood for many of the profiles studied are likely to be just around the level of Doppler detectability in the average miner; that a significant number of miners would have no detectable bubbles. The bubbles are predicted to last for many days because the slow tissues are dominating and therefore the overall decompression stress is not insignificant and it would be unwise to consider any tables predicted to give more bubbles than those reported here. The policy should continue to be directed towards further reductions in decompression bubbles.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

HSE BOOKS

First published 2003

ISBN 0 7176 2703 9

CONTENTS

1.0 INTRODUCTION

The study which is the subject of this report was undertaken by Unimed Scientific Limited at the request of UK Health and Safety Executive. It is the most recent stage of a systematic evaluation of decompression tables used in compressed air work (Flook 1998a, 2001a, 2001b). As a result of the work described in those reports the UK regulations for decompression from compressed air were changed in September 2001 to require the use of oxygen during the latter part of decompression. An addendum to " A guide to the work in compressed air regulations 1996" (HSE 1996) was issued in August 2001 (HSE 2001) which includes the new decompression tables.

In order to introduce oxygen decompression with the minimum complications and to ensure that there was no reduction in confidence within the industry, Unimed Scientific recommended that the then currently approved Blackpool Tables continue to be used but with oxygen as the breathing gas for the stops from 0.6 bar to surface pressure. This approach was tested in trials carried out by Unimed Scientific Limited at the National Hyperbaric Centre in Aberdeen in September 2000 and reported in Flook (2001b). In those trials the simple expedient of using oxygen from 0.6 bar considerably reduced the number of bubbles detected in the central venous blood following decompression from 4 hours at 1.85 bar.

Other options would have been to adopt oxygen decompression tables used in another country or to design completely new tables. Either option would have the effect of introducing procedures which had no properly validated track record. By using oxygen on Blackpool Tables a reduction in the level of decompression problems to below that detailed in the HSE data base could be expected. The data base covers the last 20 years of compressed air work in Britain, during which time the Blackpool Tables have been used with air throughout. HSE are aware that by taking this course it is possible that they might not be ensuring minimum formation of decompression bubbles, the accepted precursor to decompression sickness. Tables used by other countries may result in fewer bubbles.

The current study was commissioned to compare a number of tables used for oxygen decompression from compressed air work in order to identify the safest set of tables, if such exists. The means of making the comparison was mathematical simulations of decompression using the mathematical model described in Flook 2001a. This model proved accurate in predicting the effect of oxygen decompression on the exposure to 1.85 bar used in the trials and has been validated against other experimental work.

1.1 VALIDATION OF THE MODEL

The mathematical model was originally validated by comparing the predicted outcome of a range of decompression procedures with central venous bubble counts made in anaesthetized experimental animals using transoesophageal ultrasonic counting. This work has been reported in Flook 1998b.
More recently it has been possible to compare the predictions of the model with Kisman-Masurel Doppler bubble scores recorded in conscious animals and in humans. The Doppler

scores for the human trials were recorded by DCIEM (Toronto) staff working at Unimed Scientific Limited. This team of Doppler technicians is regarded as being the most experienced in the world. The animal experiments were submarine escape trials carried out for the UK MOD for which the Doppler technicians were trained by DCIEM. The comparisons are shown in figure 1 which is derived from a theoretical study carried out to determine gas loads following free ascent submarine escape from saturation. The model predictions are described as Pulmonary Artery (PA) gas in bubbles, which is the prediction of the volume of gas carried in bubbles in each millilitre of central venous blood.

The figure shows as numbers the Doppler scores from the conscious animals following free-ascent submarine escape procedures from saturation. These are very rapid compressions and decompressions, the whole cycle being completed in less than 2.5 minutes. Each score is placed at the point representing the saturation pressure (isobars for this not shown), the escape pressure (Dissub depth) for the experiment and the PA gas volume predicted by the model.

The hyperbaric exposures used in the human trials were quite different from each other, one was a 30 minute exposure to 40 msw with a surface oxygen decompression (Sur-D), as used in diving, the second was a 4 hour exposure at 1.85 bar followed by decompression on a Blackpool Table, as used in compressed air work. Both gave median K-M Doppler scores of Grade 3 measured at rest and for both the volume of gas predicted to be carried as bubbles in the central venous blood was 0.005 ml/ml. This is shown as the dashed line in Figure 1. The dotted line in the figure shows the predicted gas volume for the compressed air decompression using oxygen in place of air as the breathing gas for the final decompression stops. This decompression gave Doppler scores 0 in 10 of the 11 subjects taking part in the trial.

Doppler Grade 3 for the submarine escape work are mainly grouped about the line representing the model predictions for human trials in which the median scores were Grade 3; the Grade 4 results are above the line and Grade 2 below the line. This indicates that the model performs equally well for long exposures with prolonged decompression procedures and for very rapid ascents from extreme depths and gives a certain confidence in the predictions.

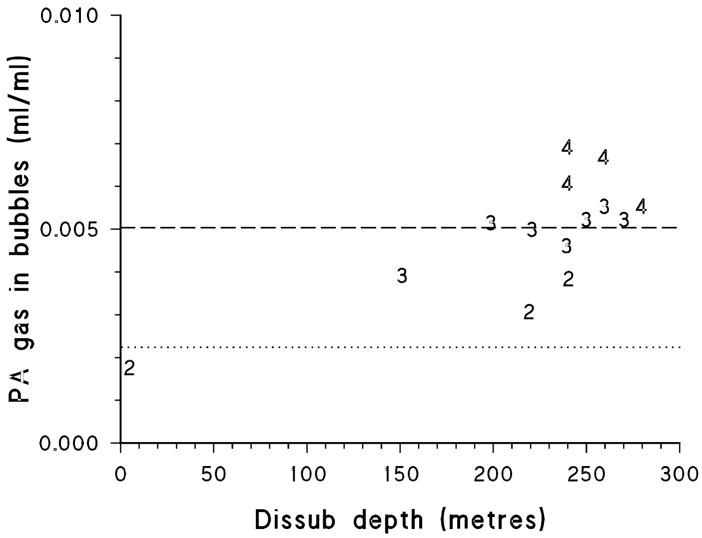

Figure 1 Derived from comparison of theoretical predictions of bubbles volumes and measurements of Doppler K-M scores. (See text for details)

1.2 DECOMPRESSION TABLES USED IN THIS STUDY

Oxygen decompression tables are used in several countries and Unimed Scientific obtained copies of most for inclusion in this study. Tables from Brazil, France, Germany, Holland, Switzerland, USA are included together with the UK tables which are Blackpool Tables with oxygen from 0.6 bar.

There are far too many decompression profiles to be included in full in this report. Tables 1 a-f contain information about the maximum duration allowed at each pressure for each table listed under nationality. Further information for other pressure/time combinations appear in tables 3 a-t in the section 2.1.

Table 1-a UK Tables

Pressure (bar)	Maximum work duration (h : min)	Decompression time (mins)
1.15	8 : 30	23
1.35	8 : 30	44
1.55	8 : 30	69
1.75	8 : 30	90
1.95	8 : 00	110
2.15	7 : 45	136
2.35	7 : 15	161
2.55	6 : 45	187
2.75	6 ; 30	212
2.95	5 : 45	253
3.15	5 : 00	298
3.45	4 : 15	344

Table 1-b French Tables

Pressure (bar)	**Maximum work duration (h : min)**	**Decompression time (mins)**
1.2	5 : 30	37
1.35	5 : 00	47
1.5	4 : 30	67
1.65	4 : 30	88
1.8	4 : 00	98
1.95	4 : 00	119
2.1	3 : 30	121
2.4	3 : 00	134
2.7	2 : 30	145
3.0	2 : 00	153
3.3	1 : 00	65
3.6	1 : 00	90
3.9	1 : 00	101
4.2	1 : 00	121
4.5	1 : 00	142
4.8	1 : 00	165

Table 1-c German Tables

Pressure (bar)	Maximum work duration (h : min)	Decompression time (mins)
0.7	7 : 30	6
0.8	7 : 30	12
0.9	7 : 30	20
1.0	7 : 00	26
1.1	7 : 00	39
1.2	7 : 00	58
1.3	6 : 30	64
1.4	6 : 30	86
1.5	6 : 00	87
1.6	6 : 00	106
1.7	6 : 00	127
1.8	5 : 30	121
1.9	5 : 00	114
2.0	4 : 45	117
2.1	4 : 15	102
2.2	4 : 00	101
2.3	3 : 45	101
2.4	3 : 30	98
2.5	3 : 30	107
2.6	3 : 15	104
2.7	3 : 00	98
2.8	3 : 00	109
2.9	2 : 45	104
3.0	2 : 45	115
3.1	2 : 30	110
3.2	2 : 30	119
3.3	2 : 15	110
3.4	2 : 15	121
3.5	2 : 00	108
3.6	2 : 00	116

Table 1-d Swiss Tables

Pressure (bar)	Maximum work duration (h : min)	Decompression time (mins)
1.0	7 : 50	21
1.1	7 : 20	41
1.2	7 : 00	60
1.3	6 : 50	84
1.4	6 : 30	105
1.5	6 : 10	122
1.6	5 : 50	136
1.7	5 : 40	156
1.8	5 : 20	164
1.9	5 : 10	180
2.0	5 : 00	194
2.1	4 : 50	206
2.2	4 : 40	217
2.3	4 : 30	226
2.4	4 : 20	234
2.5	4 : 10	245
2.6	4 : 00	255
2.7	3 : 50	265
2.8	3 : 40	271
2.9	3 : 30	276
3.0	3 : 30	300
3.1	3 : 20	303
3.2	3 : 10	303
3.3	3 : 00	303
3.4	3 : 00	323
3.5	2 : 50	318
3.6	2 : 50	338
3.7	2 : 40	349
3.8	2 : 40	349
3.9	2 : 30	340
4.0	2 : 30	357

Table 1-e USA Tables

Pressure (bar)	Maximum work duration (h : min)	Decompression time (mins)
0.8	8 : 00	13
0.9	8 : 00	39
1.1	8 : 00	49
1.2	8 : 00	70
1.3	8 : 00	90
1.5	8 : 00	116
1.6	8 : 00	141
1.8	8 : 00	172
1.9	8 : 00	202
2.0	8 : 00	213
2.2	8 : 00	253
2.3	8 : 00	289
2.4	8 : 00	339
2.6	8 : 00	400
2.7	8 : 00	500
2.8	8 : 00	571
2.9	8 : 00	1156
3.0	8 : 00	1237
3.2	8 : 00	1322
3.4	8 : 00	1358

Table 1-f Dutch Tables

Pressure (bar)	Maximum work duration (h : min)	Decompression time (mins)
0.9	6 : 00	0
1.2	7 : 00	40
1.3	7 : 00	50
1.4	7 : 00	65
1.5	6 : 30	75
1.6	6 : 30	85
1.7	6 : 00	95
1.8	5 : 30	100
1.9	5 : 00	105
2.0	5 : 00	115
2.1	5 : 00	125
2.2	4 : 30	125
2.3	4 : 00	125
2.4	4 : 00	135
2.5	4 : 00	140
2.6	4 : 00	150
2.7	4 : 00	166
2.8	3 : 30	155
2.9	3 : 30	164
3.0	3 : 30	186
3.1	3 : 00	155
3.2	3 : 00	165
3.3	3 : 00	180
3.4	2 : 45	172
3.5	2 : 45	180
3.6	2 : 30	172
3.9	2 : 15	189
4.2	2 : 00	185
4.5	2 : 00	219

1.3 THE CALCULATIONS

The intention was to compare all the different tables for a wide range of pressures and times; however this was not possible. Some tables had a restricted maximum pressure compared to the others, whilst other tables would allow higher pressures but have a reduced maximum exposure time. It has been possible to make comparisons for a reasonable number of exposures for 2 and 4 hours at pressure. For the higher pressures the exposure time for which tables could be compared was only 1 hour. The Brazilian tables are described as being for exposures in excess of 6 hours and it has only been possible to make a comparison with most other tables for a 6 hour exposure at 1.5 bar and with two other tables for an 8 hour exposure at 2 bar.

The complete list of pressures and times for which comparisons have been made is given in Table 2.

Table 2 Decompressions included in this study

Pressure	**Duration of exposure**			
1.2	2	4		
1.5	2	4	6	8
1.8	2	4		
2.0			6	
2.4	2	4		
2.7	2	4		
3.0	2	4		
3.3	2	4		
3.9	1			
4.2	1			
4.5	1			

Where there are specific instructions each decompression has been run exactly as instructed. Instructions printed with the tables deal with the length of time spent at each stop and the pressure at which oxygen breathing should commence. They usually cover the rate at which each pressure change is made. Some, but not all, give precise instructions for the switches between oxygen and air once oxygen breathing has started.

Where there are no precise instructions for oxygen:air cycles these have been taken as 25 minutes of oxygen followed by 5 minutes of air. Because this 30 minutes cycle is the most common it has also been used for the UK tables although the tables currently in use suggest 20:5 minute cycles as validated in the trials (Flook 2001b).

The rate of first move is not defined for the Dutch tables, only a maximum rate of 1 bar per minute is given. The Dutch tables have been run with the first move at 0.4 bar per minute which matches the rate for the UK tables. In addition some of the Dutch tables have been repeated with the maximum rate, 1 bar/min, for comparison.

Compressed air workers are usually undertaking some degree of physical activity whilst at maximum pressure. This would have the effect of increasing inert gas uptake in the muscle because of an increased blood flow. To take account of this the muscle time constant during the time at maximum pressure has been shortened from 51 minutes to 11 minutes. This represents a very low level of average activity at about 10 - 20% of maximum oxygen consumption and a heart rate of about 100 beats per minutes in the average untrained individual. Miners work intermittantly at a level of activity higher than this but broken by short rest periods. The time constant used reflects the overall, average, level of activity.

The total dose of oxygen delivered has been expressed in Oxygen Tolerance Units (OTU). These are calculated according to the relationship:-

$$OTU = T_x \, [\, (P_x - 0.5)/0.5 \,]^{0.833}$$

where T_x is the time spent at pressure P_x.

1.4 MAXIMUM PERMISSIBLE OXYGEN DOSE

The effects of exposure to oxygen have been discussed in some detail elsewhere (Flook CRR 201/1998a). Most changes are reversible but the possibility of myopic changes and of increased risk of cataract formation, following frequent exposure to oxygen, should be taken into account. There is evidence that more than 150 exposures to 150 OTU can lead to this problem and regular tests of vision and examination of the eyes of miners was recommended in that report.

The recommendation for maximum exposure to oxygen given in Flook 1998a is reproduced below.

"------ there are no guidelines in operation in Britain for permissible daily doses. The Swedish Navy allows 300 units per day on a daily basis for exposure on many consecutive days. For a five day working week 420 units per day can be used. The work which defined these limits was carried out by Dr H Örnhagen and Dr R W Hamilton. This figure is close to that considered acceptable by Dr W Sterk of the Netherlands. The American National Oceanic and Atmospheric Administration (NOAA) allows 350 units on a daily basis, these limits were set as a result of work by Dr R W Hamilton.

One of the problems of using oxygen on decompression is that, should it become necessary to treat decompression illness, the treatment itself incurs an oxygen load. A standard USN6 decompression treatment table has 648 OTU. Added to an allowed daily working dose of 420 the total, 1068 units, could result in vital capacity decrement of just over 6% for that day's exposure. This level would be associated with pulmonary symptoms but would be reversible. Clark considers 1425 OTU, vital capacity decrement of 10%, as acceptable for treatment of severe DCI problems.

It is recommended that an upper daily limit of 420 OTU be set for a 5 day working week. This daily limit should be reduced to 300 OTU if a 2 day break does not follow 5 working days; if more than 5 consecutive days are worked. A weekly limit of 2100 OTU should apply. On medical grounds alone any worker who has treatment for DCI should be laid off for some days. This is routine in the diving world. The period for which work should not be allowed will be longer if the treatment involved the use of hyperbaric oxygen.

The discussion about exposure levels and the recommendations about acceptable levels largely ignores the benefits derived from breaking the oxygen exposure with periods of air breathing. This is reasonable given the very small amount of work which has been carried out to quantify the effect of different cycle lengths, different oxygen:air ratios and different pressures. However oxygen is now always used with air breaks; 25:5 minutes is a common ratio, as is 30:5. Most of the experts consulted recommended a longer cycle than 20:5 on the grounds that there will be fewer gas changes and therefore fewer opportunities to refit the facemask in a way which allows an air leak. Sometimes, but not often, cycle length can be chosen to fit conveniently with the pressure change schedules."

2.0 RESULTS

2.1 COMPARISON OF TABLES

Tables 3 a-t give details of the decompressions including total decompression time and Oxygen Tolerance Units (OTU). The final column of each table gives the predicted maximum gas volume in bubbles in the central venous blood at the end of the decompression. For one procedure the predictions indicate a short lived peak of higher gas volume in bubbles during the decompression. This procedure is identified in the tables by *.

In addition to the OTU levels incurred during decompression a significant dose might be incurred during the work shift at higher working pressures on air. Each of the tables has the value for OTU during the work shift written at the bottom.

Also below each table is written the arterial inert gas pressure (P_aN_2) during the uptake phase, i.e. at the pressure of the exposure. This is the partial pressure to which each tissue will saturate. Arterial inert gas partial pressure is entirely dependent on the pressure at which uptake occurs so that a decompression which has an outcome independent of the arterial inert gas level has successfully dealt with the problems related to the pressure of exposure. Also given below each table are the inert gas levels in the slowest compartment, the fat (P_8N_2). For compressed air tables this tissue is the dominant tissue for the volume of gas which can form into bubbles after decompression is completed. The level of inert gas in this tissue is dependent on the duration of the exposure as well as on the pressure. It is therefore of interest to compare the outcome from 2 hour exposures with that from 4 hour exposures. These inert gas partial pressures are used in the correlation statistics in section 2.2.

We were sent two sets of Brazilian tables for 1.5 bar; one is called "Alemanha" and the other "After Behnke". The latter is believed to be derived on the same principles as that present by Ribeiro at the Compressed Air Symposium of 1992 (1994). These are identified in the following tables as Brazil A and Brazil B.

Table 3-a Details of decompressions

Pressure:	**1.2 bar**			**2 hours Duration:**		
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	0.3	No stop	None	4		0.00253
UK	0.4	0.2	0.2	14	12.3	0.00109
German	0.2	1	1	7	14.5	0.00236
Swiss	0.75	No stop	None	1.6		0.00261
Dutch, slow	0.4	0.3	0.3	5	6.6	0.00250
Dutch, fast	1	0.3	0.3	4	6.6	0.00253
USA	0.25	No stop	None	5		0.00253

P_aN_2 1.70 bar
P_8N_2 1.16 bar **OTU during work shift 0**

Table 3-b Details of decompressions

Pressure:	**1.2 bar**			**4 hours Duration:**		
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	0.3	0.6	0.6	17	23.0	0.00257
UK	0.4	0.4	0.4	39	38.3	0.00215
German	0.2	1	1	23	44.0	0.00237
Swiss	0.9	0.3	0.3	13	16.6	0.00279
Dutch, slow	0.4	0.3	0.3	22.25	27.7	0.00245
Dutch, fast	1	0.3	0.3	20.9	27.7	0.00247
USA	0.25	0.27	0.27	31	33.4	0.00248

P_aN_2 1.70 bar
P_8N_2 1.40 bar **OTU during work shift 0**

Table 3-c Details of decompressions

Pressure:	**1.5 bar**		**2 hours Duration:**			
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	0.3	0.9	0.9	17	27.9	0.00293
UK	0.4	0.4	0.4	29	32.7	0.00269
German	0.25	1.0	1.0	18	34	0.00277
Swiss	1.2	0.3	0.3	10	13.2	0.00297
Dutch, slow	0.4	0.3	0.3	18	21	0.00301
Dutch, fast	1	0.3	0.3	16	21	0.00299
USA	0.2	0.27	0.27	21	26	0.00297

P_aN_2 1.94 bar

P_8N_2 1.26 bar

OTU during work shift 5.4

Table 3-d Details of decompressions

Pressure:	1.5 bar		4 hours Duration:			
	First Move		Oxygen from: (bar)	Decompression time (mins)	OTU (units)	PA gas (ml/ml)
	Rate (bar/min)	Stop (bar)				
French	0.3	0.9	0.9	47	64.1	0.00235
UK	0.4	0.4	0.4	59	66.1	0.00239
German	0.25	1.0	1.0	42	74.8	0.00237
Swiss	1.2	0.3	0.3	50	68.5	0.00271
Dutch, slow	0.4	0.6	0.6	48	64.7	0.00241
Dutch, fast	1.0	0.6	0.6	47	64.7	0.00244
USA	0.25	0.544	0.27	56	61	0.00243

P_aN_2 1.94 bar
P_8N_2 1.55 bar **OTU during work shift 10.7**

Table 3-e Details of decompressions

Pressure: 1.5 bar			**6 hours Duration:**			
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	Not allowed					
UK	0.4	0.6	0.6	69	76.71	0.00291
German	0.25	1.0	1.0	87	147.5	0.00284
Swiss	0.9	0.6	0.6	114	145.2	0.00274
Dutch	0.4	0.6	0.6	72	98.9	0.00296
USA	0.23	0.82	0.54	83	101.9	0.00300
Brazil A	0.3	0.3	0.3	36	35.6	0.00514
Brazil B	0.3	0.6	0.6	75	109.6	0.00281

P_aN_2 1.94 bar
P_8N_2 1.72 bar

OTU during work shift 16.2

Table 3-f Details of decompressions

Pressure:	**1.5 bar**			**8 hours Duration:**		
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	Not allowed					
UK	0.4	0.6	0.6	69	76.7	0.00478
German	Not allowed					
Swiss	Not allowed					
Dutch,	Not allowed					
USA	0.23	0.82	0.54	83	146.2	0.00301
Brazil B	0.3	0.62	0.62	75	109.6	0.00313

P_aN_2 1.94 bar

P_8N_2 1.82 bar **OTU during work shift 21.6**

Table 3-g Details of decompressions

Pressure:	**1.8 bar**		**2 hours Duration:**			
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	0.3	0.9	0.9	33	48.1	0.00273
UK	0.4	0.6	0.6	59.5	70.4	0.00200
German	0.267	1.0	1.0	29	55.6	0.00253
Swiss	0.750	0.3	0.3	27	34.6	0.00319
Dutch, slow	0.4	0.6	0.6	34.5	49.3	0.00250
Dutch, fast	1.0	0.6	0.6	33.2	48.7	0.00233
USA	0.245	0.544	0.272	30	26.9	0.00337

P_aN_2 2.17 bar
P_8N_2 1.37 bar **OTU during work shift 25.0**

Table 3-h Details of decompressions

Pressure:	**1.8 bar**			**4 hours Duration:**		
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	0.3	0.9	0.9	83	128	0.00291
UK	0.4	0.8	0.6	99	109	0.00278
German	0.267	1	1	65	108	0.00288
Swiss	1.2	0.6	0.6	95	116	0.00312
Dutch, slow	0.4	0.6	0.6	73.5	101	0.00302
Dutch, fast	1	0.6	0.6	71.7	101	0.00302
USA	0.24	0.816	0.544	85	95.4	0.00284

P_aN_2 2.17 bar

P_8N_2 1.72 bar

OTU during work shift 49.3

Table 3-i Details of decompressions

Pressure:	2.0 bar		6 hours Duration:			
	First Move		Oxygen from: (bar)	Decompression time (mins)	OTU (units)	PA gas (ml/ml)
	Rate (bar/min)	Stop (bar)				
French	Not allowed					
UK	0.4	1.0	0.6	136	147.4	0.00385
German	Not allowed					
Swiss	Not allowed					
Dutch	Not allowed					
USA	0.23	1.09	0.82	163	218.1	0.00369
Brazil B	0.36	0.95	0.95	105	195.4	0.00374

P_aN_2 2.33 bar
P_8N_2 2.05 bar **OTU during work shift 108.1**

Table 3-j Details of decompressions

Pressure:	**2.4 bar**			**2 hours Duration:**		
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	0.3	0.9	0.9	70	101	0.00280
UK	0.4	0.8	0.6	107	120	0.00220
German	0.28	1.0	1.0	51	100	0.00340
Swiss	0.75	0.9	0.9	64	96.9	0.00322
Dutch, slow	0.4	0.9	0.9	69	103	0.00256
Dutch, fast	1	0.9	0.9	67	103	0.00260
USA	0.26	1.09	0.816	69	84.7	0.00414

P_aN_2 2.65 bar
P_8N_2 1.58 bar **OTU during work shift 56.4**

Table 3-k Details of decompressions

Pressure:	**2.4 bar**			**4 hours Duration:**		
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	Not allowed					
UK	0.4	1.2	0.6	157	149	0.00380
German	Not allowed					
Swiss	0.75	0.9	0.9	208	287	0.00344
Dutch, slow	0.4	1.2	1.2	138	228	0.00365
Dutch, fast	1	1.2	1.2	136	228	0.00365
USA	0.25	1.36	1.09	149	220	0.00385

P_aN_2 2.65 bar

P_8N_2 2.03 bar

OTU during work shift 112.6

Table 3-I Details of decompressions

Pressure:	2.7 bar		2 hours Duration:			
	First Move		Oxygen from: (bar)	Decompression time (mins)	OTU (units)	PA gas (ml/ml)
	Rate (bar/min)	Stop (bar)				
French	0.3	1.2	0.9	94	139	0.00260
UK	0.4	1.0	0.6	124	134	0.00268
German	0.28	1	1	62	112	0.00326
Swiss	0.9	0.9	0.9	86	120	0.00301
Dutch, slow	0.4	1.2	1.2	79	122	0.00288
Dutch, fast	1	1.2	1.2	77	121	0.00292
USA	0.267	1.09	0.816	86	112	0.00301

P_aN_2 2.88 bar
P_8N_2 1.69 bar **OTU during work shift 70.8**

Table 3-m Details of decompressions

Pressure:	2.7 bar			4 hours Duration:		
	First Move		Oxygen from: (bar)	Decompression time (mins)	OTU (units)	PA gas (ml/ml)
	Rate (bar/min)	Stop (bar)				
French	Not allowed					
UK	0.4	1.2	0.6	165	150	0.00444
German	Not allowed					
*** Swiss**	0.75	1.2	0.9	265	334	0.00235
Dutch, slow	0.4	1.5	1.2	169	259	0.00428
Dutch, fast						
USA	0.268	1.36	1.09	180	261	0.00422

P_aN_2 2.88 bar
P_8N_2 2.20 bar **OTU during work shift 141.3**

Table 3-n Details of decompressions

Pressure:	**3.0 bar**			**2 hours Duration:**		
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	0.3	1.5	0.9	133	174	0.00288
UK	0.4	1.2	0.6	150	142	0.00291
German	0.3	1.2	1.0	74.5	129	0.00363
Swiss	0.9	1.2	0.9	115	149	0.00294
Dutch, slow	0.4	1.2	1.2	105	172	0.00315
Dutch, fast						
USA	0.272	1.36	1.09	106	142	0.00327

P_aN_2 3.12 bar
P_8N_2 1.79 bar **OTU during work shift 84.5**

Table 3-o Details of decompressions

Pressure:	**3.0 bar**			**4 hours Duration:**		
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	Not allowed					
UK	0.4	1.6	0.6	194	151	0.00405
German	Not allowed					
Swiss	Not allowed					
Dutch, slow	Not allowed					
Dutch, fast						
USA	0.28	1.6	1.36	195	311	0.00398

P_aN_2 3.12 bar
P_8N_2 2.36 bar **OTU during work shift 168.8**

Table 3-p Details of decompressions

Pressure:	**3.3 bar**			**2 hours Duration:**		
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	Not allowed					
UK	0.4	1.2	0.6	164	143	0.00340
German	0.3	1.5	1	93	151	0.00356
Swiss	1.05	1.2	0.9	149	181	0.00333
Dutch, slow	0.4	1.5	1.5	119.5	193	0.00348
Dutch, fast	1	1.5	1.5	117.5	192	0.00342
USA	0.28	1.63	1.36	127	174	0.00425

P_aN_2 3.36 bar

P_8N_2 1.91 bar **OTU during work shift 97.8**

Table 3-q Details of decompressions

Pressure:	3.3 bar		4 hours Duration:			
	First Move		Oxygen from: (bar)	Decompression time (mins)	OTU (units)	PA gas (ml/ml)
	Rate (bar/min)	Stop (bar)				
French	Not allowed					
UK	0.4	1.6	0.6	219	152	0.00553
German	Not allowed					
Swiss	Not allowed					
Dutch, slow	Not allowed					
Dutch, fast						
USA	0.28	1.9	1.36	252	376	0.00535

P_aN_2 3.36 bar

P_8N_2 2.53 bar

OTU during work shift 195.4

Table 3-r Details of decompressions

Pressure:	**3.9 bar**			**1 hour Duration:**		
	First Move		**Oxygen from: (bar)**	**Decompression time (mins)**	**OTU (units)**	**PA gas (ml/ml)**
	Rate (bar/min)	**Stop (bar)**				
French	0.3	1.5	0.9	94	105	0.00434
UK	Not allowed					
German	Not allowed					
Swiss	0.9	1.3	0.9	73	98.6	0.00487
Dutch, slow	0.4	1.5	1.5	76	130	0.00393
Dutch, fast						
USA	Not allowed					

P_aN_2 3.83 bar
P_8N_2 1.53 bar **OTU during work shift 62.8**

Table 3-s Details of decompressions

Pressure: 4.2 bar			1 hour Duration:			
	First Move		Oxygen from: (bar)	Decompression time (mins)	OTU (units)	PA gas (ml/ml)
	Rate (bar/min)	Stop (bar)				
French	0.3	1.8	0.9	111	128	0.00481
UK	Not allowed					
German	Not allowed					
Swiss	Not allowed					
Dutch, slow	0.4	1.8	1.5	88	147	0.00456
Dutch, fast						
USA	Not allowed					

P_aN_2 4.07 bar

P_8N_2 1.61 bar

OTU during work shift 70.0

Table 3-t Details of decompressions

Pressure:	4.5 bar		1 hour Duration:			
	First Move		Oxygen from: (bar)	Decompression time (mins)	OTU (units)	PA gas (ml/ml)
	Rate (bar/min)	Stop (bar)				
French	0.3	1.8	0.9	142	146	0.00428
UK	Not allowed					
German	Not allowed					
Swiss	Not allowed					
Dutch, slow	0.4	2.1	1.5	94	158	0.00505
Dutch, fast	1	2.1	1.5	92	155	0.00503
USA	Not allowed					

P_aN_2 4.31 bar
P_8N_2 1.66 bar **OTU during work shift 76.1**

2.1.1 Maximum gas at end of decompression

The main findings of this study are summarised in tables 4 a-t which rank the tables in the order of least gas in bubbles to most, for each of the exposures studied. Although there appears to be a wide range of volume of gas carried as bubbles for some exposures many of these results indicate an average level of bubbling which would be undetectable in most subjects. As reported earlier (Flook CRC 369/2001b), the predicted volume of gas in bubbles following decompression on oxygen in human trials was 0.0022 ml/ml and the median of maximum Doppler scores for that procedure was grade 0. Decompression on air was predicted to give a gas volume of 0.005 ml/ml and that gave a median Doppler score of grade 3. Most of the decompressions reported in Table 4 are predicted to be between these two levels with most at the lower end of the range. The range of gas volumes predicted for most exposures is small and it is unlikely that the different profiles could be distinguished by Doppler recordings.

1.2 bar 2 hours

Table 4-a

Tables	PA gas
UK	0.00109
German	0.00236
Dutch	0.00250
French	0.00253
USA	0.00253
Swiss	0.00261

The UK table is predicted to have the smallest volume of gas forming into bubbles. This is the procedure which has the longest decompression time and close to the most oxygen. It is the only table which has zero bubbles predicted for fat. The tables predicted to have the most gas are those which have no stops and therefore no oxygen.

For this exposure the time taken to decompress has a statistically significant linear correlation with predicted gas volume (at a 5% level of significance). OTU does not correlate at a significant level.

1.2 bar 4 hours

Table 4-b

Tables	PA gas
UK	0.00215
German	0.00237
USA	0.00245
Dutch	0.00248
French	0.00258
Swiss	0.00279

The UK table is predicted to have the smallest volume of gas forming into bubbles. This is the procedure which has the longest decompression time and close to the most oxygen. The Swiss table, with the highest value for predicted gas, has the shortest decompression time and the least oxygen.

OTU and decompression time correlate significantly with predicted gas volume.

1.5 bar 2 hours

Table 4-c

Tables	PA gas
German	0.00269
UK	0.00277
French	0.00293
USA	0.00297
Dutch	0.00297
Swiss	0.00301

The table with the least gas, the German, has the highest oxygen dose but not the longest decompression time. The UK table is close to the German in outcome and
uses more decompression time and less oxygen. The table predicted to perform worst, the Swiss, has the shortest decompression and the least oxygen.

The correlation between predicted gas volume and OTU is significant at 5%.

1.5 bar 4 hours

Table 4-d

Tables	PA gas
German	0.00235
French	0.00237
UK	0.00239
Dutch	0.00241
USA	0.00243
Swiss	0.00271

The tables are not so easily distinguished for this exposure and span a narrow range. Neither decompression time nor OTU correlate with the predicted outcome.

1.5 bar 6 hours

Table 4-e

Tables	PA gas
Swiss	0.00274
Brazil B	0.00281
German	0.00284
UK	0.00291
Dutch	0.00296
USA	0.00300
Brazil A	0.00514
French	Not allowed

The procedure which has a decompression time over 25% more than the next longest and with a high oxygen dose has the least gas in bubbles. In contrast the Brazil A profile has a decompression time only about 50% of the next lowest and a very low oxygen dose and performs relatively badly.

Both decompression time and oxygen dose correlate significantly with predicted outcome.

1.5 bar 8 hours

Table 4-f

Table	PA gas
USA	0.00301
Brazil B	0.00313
UK	0.00478
French	Not allowed
German	Not allowed
Swiss	Not allowed
Dutch	Now allowed

The table with by far the highest oxygen dose gives the least gas. In contrast the UK table has only about 50% the oxygen dose, similar decompression time and gives the most gas.

1.8 bar 2 hours

Table 4-g

Tables	PA gas
UK	0.00200
Dutch	0.00233
German	0.00253
French	0.00273
Swiss	0.00319
USA	0.00337

The UK table is predicted to give least gas and has the longest decompression time and most oxygen. The table which performs worst, USA, has a similar decompression time to most others but has a lower oxygen dose.

The correlation between predicted gas volume and OTU is significant at a 5% level.

1.8 bar 4 hours

Table 4-h

Tables	PA gas
UK	0.00278
USA	0.00284
German	0.00288
French	0.00291
Dutch	0.00302
Swiss	0.00312

Again for this exposure the results cover a narrow range and it is not easy to distinguish between decompression profiles. This pattern indicates that the effects of the extra bottom time, in terms of gas loading, has been taken into account equally well in the design of all procedures.

2.0 bar 6 hours

Table 4-i

Table	PA gas
USA	0.00369
Brazil B	0.00374
UK	0.00385
French	Not allowed
German	Not allowed
Swiss	Not allowed
Dutch	Not allowed

The table with the longest decompression time and the highest oxygen dose gives the best performance whilst the UK table, with the smallest oxygen dose but not the shortest decompression time, performs least well. Comparison between the UK and Brazil B tables shows the trade-off between decompression time and oxygen dose.

2.4 bar 2 hours

Table 4-j

Tables	PA gas
UK	0.00220
Dutch	0.00256
French	0.00280
Swiss	0.00322
German	0.00340
USA	0.00414

The longest decompression time combined with most oxygen gives the lowest value for predicted gas, in the UK table. The table which performs worst has the least oxygen and a relatively short decompression time.The correlation between OTU and predicted gas volume is significant at a 5% level.

2.4 bar 4 hours

Table 4-k

Tables	PA gas
Swiss	0.00344
USA	0.00365
Dutch	0.00380
UK	0.00385
French	Not allowed
German	Not allowed

Only four of the nations have tables available for this exposure. Within those four there is a wide spread of oxygen doses. The longest decompression time combined with the highest oxygen dose results in the most favourable outcome. The UK table with the smallest oxygen dose has a prediction not so far from the those for the Dutch and USA tables which both use much more oxygen. The Swiss table performs best but brings the total oxygen dose (decompression plus time at work) to within 20 units of the recommended maximum for a daily exposure for a 5 out of 7 day working week.

2.7 bar 2 hours

Table 4-l

Tables	PA gas
French	0.00260
UK	0.00268
Dutch	0.00288
Swiss	0.00301
USA	0.00301
German	0.00326

As with the other decompressions from 2 hour exposures the highest oxygen doses combined with longer decompression times results in the lowest predicted gas in bubbles. The lowest oxygen with the shortest decompression times gives the highest values for predicted gas.

The correlation between OTU and and decompression time both correlate with predicted gas volume at a significant, 5% level.

2.7 bar 4 hours

Table 4-m

Tables	PA gas
Swiss	0.00235
USA	0.00422
Dutch	0.00428
UK	0.00444
French	Not allowed
German	Not allowed

Again this four hour exposure is allowed by only four of the six national tables. There is a wide range of oxygen doses and of decompression times resulting in a relatively wide range of predicted gas volumes. The Swiss table would result in the recommended daily oxygen dose being exceeded. There are no significant correlations.

3 bar 2 hours

Table 4-n

Tables	PA gas
French	0.00288
Swiss	0.00291
Dutch	0.00294
UK	0.00315
USA	0.00327
German	0.00363

The decompression with most oxygen and a relatively long decompression time gives the best result, least oxygen with the shortest decompression the worst result.

There is a significant correlation between predicted gas volume and decompression time.

3 bar 4 hours

Table 4-o

Tables	PA gas
USA	0.00398
UK	0.00405
French	Not allowed
German	Not allowed
Swiss	Not allowed
Dutch	Not allowed

This exposure is not allowed by four of the six nations. The extra oxygen on the USA table brings very little advantage and takes the whole work shift over the recommended level for a 5 day in 7 working week.

3.3 bar 2 hours

Table 4-p

Tables	PA gas
Swiss	0.00333
UK	0.00340
Dutch	0.00342
German	0.00356
USA	0.00425
French	Not allowed

The results for the UK and Dutch tables show the benefit of trading off a lower decompression time against a higher oxygen dose. The Dutch and the German tables have much shorter decompression times than the UK and Swiss.

3.3 bar 4 hours

Table 4-q

Tables	PA gas
USA	0.00535
UK	0.00553
French	Not allowed
German	Not allowed
Swiss	Not allowed
Dutch	Not allowed

Only two sets of tables allow this exposure and once more the USA table takes the oxygen dose over the recommended limit without much benefit in terms of outcome.

3.9 bar 1 hour

Table 4-r

Tables	PA gas
Dutch	0.00393
French	0.00434
Swiss	0.00487
German	Not allowed
UK	Not allowed
USA	Not allowed

4.2 bar 1 hour

Table 4-s

Tables	PA gas
Dutch	0.00456
French	0.00481
UK	Not allowed
German	Not allowed
Swiss	Not allowed
USA	Not allowed

4.5 bar 1 hour.

Table 4-t

Tables	PA gas
French	0.00428
Dutch	0.00505
UK	Not allowed
German	Not allowed
Swiss	Not allowed
USA	Not allowed

2.1.2 Comparison of Dutch tables using two rates of move

The Dutch tables carry the instructions that the maximum rate of move to the first stop should be 1 bar/minute. As this means that these tables might be used with different rates of decompression it was decided to simulate two different decompression rates for some of the exposures. Table 5 shows the effect of the decompression rate on predicted PA gas.

Table 5 Predicted maximum PA gas in bubbles

Pressure/time	0.4 bar/min	1.0 bar/min
1.2/2	0.00250	0.00253
1.2/4	0.00245	0.00247
1.5/2	0.00301	0.00299
1.5/4	0.00241	0.00244
1.8/2	0.00250	0.00233
1.8/4	0.00302	0.00302
2.4/2	0.00256	0.00260
2.4/4	0.00365	0.00365
2.7/2	0.00288	0.00292
3.3/2	0.00348	0.00342
4.5/1	0.00505	0.00503

The results show that for these particular tables the speed of the initial pressure change has no significant impact on the maximum extent of bubble formation at the end of the decompression.

2.2 FACTORS INFLUENCING PREDICTED GAS VOLUME

Those who produce decompression tables have several factors to manipulate including;

decompression time,

rate of change of pressure,

pressures of stops,

duration at stops and, for oxygen decompression,

the pressure at which oxygen breathing can start and

the total oxygen dose used.

In fact there is an apparently infinite number of possible combinations. In working through the tables in this study it was possible to detect, in the overall shape of the tables, differences in the basic approach between the different countries. Despite these differences it is possible to determine the relative importance of some of these contributing factors from the results of this study.

In addition to the characteristics of the decompression which could be a significant influence on the decompression outcome so too could be the gas loads at the start of decompression. Arterial nitrogen partial pressure at the start of decompression is determined by the pressure of the exposure and would influence the outcome if the decompression were inadequate. If there is no significant relationship between arterial nitrogen at the start of the decompression and the outcome of the decompression then the decompression procedure has dealt with the gas load equally effectively for all pressures.

For most procedures considered in this study the decompression appears to be successful at ensuring that only the slowest tissues contribute to the gas volume in bubbles on return to normal pressure. This means that of the tissue gas loads at the start of decompression only the inert gas partial pressure in the fat is likely to influence the outcome. Whereas arterial nitrogen partial pressure of inert gas relates to pressure of exposure the slow tissue gas load relates to the duration of the time spent at working pressure. Once again equally successful decompressions will result in there being no correlation between the gas load in fat at the start of the decompression and the maximum gas in bubbles.

Statistical analysis of the results shows a significant correlations between arterial partial pressure of nitrogen and predicted gas volume in bubbles. Figure 2 shows this relationship together with the line of best fit and the 95% confidence limits. The decompression procedures fail to fully take account of the increased arterial nitrogen levels with increasing exposure pressure. Each 1 bar increase in P_aN_2 adds another 0.00078 ml to the volume of gas carried as bubbles.

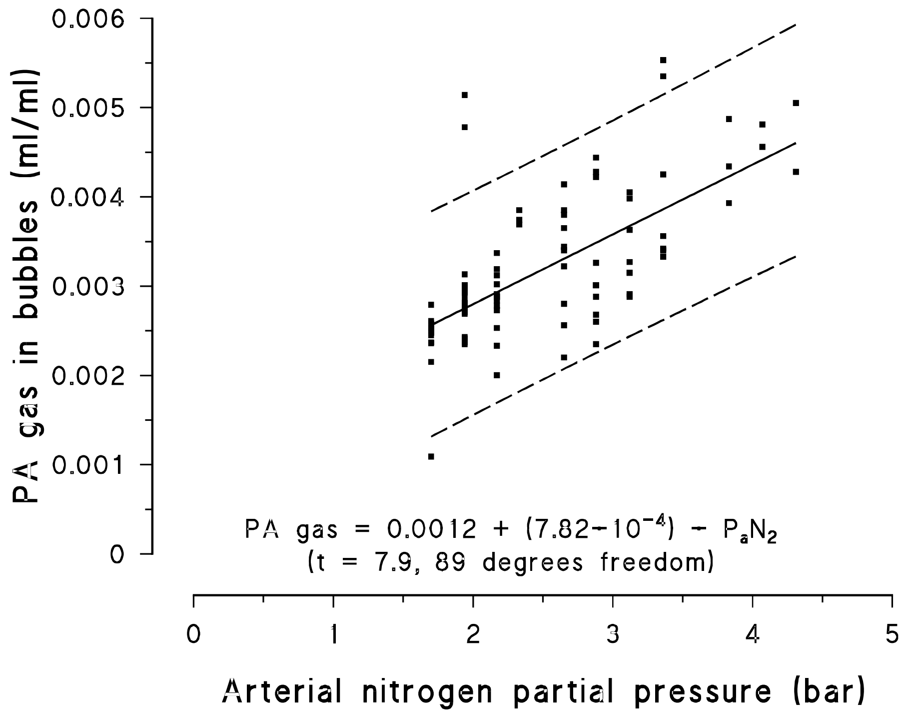

Figure 2 Predicted gas volume correlated with arterial nitrogen gas load at the start of decompression

The relationship between fat inert gas partial pressure and predicted gas in bubbles is also statistically significant both when all exposures are taken together and for the 2 and 4 hour exposures separately. Figure 3 shows the information for the partial pressure of nitrogen in fat for the 2 hour (Figure 3a) and the 4 hour (figure 3b) exposures. The decompressions from the 2 hour exposures are marginally more successful than those following 4 hours in that each addition of 1 bar of nitrogen to the fat resulted in an increase in gas in bubbles following the 2 hour exposure of 0.00068 ml compared to 0.0011 ml following the 4 hour exposure.

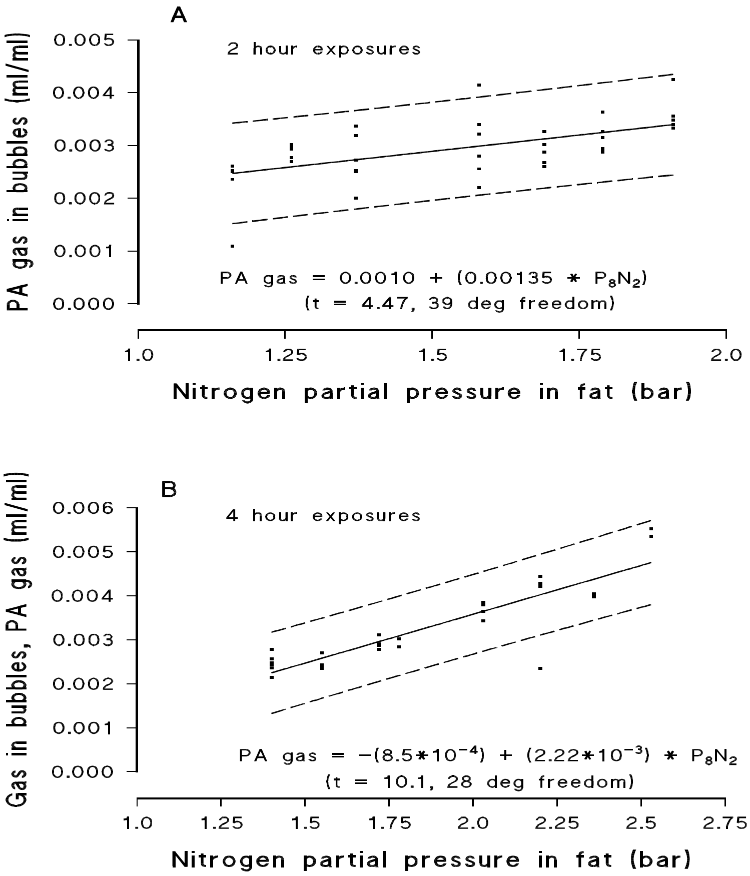

Figure 3 Predicted gas volume correlated with slow tissue nitrogen gas load at the start of decompression.

Decompression profiles are designed to take into account the arterial and tissue nitrogen loads in that the characteristics of the profiles are determined by the depth and duration of the exposure. This means that decompressions from higher arterial loads take longer, usually have the first stop deeper, start oxygen at a deeper stop and deliver more oxygen. Decompressions from longer exposures, higher fat inert gas loads, last longer, deliver more oxygen. Thus the parameters which describe the decompression profile are to some extent linked and cannot be taken as being independent of each other. Therefore it is highly likely that if one parameter correlates significantly with the predicted output all will. In the present study the only parameter which seems to have had no effect at all on the predicted volume of gas in bubbles is the rate of change of pressure. Decompression duration, oxygen dose, depth of first stop and depth at which oxygen is first used all correlate with the outcome.

Figure 4 shows the relationship between decompression duration and predicted volume of gas in bubbles. The longer decompressions are least successful. The increase in decompression time, to take account of the more severe exposure, is not enough to take care of the extra gas load.

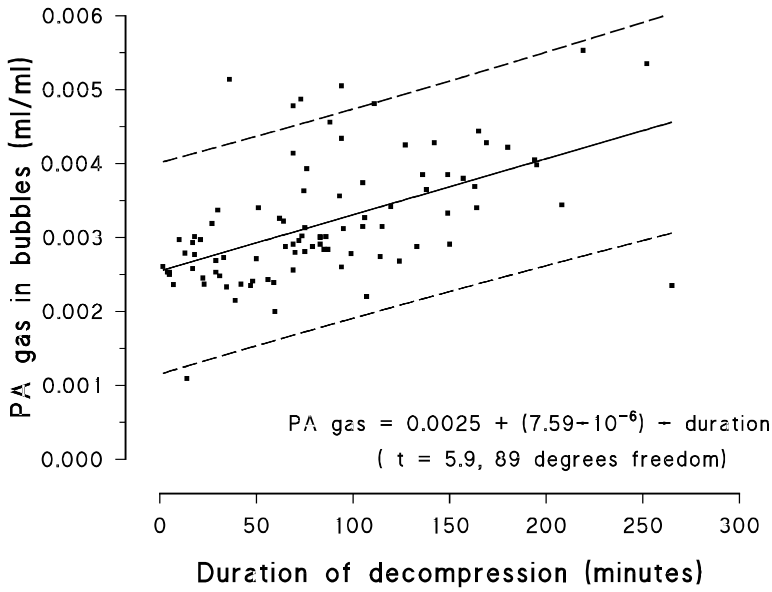

Figure 4 The relationship between predicted gas load and the duration of decompression

Figure 5 shows the relationship between the gas in bubbles and the total oxygen dose used on the decompression. Once again the correlation is significant; not enough oxygen is used for the more severe exposures.

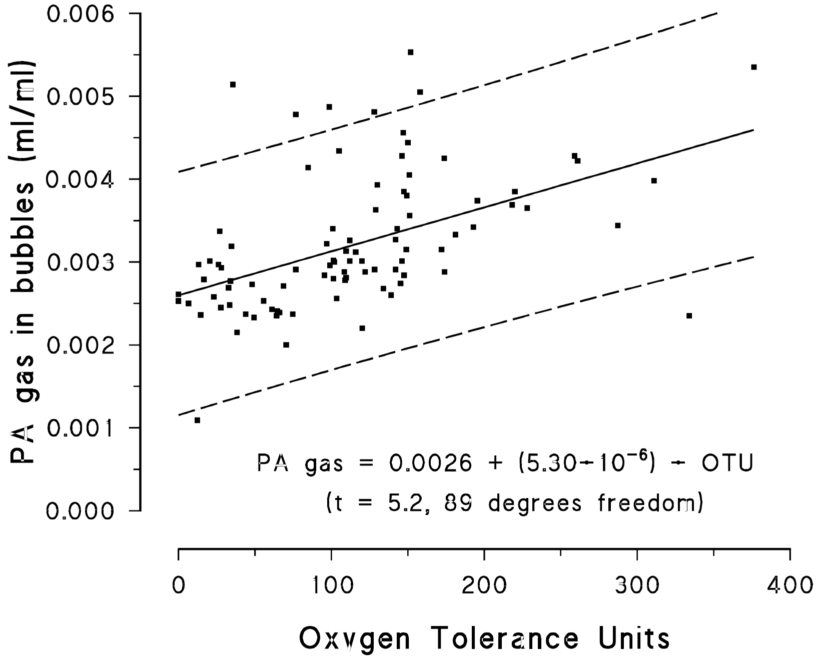

Figure 5 The relationship between predicted gas load and the total oxygen used

Figures 4 and 5 show a small number of points outwith the 95% confidence lines, two below the lower line and several above the higher line. These profiles can be identified and Table 6 lists them. Those which lie above the upper line could be improved by either more oxygen, a longer decompression or a combination of both. Table 6 identifies which need to be increased. Those which lie below the lower line are performing better than the group because of more oxygen, longer decompression time or a combination of both. Table 6 shows that the Swiss table would perform as well as the group as a whole with less oxygen and decompression time; the UK table would perform as well as the group even with shorter decompression time.

Table 6

More gas in bubbles than 95% of profiles	
Dutch 4.5/1	OTU and decompression time
UK 3.3/4	OTU
Swiss 3.9/1	OTU and decompression time
French 4.2/1	OTU
Brazil A 1.5/6	OTU and decompression time
UK 1.5/8	OTU and decompression time
Less gas in bubbles than 95% of profiles	
Swiss 2.7/4	OTU and decompression time
UK 1.2/2	Decompression time

Figures 4 and 5 can also be used to calculate the extent to which the decompression time, or the oxygen dose, would have to be increased to make the average decompression from the more severe exposures result in the same volume of gas carried as bubbles as the average for the least severe exposures. That is, to ensure that the gas volume predicted to be carried as bubbles is the same for all exposures, the lines on the graphs become horizontal. Table 7 gives the current values and the values which would have to be used to gain the improvement. These figures have been calculated on the basis that either decompression time has been extended or the oxygen dose increased. Some of the increased oxygen doses are above the daily limit and the longer decompression times are commercially unattractive. In practise each could be increased less by using a combination of the two. In some instances it would not be possible to achieve the required increase in oxygen dose without increasing the decompression time.

Table 7

Decompression duration		**Oxygen dose**	
Average now	**New**	**Average now**	**New**
30	30	50	50
60	90	100	130
90	150	150	210
120	210	200	290
150	270	250	370
180	330	300	450
210	370	350	530
240	450	400	610
270	510		
300	570		

3.0 DISCUSSION

There were two main objectives for this study;

> to look at the current practise in UK, the Blackpool Tables with oxygen as the breathing gas from the 0.6 bar stop, and compare the predicted outcome with that for the procedures used in other countries
>
> to look at the predicted outcome for tables used in other countries to determine which would be acceptable for use in UK should a contractor wish to do so.

From the information included in section 2.1 it is apparent that the procedures adopted by UK HSE are comparable to those used in other countries.

No country's procedures stand out as being better than any other across the whole range of allowed exposures. Likewise no country stands out as having procedures which are worse than any other. This means that any of the sets of tables considered in this report could be used with equal confidence.

For extremes of pressure or of exposure time the number of alternatives is limited. The UK tables allow longer exposure times but do not permit such high pressures, the maximum pressure being 3.45 bar. The American tables allow longer time at 3.4 bar but some of those tables use more oxygen than the recommended daily limit. The French tables permit exposure to 4.8 bar but for very short exposure times. The knowledge gained from this study makes it a relatively simple matter to design decompression tables for the deeper and longer exposures and to extend the range.

3.1 DECOMPRESSION STRESS

Until recently the main objective in designing decompression tables was to reduce the incidence of symptoms of decompression illness. Modern thinking accepts the fact that the symptoms are caused by decompression bubbles and that the occurrence of symptoms is a statistical phenomenon. This leads on to the concept that sub-symptomatic bubbles are likely to be causing damage and to the current idea that a reduction in the extent of bubble formation should underlie decompression table design.

This raises questions about the nature of decompression stress. Is decompression stress related to the maximum number of bubbles, to the duration for which bubbles are present or to a combination of both? It seems logical to suppose that if bubbles cause damage more bubbles will cause more damage and the longer there are bubbles the more damage can occur.

Figure 6 shows that for a decompression for which the maximum predicted gas in bubbles was 0.0013 ml/ml the bubbles would last just over 5 days. Decompression with predicted gas in bubbles in the region of 0.005 ml/ml are predicted to have bubbles lasting in the region of 10 days. This prolonged existence of bubbles is a consequence of the fact that the slowest compartments dominate the bubbles following compressed air decompressions. In non-saturation diving where both exposure and decompression times are shorter it is possible to reach similar, or even higher, levels of bubbles which resolve very much more quickly because the slow tissues are not involved. This dependence of the time course of bubbles on the type of hyperbaric exposure is clearly demonstrated in the report of the compressed air trials (Flook 2001b).

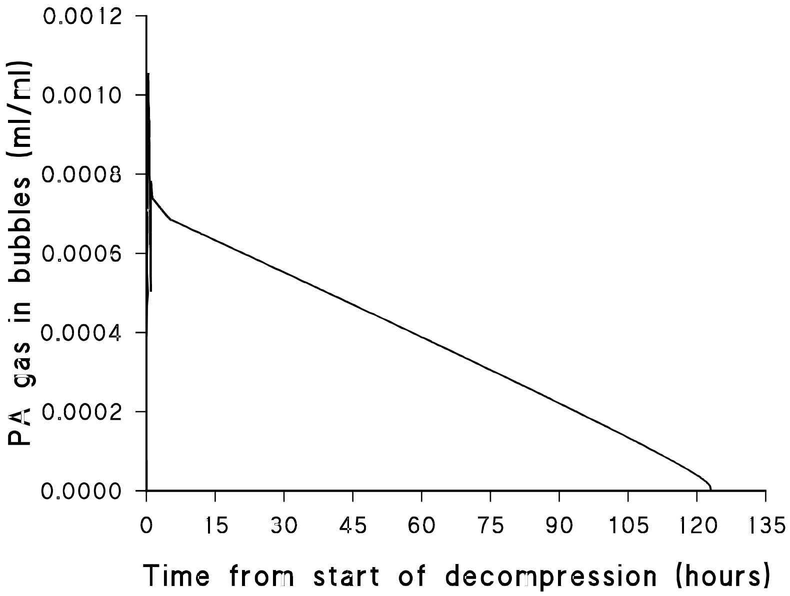

Figure 6 The time course for predicted gas volume in bubbles for the whole duration of bubbles in fat.

If decompression stress is determined by both the extent of bubble formation and the duration of bubbles then for similar bubble counts the compressed air workers are at greater risk than divers. The evidence that frequent exposure to bubbles causes long term health damage is proving somewhat elusive but the studies which have been conducted to date have been in divers, have been retrospective and have made no attempt to quantify the subject's exposure to bubbles. Until there are clear indications that prolonged exposure to bubbles does not cause damage to health it would be unwise to be complacent about the degree of bubble formation predicted in this report. Some of the profiles studied may well give undetectable levels of bubbling in many subjects but that should not be taken to mean that less conservative decompression procedures could be used.

3.2 REPEAT EXPOSURES

A second consequence of the prolonged duration of bubbles is very important in operational terms. As long as bubbles exist the removal of inert gas from the body is slowed down. The partition coefficient for nitrogen between tissue or blood and the gas phase is such that the bubbles grab most of the gas and hold it. A subsequent work shift at pressure will compress the bubbles and release the gas back into solution which means the body starts the second exposure much closer to saturation. There will be more bubbles on the subsequent decompression. This will not go on endlessly because the second or third exposure would result in saturation and thereafter all exposures will be the same. Figure 6 shows how relatively short is the 16 or 20 hours which is the usual gap between work shifts.

3.3 CONCLUSIONS

There are two main conclusions from this study:

> that the Blackpool Tables used with oxygen as the breathing gas from the 0.6 bar stop have predicted gas in bubbles within the same range as that for the other tables studied
>
> that the other tables studied could all be considered acceptable for use in UK.

The predictions are that the bubble numbers in the central venous blood for many of the profiles studied are likely to be just around the level of detectability in the average miner; that at least significant numbers of miners would have no detectable bubbles.

As a result of the slowest compartments having the main influence on bubble numbers. the bubbles will last for many days. This means that the overall decompression stress could still be significant and it would be unwise to consider any tables which were predicted to give more bubbles than those reported here. The policy should continue to be directed towards further reductions in decompression bubbles

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Printed and published by the Health and Safety Executive
C1.25 07/03

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ISBN 0-7176-2703-9

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