# 12

# *American Decompression Theory and Practice*

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The object of decompression research is the development of ascent procedures which are feasible in diving operations and which will not permit formation of inert gas bubbles in the tissues of the diver. Exposure to the oxygen content of the breathing mixture must not induce manifestations of acute or chronic toxicity. The choice of the inert gas component is limited by breathing resistance induced by density, tissue solubility and manifestations of narcosis affecting performance of the diver.

Operational considerations dictate that the diver must be returned to the surface in all sea states and water temperature conditions in the minimum time consistent with the avoidance of all possible risk of decompression sickness. Logistics of gas handling aboard ship restrict the number of different breathing mixtures that may be employed to hasten the elimination of inert gas from the tissues of the diver. A further constraint is imposed by the fire hazard associated with use of high-oxygen tensions in the pressure chamber breathing atmosphere.

All these and other limiting factors must be considered in developing safe, efficient decompression procedures. The most crucial, and still controversial, aspect of decompression is the mathematical treatment of inert gas transport in the body tissues. This must meet two key criteria: it must be capable of dealing adequately with the limitations imposed by operational diving and it must permit the extraction of information from diving experience that is of predictive value to increase the probability of successful decompression under diving conditions in which parameters of pressure exposure, time and composition of the breathing mixture have been changed.

The mathematical models of inert gas transport and bubble formation in use today and developed through years of experience in diving, differ mainly in their interpretation of three basic concepts. These are (1) the nature of the rate-limiting process in inert gas transport, (2) the character



of the body tissues as this affects gas transport, (3) the process of gas phase separation leading to formation of gas bubbles in body fluids and tissues, and thus to decompression sickness.

## EARLY DEVELOPMENT OF DECOMPRESSION PROCEDURES IN THE U.S. NAVY

The history of use and development of decompression procedures by the U.S. Navy relates primarily to the decompression schedules developed for use of the Royal Navy by J. S. Haldane and co-workers (Boycott, Damant & Haldane 1908) and submitted in the Report to the Admiralty of the Deep-Water Diving Committee (1907). These schedules provided stage decompression of the diver breathing air for diving depths to 204 ft (7·2 ATA). It is certain that the Haldane Tables, as they became known, were soon thereafter introduced into use by divers of the U.S. Navy by French, who received diving training in the Royal Navy and by Stillson who directed the first experimental diving studies of the U.S. Navy at the Brooklyn Navy Yard (Stillson 1915).

Experience in air diving at greater depths than provided by the Haldane Tables was begun under direction of French and Stillson, and culminated in a number of successful dives at a depth of 304 ft (10·4 ATA) during the salvage operation of the F-4 off Honolulu in 1915 (French 1916). Publication of schedules to provide for deeper air dives for use by the Royal Navy followed the work of Damant in 1933 (Davis 1962). Uniformly safe decompression from depths of 204 to 304 ft (7·2 to 10·4 ATA) required use of oxygen decompression from a stage depth of 60 ft (2·8 ATA) to the surface in the Davis submersible decompression chamber, which the diver entered for decompression following his depth exposure.

The Haldane Tables of the Royal Navy remained in use by the U.S. Navy until revised decompression schedules were developed and tested by the U.S. Navy Experimental Diving Unit in Washington DC in 1937. These schedules, as well as those for helium–oxygen diving developed at that time, employed the basic concepts and calculation procedures developed by Haldane. The primary difference was in the use of varying supersaturation criteria for the various half-time tissues controlling the ascent rather than the 2 to 1 ratio employed by Haldane for each tissue considered. (All ratios calculated using absolute pressures.)

## DEVELOPMENT OF THE HALDANE METHOD OF DECOMPRESSION

The first systematic study of decompression requirements following exposure of animals and men to increased ambient pressure of air was reported by Boycott *et al.* (1908). The basic tenets of their procedure, which has become known as the 'Haldane Method' relate to the estimation of the percentage of complete saturation or desaturation of the body tissues with nitrogen during any pressure exposure time-course, and the pressure of excess nitrogen in the body tissues related to hydrostatic pressure which is permissible without symptoms of decompression sickness occurring during or following the reduction of pressure to the surface (1 ATA).

Haldane and his associates (1908) estimated that the whole body of a man weighing 70 Kg will take up about 1 L of nitrogen per atmosphere of excess air pressure, about 70% more nitrogen than an equal amount of blood would dissolve. With the weight of blood in man equal to 6·5% of the body weight, the amount of nitrogen held in solution in the completely saturated body tissues would be about 170% ÷ 6·5%, or 26 times as great as the amount held in the blood alone. If the composition of the body were the same throughout, and the blood evenly distributed to all tissues, the body would receive in one round of circulation following sudden exposure to increased air pressure, one twenty-sixth of the nitrogen acquired at complete saturation. Each successive round of circulation would add one twenty-sixth of the remaining excess of nitrogen. The body tissues would be half-saturated in less than twenty rounds of circulation, or about ten minutes, and equilibrium would be complete in about an hour. The process of tissue saturation would follow an exponential curve for a specific tissue site, but it was not considered that this rate of saturation and desaturation would apply to the body as a whole. Actually, the rate of saturation would vary widely in different parts of the body, but for any particular part the rate of saturation and desaturation would follow a curve of this form, the circulation rate remaining constant (Fig. 12.1).

The variable time-course of nitrogen uptake for various parts of the body, relating to the different tissue perfusion rates with blood and capacities for dissolving nitrogen, was simulated by use of a geometrical series of discrete hypothetical half-time tissues (5, 10, 20, 40 and 75 min) to represent the spectrum of inert gas exchange rates of the whole body.

Of equal importance to the method of estimating uptake and elimination of nitrogen is the concept of stage decompression developed from these studies. This procedure makes the fullest use of the permissible difference between nitrogen pressure in the tissues and blood to hasten the elimination of nitrogen from the body tissues. The limit applied to reduction of hydrostatic pressure was to never allow the computed nitrogen pressure in the tissues to be more than twice the ambient pressure. This 2 to 1 ratio actually assumed equilibration of the tissues to the ambient pressure of the depth exposure, rather than the nitrogen partial pressure. The absolute



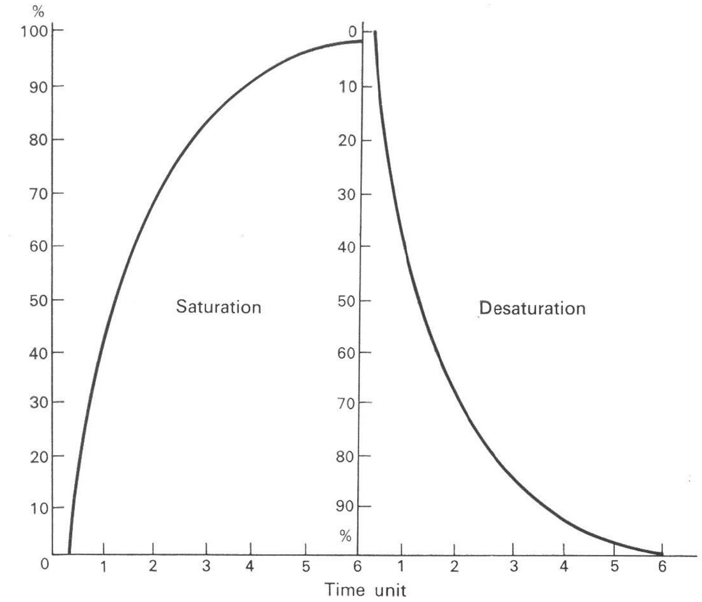


FIG. 12.1. Tissue saturation and desaturation curves. Time unit is equivalent to the specific half-time tissue considered

pressure of the maximum depth was then halved to determine the first decompression stop depth. A special case was assumed for air, for with its 79% nitrogen content the actual ratio of nitrogen pressure upon equilibration to ambient pressure would be

$$\frac{2}{1}\text{ ATA} \times 0{\cdot}79 = \frac{1{\cdot}58}{1}\text{ ATA}$$

It is true that this ignores the presence of oxygen in the breathing mixture as a factor in bubble formation. Extensive diving with nitrogen and helium mixtures enriched with oxygen in excess of 21% in air has confirmed the absence of significant effect of oxygen as a part of the total pressure in decompression. It appears that if sufficient time is permitted for excess oxygen in tissues to be metabolized during reduction of pressure, decompression sickness due to oxygen supersaturation in tissues is unlikely to occur.

Decompression schedules for men based on the 2 to 1 ratio concept have, however, not provided adequate decompression for longer and deeper exposures. Haldane himself discussed this in his book *Respiration* (1935) by stating that for air dives exceeding 165 ft (6 ATA) some reduction of this ratio was required.

## FURTHER STUDIES TO DEFINE SUPERSATURATION LIMITS IN DECOMPRESSION

Hawkins, Shilling and Hansen (1935) felt that the ratio of 2 to 1 was too conservative for fast tissues and not conservative enough for slow tissues. On the basis of an analysis of 2143 dives to depths between 100 and 200 ft (4·0 and 7·0 ATA) they determined more appropriate safe ratios for tissues of given desaturation half-times (Table 12.1). For calculation of decompression schedules, they ignored the 5 and 10 min tissues and used a ratio of 2·8 : 1 for the 20 min tissue, and 2·0 : 1 for the 40 and 75 min tissues. This modification made possible more efficient decompression in that deeper water stops than necessary are avoided and the fullest use is made of the permissible difference in pressure to hasten elimination of nitrogen from the body tissues.

TABLE 12.1

| *Half-time for tissue desaturation* (*min*) | *Safe ratio* |
|---|---|
| 5 | 5·5 : 1 |
| 10 | 4·5 : 1 |
| 20 | 3·2 : 1 |
| 40 | 2·4 : 1 |
| 75 | 1·8 : 1 to 2·0 : 1 |

Yarbrough (1937) calculated and tested revised U.S. Navy Standard Air Decompression Tables by controlling only the 20, 40 and 75 min tissues. The tissue ratios for the 5 and 10 min tissues appeared to be so high that they were not normally brought into control. The pattern of ratio reduction was somewhat irregular but the values were applied to fit empirical results (Table 12.2). Test of schedules calculated by the three-tissue method indicated that the ratios had to be reduced to the lower values after prolonged exposure at greater depths. This requirement reflected increased rates of equilibration with nitrogen during exercise performed by the divers in tests of the schedules, whereas the tests carried out by Hawkins *et al.* (1935) were at rest or with little exercise (Table 12.3).

TABLE 12.2

| *Half-time for tissue desaturation* (*min*) | *Safe ratio* |
|---|---|
| 20 | 2·45 : 1 to 2·8 : 1 |
| 40 | 1·75 : 1 to 2·0 : 1 |
| 75 | 1·75 : 1 to 2·0 : 1 |



TABLE 12.3.
U.S. Navy standard air decompression table (1943)

| *Depth of dive* (*ft*) | *Time on bottom* (*min*) | *Stops* (*ft & min*) | | | | | | | | | *Sum of times at various stops* (*min*) | *Approximate total decompression time* (*min*) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *ft* 90 | *ft* 80 | *ft* 70 | *ft* 60 | *ft* 50 | *ft* 40 | *ft* 30 | *ft* 20 | *ft* 10 | | |
| 40 | 120 | — | — | — | — | — | — | — | — | 0 | 0 | 2 |
| 40 | 180 | — | — | — | — | — | — | — | — | 2 | 2 | 4 |
| 40 | Opt.* *240* | — | — | — | — | — | — | — | — | 4 | 4 | 6 |
| 40 | 300 | — | — | — | — | — | — | — | — | 6 | 6 | 8 |
| 50 | 78 | — | — | — | — | — | — | — | — | 0 | 0 | 2 |
| 50 | 120 | — | — | — | — | — | — | — | — | 2 | 2 | 5 |
| 50 | 150 | — | — | — | — | — | — | — | — | 5 | 5 | 8 |
| 50 | Opt.* *190* | — | — | — | — | — | — | — | — | 9 | 9 | 12 |
| 50 | 300 | — | — | — | — | — | — | — | — | 12 | 12 | 15 |
| 60 | 55 | — | — | — | — | — | — | — | — | 0 | 0 | 3 |
| 60 | 75 | — | — | — | — | — | — | — | — | 2 | 2 | 5 |
| 60 | 110 | — | — | — | — | — | — | — | — | 13 | 13 | 16 |
| 60 | Opt.* *150* | — | — | — | — | — | — | — | 5 | 15 | 20 | 24 |
| 60 | 180 | — | — | — | — | — | — | — | 7 | 16 | 23 | 27 |
| 60 | 210 | — | — | — | — | — | — | — | 8 | 18 | 26 | 30 |
| 70 | 43 | — | — | — | — | — | — | — | — | 0 | 0 | 3 |
| 70 | 60 | — | — | — | — | — | — | — | — | 4 | 4 | 8 |
| 70 | 75 | — | — | — | — | — | — | — | — | 13 | 13 | 17 |
| 70 | 90 | — | — | — | — | — | — | — | 4 | 16 | 20 | 24 |
| 70 | Opt.* *120* | — | — | — | — | — | — | — | 13 | 16 | 29 | 33 |
| 70 | 150 | — | — | — | — | — | — | — | 18 | 21 | 39 | 43 |
| 70 | 180 | — | — | — | — | — | — | — | 21 | 32 | 53 | 57 |
| 80 | 35 | — | — | — | — | — | — | — | — | 0 | 0 | 3 |
| 80 | 50 | — | — | — | — | — | — | — | — | 6 | 6 | 10 |
| 80 | 70 | — | — | — | — | — | — | — | 6 | 16 | 22 | 27 |
| 80 | 100 | — | — | — | — | — | — | — | 20 | 16 | 36 | 41 |
| 80 | Opt.* *115* | — | — | — | — | — | — | — | 22 | 26 | 48 | 53 |
| 80 | 150 | — | — | — | — | — | — | — | 28 | 29 | 57 | 62 |
| 90 | 30 | — | — | — | — | — | — | — | — | 0 | 0 | 4 |
| 90 | 45 | — | — | — | — | — | — | — | — | 6 | 6 | 10 |
| 90 | 60 | — | — | — | — | — | — | — | 9 | 16 | 25 | 30 |
| 90 | 75 | — | — | — | — | — | — | — | 18 | 14 | 32 | 37 |
| 90 | Opt.* *95* | — | — | — | — | — | — | 2 | 27 | 21 | 50 | 56 |
| 90 | 130 | — | — | — | — | — | — | 9 | 27 | 29 | 65 | 71 |
| 100 | 25 | — | — | — | — | — | — | — | — | 0 | 0 | 4 |
| 100 | 40 | — | — | — | — | — | — | — | — | 12 | 12 | 17 |
| 100 | 60 | — | — | — | — | — | — | — | 18 | 16 | 34 | 39 |
| 100 | 75 | — | — | — | — | — | — | — | 27 | 21 | 48 | 53 |
| 100 | Opt.* *85* | — | — | — | — | — | — | 6 | 28 | 21 | 55 | 61 |
| 100 | 90 | — | — | — | — | — | — | 8 | 27 | 24 | 59 | 65 |
| 100 | 120 | — | — | — | — | — | — | 17 | 28 | 48 | 93 | 99 |
| 110 | 20 | — | — | — | — | — | — | — | — | 0 | 0 | 5 |
| 110 | 35 | — | — | — | — | — | — | — | — | 12 | 12 | 17 |
| 110 | 55 | — | — | — | — | — | — | — | 22 | 21 | 43 | 49 |
| 110 | Opt.* *75* | — | — | — | — | — | — | 14 | 27 | 37 | 78 | 84 |
| 110 | 105 | — | — | — | — | — | 2 | 22 | 29 | 50 | 103 | 110 |
| 120 | 18 | — | — | — | — | — | — | — | — | 0 | 0 | 5 |
| 120 | 30 | — | — | — | — | — | — | — | — | 11 | 11 | 17 |
| 120 | 45 | — | — | — | — | — | — | — | 18 | 21 | 39 | 45 |

Table 12.3—*contd.*

| *Depth of dive (ft)* | *Time on bottom (min)* | *Stops (ft & min)* ft 90 | ft 80 | ft 70 | ft 60 | ft 50 | ft 40 | ft 30 | ft 20 | ft 10 | *Sum of times at various stops (min)* | *Approximate total decompression time (min)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 120 | Opt.* *65* | — | — | — | — | — | — | 13 | 28 | 32 | 73 | 80 |
| 120 | 100 | — | — | — | — | — | 5 | 22 | 27 | 69 | 123 | 130 |
| 130 | 15 | — | — | — | — | — | — | — | — | 0 | 0 | 5 |
| 130 | 35 | — | — | — | — | — | — | — | 11 | 15 | 26 | 32 |
| 130 | 52 | — | — | — | — | — | — | 6 | 28 | 28 | 62 | 69 |
| 130 | Opt.* *60* | — | — | — | — | — | — | 13 | 28 | 28 | 69 | 76 |
| 130 | 90 | — | — | — | — | — | 9 | 22 | 28 | 69 | 128 | 136 |
| 140 | 15 | — | — | — | — | — | — | — | — | 4 | 4 | 10 |
| 140 | 30 | — | — | — | — | — | — | — | 8 | 21 | 29 | 36 |
| 140 | 45 | — | — | — | — | — | — | 5 | 27 | 27 | 59 | 67 |
| 140 | Opt.* *55* | — | — | — | — | — | — | 15 | 28 | 32 | 75 | 82 |
| 140 | 85 | — | — | — | — | — | 14 | 22 | 32 | 69 | 137 | 145 |
| 150 | 15 | — | — | — | — | — | — | — | — | 7 | 7 | 14 |
| 150 | 30 | — | — | — | — | — | — | — | 13 | 21 | 34 | 41 |
| 150 | 38 | — | — | — | — | — | — | — | 28 | 30 | 58 | 65 |
| 150 | Opt.* *50* | — | — | — | — | — | — | 16 | 28 | 32 | 76 | 84 |
| 150 | 80 | — | — | — | — | — | 18 | 23 | 32 | 69 | 141 | 150 |
| 160 | 15 | — | — | — | — | — | — | — | — | 9 | 9 | 16 |
| 160 | 34 | — | — | — | — | — | — | — | 27 | 28 | 55 | 63 |
| 160 | Opt.* *45* | — | — | — | — | — | — | 17 | 28 | 43 | 88 | 96 |
| 160 | 75 | — | — | — | — | 3 | 19 | 23 | 34 | 68 | 147 | 156 |
| 170 | 15 | — | — | — | — | — | — | — | — | 11 | 11 | 18 |
| 170 | 30 | — | — | — | — | — | — | — | 24 | 27 | 51 | 59 |
| 170 | Opt.* *40* | — | — | — | — | — | — | 19 | 28 | 46 | 93 | 102 |
| 170 | 75 | — | — | — | — | 9 | 19 | 23 | 38 | 68 | 157 | 167 |
| 185 | 15 | — | — | — | — | — | — | — | — | 25 | 25 | 33 |
| 185 | 26 | — | — | — | — | — | — | — | 24 | 37 | 61 | 70 |
| 185 | Opt.* *35* | — | — | — | — | — | — | 19 | 28 | 46 | 93 | 102 |
| 185 | 65 | — | — | — | 18 | 18 | 23 | 37 | 65 | 51 | 212 | 223 |
| 200 | 15 | — | — | — | — | — | — | — | — | 32 | 32 | 41 |
| 200 | 23 | — | — | — | — | — | — | — | 23 | 37 | 60 | 69 |
| 200 | Opt.* *35* | — | — | — | — | — | — | 22 | 28 | 46 | 96 | 106 |
| 200 | 60 | — | — | 5 | 18 | 18 | 23 | 37 | 65 | 51 | 217 | 229 |
| 210 | 15 | — | — | — | — | — | — | — | — | 35 | 35 | 44 |
| 210 | Opt.* *30* | — | — | — | — | — | 5 | 16 | 28 | 40 | 89 | 100 |
| 210 | 55 | — | — | 6 | 18 | 18 | 23 | 37 | 65 | 51 | 218 | 231 |
| 225 | 15 | — | — | — | — | — | — | — | 6 | 35 | 41 | 51 |
| 225 | Opt.* *27* | — | — | — | — | — | 22 | 26 | 35 | 48 | 131 | 143 |
| 225 | 60 | — | — | 13 | 18 | 18 | 23 | 47 | 65 | 83 | 267 | 280 |
| 250 | 15 | — | — | — | — | — | — | — | 17 | 37 | 54 | 66 |
| 250 | Opt.* *25* | — | — | — | — | 2 | 23 | 26 | 35 | 51 | 137 | 150 |
| 250 | 50 | — | 12 | 14 | 17 | 19 | 29 | 49 | 65 | 83 | 288 | 303 |
| 300 | 12 | — | — | — | — | — | — | — | 20 | 37 | 57 | 70 |
| 300 | Opt.* *20* | — | — | — | — | 9 | 23 | 26 | 35 | 51 | 144 | 159 |
| 300 | 45 | 6 | 14 | 15 | 17 | 18 | 31 | 49 | 65 | 83 | 298 | 315 |

Opt.* schedules are the optimum exposure times for each depth which represent the best balance between length of work period and amount of useful work for the average diver.

Further extensive evaluation of these decompression schedules was carried out by Van Der Aue, Brinton and Kellar (1945) in tests of surface



decompression using air. They reported that 24% of 81 subjects developed symptoms of decompression sickness when standard decompression was used for working dives of long duration.

They further analysed available data to find logical values for tissue ratios. As a result of calculation and extensive testing of a series of surface decompression schedules using oxygen (Van Der Aue *et al.* 1951) it was found that tissue ratios must be reduced considerably for all components in longer, deeper dives (2·2 : 1 to 2·0 : 1), that the fast tissues sometimes control deep stops even with high tissue ratios and that the surfacing ratios could be increased (Table 12.4).

TABLE 12.4

| *Half-time for tissue desaturation (min)* | *Safe ratio* |
|---|---|
| 5 | 3·8 : 1 |
| 10 | 3·4 : 1 |
| 20 | 2·8 : 1 |
| 40 | 2·27 : 1 |
| 75 | 2·06 : 1 |
| 120 | 2·00 : 1 |

Tissue ratios used to determine safety during the brief surface interval before recompression to 40 ft (2·2 ATA) with oxygen breathing are shown in Table 12.5.

TABLE 12.5

| *Half-time for tissue desaturation (min)* | *Safe ratio* |
|---|---|
| 20 | 3·54 : 1 |
| 40 | 3·54 : 1 |
| 75 | 2·94 : 1 |
| 120 | 2·60 : 1 |

Reduction of tissue ratios from values permissible upon surfacing to control supersaturation at decompression stops appears to be essential for calculations of safe decompression schedules by the Haldane method (Van Der Aue *et al.* 1951; Behnke 1947). There are several mathematical physical evaluations to support this concept. Bateman (1951) derived a mathematical relationship between 'decompression ratio for symptom threshold' and 'body saturation with air before decompression'. Basically it results in a smooth reduction of tissue ratio with increased pressure. Piccard (1941) discussed the mathematical probability of a reduction in allowable supersaturation as the total mass of dissolved gas increases with increasing pressure. Russian studies have attempted to analyse permissible supersaturation ratios for air, helium–oxygen and helium–nitrogen–oxygen mixtures in diving (Brestkin 1965; Aleksandrov & Brestkin 1965; Brestkin, Gramenitskii & Sidorov 1965; Zal'tsman & Zinov'eva 1965). The permissible supersaturation value of the body with nitrogen following 6-hour air exposure of divers at 1 ATA and 7 ATA decreased from a ratio of 1·72 : 1 at 1 ATA to 1·3 : 1 at 7 ATA. For helium–oxygen mixtures breathed during dives at 3·25 ATA, a value of 2·66 : 1 was obtained, as compared with 2·4 : 1 at 2·95 ATA for air after 6-hour exposures under pressure.

Brestkin (1965) has attempted to analyse the changing critical ratio, initial gas tension/final absolute pressure ($Po/P$), of helium, nitrogen and carbon dioxide in water, with the production of visible bubbles as an end point. With an increase in gas tension, the critical ratio decreases as tension of gas increases up to 20 atmospheres and remains constant for further increases for helium and nitrogen. The absolute value of the critical ratio, as well as the magnitude of decrease with pressure, is greater for nitrogen than for helium. The pressure dependent function of the critical ratio is explained by Laplacian surface tension and radius factors. The significance of these studies to operational diving has also been discussed with emphasis on the difference between physical and physiological systems (Zal'tsman & Zinov'eva 1965).

Calculation of revised U.S. Navy Standard Air Decompression Schedules using a tenth-power relationship between tissue ratio at surface (1 ATA) and at depth of the decompression stop, with surfacing ratios and permissible depth ratios indicated by Van Der Aue *et al.* (1951), was reported by Des Granges (1956). The equation used to project the tissues ratios at depth, as developed by Dwyer (1956), is as follows:

$$M = 33\left(\frac{rs}{rd}\right)^{10} + rd - 1$$

$M$ = maximum safe tissue pressure of nitrogen in feet of sea water absolute, $rs$ = surfacing ratio in ATA, $rd$ = depth ratio at decompression stop in ATA.

Decompression schedules for air dives to a depth of 190 ft (6·8 ATA) were developed and tested at the U.S. Navy Experimental Diving Unit, becoming available for fleet use in 1960 (Table 12.6). A review (Doll 1965) of decompression sickness resulting from use of these schedules over a two-year period reported an incidence of 0·69% as compared to 1·1% when using the schedules developed by Yarbrough (1937).

The current air decompression schedules (*U.S. Navy Diving Manual 1963*) provide more adequately for scuba diving operations, in that depth increments of 10 ft and exposure time increments of 5 to 10 min are available for use. A 60 ft/min rate of ascent to the first decompression stop or to the surface permits ascent at an easy swim rate, where the 25 ft/min ascent rate of the previous air decompression schedules was considered too slow.



## DEVELOPMENT OF REPETITIVE DIVE SCHEDULES FOR AIR DIVING

Operational use of scuba requires that many dives to various depths be performed over a period of hours. Thus, once the revised Standard Air Decompression Tables were developed, it became a necessity to devise a repetitive dive procedure employing them for use with scuba. After any dive in which compressed air is breathed, variable and diminishing amounts of residual nitrogen remain in the body tissues of the diver for periods of 24 hours or more. This partial saturation will shorten the exposure time permitted for any subsequent repetitive dive deeper than 33 ft (2 ATA). The longer and deeper the first dive, the greater is the amount of residual tissue nitrogen remaining to obligate decompression for subsequent dives. Under such circumstances, the no-decompression depth-time allowances can no longer be employed with safety.

The many possible combinations of depth and exposure time of dives were grouped according to the initial surfacing tissue tension of nitrogen. It was then possible to determine the amount that the diver had desaturated during his surface time interval before diving again. It was then determined how many minutes it would require, at the depth of any subsequent dive, to equilibrate to the condition with which descent commenced. This permits addition of that time obligation to the actual exposure time to obtain an adequate decompression schedule from the Standard Air Decompression Table (Table 12.6).

This procedure was implemented by assigning a letter group obligation in 2-ft increments to nitrogen supersaturation in the 120-min half-time tissue upon surfacing from any pressure exposure permitted from 0 ft (1 ATA) to 33 ft (2 ATA). Each dive schedule upon surfacing was then assigned a tissue group obligation from A through O, each of which represents 2 ft of inert gas in excess of 0 ft (1 ATA). Dive schedules requiring no decompression were also assigned letter group obligations on this basis. A surface interval credit table was then developed in hours and minutes required to lose tissue nitrogen and thus decrease obligation for decompression time of subsequent dives.

Equivalent depth-time exposures in terms of the same repetitive letter group obligations were developed in a repetitive dive timetable. Thus,

TABLE 12.6

U.S. Navy standard air decompression table (1959)

| *Depth (ft)* | *Bottom time (mins)* | *Time to first stop* | *Decompression stops* 50 | 40 | 30 | 20 | 10 | *Total ascent time* | *Repet. group* |
|---|---|---|---|---|---|---|---|---|---|
| 40 | 200 | | | | | | 0 | 0·7 | * |
| | 210 | 0·5 | | | | | 2 | 2·5 | N |
| | 230 | 0·5 | | | | | 7 | 7·5 | N |
| | 250 | 0·5 | | | | | 11 | 11·5 | O |
| | 270 | 0·5 | | | | | 15 | 15·5 | O |
| | 300 | 0·5 | | | | | 19 | 19·5 | Z |
| 50 | 100 | | | | | | 0 | 0·8 | * |
| | 110 | 0·7 | | | | | 3 | 3·7 | L |
| | 120 | 0·7 | | | | | 5 | 5·7 | M |
| | 140 | 0·7 | | | | | 10 | 10·7 | M |
| | 160 | 0·7 | | | | | 21 | 21·7 | N |
| | 180 | 0·7 | | | | | 29 | 29·7 | O |
| | 200 | 0·7 | | | | | 35 | 35·7 | O |
| | 220 | 0·7 | | | | | 40 | 40·7 | Z |
| | 240 | 0·7 | | | | | 47 | 47·7 | Z |
| 60 | 60 | | | | | | 0 | 1·0 | * |
| | 70 | 0·8 | | | | | 2 | 2·8 | K |
| | 80 | 0·8 | | | | | 7 | 7·8 | L |
| | 100 | 0·8 | | | | | 14 | 14·8 | M |
| | 120 | 0·8 | | | | | 26 | 26·8 | N |
| | 140 | 0·8 | | | | | 39 | 39·8 | O |
| | 160 | 0·8 | | | | | 48 | 48·8 | Z |
| | 180 | 0·8 | | | | | 56 | 56·8 | Z |
| | 200 | 0·6 | | | | 1 | 69 | 70·6 | Z |
| 70 | 50 | | | | | | 0 | 1·2 | * |
| | 60 | 1·0 | | | | | 8 | 9·0 | K |
| | 70 | 1·0 | | | | | 14 | 15·0 | L |
| | 80 | 1·0 | | | | | 18 | 19·0 | M |
| | 90 | 1·0 | | | | | 23 | 24·0 | N |
| | 100 | 1·0 | | | | | 33 | 34·0 | N |
| | 110 | 0·8 | | | | 2 | 41 | 43·8 | O |
| | 120 | 0·8 | | | | 4 | 47 | 51·8 | O |
| | 130 | 0·8 | | | | 6 | 52 | 58·8 | O |
| | 140 | 0·8 | | | | 8 | 56 | 64·8 | Z |
| | 150 | 0·8 | | | | 9 | 61 | 70·8 | Z |
| | 160 | 0·8 | | | | 13 | 72 | 85·8 | Z |
| | 170 | 0·8 | | | | 19 | 79 | 98·8 | Z |
| 80 | 40 | | | | | | 0 | 1·3 | * |
| | 50 | 1·2 | | | | | 10 | 11·2 | K |
| | 60 | 1·2 | | | | | 17 | 18·2 | L |
| | 70 | 1·2 | | | | | 23 | 24·2 | M |
| | 80 | 1·0 | | | | 2 | 31 | 34·0 | N |
| | 90 | 1·0 | | | | 7 | 39 | 47·0 | N |
| | 100 | 1·0 | | | | 11 | 46 | 58·0 | O |
| | 110 | 1·0 | | | | 13 | 53 | 67·0 | O |
| | 120 | 1·0 | | | | 17 | 56 | 74·0 | Z |
| | 130 | 1·0 | | | | 19 | 63 | 83·0 | Z |
| | 140 | 1·0 | | | | 26 | 69 | 96·0 | Z |
| | 150 | 1·0 | | | | 32 | 77 | 110·0 | Z |
| 90 | 30 | | | | | | 0 | 1·5 | * |
| | 40 | 1·3 | | | | | 7 | 8·3 | J |
| | 50 | 1·3 | | | | | 18 | 19·3 | L |
| | 60 | 1·3 | | | | | 25 | 26·3 | M |
| | 70 | 1·2 | | | | 7 | 30 | 38·2 | N |
| | 80 | 1·2 | | | | 13 | 40 | 54·2 | N |
| | 90 | 1·2 | | | | 18 | 48 | 67·2 | O |
| | 100 | 1·2 | | | | 21 | 54 | 76·2 | Z |
| | 110 | 1·2 | | | | 24 | 61 | 86·2 | Z |
| | 120 | 1·2 | | | | 32 | 68 | 101·2 | Z |
| | 130 | 1·0 | | | 5 | 36 | 74 | 116·0 | Z |
| 100 | 25 | | | | | | 0 | 1·7 | * |
| | 30 | 1·5 | | | | | 3 | 4·5 | I |
| | 40 | 1·5 | | | | | 15 | 16·5 | K |
| | 50 | 1·3 | | | | 2 | 24 | 27·3 | L |
| | 60 | 1·3 | | | | 9 | 28 | 38·3 | N |
| | 70 | 1·3 | | | | 17 | 39 | 57·3 | O |
| | 80 | 1·3 | | | | 23 | 48 | 72·3 | O |
| | 90 | 1·2 | | | 3 | 23 | 57 | 84·2 | Z |
| | 100 | 1·2 | | | 7 | 23 | 66 | 97·2 | Z |
| | 110 | 1·2 | | | 10 | 34 | 72 | 117·2 | Z |
| | 120 | 1·2 | | | 12 | 41 | 78 | 132·2 | Z |
| 110 | 20 | | | | | | 0 | 1·8 | * |
| | 25 | 1·7 | | | | | 3 | 4·7 | H |
| | 30 | 1·7 | | | | | 7 | 8·7 | J |
| | 40 | 1·5 | | | | 2 | 21 | 24·5 | L |
| | 50 | 1·5 | | | | 8 | 26 | 35·5 | M |
| | 60 | 1·5 | | | | 18 | 36 | 55·5 | N |
| | 70 | 1·3 | | | 1 | 23 | 48 | 73·3 | O |
| | 80 | 1·3 | | | 7 | 23 | 57 | 88·3 | Z |
| | 90 | 1·3 | | | 12 | 30 | 64 | 107·3 | Z |
| | 100 | 1·3 | | | 15 | 37 | 72 | 125·3 | Z |

| *Depth (ft)* | *Bottom time (min)* | *Time to first stop* | *Decompression stops* 50 | 40 | 30 | 20 | 10 | *Total ascent time* | *Repet. group* |
|---|---|---|---|---|---|---|---|---|---|
| 120 | 15 | | | | | | 0 | 2·0 | * |
| | 20 | 1·8 | | | | | 2 | 3·8 | H |
| | 25 | 1·8 | | | | | 6 | 7·8 | I |
| | 30 | 1·8 | | | | | 14 | 15·8 | J |
| | 40 | 1·7 | | | | 5 | 25 | 31·7 | L |
| | 50 | 1·7 | | | | 15 | 31 | 47·7 | N |
| | 60 | 1·5 | | | 2 | 22 | 45 | 70·5 | O |
| | 70 | 1·5 | | | 9 | 23 | 55 | 88·5 | O |
| | 80 | 1·5 | | | 15 | 27 | 63 | 106·5 | Z |
| | 90 | 1·5 | | | 19 | 37 | 74 | 131·5 | Z |
| | 100 | 1·5 | | | 23 | 45 | 80 | 149·5 | Z |
| 130 | 10 | | | | | | 0 | 2·2 | * |
| | 15 | 2·0 | | | | | 1 | 3·0 | F |
| | 20 | 2·0 | | | | | 4 | 6·0 | H |
| | 25 | 2·0 | | | | | 10 | 12·0 | J |
| | 30 | 1·8 | | | | 3 | 18 | 22·8 | M |
| | 40 | 1·8 | | | | 10 | 25 | 36·8 | N |
| | 50 | 1·7 | | | 3 | 21 | 37 | 62·7 | O |
| | 60 | 1·7 | | | 9 | 23 | 52 | 85·7 | Z |
| | 70 | 1·7 | | | 16 | 24 | 61 | 102·7 | Z |
| | 80 | 1·5 | | 3 | 19 | 35 | 72 | 130·5 | Z |
| | 90 | 1·5 | | 8 | 19 | 45 | 80 | 153·5 | Z |
| 140 | 10 | | | | | | 0 | 2·3 | * |
| | 15 | 2·2 | | | | | 2 | 4·2 | G |
| | 20 | 2·2 | | | | | 6 | 8·2 | I |
| | 25 | 2·0 | | | | 2 | 14 | 18·0 | J |
| | 30 | 2·0 | | | | 5 | 21 | 28·0 | K |
| | 40 | 1·8 | | | 2 | 16 | 26 | 45·8 | N |
| | 50 | 1·8 | | | 6 | 24 | 44 | 75·8 | O |
| | 60 | 1·8 | | | 16 | 23 | 56 | 96·8 | Z |
| | 70 | 1·7 | | 4 | 19 | 32 | 68 | 124·7 | Z |
| | 80 | 1·7 | | 10 | 23 | 41 | 79 | 154·7 | Z |
| 150 | 5 | | | | | | 0 | 2·5 | C |
| | 10 | 2·3 | | | | | 1 | 3·3 | E |
| | 15 | 2·3 | | | | | 3 | 5·3 | G |
| | 20 | 2·2 | | | | 2 | 7 | 11·2 | H |
| | 25 | 2·2 | | | | 4 | 17 | 23·2 | K |
| | 30 | 2·2 | | | | 8 | 24 | 34·2 | L |
| | 40 | 2·0 | | | 5 | 19 | 33 | 59·0 | N |
| | 50 | 2·0 | | | 12 | 23 | 51 | 88·0 | O |
| | 60 | 1·8 | | 3 | 19 | 26 | 62 | 111·8 | Z |
| | 70 | 1·8 | | 11 | 19 | 39 | 75 | 145·8 | Z |
| | 80 | 1·7 | 1 | 17 | 19 | 50 | 84 | 172·7 | Z |
| 160 | 5 | | | | | | 0 | 2·7 | D |
| | 10 | 2·5 | | | | | 1 | 3·5 | F |
| | 15 | 2·3 | | | | 1 | 4 | 7·3 | H |
| | 20 | 2·3 | | | | 3 | 11 | 16·3 | J |
| | 25 | 2·3 | | | | 7 | 20 | 29·3 | K |
| | 30 | 2·2 | | | 2 | 11 | 25 | 40·2 | M |
| | 40 | 2·2 | | | 7 | 23 | 39 | 71·2 | N |
| | 50 | 2·0 | | 2 | 16 | 23 | 55 | 98·0 | Z |
| | 60 | 2·0 | | 9 | 19 | 33 | 69 | 132·0 | Z |
| | 70 | 1·8 | 1 | 17 | 22 | 44 | 80 | 165·8 | Z |
| 170 | 5 | | | | | | 0 | 2·8 | D |
| | 10 | 2·7 | | | | | 2 | 4·7 | F |
| | 15 | 2·5 | | | | 2 | 5 | 9·5 | H |
| | 20 | 2·5 | | | | 4 | 15 | 21·5 | J |
| | 25 | 2·3 | | | 2 | 7 | 23 | 34·3 | L |
| | 30 | 2·3 | | | 4 | 13 | 26 | 45·3 | M |
| | 40 | 2·2 | | 1 | 10 | 23 | 45 | 81·2 | O |
| | 50 | 2·2 | | 5 | 18 | 23 | 61 | 109·2 | Z |
| | 60 | 2·0 | 2 | 15 | 22 | 37 | 74 | 152·0 | Z |
| | 70 | 2·0 | 8 | 17 | 19 | 51 | 86 | 183·0 | Z |
| 180 | 5 | | | | | | 0 | 3·0 | D |
| | 10 | 2·8 | | | | | 3 | 5·8 | F |
| | 15 | 2·7 | | | | 3 | 6 | 11·7 | I |
| | 20 | 2·5 | | | 1 | 5 | 17 | 25·5 | K |
| | 25 | 2·5 | | | 3 | 10 | 24 | 39·5 | L |
| | 30 | 2·5 | | | 6 | 17 | 27 | 52·5 | N |
| | 40 | 2·3 | | 3 | 14 | 23 | 50 | 92·3 | O |
| | 50 | 2·2 | 2 | 9 | 19 | 30 | 65 | 127·2 | Z |
| | 60 | 2·2 | 5 | 16 | 19 | 44 | 81 | 167·2 | Z |
| 190 | 5 | | | | | | 0 | 3·2 | D |
| | 10 | 2·8 | | | | 1 | 3 | 6·8 | G |
| | 15 | 2·8 | | | | 4 | 7 | 13·8 | I |
| | 20 | 2·7 | | | 2 | 6 | 20 | 30·7 | K |
| | 25 | 2·7 | | | 5 | 11 | 25 | 43·7 | M |
| | 30 | 2·5 | | 1 | 8 | 19 | 32 | 62·5 | N |
| | 40 | 2·5 | | 8 | 14 | 23 | 55 | 102·5 | O |
| | 50 | 2·3 | 4 | 13 | 22 | 33 | 72 | 146·3 | Z |
| | 60 | 2·3 | 10 | 17 | 19 | 50 | 84 | 182·3 | Z |

TABLE 12.7.

U.S. Navy standard air decompression table for exceptional exposures (1959)

| Depth (ft) | Bottom time (min) | Time to first stop | 130 | 120 | 110 | 100 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | Total ascent time |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Decompression stops | | | | | | | | | | | | | |
| 40 | 360 | ·5 | | | | | | | | | | | | | 23 | 24 |
| | 480 | 0·5 | | | | | | | | | | | | | 41 | 42 |
| | 720 | 0·5 | | | | | | | | | | | | | 69 | 70 |
| 60 | 240 | 0·7 | | | | | | | | | | | | 2 | 79 | 82 |
| | 360 | 0·7 | | | | | | | | | | | | 20 | 119 | 140 |
| | 480 | 0·7 | | | | | | | | | | | | 44 | 148 | 193 |
| | 720 | 0·7 | | | | | | | | | | | | 78 | 187 | 266 |
| 80 | 180 | 1·0 | | | | | | | | | | | | 35 | 85 | 121 |
| | 240 | 0·8 | | | | | | | | | | | 6 | 52 | 120 | 179 |
| | 360 | 0·8 | | | | | | | | | | | 29 | 90 | 160 | 280 |
| | 480 | 0·8 | | | | | | | | | | | 59 | 107 | 187 | 354 |
| | 720 | 0·7 | | | | | | | | | | 17 | 108 | 142 | 187 | 455 |
| 100 | 180 | 1·0 | | | | | | | | | | 1 | 29 | 53 | 118 | 202 |
| | 240 | 1·0 | | | | | | | | | | 14 | 42 | 84 | 142 | 283 |
| | 360 | 0·8 | | | | | | | | | 2 | 42 | 73 | 111 | 187 | 416 |
| | 480 | 0·8 | | | | | | | | | 21 | 61 | 91 | 142 | 187 | 502 |
| | 720 | 0·8 | | | | | | | | | 55 | 106 | 122 | 142 | 187 | 613 |
| 120 | 120 | 1·3 | | | | | | | | | | 10 | 19 | 47 | 98 | 176 |
| | 180 | 1·2 | | | | | | | | | 5 | 27 | 37 | 76 | 137 | 283 |
| | 240 | 1·2 | | | | | | | | | 23 | 35 | 60 | 97 | 179 | 395 |
| | 360 | 1·0 | | | | | | | | 18 | 45 | 64 | 93 | 142 | 187 | 550 |
| | 480 | 0·8 | | | | | | | 6 | 41 | 64 | 93 | 122 | 142 | 187 | 653 |
| | 720 | 0·8 | | | | | | | 32 | 74 | 100 | 114 | 122 | 142 | 187 | 772 |
| 140 | 90 | 1·5 | | | | | | | | | 2 | 41 | 18 | 42 | 88 | 166 |
| | 120 | 1·5 | | | | | | | | | 12 | 14 | 36 | 56 | 120 | 240 |
| | 180 | 1·3 | | | | | | | | 10 | 26 | 32 | 54 | 94 | 168 | 386 |
| | 240 | 1·2 | | | | | | | 8 | 28 | 34 | 50 | 78 | 124 | 187 | 511 |
| | 360 | 1·0 | | | | | | 9 | 32 | 42 | 64 | 84 | 122 | 142 | 187 | 683 |
| | 480 | 1·0 | | | | | | 31 | 44 | 59 | 100 | 114 | 122 | 142 | 187 | 800 |
| | 720 | 0·8 | | | | | 16 | 56 | 88 | 97 | 100 | 114 | 122 | 142 | 187 | 923 |
| 170 | 90 | 1·8 | | | | | | | | 12 | 12 | 14 | 34 | 52 | 120 | 232 |
| | 120 | 1·5 | | | | | | 2 | 10 | 12 | 18 | 32 | 42 | 82 | 156 | 356 |
| | 180 | 1·3 | | | | | 4 | 10 | 22 | 28 | 34 | 50 | 78 | 120 | 187 | 535 |
| | 240 | 1·3 | | | | | 18 | 24 | 30 | 42 | 50 | 70 | 116 | 142 | 187 | 681 |
| | 360 | 1·2 | | | | 22 | 34 | 40 | 52 | 60 | 98 | 114 | 122 | 142 | 187 | 873 |
| | 480 | 1·0 | | | 14 | 40 | 42 | 56 | 91 | 97 | 100 | 114 | 122 | 142 | 187 | 1006 |
| 230 | 5 | 3·7 | | | | | | | | | | | | | 2 | 6 |
| | 10 | 3·3 | | | | | | | | | | | 1 | 2 | 6 | 13 |
| | 10 | 3·3 | | | | | | | | | | | 3 | 6 | 18 | 31 |
| | 20 | 3·2 | | | | | | | | | | 2 | 5 | 12 | 26 | 49 |
| | 25 | 3·2 | | | | | | | | | | 4 | 8 | 22 | 37 | 75 |
| | 30 | 3·0 | | | | | | | | | 2 | 8 | 12 | 23 | 51 | 99 |
| | 40 | 2·8 | | | | | | | | 1 | 7 | 15 | 22 | 34 | 74 | 156 |
| | 50 | 2·8 | | | | | | | | 5 | 14 | 16 | 24 | 51 | 89 | 202 |
| 240 | 5 | 3·8 | | | | | | | | | | | | | 2 | 6 |
| | 10 | 3·5 | | | | | | | | | | | 1 | 3 | 6 | 14 |
| | 15 | 3·5 | | | | | | | | | | | 4 | 6 | 21 | 35 |
| | 20 | 3·3 | | | | | | | | | | 3 | 6 | 15 | 25 | 53 |
| | 25 | 3·2 | | | | | | | | | 1 | 4 | 9 | 24 | 40 | 82 |
| | 30 | 3·2 | | | | | | | | | 4 | 8 | 15 | 22 | 56 | 109 |
| | 40 | 3·0 | | | | | | | | 3 | 7 | 17 | 22 | 39 | 75 | 166 |
| | 50 | 2·8 | | | | | | | 1 | 8 | 15 | 16 | 29 | 51 | 94 | 217 |
| 250 | 5 | 3·8 | | | | | | | | | | | | 1 | 2 | 7 |
| | 10 | 3·7 | | | | | | | | | | | 1 | 4 | 7 | 16 |
| | 15 | 3·5 | | | | | | | | | | 1 | 4 | 7 | 22 | 38 |
| | 20 | 3·5 | | | | | | | | | | 4 | 7 | 17 | 27 | 59 |
| | 25 | 3·3 | | | | | | | | | 2 | 7 | 10 | 24 | 45 | 92 |
| | 30 | 3·3 | | | | | | | | | 6 | 7 | 17 | 23 | 59 | 116 |
| | 40 | 3·2 | | | | | | | | 5 | 9 | 17 | 19 | 45 | 79 | 178 |
| | 60 | 2·7 | | | | | 4 | 10 | 10 | 10 | 12 | 22 | 36 | 64 | 126 | 297 |
| | 90 | 2·2 | | 8 | 10 | 10 | 10 | 10 | 10 | 28 | 28 | 44 | 68 | 98 | 186 | 513 |
| | 120 | | (SEE EXTREME EXPOSURES BELOW) | | | | | | | | | | | | | |
| | 180 | | | | | | | | | | | | | | | |
| | 240 | | | | | | | | | | | | | | | |
| 260 | 5 | 4·0 | | | | | | | | | | | | 1 | 2 | 7 |
| | 10 | 3·8 | | | | | | | | | | | 2 | 4 | 9 | 19 |
| | 15 | 3·7 | | | | | | | | | | 2 | 4 | 10 | 22 | 42 |
| | 20 | 3·5 | | | | | | | | | 1 | 4 | 7 | 20 | 31 | 67 |
| | 25 | 3·5 | | | | | | | | | 3 | 8 | 11 | 23 | 50 | 99 |
| | 30 | 3·3 | | | | | | | | 2 | 6 | 8 | 19 | 26 | 61 | 125 |
| | 40 | 3·2 | | | | | | | 1 | 6 | 11 | 16 | 19 | 49 | 84 | 190 |



| Depth (ft) | Bottom time (min) | Time to first stop | 130 | 120 | 110 | 100 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | Total ascent time |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 200 | 5 | 3·2 | | | | | | | | | | | | | 1 | 5 |
| | 10 | 3·0 | | | | | | | | | | | | 1 | 4 | 8 |
| | 15 | 2·8 | | | | | | | | | | | 1 | 4 | 10 | 18 |
| | 20 | 2·8 | | | | | | | | | | | 3 | 7 | 27 | 40 |
| | 25 | 2·8 | | | | | | | | | | | 7 | 14 | 25 | 49 |
| | 30 | 2·7 | | | | | | | | | | 2 | 9 | 22 | 37 | 73 |
| | 40 | 2·5 | | | | | | | | | 2 | 8 | 17 | 23 | 59 | 112 |
| | 50 | 2·5 | | | | | | | | | 6 | 16 | 22 | 39 | 75 | 161 |
| | 60 | 2·3 | | | | | | | | 2 | 13 | 17 | 24 | 51 | 89 | 199 |
| | 90 | 1·8 | | | | | 1 | 10 | 10 | 12 | 12 | 30 | 38 | 74 | 134 | 323 |
| | 120 | 1·7 | | | | 6 | 10 | 10 | 10 | 24 | 28 | 40 | 64 | 98 | 180 | 472 |
| | 180 | 1·3 | | 1 | 10 | 10 | 18 | 24 | 24 | 42 | 48 | 70 | 106 | 142 | 187 | 684 |
| | 240 | 1·3 | | 6 | 20 | 24 | 24 | 36 | 42 | 54 | 68 | 114 | 122 | 142 | 187 | 841 |
| | 360 | 1·2 | 12 | 22 | 36 | 40 | 44 | 56 | 82 | 98 | 100 | 114 | 122 | 142 | 187 | 1057 |
| 210 | 5 | 3·3 | | | | | | | | | | | | | 1 | 5 |
| | 10 | 3·2 | | | | | | | | | | | | 2 | 4 | 10 |
| | 15 | 3·0 | | | | | | | | | | | 1 | 5 | 13 | 22 |
| | 20 | 3·0 | | | | | | | | | | | 4 | 10 | 23 | 40 |
| | 25 | 2·8 | | | | | | | | | | 2 | 7 | 17 | 27 | 56 |
| | 30 | 2·8 | | | | | | | | | | 4 | 9 | 24 | 41 | 81 |
| | 40 | 2·7 | | | | | | | | | 4 | 9 | 19 | 26 | 63 | 124 |
| | 50 | 2·5 | | | | | | | | 1 | 9 | 17 | 19 | 45 | 80 | 174 |
| 220 | 5 | 3·5 | | | | | | | | | | | | | 2 | 6 |
| | 10 | 3·3 | | | | | | | | | | | | 2 | 5 | 11 |
| | 15 | 3·2 | | | | | | | | | | | 2 | 5 | 16 | 27 |
| | 20 | 3·0 | | | | | | | | | | 1 | 3 | 11 | 24 | 43 |
| | 25 | 3·0 | | | | | | | | | | 3 | 8 | 19 | 33 | 66 |
| | 30 | 2·8 | | | | | | | | | 1 | 7 | 10 | 23 | 47 | 91 |
| | 40 | 2·8 | | | | | | | | | 6 | 12 | 22 | 29 | 68 | 140 |
| | 50 | 2·7 | | | | | | | | 1 | 12 | 17 | 18 | 51 | 86 | 190 |
| 270 | 5 | 4·2 | | | | | | | | | | | | 1 | 3 | 9 |
| | 10 | 4·0 | | | | | | | | | | | 2 | 5 | 11 | 22 |
| | 15 | 3·8 | | | | | | | | | | 3 | 4 | 11 | 24 | 46 |
| | 20 | 3·7 | | | | | | | | | 2 | 3 | 9 | 21 | 35 | 74 |
| | 25 | 3·5 | | | | | | | | 2 | 3 | 8 | 13 | 23 | 53 | 106 |
| | 30 | 3·5 | | | | | | | | 3 | 6 | 12 | 22 | 27 | 64 | 138 |
| | 40 | 3·3 | | | | | | | 5 | 6 | 11 | 17 | 22 | 51 | 88 | 204 |
| 280 | 5 | 4·3 | | | | | | | | | | | | 2 | 2 | 9 |
| | 10 | 4·0 | | | | | | | | | | 1 | 2 | 5 | 13 | 25 |
| | 15 | 3·8 | | | | | | | | | 1 | 3 | 4 | 11 | 26 | 49 |
| | 20 | 3·8 | | | | | | | | | 3 | 4 | 8 | 23 | 39 | 81 |
| | 25 | 3·7 | | | | | | | | 2 | 5 | 7 | 16 | 23 | 56 | 113 |
| | 30 | 3·5 | | | | | | | 1 | 3 | 7 | 13 | 22 | 30 | 70 | 150 |
| | 40 | 3·3 | | | | | | 1 | 6 | 6 | 13 | 17 | 27 | 51 | 93 | 218 |
| 290 | 5 | 4·5 | | | | | | | | | | | | 2 | 3 | 10 |
| | 10 | 4·2 | | | | | | | | | | 1 | 3 | 5 | 16 | 30 |
| | 15 | 4·0 | | | | | | | | | 1 | 3 | 6 | 12 | 26 | 52 |
| | 20 | 4·0 | | | | | | | | | 3 | 7 | 9 | 23 | 43 | 89 |
| | 25 | 3·8 | | | | | | | | 3 | 5 | 8 | 17 | 23 | 60 | 120 |
| | 30 | 3·7 | | | | | | | 1 | 5 | 6 | 16 | 22 | 36 | 72 | 162 |
| | 40 | 3·5 | | | | | | 3 | 5 | 7 | 15 | 16 | 32 | 51 | 95 | 294 |
| 300 | 5 | 4·7 | | | | | | | | | | | | 3 | 3 | 11 |
| | 10 | 4·3 | | | | | | | | | | 1 | 3 | 6 | 17 | 32 |
| | 15 | 4·2 | | | | | | | | | 2 | 3 | 6 | 15 | 26 | 56 |
| | 20 | 4·0 | | | | | | | | 2 | 3 | 7 | 10 | 23 | 47 | 104 |
| | 25 | 3·8 | | | | | | | 1 | 3 | 6 | 8 | 19 | 26 | 61 | 128 |
| | 30 | 3·8 | | | | | | | 2 | 5 | 7 | 17 | 22 | 39 | 75 | 171 |
| | 40 | 3·7 | | | | | | 4 | 6 | 9 | 15 | 17 | 34 | 51 | 90 | 234 |
| | 60 | 3·0 | | 4 | 10 | 10 | 10 | 10 | 10 | 14 | 28 | 32 | 50 | 90 | 187 | 458 |
| | 90 | | (SEE EXTREME EXPOSURES BELOW) | | | | | | | | | | | | | |
| | 120 | | | | | | | | | | | | | | | |
| | 180 | | | | | | | | | | | | | | | |

(Rev. 1958)

Extreme exposures—250 and 300 ft

| Depth (ft) | Bottom time (min) | Time to first stop | 200 | 190 | 180 | 170 | 160 | 150 | 140 | 130 | 120 | 110 | 100 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 10 | Total ascent time |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Decompression stops | | | | | | | | | | | | | | | | | | | | |
| 250 | 120 | 1·8 | | | | | | | 5 | 10 | 10 | 10 | 10 | 16 | 24 | 24 | 36 | 48 | 64 | 94 | 142 | 187 | 682 |
| | 180 | 1·5 | | | | | 4 | 8 | 8 | 10 | 22 | 24 | 24 | 32 | 42 | 44 | 60 | 84 | 114 | 122 | 142 | 187 | 929 |
| | 240 | 1·5 | | | | | 9 | 14 | 21 | 22 | 22 | 40 | 40 | 42 | 56 | 76 | 98 | 100 | 114 | 122 | 142 | 187 | 1107 |
| 300 | 90 | 2·3 | | | | | 3 | 8 | 8 | 10 | 10 | 10 | 10 | 16 | 24 | 24 | 34 | 48 | 64 | 90 | 142 | 187 | 691 |
| | 120 | 2·0 | | | 4 | 8 | 8 | 8 | 8 | 10 | 14 | 24 | 24 | 24 | 24 | 42 | 58 | 66 | 102 | 122 | 142 | 187 | 887 |
| | 180 | 1·7 | 6 | 8 | 8 | 8 | 14 | 20 | 21 | 21 | 28 | 40 | 40 | 48 | 56 | 82 | 98 | 100 | 114 | 122 | 142 | 187 | 1165 |

following the surface interval, obligation to exposure time at various depths could be related to accumulated decompression obligation for subsequent dives. The Repetitive Dive Decompression Tables reported by Des Granges (1957) and detailed in the *U.S. Navy Diving Manual* (NAVSHIPS 250–538, 1963), have been used safely and effectively to make thousands of repetitive dives breathing air since official approval for use by fleet divers in 1960.

*Air decompression schedules for exceptional exposures*

The revised Standard Air Decompression Table (Des Granges 1957) was developed to provide safe decompression for dives up to 190 ft (6·7 ATA) for 60 min. Dives between 200 and 300 ft (7·1 and 10·1 ATA) were tested and reported as a part of that study, but were included in a second report (Workman 1957) as the second half of the Revised Tables for exceptional exposures (Table 12.7). It was considered that air dives to greater depths than 190 ft (7·6 ATA) for 60 min would not be a part of routine diving practice and should be in a separate table of dives for longer and deeper exposures.

An Air Saturation Decompression Table to provide for the emergency situation of the trapped diver whose exposure exceeded that of the Standard Air Decompression Table had been developed previously on the basis of the Haldane method in which the 75-min half-time tissue was controlled on a constant 2 to 1 ratio of absolute pressure. Though this Table had been in the *U.S. Navy Diving Manual* for years, there was little information on the safety in its use following prolonged exposure to compressed air. Following the extensive testing of decompression schedules reported by Des Granges (1957), it became recognized that marked reduction in ratios for slower tissues than 75 min was required at decompression stops in the water and upon surfacing. An attempt was made to develop and test schedules to provide safe decompression from deeper and longer air dives (Workman 1957).

The tenth-power reduction of depth ratios reported by Dwyer (1956), used to calculate the revised Standard Air Decompression Tables (Des Granges 1957), was used initially to develop decompression schedules to be tested for air dives of 140 ft (5·25 ATA) for 90- to 360-min exposures. This type of supersaturation control, and several other empirical approaches, proved inadequate until applied to half-time tissues of 120, 160 and 240 min. Review of a series of air exposures evaluated by Van der Aue (1945, unpublished) of 12 hours at 99 ft (4 ATA), followed by 12 to 24 hours at 33 ft (2 ATA), showed that a 2 to 1 ratio was unsafe upon surfacing and that half-time tissues of 240 min required control in decompression.



Using an empirical reduction of tissue ratio for the 40, 80, 120, 160 and 240 min half-time tissues based on safe values at 33 ft (2 ATA), decompression schedules were developed to provide for air exposures of 40 ft (2·2 ATA) to 140 ft (5·25 ATA) for 12 hours, 170 ft (6·15 ATA) for 8 hours, 200 ft (7 ATA) for 6 hours, 250 ft (8·6 ATA) for 4 hours and 300 ft (10 ATA) for 3 hours. Test of these schedules was only possible for 140 ft (5·25 ATA) for 6 hours and 300 ft (10 ATA) for 1 hour in which the results were sufficiently good to warrant promulgation for use on an emergency basis.

## STUDIES OF THE RATE LIMITING PROCESS IN INERT GAS TRANSPORT

While the use of 160- and 240-min half-time compartments in control of air decompression has been questioned (Behnke 1967; Hempleman 1967) Jones (1950), in one very fully studied case, demonstrated a nitrogen elimination rate constant ($K_5 = 0{\cdot}0025$) equivalent to 277 min half-time. Recent studies in dogs show that 80 to 90% of the total nitrogen is stored in slow compartments perfused by 10 to 15% of the cardiac output and has a time constant of 150 to 250 min (Farhi, Homma & Berger 1962). It is also considered a distinct possibility that whole body nitrogen elimination studies, performed by analysis of nitrogen in exhaled gas during oxygen breathing, may be quite limited in determination of the trace amounts of nitrogen in mixed venous blood returned to the lungs from poorly perfused tissue depots. Thus the slowest rate constants for inert gas elimination would never be defined by this method.

In carefully performed determinations of the bends threshold depth for large dogs (48 to 82 lb) exposed to air for 7, 12, 18 and 24 hours followed by direct ascent to surface (1 ATA), Reeves and Beckman (1966) reported that the bends threshold was consistently reproducible for each individual animal, that the range of threshold depth varied between animals from 57 ft (2·7 ATA) and 86 ft (3·6 ATA) and that the threshold depth was less following durations of pressure exposure of 18 and 24 hours than at 7 hours' exposure. It would appear that equilibration with the nitrogen pressure in air was not achieved following 7 hours exposure, and that the additional nitrogen taken up by body tissues following 18- to 24-hour exposures resulted in decompression sickness being manifest in these animals when exposed at the same depth as for 7 hours. Since it is considered that animals with less body mass have a greater rate of tissue perfusion with blood than man (Kindwall 1962), equilibration time of 18 hours for large dogs would predict even longer equilibration time for man. In these studies, equivalence of rate of gas uptake and elimination is not in question since ascent was made directly to surface (1 ATA) where the animals were observed for onset of decompression sickness. This was readily evident when it occurred and was promptly resolved with recompression of the animal such that end point criteria were decisively demonstrated.

## DEVELOPMENT OF HELIUM–OXYGEN DECOMPRESSION SCHEDULES FOR DEEP DIVING

Initial interest in the use of helium–oxygen mixtures in diving originated in a series of letters by Elihu Thomson to W. R. Watson of the General Electric Laboratories in which it was suggested that helium be used in caisson and diving work (Roth 1967). Its use was to avoid the limit set on diving depth by the supposed unavailability of oxygen from compressed air at great depths. The idea was based on 'the principle of superior rapidity of diffusion of the low density gas' (Thomson 1927). Shortly thereafter, the eminent physical chemist J. H. Hildebrand suggested to Sayers and Yant of the Bureau of Mines that the lesser coefficient of solubility of helium than nitrogen would make it of use in preventing cassion disease. Sayers and Yant (1925, 1926) performed experiments using helium–oxygen mixtures with guinea pigs to show decompression advantage over compressed air and suggested that helium be tried in human dives. End (1937) reported on the use of helium in human diving with decompression time as low as one twenty-third of that predicted by the air schedules used at that time.

Behnke and Yarbrough (1938) reported their experience with helium in diving operations in which it was used primarily to avoid the narcotic effects of nitrogen at depths as great as 300 ft (10 ATA). They suggested that the lower oil/water solubility ratio of helium should decrease decompression sickness as well as nitrogen narcosis. In their studies it was reported that there was a distinct absence of severe symptoms of decompression sickness in divers who experienced bends. No cases of unconsciousness or paralysis were reported and itching and skin rash occurred without other sequelae. This compared to air diving in which neurocirculatory collapse and paralysis occurred. Pains which occurred following helium dives were promptly relieved by recompression, whereas pain tended to persist following equivalent air dives. Behnke postulated that when helium–oxygen mixtures were breathed in diving, the controlling tissues during decompression are those which are rapidly saturated and desaturated, whereas with nitrogen the slow or fatty tissues controlled.

Behnke and Willmon (1941) compared the saturation–desaturation curves for nitrogen and helium. The helium capacity of the body was found to be 8·0 ± 1·3 cm³/Kg of body weight when the tissues are in equilibrium with a helium alveolar pressure of 1 ATA. This value is about 40% of the total nitrogen absorbed under these conditions. However, helium–oxygen saturation periods of only 3·5 hours were used which may not have been sufficiently long to establish equilibrium of body tissues with alveolar helium partial pressure. They also found that the time required to eliminate absorbed helium is 50% of the time required for nitrogen elimination. This period for helium elimination was decreased by half with exercise.



Exposure time at depth is an important factor in predicting decompression hazard. The total amount of gas dissolved in the body tissues at depth is determined by the saturation-time relationship implied by desaturation curves for nitrogen and helium. Behnke (1947) in analysing this, suggested that 75% of the total body nitrogen is eliminated from the body tissues of lean men in about 2 hours. Following exposure at the usual diving depths, this rapidly exchanging nitrogen is eliminated without causing symptoms. It is the small amount of nitrogen dissolved in fatty tissues that requires many hours for elimination. Behnke demonstrated that, for a subject breathing air at 90 ft (3·7 ATA) for 9 hours, about 12 hours of decompression were required. If helium–oxygen mixtures were used instead of air no more than 79 min of oxygen breathing decompression were required after all durations of exposure to this depth up to 9 hours.

If lipid substances are responsible for the prolongation of nitrogen absorption and elimination, helium, possessing a lesser solubility coefficient in slowly perfusing fatty tissue, should be eliminated in a shorter period of time. We have seen that total body nitrogen elimination curves have been interpreted to demonstrate slow compartments of 150 to 280 min half-time. Comparable total body helium elimination curves have been published by Jones (1950), Behnke and Willmon (1941) and Duffner and Snider (1958). These studies report the slowest compartment to be 70, 115 and 95 min half-time, respectively. The studies of Duffner and Snider followed 12-hour exposures at depths to 50 ft (2·5 ATA), whereas the other two studies were conducted following much shorter exposures. It would appear that half-time tissues at least as slow as 115 min would require control in calculation of helium–oxygen dives. Comparing the accepted values of the partition coefficient (water/tissue) for nitrogen as $a_1$ and helium as $a_2$, where $a_1 = 1/5{\cdot}2$ and $a_2 = 1/1{\cdot}7$, then $a_1/a_2 = 1/3$. This means that the very slow fat compartment seen when breathing nitrogen will be altered when breathing helium to a tissue with a half-time three times smaller. Taking 280 min as an upper range for the half-time on nitrogen, one would expect the corresponding half-time on helium to be approximately 100 min, which is very close to that derived by the studies discussed previously. The effective saturation time for helium would then be of the order of 10 to 12 hours.

If the error of analysis for helium is comparable to nitrogen, the lesser quantity of helium eliminated in alveolar gas should cause the elimination curve to approach an asymptote sooner than for nitrogen, thus giving the impression that helium had all been eliminated from the body tissues when it had not. Thus, there is a possibility for somewhat slower half-time tissues to exist for helium than determined in whole body elimination studies by the alveolar gas analysis method.

The first helium–oxygen decompression schedules developed for use of operational fleet divers were reported by Momsen and Wheland (1939). These schedules were subsequently revised by Molumphy (1950) by reducing the depth of oxygen breathing stops during decompression from 60 ft (2·8 ATA) and 50 ft (2·5 ATA) to 50 ft (2·5 ATA) and 40 ft (2·2 ATA) (Table 12.8).

TABLE 12.8
Helium–oxygen decompression table for helium partial pressure of 250 ft
Oxygen is breathed at 50 and 40 ft
(Partial pressure 250)

| *Time of dive* | *To first stop* | *Ft and min* | | | | | | | | | *Total time* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 120 | 110 | 100 | 90 | 80 | 70 | 60 | 50 | 40 | |
| *10 | 4 | 0 | 0 | 7 | 0 | 0 | 1 | 4 | 10 | 35 | 62 |
| 20 | 4 | 0 | 0 | 7 | 0 | 2 | 5 | 7 | 10 | 68 | 103 |
| 30 | 4 | 0 | 7 | 0 | 2 | 6 | 7 | 10 | 10 | 87 | 133 |
| 40 | 4 | 0 | 7 | 0 | 5 | 8 | 9 | 14 | 12 | 96 | 155 |
| 60 | 4 | 0 | 7 | 4 | 8 | 11 | 14 | 19 | 16 | 99 | 182 |
| 80 | 4 | 0 | 7 | 7 | 11 | 16 | 18 | 23 | 16 | 99 | 201 |
| 100 | 4 | 0 | 7 | 10 | 14 | 19 | 23 | 23 | 16 | 99 | 215 |
| 120 | 4 | 7 | 3 | 12 | 17 | 19 | 23 | 23 | 16 | 99 | 223 |
| 140 | 4 | 7 | 4 | 15 | 18 | 19 | 23 | 23 | 16 | 99 | 228 |
| 160 | 4 | 7 | 7 | 16 | 19 | 19 | 23 | 23 | 16 | 99 | 233 |
| 180 | 4 | 7 | 9 | 17 | 19 | 20 | 23 | 23 | 16 | 99 | 237 |
| 200 | 4 | 7 | 11 | 17 | 19 | 20 | 23 | 23 | 16 | 99 | 239 |
| 220 | 4 | 7 | 12 | 17 | 19 | 20 | 23 | 23 | 16 | 99 | 240 |
| 240 | 4 | 7 | 13 | 17 | 19 | 20 | 23 | 23 | 16 | 99 | 241 |

* Take 1 extra min from first stop to next stop.

The method used to calculate these schedules was basically that developed by Haldane with certain modifications required for the helium–oxygen diving equipment and mixtures to be used at great depths. These modifications are as follows:

(1) The partial pressure of helium in the mixture breathed at the depth of the dive was used to compute schedules from 60 ft (2·8 ATA) to 410 ft (12·4 ATA) in 10-ft increments.

(2) Exposure time on each partial pressure schedule was provided in 10- to 20-min increments from 10 to 240 min.



(3) The minimum oxygen percentage permitted was 16%, with all calculations made on an 86% helium–14% oxygen mixture to allow for oxygen use by the diver in a recirculating system.

(4) All dives were calculated for twice the exposure time of the schedule to allow for increased helium uptake by body tissues during exercise on working dives.

(5) Half-time tissues were considered in arithmetical progression, i.e. 5, 10, 20, 30, 40, 50, 60 and 70 min.

(6) A ratio of 1·7 to 1 of tissue helium pressure to absolute pressure of the decompression stop depth was used to control the limit of supersaturation. This is equivalent to a 2·15 to 1 ratio of absolute pressure of the exposure depth to absolute pressure of the decompression stop as used by Haldane where air is considered 100% nitrogen. It was not stated in the report how the 1·7 to 1 ratio was derived, but its value of 56 to 33 ft absolute coincides with the minimum safe surfacing value determined by Duffner and Snider (1958) following 12-hour exposures at 37 ft (2·12 ATA) while breathing an 80% helium–20% oxygen mixture.

(7) Divers breathed 100% oxygen at decompression stops at 60 ft (2·8 ATA) and 50 ft (2·5 ATA) to complete decompression, following which they surfaced directly. The oxygen was considered to contain 20% helium or to be 80% efficient.

(8) A method of surface decompression was developed by which divers breathed oxygen at 50 ft (2·5 ATA) for time equal to the oxygen period at 60 ft (2·8 ATA) before surfacing directly, to be recompressed again within 5 min to 50 ft (2·5 ATA) to complete the full scheduled oxygen breathing time at that depth in the deck pressure chamber.

(9) Rate of ascent to the first water stop and between water stops varied from 10 to 75 ft/min, increasing with depth and oxygen percentage in the breathing mixture. Ascent time for all except the initial ascent to the first stop was included in the decompression time of the subsequent stop.

(10) Repetitive diving was not allowed for a period of 12 hours after surfacing from a dive.

The first operational use of the helium–oxygen tables for deep diving was reported by Behnke and Willmon (1939) during salvage operations on the submarine *Squalus*. A review of incidence of decompression sickness in use of these helium–oxygen schedules (Doll 1965) reported 6 cases in 721 dives, an incidence of 0·83%.

Molumphy (1950) reported results of 49 dives at greater depth than the published schedules performed at the U.S. Navy Experimental Diving Unit. Dives of 10-min exposure were made to depths of 495 ft (16 ATA) and 561 ft (18 ATA) with freedom from symptoms. A number of attempts were made to perform working dives at 495 ft (16 ATA) for 20-min exposures, with bends resulting in 12 of 26 dives, though the supersaturation ratio controlling decompression was reduced to 1·5 to 1 from 1·7 to 1, and half-time tissues to 100 min were considered. Symptoms occurred at decompression stops as deep as 110 ft, as an indication of the relative inadequacy of the decompression. As a matter of interest, two 10-min dives to 485 ft (15·7 ATA) were made in the open sea off Key West and a 500-ft (16·2-ATA) dive was made off Panama in 1949 without incident.

*Use of helium–oxygen in mixed-gas scuba*

Further study of helium–oxygen decompression was undertaken by Duffner, Snyder and Smith (1959) in a task to develop schedules for use of helium–oxygen mixtures in semi-closed mixed gas scuba. It was considered desirable to avoid risk of carbon dioxide retention, oxygen toxicity and narcosis at depth by substituting a less dense breathing mixture for nitrogen–oxygen, in current use by operational swimmers at that time. A minimal decompression curve for dives in which 80% helium–20% oxygen was breathed by subjects was established during 109 test dive schedules at various depth-time exposures. Seventy-eight dive schedules employing decompression were tested to determine adequacy of decompression predicted by a calculation procedure developed by Rashbass (1955). This procedure considered only one critical hypothetical tissue in which inert gas diffuses slowly across a tissue slab linearly rather than by perfusion or transcapillary radial diffusion. The structure and inert gas equilibration characteristics were made consistent with well established ascent schedules in diving. The time course of the quantity of nitrogen or helium in the tissue following a step function in the blood gas tension at a time when the tissue and blood are in equilibrium was analysed by Hill's (1928) solution of the Fick equation. In contrast to a limiting supersaturation ratio of the Haldane approach, the Rashbass method used a finite tissue pressure head of inert gas ($\Delta P$) exceeding ambient pressure as critical. This was fixed at 30 ft (0·9 ATA) of water for nitrogen by Rashbass, and 37 ft (1·12 ATA) of water for helium by Duffner.

The minimal decompression curve for 80% helium–20% oxygen was projected as a function of pressure ($P$) and the square root of time ($t$) at depth ($Pt^{1/2}$ = constant). Comparison of safe minimal decompression dives for helium–oxygen show a significantly longer exposure time permitted at all depths tested than for comparable air dives. Similar to air diving practice, a 60-ft/min ascent rate was found safe for both minimal dives and decompression dives.

Workman and Reynolds (1965) evaluated the complete log of all dives performed in the study by Duffner *et al.* (1959) and determined that decompression prediction by the calculation method of Duffner, modified from Rashbass (1955), was not adequate for longer exposures. This, and the necessity to develop a repetitive dive method for helium–oxygen dives which had been done successfully for air dives by the modified Haldane method (Des Granges 1957), encouraged them to utilize this method of calculation. Recalculation of existing safe dive schedules permitted determination of permissible surfacing tissue tension values for minimal and decompression dives (Table 12.9). It will be noted that the ratio, and its



TABLE 12.9

| *Half-time for tissue desaturation (min)* | *Safe ratio* | *Safe He + $N_2$ tissue tension (ft)* |
|---|---|---|
| 5 | 3·50 | 116 |
| 10 | 2·80 | 92 |
| 20 | 2·24 | 74 |
| 40 | 1·88 | 62 |
| 80 | 1·70 | 56 |
| 120 | 1·60 | 53 |

statement in feet of sea water tissue tension of helium and nitrogen residual in tissues, differs from the ratio used by Haldane for air diving in which total pressure of the exposure was considered to be with 100% nitrogen. In the helium–oxygen schedules of Momsen and Wheland (1939) and Molumphy (1950), the helium pressure of the inspired mixture was used in calculation, as well as 26 ft (0·79 ATA) of nitrogen to which the tissues were equilibrated on air prior to the helium dive. In calculation of the helium–oxygen schedules for mixed gas diving, it was determined that the sum of the gas exchange gradients for helium and nitrogen during uptake and elimination was equal to that when only one inert gas was considered. This would be the worst case that could occur, even though the anatomical tissue sites represented by the same theoretical half-time tissue differ for helium and nitrogen.

The surfacing ratios of helium and nitrogen were not projected to depth as constant ratios ($Po/P$), but rather as a constant value of tissue tension exceeding ambient or hydrostatic pressure by the following equation:

$$Po - P = \text{constant}$$

where $Po$ = tissue tension of He + $N_2$ (feet, sea water); $P$ = hydrostatic pressure (feet, sea water). The values for control of supersaturation at decompression stops are shown in Table 12.10. The $Po - P = K$ control for each half-time tissue was used when it became apparent that somewhat deeper decompression stops were required for helium dives than air dives,

TABLE 12.11

Helium–oxygen decompression table for mixed gas scuba using 68% Helium, 32% oxygen supply mixture

| *Depth (ft)* | *Bottom time (min)* | *Time to first stop* | *Decompression stops* 50 | 40 | 30 | 20 | 10 | *Total ascent time* | *Repet. group* |
|---|---|---|---|---|---|---|---|---|---|
| 40 | 260 | | | | | | 0 | 0·7 | L |
| 50 | 180 | | | | | | 0 | 0·8 | L |
| | 200 | 0·7 | | | | | 0 | 0·8 | L |
| 60 | 130 | | | | | | 0 | 1·0 | L |
| | 150 | 0·8 | | | | | 20 | 20·8 | L |
| | 170 | 0·8 | | | | | 35 | 35·8 | L |
| 70 | 85 | | | | | | 0 | 1·2 | J |
| | 100 | 1·0 | | | | | 15 | 16·0 | K |
| | 115 | 1·0 | | | | | 25 | 26·0 | L |
| | 130 | 1·0 | | | | | 40 | 41·0 | L |
| 80 | 60 | | | | | | 0 | 1·3 | I |
| | 70 | 1·0 | | | | 5 | 10 | 16·0 | J |
| | 80 | 1·0 | | | | 10 | 15 | 26·0 | K |
| | 90 | 1·0 | | | | 10 | 25 | 36·0 | K |
| | 100 | 1·0 | | | | 10 | 35 | 46·0 | K |
| 90 | 45 | | | | | | 0 | 1·5 | H |
| | 60 | 1·3 | | | | 5 | 10 | 16·3 | J |
| | 70 | 1·2 | | | | 5 | 20 | 26·2 | K |
| | 85 | 1·2 | | | | 10 | 30 | 41·2 | L |
| 100 | 35 | | | | | | 0 | 1·7 | G |
| | 50 | 1·3 | | | | 5 | 15 | 21·3 | J |
| | 60 | 1·3 | | | | 10 | 20 | 31·3 | K |
| | 70 | 1·2 | | | 5 | 15 | 20 | 41·2 | K |
| 110 | 30 | | | | | | 0 | 1·8 | G |
| | 40 | 1·5 | | | | 5 | 10 | 16·5 | H |
| | 50 | 1·5 | | | | 10 | 20 | 31·5 | J |
| | 65 | 1·3 | | | 5 | 15 | 25 | 46·3 | L |
| 120 | 25 | | | | | | 0 | 2·0 | G |
| | 35 | 1·7 | | | | 5 | 10 | 16·7 | I |
| | 45 | 1·5 | | | 5 | 10 | 15 | 31·5 | K |
| | 55 | 1·5 | | | 10 | 15 | 20 | 46·5 | L |
| 130 | 20 | | | | | | 0 | 2·2 | F |
| | 30 | 1·8 | | | | 5 | 10 | 16·8 | I |
| | 40 | 1·7 | | | 5 | 10 | 15 | 31·7 | J |
| | 50 | 1·5 | | 5 | 5 | 15 | 20 | 46·5 | L |
| 140 | 15 | | | | | | 0 | 2·3 | E |
| | 25 | 2·0 | | | | 5 | 10 | 17·0 | G |
| | 35 | 1·8 | | | 5 | 10 | 20 | 36·8 | J |
| | 45 | 1·7 | | 5 | 5 | 15 | 25 | 51·7 | K |
| 150 | 15 | | | | | | 0 | 2·5 | E |
| | 20 | 2·2 | | | | 5 | 10 | 17·2 | G |
| | 30 | 2·0 | | | 5 | 10 | 15 | 32·0 | J |
| | 40 | 1·8 | | 5 | 10 | 15 | 20 | 51·8 | K |
| 160 | 10 | | | | | | 0 | 2·7 | E |
| | 20 | 2·2 | | | 5 | 5 | 10 | 22·2 | G |
| | 35 | 2·0 | | 5 | 10 | 10 | 20 | 47·0 | K |
| 170 | 10 | | | | | | 0 | 2·8 | E |
| | 20 | 2·3 | | | 5 | 5 | 10 | 22·3 | H |
| | 35 | 2·2 | | 5 | 10 | 15 | 20 | 52·2 | K |
| 180 | 5 | | | | | | 0 | 3·0 | C |
| | 10 | 2·7 | | | | 5 | 10 | 17·7 | E |
| | 20 | 2·3 | | 5 | 5 | 10 | 10 | 32·3 | H |
| | 30 | 2·3 | | 5 | 10 | 15 | 20 | 52·3 | K |
| 190 | 10 | 2·8 | | | | 5 | 10 | 17·8 | E |
| | 20 | 2·5 | | 5 | 5 | 10 | 20 | 42·5 | H |
| | 30 | 2·3 | 5 | 5 | 10 | 15 | 25 | 62·3 | K |
| 200 | 10 | 3·0 | | | | 5 | 15 | 23·0 | F |
| | 20 | 2·7 | | 5 | 5 | 10 | 20 | 42·7 | I |
| | 30 | 2·5 | 5 | 5 | 10 | 15 | 35 | 72·5 | K |



TABLE 12.10

| *Half-time for tissue desaturation (min)* | *Po − P ATS* | *Po − P ft sea water* |
|---|---|---|
| 5 | 2·50 | 83 |
| 10 | 1·80 | 59 |
| 20 | 1·24 | 41 |
| 40 | 0·88 | 29 |
| 80 | 0·70 | 23 |
| 120 | 0·60 | 20 |

after the tenth-power air controls of supersaturation had been employed with little success.

Once single dive decompression schedules were proved adequate for dives in a range of 50 ft (2·5 ATA) for 200 min, to 200 ft (7 ATA) for 30 min with a 75% helium to 25% oxygen breathing mixture (Table 12.11), a repetitive dive format identical to that developed for air dives was constructed. Twenty-seven series of three repetitive dives per series were evaluated to test all possible variables of shallow, medium and deep depth and short, medium and long exposure time and surface interval time. These dive series were made up to avoid duplication of depth and exposure time, to permit testing as many different individual dive schedules as possible throughout the test series. Uniformly safe results of these tests confirmed the prediction of safe decompression from repetitive dives when helium–oxygen was breathed, a matter which had no prior verification.

A method utilizing oxygen decompression at 30 ft (1·9 ATA) and 20 ft (1·6 ATA) depth water stops was also provided as optional for both single and repetitive dives to decrease decompression time and provide maximum freedom from symptoms of decompression sickness (Table 12.12). More than 400 single and repetitive open sea dives at depths to 200 ft (7 ATA) have been performed without decompression sickness or oxygen toxicity occurring during use by operational diving personnel.

## DECOMPRESSION AFTER SATURATION DIVING

For project Sealab of the U.S. Navy and Operation Genesis which preceded it, the Experimental Diving Unit was asked to formulate and test decompression schedules from exposures of several days duration at 100 ft (4 ATA), 200 ft (7 ATA) 300 ft (10 ATA) and 450 ft (14·6 ATA). Operation Genesis was a series of laboratory investigations by Bond (1963, 1964) to test methods and procedures for saturation diving prior to placing human divers on the sea bottom to operate from an undersea station, the Sealab operations of 1964 and 1965.

TABLE 12.12

Helium–oxygen decompression table for mixed gas scuba using 68–32% supply mixture and oxygen decompression

| *Depth (ft)* | *Time (min)* | *Decompression stops* $HeO_2$ *50 ft* | *40 ft* | | *Oxygen 30 ft* | *20 ft* | *Repetitive group* |
|---|---|---|---|---|---|---|---|
| 60 | 170 | | | Allow 2 min to complete bag purge to oxygen | | 20 | L |
| 70 | 115 | | | | | 15 | L |
| | 130 | | | | | 25 | L |
| 80 | 80 | | | | | 15 | K |
| | 90 | | | | | 20 | K |
| | 100 | | | | | 25 | K |
| 90 | 70 | | | | | 15 | K |
| | 85 | | | | | 25 | L |
| 100 | 50 | | | | | 15 | J |
| | 60 | | | | | 20 | K |
| | 70 | | | | 5 | 20 | K |
| 110 | 50 | | | | | 15 | J |
| | 65 | | | | 5 | 20 | L |
| 120 | 45 | | | | 5 | 15 | K |
| | 55 | | | | 10 | 20 | L |
| 130 | 40 | | | | 5 | 15 | J |
| | 50 | | 5 | | 5 | 20 | L |
| 140 | 35 | | | | 5 | 15 | J |
| | 45 | | 5 | | 5 | 20 | K |
| 150 | 30 | | | | 5 | 15 | J |
| | 40 | | 5 | | 10 | 20 | K |
| 160 | 20 | | | | 5 | 10 | G |
| | 35 | | 5 | | 10 | 20 | K |
| 170 | 20 | | | | 5 | 10 | H |
| | 35 | | 5 | | 10 | 20 | K |
| 180 | 20 | | 5 | | 5 | 10 | H |
| | 30 | | 5 | | 10 | 20 | K |
| 190 | 20 | | 5 | | 5 | 15 | H |
| | 30 | 5 | 5 | | 10 | 20 | K |
| 200 | 20 | | 5 | | 5 | 20 | I |
| | 30 | 5 | 5 | | 10 | 25 | K |



The inert gas of the breathing mixture used in these studies was principally helium. The oxygen partial pressure was carefully controlled between 0·2 and 0·5 ATS to avoid manifestation of long-term pulmonary oxygen toxicity.

As the duration of pressure exposure increases, the obligated decompression increases since a greater amount of inert gas dissolves in the more slowly desaturating tissues. An advantage is offered through the application of saturation diving in that after some finite period of time the body tissues become completely equilibrated with inert gas in the atmosphere at the pressure of the exposure. The decompression obligation is limited to that amount. Further exposure should result in no increase in decompression requirement and the ratio of dive time to decompression time becomes more favourable. Since even the slowest equilibrating tissues are saturated with inert gas at the exposure depth, decompression will be regulated by the rate at which these tissues eliminate the inert gas. Therefore the technique of a uniform rate of ascent appears to be most appropriate for decompression from saturation exposures.

Schreiner and Kelley (1967) have provided an excellent review of the mathematical and theoretical aspects of linear ascent of saturation and non-saturation exposures. Their approach is that of Haldane inert gas exchange concepts, but with the extent of tissue supersaturation with inert gas as a function of ambient pressure and the rate constant of gas exchange as described by Workman (1965).

$$\sum \pi \leq M \text{ (ATA)}$$

$$M = f(D \text{ ATA}, K)$$

where $\sum \pi$ = sum of partial pressure of dissolved inert gas in tissue, $M$ = permissible inert gas partial pressure as supersaturation criteria, $K$ = specific time constant of inert gas exchange in tissue = $\ln 2/t_{1/2}$, $t_{1/2}$ = half-time and $D$ = sea water depth. The rate at which inert gas is taken up or released by a given half-time tissue is proportional to the difference between the ambient inert gas partial pressure and the partial pressure of the same inert gas dissolved in a given tissue. Thus

$$\frac{d\pi}{dt} = K(P - \pi)$$

with the boundary condition $t = 0$, $\pi = \pi_0$, where $P$ = partial pressure of inspired inert gas $t$ = time (min). In the special case of saturation diving with helium–oxygen with $P_{O_2}$ = constant

$$M = H + \Delta P \quad \Delta P_{240} = \text{constant}$$

where $H$ = absolute hydrostatic pressure, $\Delta P$ = excess supersaturation pressure of inert gas dissolved in tissue = $(\pi - H)$, and 240 = minutes of half-time tissue.

$$P = D + A - Po_2$$

where $A$ = atmospheric sea level pressure (1 ATA) and $D = \pi - \Delta P - A$. Then

$$P = \pi - \Delta P - Po_2$$

$$(\Delta P + Po_2) = (P - \pi) = \text{constant}$$

$$\frac{d\pi}{dt} = K(\pi - \Delta P - Po_2 - \pi) = -K(\Delta P + Po_2)$$

Thus, when a constant $Po_2$ and a constant $\Delta P$ are specified for a given theoretical half-time tissue, it follows that the driving force for gas exchange $(P - \pi)$ is also constant. In this case the ascent function must be linear. The ascent rate must be such that 1 ft of inert gas will desaturate from the 240-min half-time tissue during the time required to decrease ambient pressure by 1 ft.

$$\frac{d\pi}{dt} = -\frac{0{\cdot}693}{240H}(20 + 10) = \frac{11{\cdot}6 \text{ min}}{1 \text{ ft}}$$

$0{\cdot}693 = \ln 2$, $K = 0{\cdot}693/t_{1/2}$, $\Delta P = 20$ ft sea water, $Po_2 = 0{\cdot}3$ ATA = 10 ft sea water. Therefore, about 12 min are required to ascend 1 ft of sea water depth when the 240-min half-time tissue controls the helium elimination at a permissible supersaturation ($\Delta P$) of 20 ft sea water pressure of helium.

A series of 24-hour exposures dives at 200 ft (7 ATA), 300 ft (10 ATA) and 400 ft (13 ATA) with subjects breathing a helium–oxygen atmosphere in a dry chamber, with $Po_2$ maintained at 0·5 ATA, was made to determine subject performance and adequacy of decompression. It was assumed initially that a limiting 180-min half-time tissue would provide conservative decompression and that a 150-min half-time might be the slowest to be considered. Three subjects were decompressed without symptoms following a 12-day exposure at 200 ft (7 ATA) at a constant rate of 8·25 min/ft sea water depth.

During the decompression from the first exposure of two subjects to 300 ft (10 ATA) for 24 hours, one diver noted onset of pain in one knee at 75 ft (3·28ATA) with use of the 8·25 min/ft ascent rate. Recompression was effective in resolving symptoms and he was brought to the surface safely at the twice slower rate of 16·5 min/ft.

It was now considered necessary to control half-time tissues as slow as 240 min, since the 180-min half-time control proved unsafe for this subject. With a constant $Po_2$ of 0·5 ATA maintained in the helium–oxygen atmosphere and a $\Delta P$ supersaturation of 20 ft (0·6 ATA), the constant rate of ascent required would be 11 min/ft.



Another pair of divers completed a similar exposure to 300 ft (10 ATA) and were decompressed without incident at this rate. A third pair of divers were exposed for 24 hours to a pressure of 400 ft (13 ATA) and similarly decompressed without incident (Bornmann 1967).

The method of continuous ascent at a constant rate was used to decompress four divers in Sealab I following a 12-day exposure at 193 ft (6·9 ATA) without incident. In the Sealab II operation at 204 ft (7·2 ATA), 28 successful decompressions were made at a constant rate of 10 min/ft of ascent. The length of the dives was 2 weeks, except for one subject who stayed at depth for 4 weeks. One diver who celebrated his fiftieth birthday during the dive developed knee pain at 35 ft (2·1 ATA) which was treated successfully by recompression, oxygen breathing and slower ascent to the surface.

In preparatory dives for Sealab III at the Experimental Diving Unit, teams of 4 men on each dive have been exposed up to 72 hours at depths to 450 ft (14·6 ATA), during which they have completed excursion dives from 450 ft (14·6 ATA) to 600 ft (19·2 ATA) to perform useful work for 1 hour, with direct return to 450 ft (14·6 ATA) without incident. These simulated dives in the wet–dry pressure complex have demonstrated the feasibility of divers working down to the depth of the continental shelf limits from an underwater station at 450 ft (14·6 ATA).

During these deeper saturation dives with rapid compression to depth, joint pain has been noticed in all subjects within several hours after reaching maximum depth of 200 ft (7 ATA) or more. Linear compression at a rate of 1·5 min/ft was instituted to permit hydrostatic pressure distribution in semi-rigid tissues such as cartilage, in which it has been hypothesized that shearing forces were developed by rapid compression, and maintained for sufficient time to induce tissue injury in painful joints. By this means symptoms incidental to compression have been largely avoided. This avoidance of tissue injury is felt to be important to provide safe decompression for these divers.

In these dives, a $Po_2$ of 0·3 ATS has been maintained in the chamber atmosphere to reduce risk of pulmonary oxygen effects and of combustion hazard. Therefore, it was necessary to reduce the ascent rate to 12·5 min/ft depth decrease. As this rate did not provide freedom from symptoms in some subjects, a rate of 15 min/ft and stages of 4 hours at depth changes of 100 ft (3 ATA) up to 150 ft (5·55 ATA) and at 50-ft stages to the surface, were instituted. This was an attempt to interrupt the excess supersaturation time-dependent probability function in bubble formation. It is apparent that supersaturation of tissues with inert gas is maintained for much longer periods of time during ascent from deeper dives. In any event, decompression from the 450-ft (14·6 ATA) exposures has been rendered symptom-free by this procedure.

## EXCURSION DIVING FROM SATURATION EXPOSURES AT DEPTH

Prior to Sealab II in 1965, a study was initiated at the Naval Medical Research Laboratory, New London, Connecticut to establish safe depth-time limits for excursion dives from saturation exposures at depth (Larsen & Mazzone 1967). This could more easily be done with air exposure than helium atmospheres due to the complexity and cost of establishing and maintaining a closed-chamber environment of helium–oxygen mixture for the numerous exposures required. It was considered that information derived from such dives would be applicable to later excursion diving with helium–oxygen.

A series of permissible exposure times at depth greater than the saturation depth of 35 ft (2·06 ATA) was calculated in accordance with the method described (Workman 1965) (Fig. 12.2). Twenty-four hours' exposure at the saturation depth was made before each excursion dive,

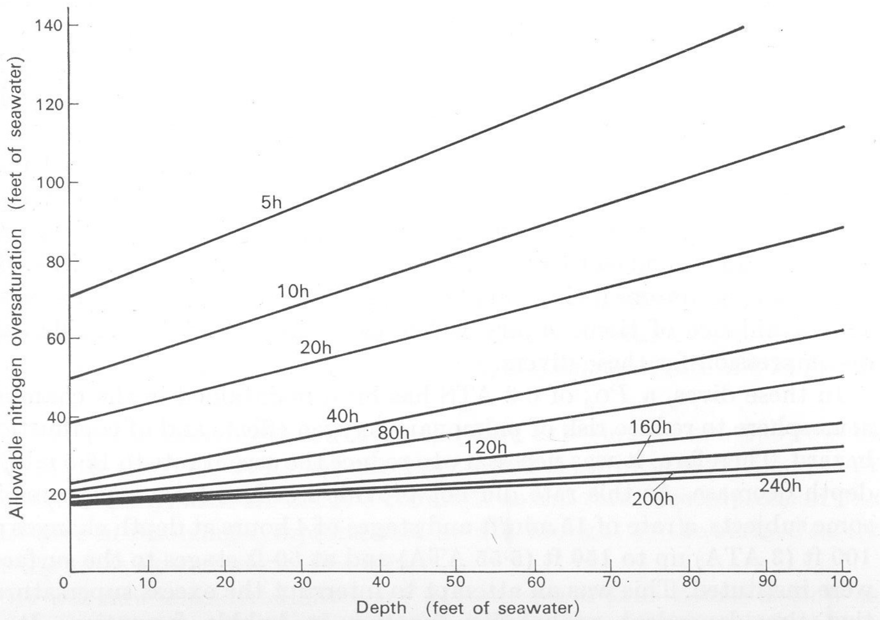


FIG. 12.2. Allowable nitrogen oversaturation related to depth in feet of sea water for half-time tissues (*h*) from 5 through 240 min



followed by direct return with ascent rate of 60 ft/min to the saturation depth of 35 ft (2·06 ATA). Subjects were observed for 6 hours at this depth for symptoms of decompression sickness, followed by decompression to the surface.

The entire series of dives was first performed using large dogs, then repeated using human subjects. In the animal series, repetitive excursions were made, as many as 8 in a single dive series, with intervals of 75 to 120 min at 35 ft (2·06 ATA) separating these excursions. In the human series, repetitive excursions were made only once. Two excursions were made to 165 ft (6 ATA) for 30 min, with an interval of 4 hours at 35 ft (2·06 ATA) between excursions (Table 12.13).

TABLE 12.13
Excursion air dives following 24-hour exposure at 35 ft with direct return to this depth

| *Depth (ft)* | *Time (min)* | *ΔDepth (ft)* | *No decompression dive* | |
|---|---|---|---|---|
| | | | *Depth (ft)* | *Time (min)* |
| 165 | 30 | 130 | 90 | 30 |
| 135 | 60 | 100 | 60 | 60 |
| 117 | 90 | 82 | 50 | 100 |
| 109 | 120 | 74 | 48 | 120 |
| 105 | 150 | 70 | 45 | 150 |
| 100 | 240 | 65 | 38 | 240 |

Two subjects were exposed on each schedule. Six-hour stay at 35 ft level followed by 3 to 4 hour stage ascent to surface, with last hour breathing oxygen. No decompression sickness in series.

A total of 7 saturation exposures with 36 excursion dives was completed with large dogs with no decompression sickness observed in these animals. This was followed by a series of 15 saturation exposures with a total of 17 excursions performed by divers with no cases of decompression sickness resulting. This series demonstrated that an appreciable increase in depth of excursion dive is possible at 35 ft (2·06 ATA) than from the surface (1 ATA) and that further increase should be possible at greater saturation depths. While similar dives remain to be performed with helium–oxygen, the supersaturation criteria developed previously for nitrogen predicted satisfactorily, excursion dives from saturation depths (Fig. 12.2).

## DEEPER WORKING DIVES WITH HELIUM–OXYGEN

Through use of the submersible decompression chamber (SDC), it has become possible for the diver to be placed at the underwater site to carry out productive work for a period of hours, then returned to a deck decompression chamber (DDC) for final decompression. Series of work dives may be carried out by teams of divers from a saturation depth in the DDC,

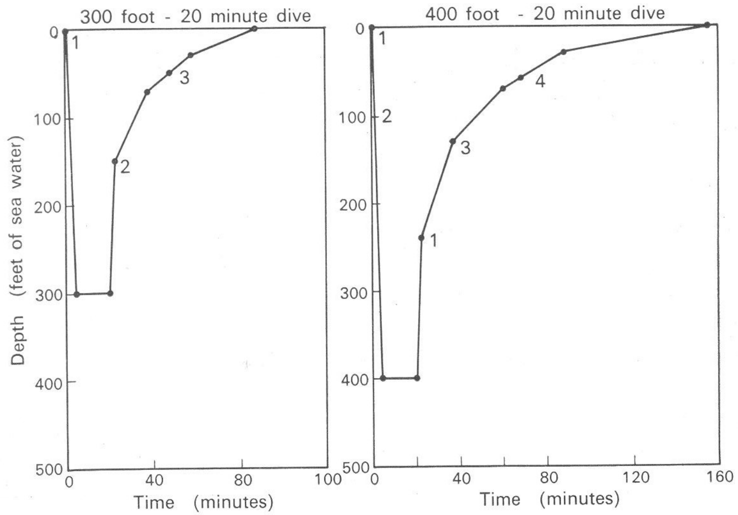


FIG. 12.3. Helium–oxygen dive schedules with continuous ascent decompression for 20 min exposure at 300 and 400 ft sea water depth

Breathing mixtures at 300 ft: (1) 80% helium, 20% oxygen, (2) 60% nitrogen, 40% oxygen, (3) 100% oxygen; and at 400 ft: (1) 37% nitrogen, 37% helium, 26% oxygen, (2) 85% helium, 15% oxygen, (3) 30% nitrogen, 30% helium, 40% oxygen, (4) 100% oxygen.

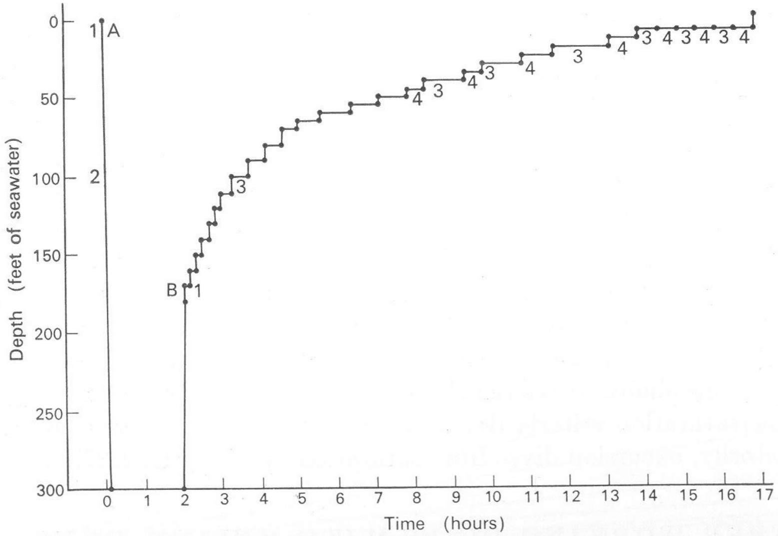


FIG. 12.4. 300-ft, 2-hour helium–oxygen dive with decompression on air and oxygen

Breathing mixtures (1) 80% helium, 20% oxygen; (2) 90% helium, 10% oxygen; (3) Air; (4) 100% oxygen. (A) Wet chamber; (B) Dry chamber.

being transferred to and from the work site by the SDC. Decompression is then required only upon completion of the work period (Krasberg 1966).

Working dives with 15 min actual time at depth have been completed



successfully for depths from 300 ft (10 ATA) to 600 ft (19·2 ATA) in the Experimental Diving Unit wet–dry pressure facilities using helium–oxygen breathing mixtures at depth and nitrogen–oxygen or helium–nitrogen–oxygen mixtures for decompression (Fig. 12.3). Both stage and linear ascent decompression at a varying rate have been used successfully (Workman 1967).

It was decided that working dives of 1 and 2 hours would be needed to accomplish work which would require a considerable number of shorter dives to complete. The considerable amount of inert gas taken up in slowly equilibrating tissues during such long pressure exposures obligates a prolonged decompression which is only possible through use of the SDC-DDC technique to remove the diver from the water.

For simplicity, an air atmosphere has been used in the decompression chamber, with divers continuing to breathe a helium–oxygen mixture supplied by demand regulators and masks in the chamber until a depth of 100 ft (4 ATA) is reached. Air breathing is then begun to aid helium elimination, supplemented by intermittent oxygen breathing at depths less than 40 ft (2·2 ATA) to increase elimination of both nitrogen and helium from body tissues.

Working dives of 2 hours duration have been accomplished by this technique to depths through 300 ft (10 ATA) (Figs. 12.4 and 5) and for

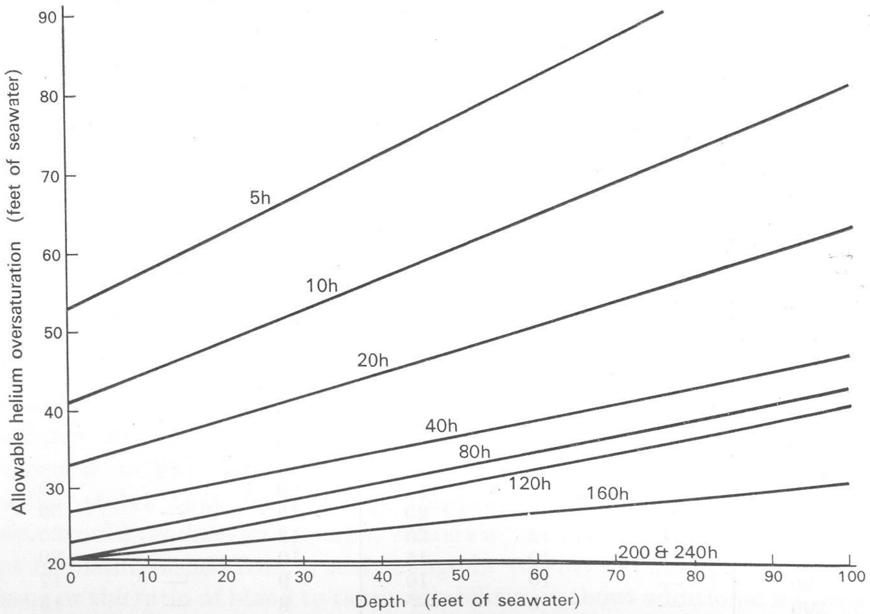


FIG. 12.5. Allowable helium oversaturation related to depth in feet of sea water for half-time tissues (h) from 5 through 240 min

1 hour to 450 ft (14·6 ATA). While 15 hours' ascent time is required after 2-hour working dives at 300 ft (10 ATA) and 22 hours' after 1 hour at 450 ft (14·6 ATA) it is considered that the ratio of productive work to decompression time is more favourable for such dives than those with shorter bottom time.

## DECOMPRESSION WITH HELIUM–NITROGEN–OXYGEN MIXTURES WITH CONSTANT $Po_2$ MIXED GAS SCUBA

In addition to work with deeper diving systems, a considerable number of dives have been made to evaluate a closed-circuit constant $Po_2$ mixed gas scuba. Working dives of a range from 300 ft (10 ATA) for 20 min to 70 ft (3·12 ATA) for 220 min have been made to demonstrate depth and duration capabilities. Separate inert gas supply for helium and nitrogen permit switching of the inert gas fraction of the mixture during the dive and decompression.

A series of minimal decompression dives, and those of duration permitted by 15-min decompression time, using helium–nitrogen inert gas mixture with $Po_2$ of 1·3 to 1·6 ATS have been evaluated at the Experimental Diving Unit. Significant extension of dive duration has been observed with this procedure over that possible with helium–oxygen used in semi-closed mixed gas scuba (Workman 1967) (Table 12.14). The mechanism to

TABLE 12.14

Comparison of dives on $He–O_2$ and $N_2–He–O_2$ with no decompression and with 15 minutes' decompression

| *Depth (ft)* | *Bottom time (min)* *75–25% helium–oxygen* (*A*) | (*B*) | (*C*) | *Bottom time (min)* *Nitrogen–helium–oxygen* (*D*) | | (*E*) | (*F*) |
|---|---|---|---|---|---|---|---|
| 70 | 85 | 100 | 115 | 240 | | — | — |
| 80 | 60 | 70 | 80 | 140 | | — | — |
| 90 | 45 | 60 | 70 | 70 | 1·3 | 130 | — |
| 100 | 35 | 45 | 50 | 50 | Ata. $Po_2$ | 100 | — |
| 110 | 30 | 40 | 50 | 40 | ↑ | 70 | — |
| 120 | 25 | 35 | 40 | 35 | ↓ | 60 | — |
| 130 | 20 | 30 | 35 | 30 | 1·6 | 45 | — |
| 140 | 15 | 25 | 30 | 25 | Ata. $Po_2$ | 40 | — |
| 150 | 15 | 25 | 25 | 20 | | — | 40 |
| 160 | 10 | 15 | 20 | 15 | | — | 30 |
| 170 | 10 | 12 | 20 | 12 | | — | 25 |
| 180 | 5 | 10 | 15 | 10 | | — | 20 |
| 190 | — | 10 | 10 | 9 | | — | 17 |
| 200 | — | 8 | — | 8 | | — | 15 |

(A) No decompression. (B) 15 min decompression. (C) 15 min oxygen decompression.
(D) No decompression—$Po_2$ 1·3 to 1·6 ATA. (E) 15 min decompression—1·3 ATA $Po_2$.
(F) 15 min decompression—1·6 ATA $Po_2$.



explain this difference may relate to varying inert gas distribution in body tissues in accordance with solubilities of the gases, as described by Bjurstedt and Severin (1948), and nucleation and bubble growth characteristics differing with tensions of several inert gases in solution in body tissues.

## RATIONALE FOR MODIFICATIONS MADE TO THE HALDANE METHOD OF DECOMPRESSION CALCULATION IN THE U.S. NAVY

Subsequent experiments on uptake and elimination of nitrogen and helium by Shaw, Behnke, Messer, Thomson and Motley (1935) and Behnke, Thomson and Shaw (1935) have yielded quantitative data to validate the gas exchange processes indicated by Boycott *et al.* (1908). From data obtained in a series of studies on dogs and human subjects they concluded that nitrogen absorption is proportional to the partial pressure of nitrogen in the lungs, that with the same pressure gradient, the rate of nitrogen absorption is equal to the rate of elimination, and that the time for complete nitrogen elimination, and percentage rate of nitrogen elimination for corresponding periods of time, are the same irrespective of the quantity of nitrogen absorbed by the body.

Forster (1964) concluded on the basis of theoretical calculation that nitrogen in the alveolus would achieve 99% equilibration with alveolar capillary blood in 0·01 sec, and thus have plenty of time to equilibrate completely in transit time through the capillary. He also concluded from a mathematical evaluation of inert gas transport in resting muscle by radial diffusion from a capillary that the half-time for equilibration would be 54·7 sec. Thus, an inert gas will only equilibrate between capillary blood and the surrounding tissue in one transit time in tissues with a high capillary density, but it appears likely that equilibration will not occur in tissues with a lower capillary density. The time constant ($K$) for exchange of inert gas in the tissue is equal to the volume of blood flow per minute per volume of tissue multiplied by the ratio of solubility of the inert gas in blood to the solubility in tissue. This is the same rate constant for inert gas exchange derived by Jones (1950) in elimination studies of gases with molecular weight varying from helium through xenon. Forster (1964) further states that lack of equilibration between venous blood and tissue would produce an apparent change in the rate constant, which could not be distinguished from a real change in volume of blood per volume of tissue or the ratio of blood to tissue solubilities without additional information not presently available for inert gases.

It is recognized that inert gas uptake in body tissues during exercise will be far greater than during rest due to increased cardiac output, tissue perfusion and decreased intercapillary diffusion distance. For resting muscle, capillary blood flow may vary by a factor of 25 from the exercise state. Tissues with even less vascularity, as connective tissue and cartilage, may have even less blood perfusion and limit greatly the inert gas exchange rate, though inert gas solubility in these tissues is less than for body fat.

Determination of safe supersaturation limits for working dives with direct return to 1 ATA does provide, in some measure, for the difference in inert gas exchange between exercise and rest. However, as the depth of the dive increases the inert gas exchange gradient between blood and tissues becomes greater than for the minimal decompression dives for which surfacing supersaturation limits are derived, to magnify the error in predicted inert gas uptake. It appears that for dives in excess of 200 ft (7 ATA), some factor must be multiplied by the time interval of exposure to provide for the additional inert gas uptake with exercise. A factor of 1·5 provides well for many dives tested, though a factor of 2·0 was used in calculation of helium–oxygen schedules in the present *U.S. Navy Diving Manual.* Further studies will be required to define this factor of difference to provide for safe decompression.

Several studies of effects of oxygen breathing at increased pressure have demonstrated a reduction in the volume of blood perfusing organs and extremities. This effect is both $Po_2$ and time dependent. Blood flow reduction of 25% has been shown in the lower extremity of men breathing oxygen at 2 ATS $Po_2$ (Bird & Telfer 1965). Time for equivalent tissue perfusion of blood for inert gas elimination would be increased 133%. This, however, does not allow for increase in intercapillary diffusion distances, as discussed earlier, in slowing gas exchange in all body tissues. Use of intermittent air and oxygen breathing during decompression may take advantage of increased perfusion of tissues with reduction of the inspired $Po_2$. In any event, the efficiency of inert gas elimination during oxygen breathing is diminished to less than predicted on the basis of the gradient between the inert gas tension in arterial blood and tissue as a result of decreased tissue perfusion.

The necessity to consider larger values of tissue half-time to calculate decompression for both helium and nitrogen dives has been discussed previously. The inadequacy of methods used to study inert gas elimination has also been described. Recent studies by Groom and Farhi (1967) in which nitrogen elimination from large dogs surrounded by an oxygen atmosphere permitted precise definition of rate constants of the slowest tissue components, reported half-times as slow as 190 min. Thus, the range of half-time tissues considered appropriate for man in decompression calculations for air dives relates well to these studies on animals of lesser body mass.



The depth and half-time dependence of the supersaturation criteria have been discussed earlier in some detail as this varies from the original theory of Haldane. Further definition of the mechanism of pressure and time-concentration dependence of nucleation and bubble growth is required in living animal preparations to extend the information available to permit calculation of more efficient, safe decompression.

## APPENDIX: COMPUTATIONS FOR DECOMPRESSION

The conventional Haldane method of decompression rests on the assumption that the time-rate of change ($dP/dt$) of the inert gas tissue tension ($P$) is proportional to the difference between the inspired partial pressure of the inert gas ($P_I$) and the instantaneous value of $P$.
Thus

$$\frac{dP}{dt} = K(P_I - P) \tag{1}$$

If $P_I$ is constant from time zero ($t = 0$), and if $P_0$ is the inert gas tension at $t = 0$, then the inert gas tissue tension ($P$) at time $t$ can be determined as a function of $P_I$, $P_0$ and $t$. Upon separation of the variables of equation (1) and the insertion of limits,

$$\int_{P_0}^{P} \frac{dP}{(P_I - P)} = \int_0^t K\, dt$$

The solution of this equation is

$$\ln (P_I - P)\Big|_{P_0}^{P} = -Kt \tag{2}$$

or

$$P_I - P = (P_I - P_0)\, e^{-Kt}$$

Subtraction of $P_0$ from both sides and rearrangement of terms lead to the desired expression

$$P = P_0 + (P_I - P_0)(l - e^{-Kt}) \tag{3}$$

During decompression, $P_I$ is reduced in steps at intervals intended to effect rapid but safe elimination of the inert gas absorbed in the tissues ($P$). The time for ($P_I - P$) to decrease to one half its value immediately after a reduction of $P_I$ is called the half-time ($t_{1/2}$). This time is characteristic of the particular tissue and inert gas involved, but it is independent of the actual values of $P_I$ and $P$ within the range of pressures for which equation (1) is valid. Then from equation (2)

$$\ln \frac{P_I - Pt_{1/2}}{P_I - P_0} = \ln \tfrac{1}{2} = -Kt_{1/2}$$

and

$$K = \frac{\ln 2}{t_{1/2}} = \frac{0{\cdot}693}{t_{1/2}} \tag{4}$$

Then the exponent in equation (3) can be expressed as

$$-\frac{0{\cdot}693t}{t_{1/2}}$$

The acceptance of equation (1) requires the further assumption that inert gas is uniformly distributed throughout the tissue represented by $t_{1/2}$ at all times. Jones (1950) used radioactive tracers to examine the distribution of inert gas in tissues. Roughton (1952) examined the relationship among the tissue half-times, the coaxial diffusion cylinder of the capillary, and the diffusion coefficients of inert gases in tissues. It was concluded from this study that the inert gas diffuses immediately and uniformly throughout the tissues. Two concepts are presently employed in determining critical supersaturation values. The supersaturation ratio is the sum of dissolved gas tension ($\sum P_i$) to ambient or hydrostatic pressure ($H_p$):

$$\sum_{i=0}^{n} \sum P_i/H_p$$

The supersaturation gradient ($\Delta P$) is the difference between the sum of the dissolved gas tissue tension ($\sum P_i$) and the hydrostatic pressure:

$$\Delta P = \sum_{i=0}^{n} \sum P_i - H_p$$

where $n$ is the number of gases with significant partial pressures within the tissue of concern ($t_{1/2}$). $\Delta P$ may vary as a function of the rate constant ($K$) and with water depth ($D$).

That is

$$\Delta P = f(D \text{ ATA}, K)$$

$$\Delta P = \Delta P_s tgD$$

where $g$ = rate of change of $P$ as function of depth, $P_s = P$ at surface (1 ATA).

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