

THE ISOBARIC (OXYGEN WINDOW) PRINCIPLE OF DECOMPRESSION

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Abstract

The isobaric (oxygen window) principle of decompression embodies the assumption that the pressure of inert gas in tissues and blood stream should at no time exceed ambient pressure during decompression. Essentially in the capillaries there is an exchange of oxygen and inert gas. The fall in oxygen pressure in the capillaries creates 'a partial pressure vacancy' designated as the oxygen window. The size of the window regulates the rate of diffusion of inert gas into the blood stream and its subsequent transport and elimination in the lungs. The higher the oxygen pressure in the gas mixture breathed up to 1500 mm Hg (2 Atm), the greater the transport of inert gas. In current saturation diving operations, the rate of ascent during decompression has been in the range of 10 to 15 minutes per foot. This rate is consistent with an oxygen window that varies from 230 to 360 mm Hg, and with the slowest desaturating tissue with a half-time (helium) of 60 minutes. There appears to be no basis for the assumption that there are half-times for the slowest tissue (helium) as long as 300 minutes, and that inert gas during decompression is transported in a state of supersaturation devoid of bubbles.

INTRODUCTION

The success of saturation diving has been demonstrated by work dives of the Westinghouse Group as reported by Krasberg (1), and by chamber runs to simulated depths of 650 feet as outlined in the lucid analysis of decompression procedure by Schreiner and Kelley (2). Prolonged underwater operations supervised by Link, by Bond, and by Cousteau have been carried out with only occasional minor symptoms of decompression sickness, following an initial small drop in pressure (ΔP) of some 12 psi (27 feet). Following prolonged exposures, linear ascent in contrast to stage decompression has featured the return to normal pressure of divers and hydronauts.

It would appear superfluous to comment on these ostensibly successful decompression procedures were it not for the questionable physiologic assumptions postulated in the basic computations. Specifically, although the role of oxygen in expediting the elimination of inert gas from tissues is clearly appreciated, it is stated that varying degrees of supersaturation of inert gas exist presumably in blood as a basis for the driving force underlying gas transport and elimination. Secondly, the exponential half time postulated for the slowest desaturating tissue during the course of helium elimination has been assumed to be 3 to 5 hours chiefly because a much shorter half time was not compatible with the ΔP assumed to be operative.

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It is the purpose of this presentation to cite physiologic data in support of the isobaric principle of decompression. Essentially the transport of inert gas from tissues and its subsequent elimination without the hazard of bubble formation, is considered to be a linear function of the partial pressure of oxygen in the simple case where the same gases are breathed (although in different concentration) during the compression and decompression periods. In order to simplify this exposition, the employment of multiple gas mixtures in rotation, will not be included.

DECOMPRESSION EXPERIENCE IN EARLIER CHAMBER RUNS

Decompression according to Haldane's stage method following extended exposures in compressed air of 3 to 4 hours duration at 45 psi were frequently complicated by bends during the period 1932-1935 in the chamber at the Harvard School of Public Health. In 1934, bends developed in a healthy man at a level of 3 psi during the course of stage decompression following an exposure of 99 hours at 30 psi in the Cunningham Sphere in Cleveland. The initial drop in pressure according to a conservative schedule prepared at Harvard was from 30 to 15 psi and some 7 hours were taken to arrive at the 3 psi level. This unfavorable experience with the stage method of decompression following long exposures prompted a review by Naval Medical Officers of the 2 to 1 ratio concept and the hypothesis that gas in a state of supersaturation could be transported by circulating blood (3).

Extensive saturation chamber tests were conducted at the Experimental Diving Unit, Navy Yard, Washington, D. C., during the period from 1940 to 1945. These tests served to establish a depth of 33 feet as limiting for a saturation exposure (12 hours) followed by 'No decompression'. Exposures of longer duration were only occasionally complicated by mild bends which did not require recompression. Of special interest was the fact that the small quantity of nitrogen taken up by slowly saturating tissues after 6 hours was important in predisposing divers to bends. The stage method of decompression was employed at the deeper simulated depths, and even with oxygen inhalation bends occurred frequently (Table /).

Physiologic Principles - The principle underlying prevention of decompression sickness is slow decompression such that excess gas acquired during compression is transported from tissues and eliminated in the lungs without bubble evolution. This principle is not complied with unless many hours are utilized in the slow process of freeing excess nitrogen from tissues. Haldane (4) developed the concept of nitrogen elimination from body tissues each with different rates (k constants) of gas elimination such that exponential half time values range from less than 5 minutes in blood and watery tissue to 75 minutes or longer in fatty tissues. From measurements of nitrogen eliminated from the body during the course of oxygen inhalation (3,5), it was possible to assign k values to various tissues in relation to blood

supply and nitrogen content (Table 2). It is convenient and with good physiologic justification, to apply the exponential formulation as a tool to measure rate of inert gas elimination for any given tissue.

-kt

Thus half saturation or desaturation $(0.5) = 1 - e^{-kt}$ where $k = 0.693$ (the natural logarithm of 2), if t is one time unit. The quotient $(0.693/k)$ gives the half time in minutes for any particular value of k . The desaturation rate per minute expressed as a percentage is given by $(1 - e^{-k}) \times 100$. For low values of k , 0.01 or less, k is approximately the percentage rate; e.g., when $k = 0.01$, the rate of gas elimination is 1% of the quantity present at any given time.

The half time nitrogen elimination rate for tissue-organ group IV (Table) is approximately 85 minutes ($k = 0.008$). The half time nitrogen elimination rate (group V) for an exceptionally lean man (10% body weight as fat) is 69 minutes ($k = 0.01$). In young men of average fat content (about 16.6% of body weight), the half time of gas elimination for adipose tissue is about 120 minutes ($k = 0.0058$). It can be concluded from the tabular data, that the variable amount of fat in the bodies of different individuals renders indeterminate the value of k for adipose tissue unless body fat is actually determined by Specific Gravity (Weight/Volume) of the body as a whole and by other techniques.

By contrast, tissue groups I, II, and III, are largely aqueous and not only is the water content variable within a narrow range, but the values for k are high. A relatively small amount of tissue has the larger part of the blood supply. Because nitrogen is readily eliminated from these tissues, there has been failure generally in decompression, to allow enough time (short as it is) for these tissues to desaturate during the initial stages of decompression when ascent to the first stop is rapid. It is likely that decompression practice in the past has served to initiate bubble evolution which subsequently has been controlled by prolonged stage decompression at relatively shallow depths. The inference is sound that bubbles may accumulate to a degree in the body without producing symptoms. I have designated such nascent gas accumulation as "Silent Bubbles".

To further complicate the problem of decompression is the large individual variation apart from morphologic consideration of fat content, in blood perfusion rates of tissue. A young man at rest may have a 50 per cent faster rate of tissue gas elimination than an older man. There is the matter of physical condition, acclimatization, cold, fatigue, and a host of other factors which affect gas transport. Many of these factors can be brought under control by conditioning divers, but generally such efforts have been quiescent.

COMPARISON OF SOLUBILITIES AND SATURATION RATES OF NITROGEN AND HELIUM

If the equilibration time (98.5% saturation equivalent to 6 Time Units) for nitrogen uptake is 12 hours as shown

previously, then the saturation time required for helium based on its solubility in tissues, should not be more than six hours. The half time of the slowest desaturating tissue for young men of average fat content should not be more than 60 minutes (Table 3). This deduction is supported by the relatively few measurements that have been made of helium elimination from body tissues. More quantitative data in regard to the time required for helium elimination would serve to bolster the conclusions based on solubility data. It would appear however that slow tissue half times of 180 to 300 minutes as postulated in mathematical models of decompression following saturation dives are erroneous.

THE RATIO PRINCIPLE IN DECOMPRESSION

The problem, now that we have some idea of rates of inert gas elimination, is to determine the pressure head allowable for gas transport from tissues. Two procedures have been followed (1) the ratio concept of Haldane, and (2) the fixed pressure head expressed as psi or feet from Leonard Hill (). It has long been known from tunnel work that exposures of + 15 psi (equivalent to about 33 feet in diving depth) and even somewhat higher pressures were well tolerated for an 8-hour work day without the need for more than several minutes minimal decompression. Haldane postulated that since the body could be rapidly decompressed from 2 to 1 atmospheres (30 psi to 15 psi absolute), it would be safe to halve the absolute pressure at any level and to decompress divers according to a schedule that would never allow the nitrogen pressure in tissues to exceed twice the total ambient pressure. The diving depths and more important, the time of exposure with which Haldane was concerned, were such that the 2 to 1 ratio appeared to be satisfactory. However, short exposures in compressed air do not provide a test of adequacy of decompression tables (7). Subsequent experience following saturation exposures or dives to deep depths have demonstrated unequivocally that no fixed ratio (i.e., 2 to 1) is applicable to all tissues, and that probably no degree of supersaturation of inert gas is maintained in the circulating blood free from bubbles (3,7). The deeper the depth, however, the less the tendency of bubbles to form or symptoms to arise from a given relative difference in pressure (ΔP). Excursion dives can be made at deeper depths for longer periods of time than at shallower depths or the surface (7). If a diver can perform a no-decompression dive to a depth of 100 feet for a period of 25 minutes, he can perform the same dive from a depth of 400 feet to a depth of 500 feet for a period of one hour and return safely to 400 feet.

In a remarkable way the body tolerates abrupt reduction of ambient pressures following short exposures in compressed air. The nitrogen taken up during the early part of compression is readily eliminated by any method of decompression. In the rapid drop from 4 to 1 atmospheres, a degree of supersaturation appears to be tolerated by the body which approaches a ratio of 4 to 1. By contrast, when the body

is saturated at a pressure of 4 atmospheres (which requires an exposure time of about 12 hours for nitrogen and about 6 hours for helium) a ratio indicative of supersaturation of only 1.2 to 1 will not hold throughout the entire period of decompression. On the basis of these facts the degree to which the body appears to hold gas in a state of supersaturation is relative, and depends not only on the degree of saturation but also on the pressure level.

THE ΔP PRINCIPLE

A second method of decompression is to assume literally that a safe decrease in pressure from 2 to 1 Atm creates a pressure head of 15 psi air (12 psi nitrogen) which can be maintained at all pressure levels during decompression. Thus a tissue with a k constant equal to 0.01 would desaturate at a rate of 0.12 psi per minute or 8.5 minutes per psi. This principle was proposed many years ago (3) with the tentative provision that the value of ΔP could be increased relative to depth. Subsequently, Dwyer has formulated a tenth power relationship between ratios used at depth and those projected from surfacing values. His concept heralds a major advance in the formulation of decompression tables for one-task, surface to depth diving and return within a relatively short time period.

The ΔP principle has been employed notably in the current, special case of total body equilibration (saturation diving) which "requires a continuous ascent at a constant rate to permit the use of a maximum safe gradient for inert gas elimination from the slowest half-time tissue controlling. Even this can follow an initial more rapid reduction of pressure of the order of one atmosphere" (4).

However, there is no more physiologic or physical basis for a supersaturation head of + 12 psi, than there is for the 2 to 1 ratio. Any implication that gas can be transported by the blood from tissues to lungs in a state of supersaturation is conjecture.

THE ISOBARIC (OXYGEN WINDOW) PRINCIPLE OF DECOMPRESSION

In any gas mixture there is a certain percentage of oxygen compatible with well being. During the course of blood transport through capillaries, the oxygen is unloaded in different quantities to the various tissues. The result of this transfer of oxygen from blood to tissues renders available an equivalent amount of inert gas for transport from tissues to lungs. During the late Thirties at the Experimental Diving Unit, Washington, D. C., Momsen referred to the "space" available for transport of inert gas in solution as the "partial pressure vacancy".

At normal pressure during the inhalation of air, the oxygen pressure in arterial blood (P_{aO_2} 100 mm Hg) falls to about 40 mm Hg in the venous capillaries. If the oxygen pressure is elevated to 300 mm Hg in arterial blood as a consequence

of a richer oxygen mixture in the gas inhaled, then in the passage of blood through capillaries, oxygen pressure falls almost to the previous level or to about 50 mm of mercury. About 250 mm Hg equivalent space would therefore be available for gas transport. Noteworthy is the fact that the oxygen pressure in arterial blood can be raised to about two Atm (15 psi gage) or some 1500 mm Hg without a rise of more than several hundred mm Hg of oxygen in mixed venous blood. Since oxygen becomes abruptly toxic above this level, there is a practical limit to the size of the oxygen window.

The concept underlying the oxygen window principle is that during the course of decompression from hyperbaric atmospheres, inert gas can be eliminated from tissues via the oxygen window at a pressure isobaric with ambient pressure (Figure 7). If pure oxygen is inhaled during the later stages of decompression as it was during the salvage operations to raise the SQUALUS, inert gas is eliminated rapidly. Over 600 dives were made with no more than several cases of bends (9). In practice the isobaric principle of decompression, although mandatory following the saturation dive, calls for too long a decompression for dives up to one-hour duration, unless it is feasible to breathe pure oxygen for a prolonged period at the + 15 psi pressure level.

APPLICATION OF THE ISOBARIC PRINCIPLE TO CURRENT DIVING PRACTICE

The practicality of long exposures in diving operations oriented specifically to work objectives has been demonstrated in connection with extensive underwater replacements on the Smith Mountain Dam in Virginia. Two teams of 4 divers each have lived and worked in a helium-oxygen atmosphere for a week at a time at a pressure equivalent to 200 feet of water. Apart from the basic merit of this highly successful, pioneer effort, was the development of tables governing excursion dives which is the subject of another paper in this Conference. It is a tribute to the Westinghouse Group that long term residence in compressed atmospheres first projected for caisson and tunnel operations about 25 years ago (7), has proved to be a boon to safety and economy initially in the much more difficult enterprise of diving operations.

In the Linde Tonawanda Laboratory saturation exposure to a simulated depth of 650 feet, a successful, linear type of decompression was achieved based on an ascent rate of 14 minutes per foot. "Bearing in mind the constraints imposed by the requirement to limit the chronically sustained excess pressure in the 240-minute tissue (P_{240}) to about 10 feet and to maintain a programmed inspired oxygen partial pressure of 14.5 feet, an ascent rate had to be selected that would ensure a final driving force of about 25 feet" (8). Schreiner and Kelley (2) state that the effectiveness of oxygen increases linearly with the partial pressure to which the diver is exposed. In addition, however, a state of supersaturation of gas in the body is postulated to provide a driving force (25 feet) considerably in excess of the programmed, inspired oxygen pressure. The following

statements tie-in with the above mentioned report and serve to clarify the premises outlined in this paper.

If the partial pressure of oxygen is held constant at 345 mm Hg (15 feet), then the oxygen pressure in arterial blood following oxygen uptake-carbon dioxide exchange in the lungs, will be approximately 300 mm of mercury. In passage of blood through the capillaries there will be further decrease of oxygen pressure to a level somewhat above 40 mm Hg. With the addition of some 7 mm Hg of CO₂ from tissues, there will be a slight reduction in the size of the oxygen window to approximately 250 mm Hg, equivalent to 10.9 feet of diving depth. This value represents the pressure head for diffusion and transport of inert gas from tissues to lungs. During decompression the rate of ascent governed by the elimination of helium from the slowest tissue (half-time, 60 minutes) would require 8.4 minutes per foot (0.14 time unit x 60). A considerable safety factor appears to have been introduced to ensure the safety of the Tonawanda operation.

In SEA-LAB II (depth 200 feet equivalent to 7 Atm) during a prolonged stay of 14 days for each of two groups of divers, the percentage of oxygen in the inhaled gas mixture was reported to be about 4.5 per cent (237 mm Hg). In arterial blood the oxygen pressure is reduced to about 192 mm Hg (237 - 45), and in the venous capillaries to about 40 mm mercury. Allowing for the addition of a small amount of CO₂ (7 mm Hg) that enters capillary blood, it is estimated that the size of the oxygen window is 145 mm Hg equivalent to 6.3 feet. During decompression, if a constant oxygen pressure were maintained, the decompression rate would be limited to 15 minutes per foot. However, the ascent time was about 10 minutes per foot which turned out to be borderline in that one of the divers required treatment for bends. It is observed that a relatively small difference in the size of the oxygen window (e.g., 250 - 145 mm Hg) makes a difference of 6.6 minutes (15.0-8.4) in the per footage ascent rate of the Tonawanda simulated dive compared with SEA-LAB II decompression.

RESOLUTION OF THE DISCREPANCY CONCERNING THE HALF-TIME FOR HELIUM ELIMINATION

The calculations for decompression involving helium saturation dives are based on postulated half-time values for the slowest desaturating tissue that vary between 3 to 5 hours, greatly in excess of measurements made in an earlier era and of deductions from helium solubility in fluid and fatty tissues. If the assumption is made that the pressure head for helium elimination is 12 psi (27 feet) and that the safe time of ascent is 10 minutes per foot, then it would appear that the half-time of the slowest tissue was indeed approximately 180 minutes. If in reality the pressure for gas elimination were 4 psi (9 feet) in accord with the oxygen window concept, then the half-time of the slowest desaturating tissue would be no greater than 60 minutes.

THE PROBLEM OF DECOMPRESSION FOR THE 20-60 MINUTE WORK
DIVE (SURFACE-DEPTH-SURFACE) AT DEPTHS FROM 300-500 FEET

A current, major problem confronting divers centers in the consideration as to the degree one can compromise the oxygen window and utilize the ratio principle in the effort to shorten the duration of decompression during the early, deep depth stages. The SQUALUS operation (1939) proved that work dives to depths of 220-240 feet for periods of 20 minutes could be carried out safely by oxygen decompression chiefly at shallow depths as outlined in the Navy Diving Manual. By 1942, it appeared that a sound basis for decompression had been developed for work in helium-oxygen atmospheres (Table 4). By changing from helium-oxygen to air, and then to oxygen at the 60-foot level, it was possible to shorten decompression time much in the manner that Keller and Bühlmann are now able to accomplish for deeper depths. At the time, a saturation (6 hours) dive on helium at a wet or dry chamber depth of 150 feet required only 128 minutes decompression. It has not been possible to extrapolate from the data in Table 4 to safe decompression from deep depths. With the exception of the remarkable dives reported by Keller and Bühlmann (10), (Table 5), there has not been even a close approach to realization of the potential inherent in the earlier dives summarized in Table .

In 1964, Murray Black, Mogis, and Thompson of DIVCON performed the deepest dives to date under hazardous conditions that required as a minor difficulty, the surface decanting procedure. That is, what we formerly designated 'Surface Decompression' in which during the course of ascent to 60 feet, the diver is brought abruptly to the surface and his decompression completed in a pressure chamber. Successful ocean work dives were made by the DIVCON team to the following depths, duration indicated in parenthesis: 468 (24'), 468 (12'), 525 (28'), and 525 (14'). The decompression procedure followed (Table 5) utilized the oxygen window principle at deep depths. As much time as 42 minutes was permitted for elimination of excess helium from 5 and 10 minute tissues during ascent to a depth of 270 feet. Decompression from 270 feet to shallower depths was in accord with a 1.3 to 1 ratio for governing tissues. Air was inhaled at depths beginning as deep as 190 feet. At the 60-foot level, 100% oxygen was inhaled.

Although the decompression procedure was successful for dives of 28 minutes duration, subsequent DIVCON trials at Alverstone in the dry chamber were not satisfactory unless exceptionally long periods of decompression were utilized for exposures of one hour's duration at a simulated depth of 400 feet. It was necessary to increase decompression time from more than six hours to more than 12 hours (Table 5). It is evident that these long periods of decompression are not compatible with efficient operations. Even the Keller-Bühlmann type of decompression, if applicable to divers generally under conditions of work underwater, requires facile manipulation of gas mixtures to ensure the widest

possible oxygen window and to secure maximal benefit from an exchange of inert gases. Such control does not appear to be operationally feasible in isolated areas, say off the coast of Africa.

CONCLUDING COMMENTS

The wide discrepancy in decompression time between DIVCON and K-B dives when similar rotating gas mixtures are employed, merits careful analysis. Strict control appears to have been effected in the K-B decompressions to ensure a continuous maximum oxygen window, but the high partial pressure of oxygen breathed may not be generally tolerated.

The chief deficiency in the physiologic field, and it is a serious one, is lack of quantitative data pertaining to gas uptake and elimination. A second deficiency is failure to equate gas uptake with fat and water components of body composition which at the present time can be quantified by means of anthropometric, radiographic, densitometric, and biophysical techniques for measurement of K^{40} and exchangeable isotopes. The third deficiency is lack of performance data with reference to cardiovascular and pulmonary functions, and in general to the physical condition of the divers undergoing tests.

The blind operations to date with their heavy overlay of sophisticated mathematical analysis have given us a reasonably good range of values from about 8 minutes to 15 minutes per foot of ascent from deep depths following saturation dives. However, we do not have the necessary physiologic data to decompress divers safely who engage in work periods up to one hour at deep depths and who return immediately to normal barometric pressures. These data are readily obtained and have a precedent in earlier investigations carried out under the severe restrictions of lack of analytical equipment, lack of collateral knowledge, and practically no funds.

REFERENCES

1. Krasberg, A. R.: Saturation Diving Techniques. Fourth Int. Congress Biometeorology, Rutgers Univ., New Brunswick, New Jersey, August-September, 1966.
2. Schreiner, H. R., and Kelley, P. L.: Computation Methods for Decompression from Deep Dives. Third Underwater Symposium (Physiology), March, 1966. Nat. Acad. Sci.-Nat. Res. Council, Washington, D. C.
3. Behnke, A. R.: The Application of Measurements of Nitrogen Elimination to the Problem of Decompressing Divers. U. S. Naval Med. Bull. 35: (2) 1937.
4. Haldane, J. S.: RESPIRATION. New Haven, Yale Univ. Press, 1922.
5. Jones, H. B. in DECOMPRESSION SICKNESS (Ed. J. F. Fulton), Part II, Gas Exchange and Blood-Tissue Perfusion Factors. Philadelphia, W. B. Saunders Co., 1951.
6. Hill, L.: CAISSON SICKNESS AND THE PHYSIOLOGY OF WORK IN COMPRESSED AIR. London, Edward Arnold, 1912.
7. Behnke, A. R.: Effects of High Pressures: Prevention and Treatment of Compressed Air Illness. Medical Clinics North America, 1213 (July) 1942.
8. Workman, R. D.: Calculation of Decompression Schedules for Nitrogen-Oxygen and Helium-Oxygen Dives, p 3, U.S. Navy Experimental Diving Unit Research Report 6-65, 26 May, 1965.
9. Behnke, A. R., and Willmon, T. L.: U.S.S. SQUALUS. Medical Aspects of Rescue and Salvage Operations and the Use of Oxygen in Deep-Sea Diving. U.S. Naval Med. Bull. 37: 629, 1939.
10. Keller, H., and Buhlmann, A. A.: Deep Diving and Short Decompression by Breathing Mixed Gases. J. Applied Physiol. 20 (6): 1267, 1965.

TABLE 1. SATURATION AIR DIVES IN THE DRY OR WET TANK (1940 (Behnke) to 1945 (Van Der Aue), EXPERIMENTAL DIVING UNIT)

Number of Tests	Depth Feet	Exposure Time (hr)	Decompression		OUTCOME*
			Depth Stop	Time Min.	
4 RESTING	33	12	-	--	N.S.
4 WORK	33	12	-	-	N.S.
4 RESTING	33	24	-	-	N.S.
8 RESTING	33	36	-	-	6 N.S. 2(X)

4 RESTING	35	12	-	-	3 N.S.1(0)
4 WORK	35	12	-	-	N.S.

2 RESTING	38	12	-	-	1 N.S.1(0)
4 WORK	38	12	-	-	2 N.S.2(0)

14 RESTING	40	12	-	-	9 N.S.4(0)
14 WORK	40	12	-	-	4 N.S.5(0)5(X)

1 RESTING	60	12	60 OXYGEN	63	(X)
1 "	60	12	60 "	69	(X)
1 "	60	12	60 "	80	(X)
1 "	60	12	60 "	92	(X)

1 RESTING	90	6	40 "	111	N.S.
1 "	90	6	40 "	111	(X)

4 "	99	6	33 AIR	12 hr.	3 N.S.1(X)
2 "	99	9	33 "	12 hr.	1(X) 1(0)
2 "	99	9	33 "	18 hr.	N.S.
2 "	99	12	33 "	24 hr.	1(X) 1(0)

* N.S. NO SYMPTOMS (X) BENDS, COMPRESSION (0) MILD BENDS, NO RECOMPRESSION

TABLE 2. ATMOSPHERIC NITROGEN CONTENT OF TISSUES AND ORGANS OF A LEAN MAN (154 lb, 15.4 lb fat) IN RELATION TO BLOOD PERFUSION AND RATE OF NITROGEN ELIMINATION AT REST DURING THE INHALATION OF OXYGEN.

UNIT	TISSUE-ORGAN GROUP					
	I Blood Brain Heart Kidney	II Muscle Skin Spinal Cord Nerves	III Bone	IV* Bone marrow	V** Adipose tissue	V*** Adipose tissue
Weight grams (lb)	15,000 33	37,000 81.4	3,500 7.7	1,500 3.3	9,500 20.9	15,200 33.4
Water grams	12,000	30,000	2,000	240	2,000	2,000
Fat grams	350	100	-	1,200	7,000	12,600
Nitrogen ml	126	275	18	63	368	647
Blood perfu- sion ml/min.	4,000	1,200	80	50	375	375
Nitrogen trans- port 1st minute	40	12	0.8	0.5	3.75	3.75
Nitrogen elimination half-time min.	1.8	16	16	85	69	120
k	0.39	0.044	0.044	0.008	0.01	0.058

*Cellular bone, free of mineral and fat; weight of mineral = 3,500 gm (7.7 lb)

**Lean man, 10% body weight is fat

***Avg. young man, 16.6% body weight is fat

Exponential decay constant; half-time rate (min.) = $0.693/k$

TABLE 3. SOLUBILITY OF NITROGEN AND HELIUM IN BODY FLUIDS (WATER) AND FAT

NITROGEN (In Air Includes Argon)		HELIUM
SOLUBILITY IN WATER (ml is milliliter) (1 Quart = 946.3 ml)		
16.79 ml/Liter/1000 mm Hg		10.98 ml/Liter/1000 mm Hg
0.385 ml/Liter per foot, depth		0.258 ml/Liter per foot, depth
SOL. IN FAT (Olive Oil) (1 kg = 2.2 lb)		
83.95 ml/kg/1000 mm Hg		19.38 ml/kg/1000 mm Hg
1.925 ml/kg per foot, depth		0.455 ml/kg per foot, depth
RATIO: FAT FLUIDS		
5 to 1		1.77 to 1

GAS UPTAKE BY THE BODY per 100 feet, depth		
NITROGEN	BODY WATER	HELIUM
1733 ml	45 Liters	1161 ml

	BODY FAT	
1925	10 kg	455

SATURATION RATES (Tissue Half-Times) minutes							
NITROGEN				HELIUM			
FLUIDS		FAT		FLUIDS		FAT	
5	10	20	80 -- 120 +	5	10	20	40 -- 60 +
12.9	6.6	3.4	0.9-0.4	12.9	6.6	3.4	1.7 -- 1.1

TABLE 4. COMPARISON OF TOTAL DECOMPRESSION TIME FOLLOWING EXPOSURE IN COMPRESSED AIR AND EXPOSURE IN A HELIUM-OXYGEN ATMOSPHERE (1939 - 1940).

<u>DEPTH</u> <u>Feet</u>	<u>EXPOSURE</u> <u>Minutes</u>	<u>DECOMPRESSION (Minutes)</u>	
		<u>Air</u>	<u>Helium-Oxygen*</u>
90	100	50	75
90	180	-	77
90	360	-	79
90	540	638	79

150	80	141	121
150	180	-	126
150	360	-	128

200	65	217	154
200	90	-	164

* Oxygen inhaled at lower decompression stops

TABLE 5. VARIABILITY IN DECOMPRESSION TIME FOR NON-SATURATION (HELIUM-OXYGEN) DIVES AT DEEP DEPTHS UP TO ONE HOUR DURATION. (KELLER-BÜHLMANN (K-B) and DIVCON OPERATIONS).

K-B 300 Feet 1 Hour He - O ₂ 92-8 mix.	DIVCON 300 Feet 1 Hour He - O ₂ 90 - 10	DIVCON 500 Feet 30 min. He - O ₂ 90 - 10	K-B 500 Feet 30 min. He - O ₂ 85 - 15
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DECOMPRESSION

Depth feet	Time min.	Depth feet	Time min.	Depth feet	Time min.	Depth feet	Time min.
300	35	300	5	500	1	500	
100		250	10	460	41	O ₂ -N ₂	
O ₂ -N ₂		200		270		(15-25)	7
50-50		170	10		75	230	
50		AIR		170		O ₂ -N ₂	
Oxygen <u>75</u>		150	59	AIR		(30-70)	
Total 110		100	135	60	159		15
		50		Oxygen		100	
		Oxygen	<u>201</u>	50	23	O ₂ N ₂	
		Total	<u>420</u>	40	16	(50-50)	50
				40		50 feet	
				Total	<u>216</u>	Oxygen	<u>140</u>
					<u>421</u>	Total	<u>212</u>

DIVCON Satisfactory Dry Chamber Tests

400 feet Depth (feet)	1 hour Decompression Time (min.)	90-10 He-O ₂ ,
400	34	
270	37	
210	74	
160	142	
100	175	
50		
Oxygen	<u>267</u>	
Total	<u>729</u> minutes	

DIVCON Bends

400 feet Depth (feet)	40 min Decompression Time (min.)	90-10 He-O ₂
400	25	
250	13	
170		
AIR		
	76	
100		
50		
Oxygen	<u>133</u>	
Total	<u>369</u> minutes	

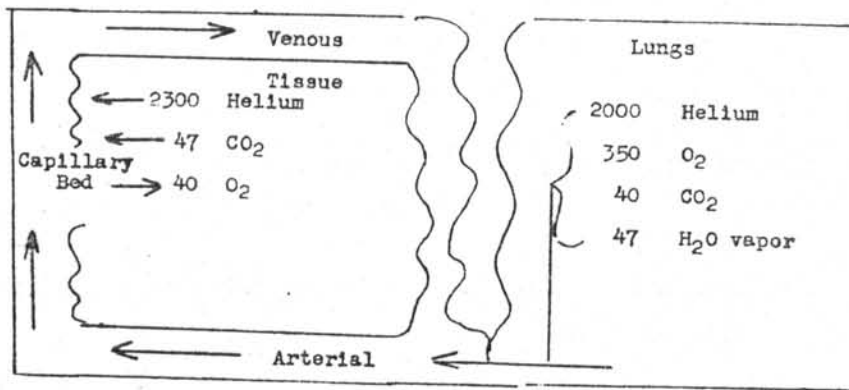


FIGURE 1. ISOBARIC (OXYGEN WINDOW)
PRINCIPLE OF DECOMPRESSION

Figures indicate pressure in mm Hg. Ambient pressure = Tissue Gas Pressure. Helium from tissues diffuses into capillary bed as O₂ is absorbed by tissues at a pressure head of 300 mm Hg.

$$\begin{array}{r}
 2300 \text{ He} \\
 + 47 \text{ CO}_2 \\
 + 40 \text{ O}_2 \\
 \hline
 2387
 \end{array}$$

$$\begin{array}{r}
 2000 \text{ He} \\
 + 350 \text{ O}_2 \\
 + 40 \text{ CO}_2 \\
 + 47 \text{ H}_2\text{O} \\
 \hline
 2637 \\
 - 2387 \\
 \hline
 250
 \end{array}$$

$$\Delta P = 250 \text{ mmHg}$$