## About the Author

Bruce Wienke is Director of the Computational Testbed For Industry in the Advanced Computing Laboratory of the Los Alamos National Laboratory, with interests in computational decompression and models, gas transport, and phase mechanics. He is a frequent contributor to underwater symposia, diving educational publications, technical periodicals, and decompression workshops, also having authored two other monographs, *Basic Decompression Theory And Application* and *High Altitude Diving*. He is co-owner of Inner Vision Divers, a full service dive shop located in Santa Fe, New Mexico.

Wienke is an Instructor Trainer with the National Association of Underwater Instructors (NAUI), serving on the Decompression Review Board, A Master Instructor with the Professional Association of Diving Instructors (PADI), serving on the Instructor Review Committee, and an Institute Director with the YMCA. He also works as a Ski Racing Coach and Instructor, functioning as Clinician with the United States Ski Coaches Association (USSCA) and the Professional Ski Instructors of America (PSIA).

Wienke received a PhD in physics from Northwestern University. He is also a member of the American Physical Society, American Nuclear Society, Society of Industrial And Applied Mathematics, South Pacific Underwater Medical Society, Undersea and Hyperbaric Medical Society, and the American Academy of Underwater Sciences, serving as a Fellow and Technical Committee Member in various capacities. Wienke is a Contributing Editor of SOURCES, the training publication of NAUI, and is retained by Scubapro Industries as a consultant for decompression algorithms.

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DIVING ABOVE SEA LEVEL

BEST PUBLISHING

# Diving Above Sea Level

by B. R. Wienke

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# DIVING ABOVE SEA LEVEL

by B. R. Wienke

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# LIST OF TABLES



# LIST OF FIGURES



# ABSTRACT


ALTITUDE IMPLIES reduced ambient pressure, which, in turn, forces changes in diving regimens. Those changes, specifically impact on diver and support equipment, are the focus of this monograph. Operational procedures and modifications at elevation are discussed, including decompression, tables, meters, buoyancy, gauges, physiology, air consumption, and pressure mechanics. A separate Appendix outlines mathematical details.

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# INTRODUCTION

MOST COASTAL AND INLAND DIVERS train and dive at, or near, sea level, pursuing activities in direct fashion. Tables and gauges are calibrated at sea level. Compressor outputs, air consumption rates, and buoyancy characteristics of materials are quoted at sea level. Density differences between salt and fresh water force slight weighting adjustments in the two environments, but affect little else. Diving is operationally simple, at least, in theory.

For those who train and dive in mountainous and high plateau regions, however, the situation is more complicated. Dive tables need be converted at altitude, because of reduced ambient pressure. Decompression computers, particularly the first generation, if not altitude compensated, may be neither functional nor correct. Capillary, diaphragm, and oil-filled gauges give different readings, none give the actual depth when calibrated at sea level. At elevation, additional weight needed to counter wet suit expansion need be balanced against buoyancy loss due to lesser fresh water density. Excursions to, and from, sites at different elevations are restricted, controlled in the same manner as flying after diving. Surface exertion rates may be limited by lower oxygen partial pressure (hypoxia), while altitude sickness and pulmonary edema can afflict the unacclimatized, particularly with increasing elevation. Air consumption rates are less than at sea level, but table restrictions do not always allow the diver full freedom to exploit this advantage. In short, altitude implies reduced ambient pressure, which, in turn, forces changes in diving regimens. The focus of this short monograph are those changes, specifically impact on diver and support equipment. Operational procedures and modifications at elevation are purposely couched within conservative protocols. Recent thinking in bubble theory, altitude decompression, and dive table interpolation are incorporated in the text.

## UNITS AND EQUIVALENCES

Standard units are employed. However, by convention, because of usage, or for ease, some non-standard units are also used. For instance, pressure and depth are both measured in feet-of-sea-water (*fsw*), with 1 *atm* = 33 *fsw*. In such system, *specific* densities, $\eta$, used in pressure relationships, are normalized by the actual density, $\rho$, of sea water, and are dimensionless. Sea water specific density of any material is just its actual density (in any set of units) divided by the actual density of sea water (in the same units).

For example, the sea water specific density of salt water is 1, the sea water specific density of fresh water is .975, and so on with any material. Elevation in altitude is measured conveniently in feet (*ft*).

Some useful equivalences include:

$$1\ lb = 0.45\ kg$$
$$1\ atm = 14.69\ lbs/in^2 = 33\ fsw = 76\ cm\ Hg = 1.01\ bars$$
$$1\ ft = .31\ m$$
$$1\ quart = 1.10\ l$$
$$1\ ft^3 = 28.31\ l$$
$$1\ lb/ft^3 = 16.02\ kg/m^3$$



# CLASSICAL DECOMPRESSION THEORY

DECOMPRESSION SICKNESS results from excessive changes in ambient pressure over a particular period of time. In simple decompression sickness, Types I and II, bubbles, or some related form of free gas phase, are thought to trigger a complex chain of physico-chemical reactions in the body, affecting the pulmonary, neurological, and circulatory systems adversely. Treatment consists of recompression, usually in a hyperbaric chamber with controlled application of ambient pressure. Increasing ambient pressure tends to shrink the bubbles by Boyle's law, reducing size, and dissolve bubbles by increasing constrictive surface tension pressure, tending to collapse them. Strategic introduction of oxygen can also aid in the washing out of inert gases during decompression.

Bubbles have been found in intravascular (arteries, veins, lymphatics) and extravascular (intracellular, extracellular) sites upon decompression. Many factors are relevant to the formation of bubbles, such as gas uptake and elimination in the tissues and blood, gas solubility and diffusivity, tissue vascularity and type, breathing mixture, amount of pressure reduction, temperature, presence of preformed nuclei, and individual susceptibility. To prevent decompression sickness, appropriate diving measures limiting depth, time, and repetitions form the basis of diving tables and schedules, now encoded into digital underwater computers.

Tables and schedules for diving at sea level can be traced to a model proposed in 1908 by the eminent English physiologist, John Scott Haldane. He observed that goats, saturated to depths of 165 feet-of-sea-water (*fsw*), did not develop decompression sickness (DCS) if subsequent decompression was limited to half the ambient pressure. Extrapolating to humans, researchers reckoned that tissues tolerate elevated dissolved gas pressures (tensions), greater than ambient by factors of two, before the onset of symptoms. Haldane then constructed schedules which limited the critical supersaturation ratio to two in hypothetical tissue compartments. Tissue compartments were characterized by their half-time, $\tau$, that is, the time required for the compartment to halve (lose) or double (gain) dissolved nitrogen.

Half-time is also termed *half-life* generically for exponential (decay) processes. Five compartments (5, 10, 20, 40, 75 minutes) were employed in decompression calculations and staged procedures for fifty years.

Some years following, in performing deep diving and expanding existing table ranges in the 1930s, Hawkins and Shilling, and Yarborough, assigned separate limiting tensions ($M$-value) to each tissue compartment. Later in the 1950s and early 1960s, Dwyer, Des Granges, and Workman, in addressing repetitive exposures for the first time, advocated the use of six tissues (5, 10, 20, 40, 80, 120 minutes) in constructing decompression schedules, with each tissue compartment again possessing its own limiting tension. Temporal uptake and elimination of inert gas was based on mechanics addressing only the macroscopic aspects of gas exchange between blood and tissue. Exact bubble production mechanisms, interplay of free and dissolved gas phases, and related transport phenomena were not quantified, since they were neither known nor understood. Today, we know much more about dissolved and free phase dynamics, bubbles, and transport mechanisms, but still rely heavily on the Haldane model. Inertia and simplicity tend to sustain its popularity and use, and it has been a workhorse.

## DISSOLVED GASES AND CRITICAL TENSIONS

Dissolved gas models limit degrees of tissue supersaturation, assuming gas exchange is controlled by perfusion (blood flow rate) or gaseous diffusion in blood-tissue media. Exchange of inert gas is driven by the local *gradient*, that is, the difference between the arterial blood and local tissue tension. Obviously the exchange process is very complicated, and models are only approximate. The dissolved gas model emerged early in the Boycott and Damant studies of decompression and dominated models for many years, as charted in the original work of Behnke, Hempleman, Buhlmann, and Workman. More recent application of the model can be seen in studies by Nishi, Thalmann, Spencer, Schreiner, Hamilton, and certainly others.

Perfusion-limited gas exchange is modeled in time by mathematical classes of *exponential* response functions, bounded by arterial and initial tissue tensions, described in the Appendix. Compartments with 1, 2.5, 5, 10, 20, 40, 80, 120, 240, 360, and 720 minute half-times, $\tau$, are employed in applications today, and half-times are assumed to be independent of pressure. A one-to-one correspondence between compartments and specific anatomic entities is neither established, nor implied. For large values of, tissue uptake and elimination of inert gas is relatively slow according to the response function. For small values of $\tau$, inert gas uptake and elimination proceed much more rapidly. According to Kety, the major controlling factor is the blood flow rate, $1/\tau$ effectively. Actually, gas uptake and elimination in all tissues is not controlled just by perfusion. Diffusion may dominate in certain tissue types, regions with lesser vascularity and greater distance between capillaries, such as bone and spinal cord. In others, both perfusion and diffusion are rate limiting.



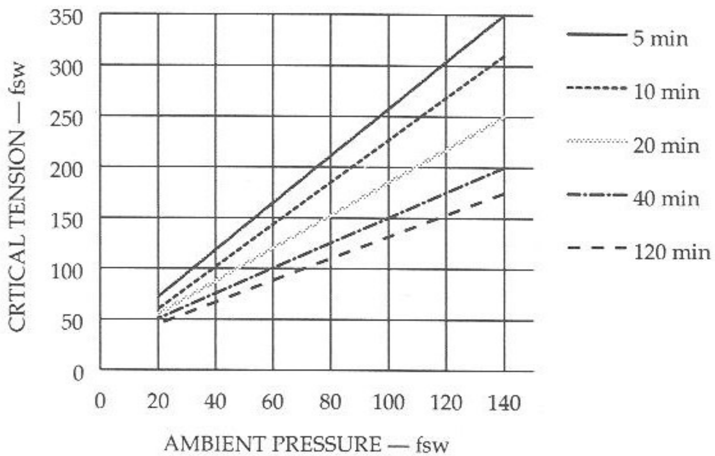


The rate of uptake and elimination of inert gas is assumed to be symmetric when the same set of tissue half-times are employed in calculations. However, this is not always the case. Microbubbles in the circulatory system, particularly venous gas emboli, render gas uptake and elimination asymmetric. Bubbles in the interstitial areas, or agglutination of red blood cells in reaction to foreign bubbles would have similar effect on local perfusion rates. In such instances, half-times for uptake are then theoretically shorter than half-times for elimination.

Haldane theory limits degrees of dissolved gas buildup, equivalently absolute compartment supersaturation, by critical values, $M$, having a modern range, $122 \le M \le 36\,fsw$, notably of American origin. Critical parameters evolved from self-consistent application of assumed tissue response to sets of exposure data, that is, trial and error bootstrapping of model equations to observed exposure time limits. Newer compilations ultimately extend older ones in like manner, as described by Schreiner and Kelley, and Schreiner and Hamilton. The critical tensions proposed and data fitted by Workman and Buhlmann for arbitrary compartments are well known, and, along with the previously mentioned exponential tissue functions, are the essential elements of the Haldane approach.

A popular set of (surfacing) critical tensions, $M_0$, and corresponding ratios, $R_0$, at sea level, and changes per foot of depth, $\Delta M$, are listed in Table 1 under appropriate headings. At depth, $d$, the critical tension is the sum of $M_0$ and $\Delta Md$, that is, $M = M_0 + \Delta Md$. These critical parameters, all according to Workman (US Navy), are also plotted in Figures 1 and 2. Such parameters form the basis for most tables and meter algorithms, with a noted recent tendency to reduce critical tensions and (consequently) non-stop time limits for safety.

### FIGURE 1. NITROGEN CRITICAL TENSIONS




Critical tensions are linear functions of pressure, obviously increasing with ambient pressure. Faster compartments permit greater amounts of dissolved nitrogen, slower compartments less. During any dive, compartment tensions must stay below the depicted curves in this modified Haldane approach. Wienke reduced the Workman critical tensions above to an approximate form (fsw),

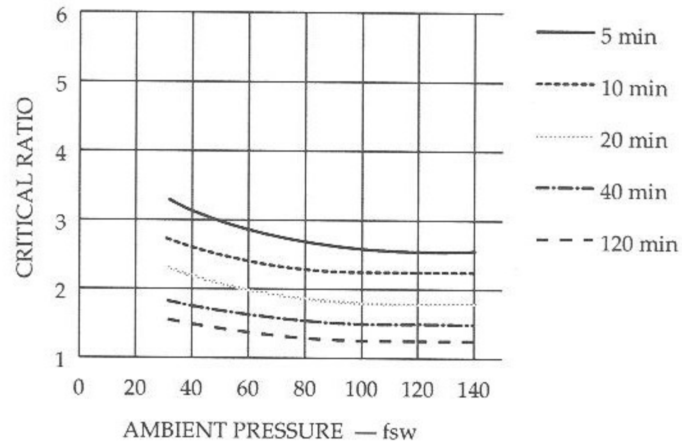
$$M = 152.7\,\tau^{-1/4} + 3.25\,d\,\tau^{-1/4} = M_0 + \Delta M d$$

for depth, d. Extensions of the curves to altitude (P < 33 fsw) have been effected linearly and exponentially. In the linear case, the zero pressure intercepts are positive, while in the exponential case the intercepts are zero. Any set of non-stop time limits can be plugged into model equations and ensuing sets of tensions for compartments can be scanned for maximum surfacing values, $M_0$, across all depths and half-times.





### FIGURE 2. NITROGEN CRITICAL RATIOS




The critical ratios, R, are simply the critical tensions divided by ambient pressures, and are seen to be hyperbolic functions of pressure. Faster compartments support larger critical ratios, and slower compartments smaller critical ratios. If critical tensions decrease linearly at altitude, critical ratios become very large as pressure drops, contrary to recent data and analysis. However, if critical tensions decrease exponentially with altitude (as in bubble models and the similarity method), critical ratios are bounded and nearly constant at decreasing ambient pressure.

| **half-time** $\tau$ *(min)* | **critical ratio** $R_0$ | **critical tension** $M_0$ *(fsw)* | **tension change** $\Delta M$ |
|---|---|---|---|
| 5 | 3.15 | 104 | 2.27 |
| 10 | 2.67 | 88 | 2.01 |
| 20 | 2.18 | 72 | 1.67 |
| 40 | 1.76 | 58 | 1.34 |
| 80 | 1.58 | 52 | 1.26 |
| 120 | 1.55 | 51 | 1.19 |

**TABLE 1. SEA LEVEL SURFACING RATIOS AND CRITICAL TENSIONS.**

## REDUCED ATMOSPHERIC PRESSURE

Decompression at reduced ambient pressure, $P < 33$ *fsw*, has been a study in itself, as reported by Buhlmann, Boni and Schibli, Edel and Carroll, Bell and Borgwardt, Bassett, Sahni, Lanphier, and Lehner, to mention just a few. Present thinking is nicely summarized by Sheffield and contributors. Decompression studies developed separately above and below sea level, referenced as, respectively, aerial and underwater decompression, also by the adjectives *hypobaric* and *hyperbaric*.

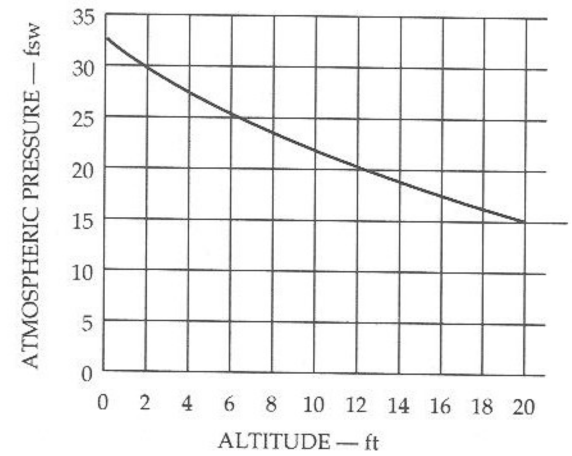
Aerial decompression differs from routine underwater decompression because the blood and tissues are equilibrated (saturated) with nitrogen ambient pressure before ascent. Breathing pure oxygen before ascent helps to protect against decompression sickness by washing out nitrogen. Up to about 18,000 *ft*, such procedure offers a considerable degree of protection. Beyond that, according to Behnke, silent bubbles may retard nitrogen elimination. Simple bubble mechanics suggest that bubble excitation and growth are enhanced as ambient pressure decreases, and so decompression problems are theoretically exacerbated by altitude. Nucleation theory also suggests that critical radii increase with decreasing pressure, offering larger, less stable gas seeds for possible excitation and growth into bubbles. Larger bubbles possess smaller constricting surface tensions, and will thus grow faster in conducive situations. Such facts have been verified in the laboratory, and follow from simple bubble theory. Certainly the same considerations confront the diver at altitude, and are compounded with increasing nitrogen tension upon surfacing at reduced atmospheric pressure.

Lower pressures at elevation, as depicted in Figure 3, and the lower density of fresh water to a lesser degree, affect gas uptake and elimination rates in tissues and blood. If critical tensions are employed to limit exposures, an immediate question centers upon their extrapolation and testing at altitude. Looking at Figure 1, a linear extrapolation of the critical tensions seems obvious, indeed just such an extrapolation of the US Navy critical tensions was proposed and tested by Bell and Borgwardt. Buhlmann, employing a different set of half-times and critical tensions, also extended the Haldane algorithm to altitudes near 10,000 *ft*. Along with reduced critical tensions at altitude, reduced non-stop time limits, compared to sea level, are a natural consequence.





**FIGURE 3. ALTITUDE AMBIENT PRESSURE.**




Atmospheric pressure, $P_h$, falls off exponentially with altitude, in the range of 1 fsw for each 1,000 ft of elevation. Such behavior affects not only diver physiology, but also gauges, instruments, buoyancy, and tables calibrated for sea level activity. The actual expression can be written (barometer equation)

$$P_h = 33\exp(-0.038h)$$

with h in multiples of 1,000 ft elevation.

Another approach reduces critical tensions exponentially with decreasing ambient pressure. Such an extrapolation turns the curves in Figure 1 down through the origin at zero ambient pressure. Intuitively, an exponential extrapolation of critical tensions through the origin is more conservative than the linear extrapolation, since corresponding critical tensions for given ambient pressure are smaller, also noted by Ingle. If the extrapolation of critical tensions is allowed to follow the same exponential decrease of ambient pressure with altitude, then the ratio of the critical tension over ambient pressure, $R$, remains constant. Non-stop time limits in the exponential scheme are also smaller than corresponding time limits in the linear scheme. As seen in Table 2, atmospheric pressure falls off approximately 1 *fsw* for every 1,000 *ft* of elevation. Exponential extrapolations of critical tensions were tested by Bassett, and discussed by Ingle, the basis for operational procedures suggested by Cross, Smith, and Wienke. Correlations of altitude chokes data for goats with constant ratio, $R$, trigger points have been described by Lanphier, while Conkin and Van Liew suggested similar correlations from the nitrogen washout data in aviators, and Wienke deduced such behavior from a bubble model treating free and dissolved gas transfer.

Parameter sets and critical values derive from data fits, iterative repetitions, hindsight, possibly venous gas emboli correlations, and bootstrapping of earlier models. Ranges are bounded, as are permissible activities. If extended to altitude, the surfacing limits decrease either exponentially (very rapidly) or linearly (more gradually). With notable parameter leeway in Table 1, additional leeway in permissible ascent and descent rates, and a set of non-stop time limits, a multiplicity of (safe) schedules are possible within the model framework. After testing, such schedules would then be fit for general diving consumption. Similar comments apply to the software driving any digital meter, effectively employing some equivalent version of Table 1.



# OPERATIONAL PROCEDURES

REPETITIVE AND DECOMPRESSION DIVING must contend with potential for a greater fraction of separated gas. And this makes extrapolations of bounce diving fits more difficult. In the early days, slower tissue compartments were added to accommodate deeper, prolonged, and decompression exposures. Ostensibly, slower compartments might track a greater proportion of separated gas, possibly dumped from tissues into gas micronuclei. Laboratory studies in decompressed gels bear witness to typical growth and elimination patterns in gas nuclei and bubbles spanning many hours. Of course, bubbles and nuclei in the body are both perfused and metabolic, adding to complexity. While not always optimal, tissue response functions with very slow compartments can be coupled to critical tensions for repetitive diving. The approach is more limited for repetitive diving than bounce diving, as possibly witnessed by slightly higher bends incidence in divers embarking on multi-day and repetitive activity, summarized by Lang and Vann, Vann and Dovenbarger. Bennett alluded to decreased Doppler scores after a few days of diving, but yet higher incidence of neurological decompression sickness. Buhlmann also reported slightly greater frequencies of skin symptoms and muscular pains in cases of repeated diving. In such repetitive application, tables and meters which do not accommodate slower compartments, like $\tau > 60$ minutes, appear further limited. For that very reason, the US Navy expanded the original set some fifty years ago, replacing the 70 minute compartment with an 80 minute compartment and adding the 120 minute compartment. Yet, the tendency today to add compartments in the several hundred minutes range, while well-intentioned, is probably not the best means for tracking separated phases. Very slow compartments, in the several hundred minute range, cannot really control multi-day and heavy repetitive diving by tracking just dissolved phases. Present consensus thus cautions against 3 or more repetitive dives in any 24 hour period, especially in the deeper categories (beyond 100 *fsw*), and relaxation periods of at least a day following 3-4 days of repetitive activity. But again, the situation is far from clear, and testing is necessary in statistically meaningful measure.

Tables and meters designed for sea level need be conservatively modified at altitude if possible, otherwise, not employed. Decomputer and table use are best left to manufacturer and designer discretion, but in any case, modification of critical tensions is central to any Haldane altitude algorithm. We will describe a general technique and, for discussion purposes, the US Navy dive tables (or derivative) will suffice.

## ALTITUDE SIMILARITY

Present diving schedules are based to large extent on the model discussed in the previous section, constraining activities so that $M$ or $R$ are never compromised. An approach to altitude diving that is roughly as conservative as the tested schemes of Buhlmann, and Bell and Borgwardt, holds the ratios, $R$, constant at altitude, forcing altitude exposures to be *similar* to sea level exposures. Such similarity will force $M$ to decrease exponentially with increasing altitude, keeping $R$ constant with commensurate exponential reduction in the ambient pressure, $P$. Constant $R$ extrapolations of this sort should be confined to nominal diving activities, certainly not heavy repetitive, decompression, nor saturation exposures.

The sought ratio constancy, $R$, at altitude induces a necessary scaling of actual depth to *sea level equivalent depth* for table entry, while all times remain unchanged. Actual depths at altitude are multiplied by factors, $\alpha$, called altitude correction factors, which are just the ratios of sea level atmospheric pressure to altitude atmospheric pressure, multiplied by the specific density of fresh water (0.975). Neglect of the specific density scaling is a conservative convenience, and one of minimal impact on these factors. Today, wrist altimeters facilitate rapid, precise estimation of $\alpha$ on site. They can also be estimated from the *barometer* equation (Appendix) and are always greater than one. Table 2 lists correction factors at various altitudes, $z$, ranging to 10,000 *ft*. Up to about 7,000 *ft* elevation, $\alpha \cong 1 + .038h$, with $h$ measured in multiples of 1,000 *ft*, that is, $z = 1000h$. The higher one ascends to dive, the deeper is his relative exposure in terms of sea level equivalent depth. Figure 4 contrasts correction factors scaled by the specific density of





fresh water for elevations up to 18,000 *ft*. Relative increases in correction factors hasten rapidly above 10,000 *ft*. As described in the Appendix and seen in Table 2, $P$ and $\alpha$ are reciprocally related, inverses actually. Again, time is measured directly, that is, correction factors are only applied to underwater depths, ascent rates, and stops.

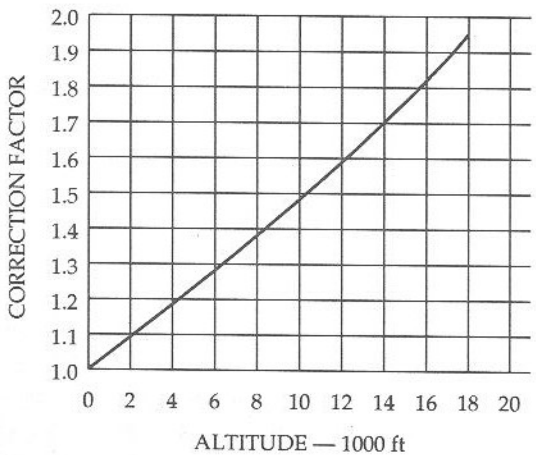
Similar hypobaric approaches and field procedures have also been discussed in the past by Cross, Smith, and Bassett, and more recently by Sahni. Connection between constant $R$ and exponentially decreasing $M$ was delineated by Wienke, as well as a phase model approach predicting constant $R$ for hypobaric exposures and linear $M$ for hyperbaric exposures.

| altitude or change $z$ (*ft*) | atmospheric pressure $P_h$ (*fsw*) | correction factor $\alpha$ | penalty group on arrival at altitude | permissible group for ascension to altitude |
|---|---|---|---|---|
| 0 | 33.00 | 1.00 | | |
| 1,000 | 31.9 | 1.04 | A | L |
| 2,000 | 30.8 | 1.07 | B | K |
| 3,000 | 29.7 | 1.11 | B | J |
| 4,000 | 28.5 | 1.16 | C | I |
| 5,000 | 27.5 | 1.20 | D | H |
| 6,000 | 26.5 | 1.24 | E | G |
| 7,000 | 25.4 | 1.29 | E | F |
| 8,000 | 24.5 | 1.34 | F | E |
| 9,000 | 23.6 | 1.39 | G | D |
| 10,000 | 22.7 | 1.45 | H | C |

**TABLE 2. ALTITUDE CORRECTION FACTORS AND US NAVY ALTITUDE GROUPS.**

The similarity rule for altitude table modification and applying correction factors to calculations is straightforward. Convert depths at altitude to sea level equivalent depths through multiplication by $\alpha$. Convert all table sea level stops and ascent rates back to actual altitude through division by $\alpha$. Ascent rates are always less than 60 *fsw/min*, while stops are always less than at sea level. Thus, a diver at 60 *fsw* at an elevation of 5,000 *ft* uses a depth correction of 72 *fsw*, taking $\alpha = 1.2$. Corresponding ascent rate is 50 *fsw/min*, and a stop at 10 *fsw* at sea level translates to 8 *fsw*. A capillary gauge at altitude performs these depth calculations automatically, and on the fly, as described below. Here the 3% density difference between salt and fresh water is neglected. Neglecting the 3% density correction is conservative, because the correction decreases equivalent depth by 3%. The effect on ascent rate or stop level is not on the conservative side, but is so small that it can be neglected in calculations anyway.

**FIGURE 4. CORRECTION FACTORS AT ALTITUDE**




Correction factors, α, are used to scale depths at altitude to sea level equivalence for use in standard tables. The factors are always greater than one, and are simply the ratios of sea level pressures to atmospheric pressures at altitude, multiplied by the specific density of of fresh water,

$$\alpha = 0.975 \left[ \frac{33}{P_h} \right]$$

with $P_h$ depicted in Figure 3.

If a diver has equilibrated with ambient pressure at any elevation, than any reduction in ambient pressure will put the diver in a repetitive group, merely because tissue tensions exceed ambient pressure. If the original and





new pressures are specified, it is possible to estimate tissue saturation and, hence, repetitive group for the excursion. Similar comments apply to to pressure reductions following any diving activity, with sea level diving the usual bill of fare. These considerations are treated as follows.

At sea level, each repetitive group represents an increment of tissue pressure over ambient ($P_0$ = 33 *fsw*). For the US Navy tables, this increment is 2 *fsw* (absolute). If we compute the difference between sea level pressure pressure and altitude pressure, and then scale the difference by the ratio of sea level atmospheric pressure to that altitude atmospheric pressure (correction factor α), we can estimate the repetitive group in which a sea level diver finds himself following immediate ascent to altitude. These group specifications are listed in column 4 of Table 2, and represent penalty time for the excursion to altitude, Entries were computed using sea level as the baseline, but are also appropriate (conservative) for any excursion between differing elevations.

In similar fashion, excursions to higher altitude following diving are limited by tissue critical tensions, and minimal repetitive group designators can be attached to any planned excursion. For the 120 minute compartment, the surfacing critical tension (sea level) is 51 *fsw* from Table 1. On the safer side, we take 47 *fsw* as the limiting tension, convert it to an absolute tension of 60 *fsw* (47/0.79), and then inversely scale it to altitude by the ratio of sea level pressure to altitude pressure, that is, α. The resulting limiting tensions at altitude can then be converted to standard US Navy groups which are tabulated in column 5 of Table 2. Entries represent maximum permissible groups for immediate altitude excursions, and do not account for any travel time. Thus a diver would have to wait some length of time after a dive, until he dropped into the permissible group category, before ascending. The *D-group* rule for flying after diving is seen as a subcase for an altitude excursion to 9,000 *ft* (maximum cabin pressure). The question of altitude delay is an interesting one, a subject of recent discussions.

## ALTITUDE DELAY

Time delays before altitude ascension, implicit to the permissible groups listed in the last column of Table 2, ultimately depend on the tissue compartment controlling the surface interval. In the US Navy tables, the 120 *minute* compartment controls surface intervals, and indeed Table 2 can be routinely applied to the US Navy Surface Interval Table to ascertain delay. With a 120 *minute* controlling compartment, corresponding time delays are compatible with a 12 hour rule for flying after diving. If a faster compartment is used to control surface intervals, a less conservative flying after diving rule would result, and similarly, if a slower compartment were employed, a more conservative rule would ensue.

Today, the 24 hour rule for flying after nominal diving is popular. Such a rule is more compatible with the 635 *minute* controlling compartment in Swiss tables (Buhlmann) than the 120 *minute* compartment in the US Navy tables (Workman). However, using a 635 *minute* compartment, we can still compute time delays for altitude excursions with the help of Table 2.

The calculation of permissible time for an altitude excursion following a dive, or flying after diving, amounts to determining the permissible altitude group from Table 2, the repetitive group following the dive, the standard (US Navy) surface interval to drop into the permissible altitude group, and multiplication of that surface interval by roughly 5.4. The factor of 5.4 results from replacement of the US Navy 120 *minute* compartment by the 635 *minute* compartment in the Surface Interval Table, so that intervals times are increased by roughly 635/120 plus rounding calculations at group boundaries. For given repetitive group and altitude excursion (change in elevation), Table 3 list minimum delay times for altitude excursions as a function of altitude and repetitive dive group. Entries are consistent with a 635

| altitude, or change | repetitive group | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *z (ft)* | D | E | F | G | H | I | J | K | L |
| 2,000 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 2:26 |
| 3,000 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 2:37 | 4:08 |
| 4,000 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 2:53 | 4:30 | 5:51 |
| 5,000 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 3:04 | 4:57 | 6:29 | 7:44 |
| 6,000 | 0:00 | 0:00 | 0:00 | 0:00 | 3:20 | 5:24 | 7:12 | 8:38 | 9:54 |
| 7,000 | 0:00 | 0:00 | 0:00 | 3:41 | 6:02 | 8:06 | 9:43 | 11:10 | 12:36 |
| 8,000 | 0:00 | 0:00 | 4:08 | 6:50 | 9:11 | 11:04 | 12:41 | 14:19 | 15:40 |
| 9,000 | 0:00 | 4:5 | 8:06 | 10:48 | 12:58 | 14:51 | 16:39 | 18:11 | 23:09 |
| 10,000 | 6:18 | 10:37 | 13.25 | 15:56 | 18.05 | 20:10 | 21:18 | 23:24 | 24:50 |

**TABLE 3. ALTITUDE DELAY CHART FOR THE 24 HOUR RULE.**





*minute* compartment controlling off-gassing, and 47 *fsw* limiting dissolved gas buildup in that compartment.

Note, in Table 3, that some 24 hours must elapse before the L-group diver can ascend to an altitude of 10,000 *ft*, reflecting the current 24 hour delay recommended before flying after diving.

## TABLES AND METERS

Operational diving often requires many dives to various depths over periods of hours, and often days. Once a standard set of decompression tables has been constructed, with bounce diving the special case of non-stop decompression, a repetitive dive procedure is a necessity. After any air dive, variable amounts of residual nitrogen remain in body tissues for periods of 24 *hours* and more. Similarly, elevated tissue tensions can promote, or sustain, bubble growth over the same time scales. This residual gas buildup (dissolved and free) will shorten the exposure time for subsequent repetitive dives. The longer and deeper the first dive, the greater the amount of residual tissue nitrogen affecting decompression on subsequent dives. Non-stop depth-time allowances for repetitive dives are reduced in such circumstance. Within bubble models, residual free gas phases are also included in procedures, imposing additional constraints on repetitive diving. The many possibilities are easily tracked in continuous time mode by computers, as mentioned, but tables face a more difficult task.

One standard table approach, developed by Workman, groups combinations of depth and exposure times according to the surfacing tension in the slowest compartment. Then it is possible to account for desaturation during any arbitrary surface interval. The remaining excess nitrogen at the start of the next dive can always be converted into equivalent time spent at the deepest point of the dive. So-called penalty time is then added to actual dive time to update appropriate tissue tensions. Surfacing tensions in excess of 33 *fsw* (absolute) in the slowest compartment are assigned letter designations (groups), A to O, for each 2 *fsw* over 33 *fsw*. Any, and all, exposures can be treated in this manner. To credit outgassing, a surface interval table, accounting for 2 *fsw* incremental drops in tensions in the slowest compartment, is also constructed. Such procedures are bases for the US Navy Air Decompression and Repetitive Surface Interval Tables, with the 120 *minute* compartment (the slowest) controlling repetitive activity. Standard US Navy tables provide safe procedures for dives up to 190 *fsw* for 60 *minutes*. Dives between 200 and 300 *fsw* were tested and reported in the exceptional exposure US Navy tables, including a 240 *minute* compartment. The Swiss tables, compiled by Buhlmann, incorporate the same basic procedures, but with a notable exception. While the US Navy tables were constructed for sea-level usage, requiring some safe extrapolation procedure to altitude as described, the Swiss tables are formulated and tested over a range of reduced ambient pressure. The controlling repetitive tissue in the Buhlmann compilation is the 635 *minute* compartment. Similar approaches focusing on deep and saturation diving have resulted in decompression tables for helium-oxygen (heliox), helium-oxygen-nitrogen (trimix), and recent mixtures with some hydrogen (hydrox).

While it is true that the table procedures just described are quite easily encoded in digital meters, and indeed such devices exist, digital meters are capable of much more than table recitations. Pulsing depth and pressure at short intervals, digital meters can monitor diving almost continuously, providing rapid estimates of any model parameter. When employing the exact same algorithms as tables, meters provide additional means to control and safety beyond table lookup. When model equations can be inverted in time, meters can easily compute time remaining before decompression, time at a stop, surface interval before flying, and optimal ascent procedure. Profiles can be stored for later analysis, and the resulting data bank used to tune and improve models and procedures. Considering utility and functionality, meter usage should increase in diving, supported by technological advance in computing power, algorithmic sophistication, and general acceptance, though it will probably be some time though before tables are supplanted.

Loyst, Huggins, and Steidley have compiled a monograph on dive computers, contrasting operating characteristics, algorithm bases, and user features. Statistics point to an enviable track record of decompression meter usage in nominal diving activities, as well as an expanding user community. When coupled to slow ascent rates and safety stops, computer usage has witnessed an extremely low incidence rate of decompression sickness, well below 0.1%, according to Gilliam, as recorded in Vann and Lang.

Operational consistency of meter algorithms might also be an implication here, and part of the reason is reflected in Table 4, which contrasts surfacing critical tensions, $M_0$, for a number of meter algorithms. Entries were estimated (computed) from quoted meter non-stop time limits, $t_{ns}$, using the 5, 10, 20, 40, 80, and 120 *minute* compartments for convenience of illustra-





tion, that is to say that arbitrary $\tau$ and $M_0$ can be fitted to any set of non-stop time limits. Ascent and descent rates of 60 *fsw/min* were also employed in calculations. The Workman, Buhlmann, and Spencer critical surfacing tensions are fixed, while the equivalent Wienke-Yount surfacing critical tensions vary, depending on repetitive exposure. Entries are also representative of critical tensions employed in related tables.

| half-time $\tau$ *(min)* | Workman $M_0$ *(fsw)* | Spencer $M_0$ *(fsw)* | Buhlmann $M_0$ *(fsw)* | Wienke-Yount $M_0$ *(fsw)* |
|---|---|---|---|---|
| 5 | 104 | 100 | 102 | 100-70 |
| 10 | 88 | 84 | 82 | 81-60 |
| 20 | 72 | 68 | 65 | 67-57 |
| 40 | 58 | 53 | 56 | 57-49 |
| 80 | 52 | 51 | 50 | 51-46 |
| 120 | 51 | 49 | 48 | 48-45 |

**TABLE 4. TABLE AND METER SURFACING CRITICAL TENSIONS ($M_0$).**

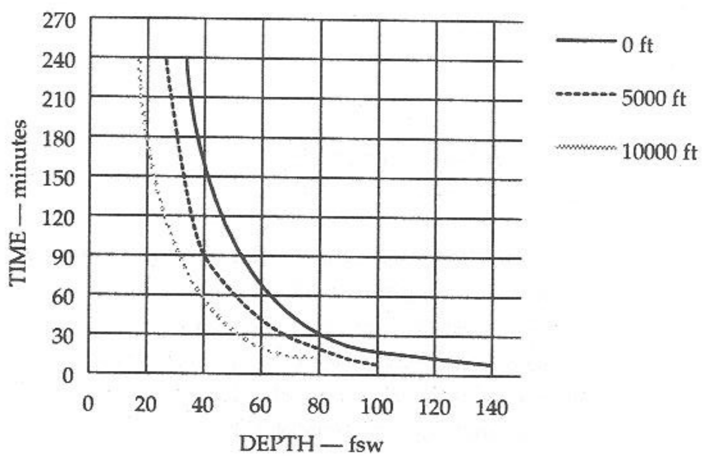
A quick glance at Table 4 underscores the operational consistency of classes of Haldane meter algorithms, with the Wienke-Yount approach effectively reducing critical tensions in multi-diving applications as the simplest meter implementation of a dual phase model. The variation in $M_0$ within the same compartments is relatively small. Table 5 collates the corresponding non-stop time limits, $t_{ns}$, for completeness.

| depth *d (fsw)* | Workman $t_{ns}$ *(min)* | Spencer $t_{ns}$ *(min)* | Buhlmann $t_{ns}$ *(min)* | Wienke-Yount $t_{ns}$ *(min)* |
|---|---|---|---|---|
| 30 | | 225 | 290 | 250 |
| 40 | 200 | 135 | 125 | 130 |
| 50 | 100 | 75 | 75 | 73 |
| 60 | 60 | 50 | 54 | 52 |
| 70 | 50 | 40 | 38 | 39 |
| 80 | 40 | 30 | 26 | 27 |
| 90 | 30 | 25 | 22 | 22 |
| 100 | 25 | 20 | 20 | 18 |
| 110 | 20 | 15 | 17 | 15 |
| 120 | 15 | 10 | 15 | 12 |
| 130 | 10 | 5 | 11 | 9 |

**TABLE 5. TABLE AND METER NON-STOP TIME LIMITS ($T_{NS}$).**

Variation in the non-stop limits is greater than in the critical tensions, with the US Navy (Workman) set the most liberal. Using the equivalent depth approach from the similarity method, the non-stop limits in Table 5 can be extrapolated to altitude. Figure 5, however, plots the Wienke-Yount non-stop time limits at various altitudes, using a bubble model constraint on the separated phase volume (instead of $M$, or $R$).

**FIGURE 5. WIENKE-YOUNT NON-STOP TIME LIMITS AT ALTITUDE.**




Non-stop time limits at altitude in any algorithm should decrease with elevation. Reductions in critical tensions (linearly, or exponentially), or near constancy of critical ratios, at altitude commensurately reduce bounce time limits. Using a phase volume limit, reductions in non-stop time limits at elevation in the Wienke-Yount model follow directly. The Buhlmann critical tensions decrease linearly at elevation, thus also directly shortening those non-stop time limits. Within the similarity method, exponential reductions in the Workman and Spencer critical tensions at altitude effectively shorten their non-stop time limits too.





## BUBBLE DYNAMICS AND IMPACTS

Farm and Hayashi, Kunkle and Beckman, and Hills suggest that the empirical practices of Hawaiian and Australian diving fishermen (deeper decompression stops, zonal safety stops, and immediate in-water recompression) underscore working cognizance of phase dynamics developed over years of trial-and-error experimentation, albeit, with considerable trauma. Their practice seems to minimize phase growth apart from dissolved gas buildup. An American Academy Of Underwater Sciences (AAUS) workshop on repetitive diving, recorded by Vann and Lang, and Divers Alert Network report that present diving practices appear riskier under increasing exposure time and pressure loading, spawning development of ancillary safety measures restricting multi-diving. Such measures are suggested within conservative table protocols, even for exposures not exceeding critical tensions, seen in Lang and Egstrom, Lang and Hamilton, Sheffield, and Lang and Vann:

1. Maintain ascent rates below 60 fsw/min, preferably slower.
2. Limit repetitive dives to a maximum of three per day, not exceeding the 100 fsw level.
3. Avoid multi-day, multi-level, or repetitive dives to increasing depths.
4. Wait 12 hrs before flying after light (bounce) diving, 24 hrs after heavier (taxing, near decompression, repetitive) diving activity, and 48 hrs after heavy (multi-day repetitive) and decompression diving.
5. Avoid multiple surface ascents and short repetitive dives (spikes) within surface intervals of 1 hr.
6. Surface intervals of more than an hour are recommended for repetitive diving.
7. Safety stops for 2-4 minutes in the 10-25 fsw zone are advisable for all diving, but particularly for deep (near 100 fsw), repetitive, and multi-day exposures.
8. Do not dive at altitudes above 10,000 ft using modified conventional tables, or extrapolations.
9. Always dive conservatively, remembering that tables and meters are not bends-proof.

Procedures such as those above are prudent, theoretically sound, and safe diving protocols. Ultimately, they can be linked to free phase and bubble dynamics. In considering bubble dynamics, it is worthwhile to amplify concerns impacting altitude diving procedures.

Generally, bubble growth and excitation are compounded at altitude because of reduced pressure. The modeling work of Van Liew, Gernhardt and Lambertson, Kislyakov and Kopyltsov, Yount and Strauss, and Wienke underscores this fact, indicating why critical tension models often fall short in hypobaric applications. Bubbles grow faster as they get bigger, and as ambient pressure drops. With decreased ambient pressure, bubbles will also expand by Boyle's law. Bigger bubbles are not as constricted by Laplacian film tension, while reduced ambient pressure supports a faster rate of tissue gas diffusion into the bubble itself.

Lanphier and Lehner performed extensive aerial decompression studies with goats, concluding that aerial decompression sickness strongly resembles underwater decompression sickness following saturation exposure. For ranging profiles followed by decompression to reduced ambient pressure, a high incidence of chokes was noted. Chokes is thought to result from microemboli interfering with pulmonary function. It is easy to speculate that rapid decompression to reduced pressure contributes to the buildup and growth of pulmonary emboli for the same reasons. Lanphier also concluded that slow tissue ($\tau \geq 80$ *minutes*) compartments do not correlate with chokes, suggesting that pulmonary microemboli are linked to fast compartments. Clearly, such an assertion also points out differences between types of decompression sickness, inferred critical tissue half-times, and bubble formation time scales. Chokes and limb bends result from different critical insults, at different places, and over possibly different time scales. Neuman and Bove have recorded severe spinal DCS precipitated by arterial gas emboli during pulmonary barotrauma, suggesting the transpulmonary escape of venous gas emboli into the arterial circulation as the culprit mechanism.

A point to be made here is that increased off-gassing pressures most likely reduce bubble growth rates dramatically in shallow zones, while impacting dissolved gas buildup in the slowest compartments minimally. Fast compartments also off-load gas and bubbles during slow ascents and safety stops. Stops and slow ascent rates are prudent, and at altitude these protocols can be underscored because of a reduced ambient pressure environment.



# BUOYANCY

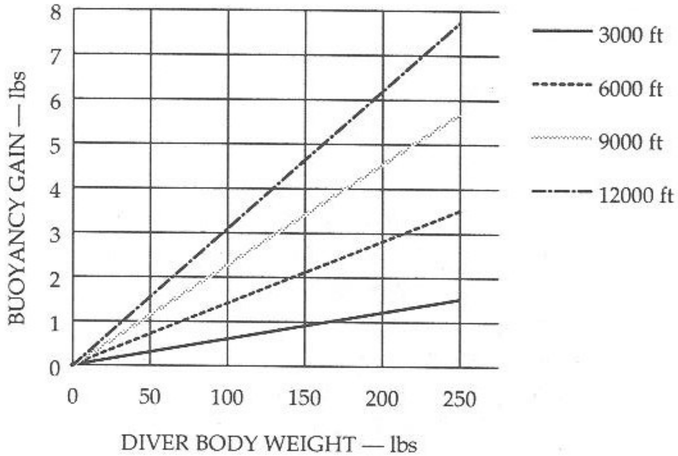
Buoyancy changes occur when divers move between fresh and salt water, and/or different elevations. Since fresh water is less dense than salt water, buoyancy is lost in fresh water relative to salt water. Similarly, since ambient pressure at altitude is less than at sea level, wet suits expand at elevation, increasing buoyancy. Effects, however, tend to offset each other. The increased wetsuit buoyancy amounts to roughly 0.2% of body weight for each multiple of 1,000 *ft* of altitude. The fresh water decrease in buoyancy, relative to salt water, is approximately 2.5% of total diver diver weight. Quantitative relationships are described in the Appendix.

## WETSUIT BUOYANCY

Altitude environments are usually sufficiently cold that wetsuits are required. The increased wetsuit buoyancy is mostly of concern near the surface, since increased water pressure will compress the suit rapidly at moderate depth. Figure 6 charts wetsuit buoyancy gains at various altitudes as a function of diver weight (body plus gear).

Assuming that suit buoyancy at the surface is balanced by the weight belt alone at sea level, the corresponding buoyancy increase, denoted $\Delta B_{alt}$, due to reduction in pressure at altitude, can be computed from Archimedes principle and Boyle's law. Wetsuit response, according to Somers, is only 55% of the response predicted by Boyle's law, and that factor scales buoyancy estimation. Assuming the weight belt is roughly 10% of diver weight and that ambient pressure drops roughly 1 *fsw* for each 1,000 *ft* increment of elevation, the buoyancy change amounts to .0019 times the diver weight, denoted *w*, for each increment of altitude in 1,000 *ft* jumps. For example, a 200 *lb* ocean diver journeying to 5,000 *ft* will gain approximately 1.8 *lbs* of positive buoyancy.

## FIGURE 6. WETSUIT BUOYANCY GAIN AT ALTITUDE




With pressure changes, wetsuits expand or compress only some 55% of predicted maximum, according to Boyle's law. Accounting for altitude pressure reduction, wetsuit buoyancy gain at elevation, relative to sea level, can be computed directly, assuming that the weight belt is 10% of diver body weight. The gain at elevation, $\Delta B_{alt}$, in lbs, is approximately

$$\Delta B_{alt} = 0.0019hw$$

given diver body weight, w, and elevation, h, in multiples of 1,000 ft.

## FRESH AND SALT WATER BUOYANCY

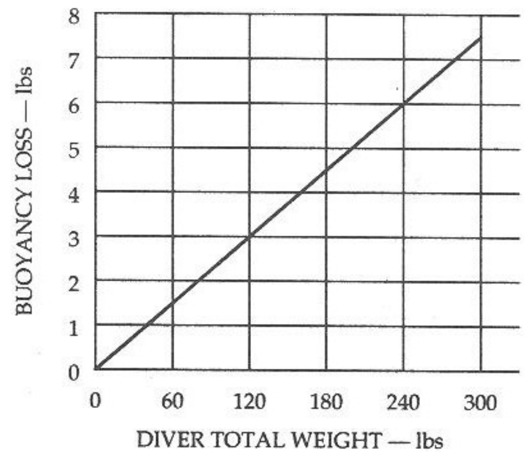
Straightforward application of Archimedes principle to a body submerged in salt and fresh water (displacing equal volumes), yields a buoyancy change, analogously denoted $\Delta B_{sea}$, that depends on the ratio of densities and the total (body plus gear) diver weight, denoted *w*. This simple correction for fresh water relative to sea water amounts to buoyancy reduction near 2.5% of total diver weight. Thus a 200 *lb* ocean diver plus gear will lose 5.0 *lbs* of





buoyancy in fresh water. Figure 7 depicts fresh water buoyancy loss against diver body weight.

## FIGURE 7. FRESH WATER BUOYANCY LOSS




Fresh water is less dense than salt water. Simple application of Archimedes' principle yields the buoyancy loss, $\Delta B_{sea}$, in terms of diver total weight (body plus gear), W, in lbs,

$$\Delta B_{sea} = -0.025W$$

with the minus sign indicating buoyancy loss in fresh water relative to salt water.

# GAUGES

Capillary, diaphragm, and bourdon depth gauges are usually calibrated at sea level for salt water. Fresh versus salt water reading errors alone, as with buoyancy changes, are small (near 3%), but all register increasing error with altitude. Diaphragm and oil filled gauges indicate depths that are too shallow, while capillary gauges indicate depths that are too deep. The capillary gauge, as mentioned, is unique in that it automatically registers sea level equivalent depths for table calculations at altitude. Today, some gauges are available with adjustable scales for re-zeroing at altitude, circumventing the problem. In any case, a few simple rules will suffice for correcting salt water, sea level gauges in fresh water at altitude. To obtain actual depths from capillary gauge readings, subtract 3.5% of the reading for each 1,000 *ft* increment of elevation. For all other gauges, add 1 *fsw* for each 1,000 *ft* increment and then add 3% of the reading. Quantitative relationships are again detailed in the Appendix.

## CAPILLARY GAUGES

Capillary gauges do not measure pressure directly, but employ Boyle's law to measure ratios. Calibrated for ocean use, and designed to interpret the ratio of surrounding water pressure to surface pressure, the capillary gauge reads 33 *fsw* whenever the pressure is twice the surface pressure. This leads to large errors in measuring actual depth at increasing altitude, but is a desirable feature for sea level table usage, since the depths registered are sea level equivalent, as mentioned. In other words, the diver at altitude directly enters the tables with capillary gauge readings. Capillary gauge readings, at various elevations, are plotted in Figure 8 for given actual depths.

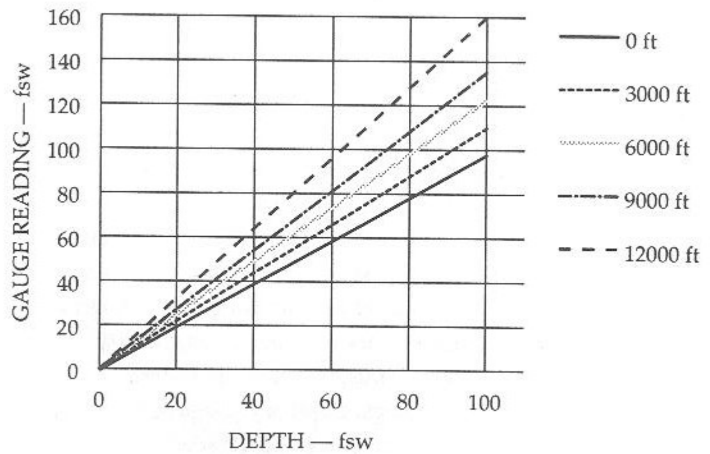
The reading, $\delta$, indicated on a capillary gauge is scaled to actual depth, $d$, by the ratio of fresh to salt water density and sea level pressure to ambient pressure at altitude, the usual multiplier. Registered depths, δ, are greater than actual depths, *d*, by roughly 3.4% of the reading for each 1,000 *ft* of elevation. For instance, at 5,000 *ft*, a capillary gauge at 60 *fsw* will register 70 *fsw*.

## BOURDON AND OIL FILLED GAUGES

Non-capillary gauges measure absolute pressures and, then, mechanically subtract one atmosphere (sea level) from the reading. Calibrated for ocean use, they register unit depth for each 1 *fsw* pressure. Figure 9, in analogy with Figure 8, depicts bourdon and oil filled gauge readings at altitude for given actual depths.

The depth reading, δ, in terms of actual depth, *d*, depends not only on the ratio of fresh to salt water density, but also directly on the difference between ambient pressure and sea level pressure. Here, registered depths, δ, are less than actual depths, *d*, by 3% of the reading plus 1 *fsw* for each 1,000 *ft* of elevation. At an elevation of 6,000 *ft*, a bourdon gauge at 38 *fsw* actual depth will register a reading of only 30 *fsw*.

**FIGURE 8. CAPILLARY GAUGE READINGS AT ALTITUDE**




Capillary gauges read sea level equivalent depth at altitude (always greater than actual depth), facilitating direct table entry



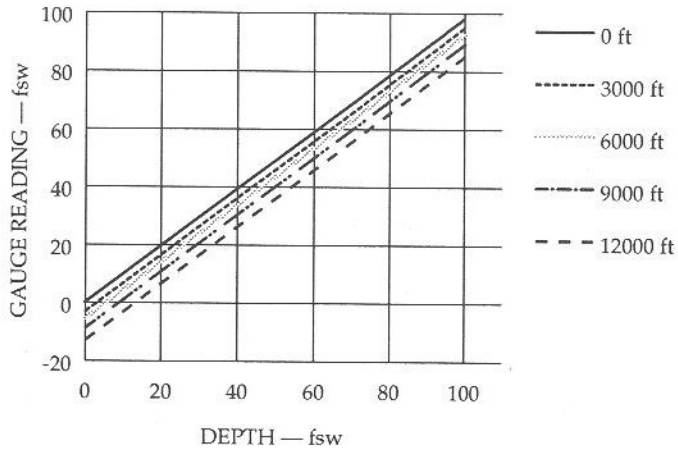


with the gauge reading. In terms of actual depth, d, the gauge reading, δ, is simply

$$\delta = 0.975 \left[ \frac{33}{P_h} \right] = \alpha d$$

with all quantities measured in fsw.

**FIGURE 9. BOURDON AND OIL FILLED GAUGE READINGS AT ALTITUDE**




Bourdon and oil filled gauges register depths at altitude that are less than actual depths. The gauge reading, δ, takes the form

$$\delta = 0.975d + P_h - 33$$

terms of the actual depth, d, and all pressures and depths in fsw.

# AIR CONSUMPTION

Having worked through the previous couple of sections, altitude reductions to sea level air consumption rates should be no surprise. Rates at altitude are less than sea level rates because of reduction in ambient pressure relative to sea level. The same comments apply to compressor pumping rates, output, and horsepower levels. Mathematical details are sketched in the Appendix. Variation in rate with ambient pressure is a gas density effect (regulator function), while variation in rate with activity is a metabolic effect (oxygen requirement).

Figure 10 graphs surface consumption rates at altitude for corresponding sea level consumption rates. Table 6 codifies nominal consumption rates at sea level for various activities, in water and on land. Certainly these activities rates vary with individual, temperature, physical condition, body morphology, lung capacity, drag, mental state, metabolism, and so on.

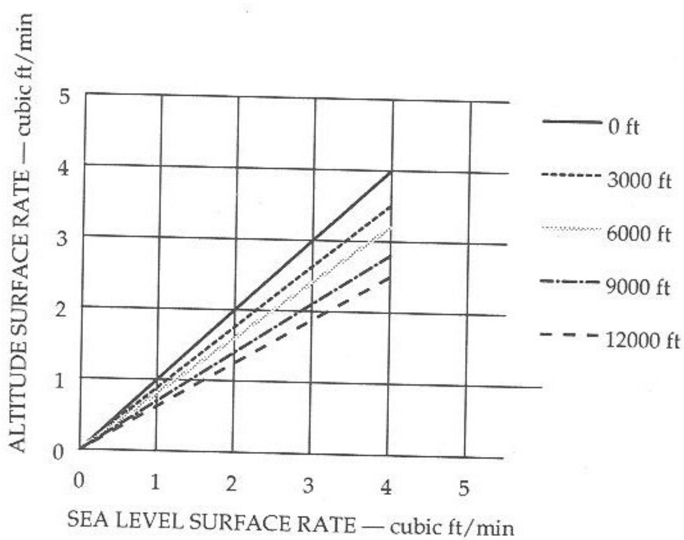
| land/water activity | sea level consumption rate $\chi_0$ *($ft^3/min$)* |
|---|---|
| reclining/floating horizontally | .6 |
| standing/floating vertically | .8 |
| walking/light treading | 1.0 |
| jogging/slow swimming | 1.3 |
| running/moderate swimming | 1.6 |
| sprinting/cold arduous diving | 2.0 |

**TABLE 6. ACTIVITIES AIR CONSUMPTION RATES AT SEA LEVEL.**

Denoting the sea level surface consumption rate, $\chi_0$, the altitude surface consumption rate, $\chi_h$, is reduced by the ratio of ambient pressure to sea level pressure, $\alpha$. Quite obviously, the surface rate at altitude decreases inversely with elevation. Underwater rates, of course, continue to increase with pressure. Thus at depth, reductions in surface pressures at altitude have increasingly lesser effect on consumption rates, an effect also seen in wetsuit buoyancy with increasing pressure.

For example, a surface consumption rate of 1.2 $ft^3$ / *min* at sea level translate into 1.0 $ft^3$ / *mi* (1.2/1.2) at 5,000 *ft* elevation. At sea level, the consumption rate at 33 *fsw* is twice the surface rate, at 66 *fsw* it is three time the surface rate, and so on. At 5,000 *ft* elevation, the consumption rate at 28 *fsw* (33/1.2) is twice the surface rate, at 56 *fsw* it is three times the surface rate, etc. Reductions in surface consumption rates at altitude amount to roughly 3.5% of the sea level rates for each 1,000 *ft* step in elevation.

**FIGURE 10. SURFACE AIR CONSUMPTION RATES AT ALTITUDE**




Air consumption rates at elevation are less than at sea level for the same depth because the density of regulator inspired air is less than at sea level. In terms of the sea level surface rate, $\chi_0$, the altitude surface rate, $\chi_h$, satisfies the relationship





$$\chi_h = \chi_0 \left[ \frac{P_h}{33} \right] = \frac{\chi_0}{\alpha}$$

The consumption rate at depth, $\chi$, is accordingly written

$$\chi = \chi_h \left[ 1 + \frac{\alpha d}{33} \right]$$

for actual depth, d. Variation in consumption rate with altitude is density effect (regulator function), while variation in consumption rate with physical activity is a metabolic effect.

# MALADIES

At altitudes above 10,000 *ft*, possible physiological complications, discussed by Sorenson and Severinghaus, Buhlmann, Hills, and Behnke, in addition to the procedural constraints mentioned, contraindicate repetitive and multi-day diving. Care must be exercised when diving near, and above, the 10,000 *ft* level. The crux of the problem is reduced pressure. At that altitude, ambient air pressure is 10 *fsw* and the partial pressure of oxygen is thus only 2 *fsw*, 1/3 less than at sea level. As seen in Figure 3, the exponential decrease of pressure with altitude markedly hastens above that level. Commensurate reduction in oxygen has a greater impact on body physiology. Cold water can induce hypothermia, while dehydration and overheating can promote hyperthermia.

## DECOMPRESSION SYNDROME

Decompression sickness is classified into four major categories, with the first two sometimes labeled *simple* decompression sickness. Categories include:

1. Type I (limb bends); characterized by local pain in the extremities, itching, red spots, swelling, or muscle stiffness affecting the knees, elbows, hips, muscles, or skin.
2. Type II (central nervous system bends); characterized by confusion, paralysis, pain in the chest, breathing difficulty, or unconsciousness, with symptoms affecting the brain, spinal cord, or lungs.
3. Type III (vestibular bends); characterized by hearing impairment, vertigo, tinnitus (ringing and buzzing), or nausea occurring with exposures beyond the 300 fsw range, affecting the balance organs of the ear.
4. Type IV (dysbaric osteonecrosis); characterized by bone lesions, structural damage, or local mineralization, occurring

with repeated exposures to high pressure environments, and affecting the long bones.

Bert first noted that when a group of subjects were decompressed together after the same exposure most would be unaffected, and only one might be afflicted with decompression sickness. Such differences are due both to the random nature of bubble formation and variations in individual tolerance to bubbles formed after every decompression. As discussed by Bennett and Elliott, individual susceptibilities depend on a number of factors:

1. Age; generally the older the person, especially over 40, the greater the susceptibility to decompression sickness.
2. Obesity; leaner subjects are less disposed to decompression sickness.
3. Exercise; exercise during, and after, decompression is thought to increase the likelihood of decompression sickness, by increased gas uptake in the former case and agitation in the latter.
4. Fluid Balance; dehydration is known to increase disposition to decompression sickness, and is physically linked to low surface tension of blood serum which does not inhibit bubble growth optimally.
5. Alcohol; alcohol also reduces blood serum surface tension, increasing decompression sickness likelihood.
6. Temperature; colder environmental temperatures are known to increase susceptibility to decompression sickness.
7. Adaptation; progressively greater tolerance to the effects of decompression during a series of consecutive exposures has been demonstrated;
8. Injuries; injury sites are more predisposed to bubble formation.
9. Physical Condition; fit subjects are also less disposed to decompression sickness.

Most believe that the pathophysiology of decompression sickness syndrome follows formation of a gas phase after decompression. Yet, the physiological evolution of the gas phase is poorly understood. Bubble detection technology has established that:

1. Moving and stationary bubbles do occur following decompression.
2. The risk of decompression sickness increases with the magnitude of detected bubbles.





3. Symptomless, or silent, bubbles are also common following decompression.
4. The variability in gas phase formation is likely less than the variability in symptom generation.

Taken together, gas phase formation is not only important to the understanding of decompression sickness, but is also a crucial model element in theory and computation.

**ALTITUDE SICKNESS**

At altitudes greater than some 7,000 *ft*, decreased partial pressures of oxygen can cause arterial hypoxemia. Under hypoxic stimulation (low oxygen tension), hyperventilation occurs with secondary lowering of arterial carbon dioxide and production of alkalosis. Newcomers to high altitude typically experience dyspnea (shortness of breath), rapid heart rate, headache, insomnia, and malaise. Symptoms disappear within a week, and general graded exercise may hasten acclimatization.

Acclimatization is usually lost within a week at lower altitudes. Although increased oxygen at depth may be beneficial, the surface malaise often precludes diving until acclimatization. In itself, altitude sickness is not life-threatening.

**PULMONARY EDEMA**

Pulmonary edema (fluid buildup in the lungs) affects non-acclimatized individuals who travel within a day or two to elevations near, or above, 10,000 *ft*. Symptoms usually appear within 18 *hrs* after arrival, consisting of rasping cough, dyspnea, and possible pain in the chest. Treatment requires immediate removal to lower altitude, hospitalization with rest, oxygen, and diuretic therapy. Prevention includes adequate acclimatization and reduced levels of exertion. A month of graded exercise may be requisite. Again, increased oxygen partial pressures at depth are helpful, but diving rigors can precipitate pulmonary edema. Symptoms might resemble the chokes (decompression sickness).

Pulmonary edema can be a serious, even fatal, affliction, as noted by its yearly toll on mountain climbers. At altitude, none with evidence of cough, shortness of breath, or tightness in the chest should dive. Rapid treatment, including lower altitude, hospitalization, and appropriate therapy, is to be underscored.

**HYPOTHERMIA**

Exposure to cold results in heat loss, with the rate dependent upon body area, temperature difference, body fat, insulation properties of wet or dry suit, and physical activity. Exercise always increases heat loss. As core temperatures drop, symptoms progress from shivering, to weakness, to muscle rigidity, to coma, and then death. Rewarming at the earliest signs of hypothermia is prudent. While more of a cold water problem, hypothermia can also occur in relatively warm and even tropical waters. Severe hypothermia is a life threatening condition.

Shivering and very cold divers need remove themselves from the water quickly, as these conditions are the first symptoms. Rewarming in dry clothing is standard and obvious treatment, as well as ingestion of balanced electrolytes. Exercise, caffeine, and alcohol are to be avoided. Care in the choice of protective suit to conserve body heat, attention to feelings of cold, and good physical condition help to minimize hypothermia.

**HYPERTHERMIA**

Inadequate ventilation and heat loss, usually in the presence of high environmental temperatures and low body fluid levels, lead to a progressive raising of temperatures in vital organs. As temperatures rise, symptoms progress from profuse sweating, to cramps, to heat exhaustion, to heat stroke, to coma, and then death. Dehydration is a contributing factor. Replacement of body fluids and reduction of body temperature are necessary in effective treatment of hyperthermia. Cool water immersion is employed in severe cases, but the usual treatment consists of fluids, salt, and full body ventilation. Like hypothermia, severe hyperthermia is a life threatening condition.

Hyperthermia can be avoided by proper attention to water intake and protection from environmental heat. Environmental temperatures above body temperature are potentially hazardous, especially with increasing levels of physical exertion.



# RECENT DEVELOPMENTS

The past fifteen years, or so, have witnessed a number of important changes in diving protocols and table procedures, such as shorter non-stop time limits, slower ascent rates, discretionary safety stops, ascending repetitive profiles, multi-level techniques, both faster and slower controlling repetitive tissue half-times, lower critical tensions ($M$-values), longer flying-after-diving surface intervals, and others. Stimulated by Doppler technology, decompression meter development, theory, statistics, or safer diving consensus, these modifications affect a gamut of activity, spanning bounce to multi-day diving. Of these changes, conservative non-stop time limits, non-decompression safety stops, and slower ascent rates (less than the standard 60 *fsw/min*) are much in vogue, and deserve a closer look. As it turns out, there is good support for shorter non-stop limits, safety stops, and slow ascent rates on operational, experimental, and theoretical grounds, and especially at altitude.

Spencer pioneered the use of Doppler bubble counting to suggest reductions in the non-stop time limits of the standard US Navy tables, on the order of a repetitive group or two at each depth in the tables (1-4 *fsw* in critical tensions), basing recommendations on lowering bubble counts at shorter non-stop time limits. Others have also made similar recommendations over the past 15 years.

Smith and Stayton noted marked reductions in precordial bubbles when ascent rates were cut from 60 *fsw/min* to 30 *fsw/min*, and, in similar studies, Pilmanis and Neuman, Hall, and Linaweaver witnessed an order of magnitude drop in venous gas emboli (VGE) counts in divers making short safety stops following nominal bounce exposures at the 100 *fsw* level, and extended excursions near 200 *fsw*.

Though incidence statistics on decompression sickness in multi-diving are still controversial, Acott indicated that some 70% of cases treated at Adelaide were collectively involved in multiple dives, multiple ascents, last dive deepest, and deep bounce diving. Dunford, Wacholz, Huggins, and Bennett noted persistent Doppler scores in divers performing repetitive, multi-day diving, suggesting the presence of VGE in divers, all the time, under such loadings.

Ascent rates, safety stops, decompression computers, and altitude diving were also the subject of extensive discussion at workshops and technical forums sponsored by the American Academy of Underwater Sciences and the Undersea And Hyperbaric Medical Society (UHMS), as summarized by Lang and Hamilton, Lang and Egstrom, and Sheffield, Results of studies, experiments, and discussions culminated in the set of recommendations summarized earlier. A closer look at reduced non-stop time limits, safety stops, and ascent rates is worthwhile at this point.

## NON-STOP TIME LIMITS

Ultrasonic techniques for monitoring moving gas emboli in the pulmonary circulation are popular today. Silent bubbles, as applied to the venous gas emboli detected in sheep undergoing bends-free US Navy table decompression by Spencer and Campbell, were a first indication that asymptomatic free phases were present in blood, even under bounce loadings. Similar results were reported by Walder, Evans, and Hempleman. After observing and contrasting venous gas emboli counts for various non-stop exposures at depth, Spencer suggested that non-stop limits be reduced below the US Navy (Workman) table limits. Enforcing a 20% drop in venous gas emboli counts compared to the US Navy limits, corresponding non-stop limits, $t_{ns}$, satisfy a reduced Hempleman relationship, that is, $dt_{ns}^{1/2} \leq 465\ fsw{\cdot}min^{1/2}$, with $d$ the depth.

Table 5 compares non-stop time limits according to the classical Workman, and more recent Spencer, Buhlmann, and Wienke-Yount algorithms. Further reduction in time limits would seem to play off optimality against safety. Limits much below the Spencer, Buhlmann, and Wienke-Yount times would restrict repetitive diving, but at the expense of bounce diving. Statistics compiled by Gilliam suggest that divers using conservative time limits (Buhlmann) have compiled an enviable track record, an incidence of decompression sickness below 0.01% in combined table and meter usage, and many regard such an incidence rate as acceptable.

A more natural way to restrict repetitive and multi-day diving, than reducing bounce time limits, is suggested within bubble models employing the so-called critical *phase volume* trigger point, whereby requisite reductions





in supersaturation gradients translate to systematic reductions in permissible tensions on successive dives, but do not restrict non-stop time limits on bounce dives. Recall that the critical, or permissible, tensions are the maximum dissolved gas partial pressures allowed in each tissue compartment, and the critical phase volume is the maximum allowable separated gas volume across all compartments. The reduced gradient bubble model (RGBM) is one such dual phase model, and systematically reduces critical tensions on repetitive dives by constraining both dissolved and free phase gas buildup.

As seen, Table 4 lists corresponding maximum (critical) surfacing tensions ($M_0$) in the Workman, Spencer, Buhlmann, and Wienke-Yount algorithms, with the first three fixed, Haldane model values and the last variable, bubble model (RGBM) limits. Note in Table 4 that critical tensions in the latter three algorithms are smaller, by some 1–4 *fsw*, compared to the Workman (US Navy) values, effectively shortening the non-stop time limits a group, or two, within US Navy tables.

While the numbers of venous gas emboli detected with ultrasound Doppler techniques can be correlated with non-stop limits, and the limits then used to fine tune the critical tension matrix for select exposure ranges, fundamental issues are not necessarily resolved by venous gas emboli measurements. Venous gas emboli are probably not the direct cause of bends per se, unless they block the pulmonary circulation, or pass through the pulmonary traps and enter the arterial system to lodge in critical sites. Intravascular bubbles might first form at extravascular sites. According to Hills, electron micrographs have highlighted bubbles breaking into capillary walls from adjacent lipid tissue beds in mice. The Lambertsen studies of vascular disruption, subcutaneous bruising, and venous emboli point to bubble formation in tissues as the culprit. Fatty tissue, draining the veins and possessing few nerve endings, is thought to be an extravascular site of venous gas emboli. Similarly, since blood constitutes no more than 8% of the total body capacity for dissolved gas, the bulk of circulating blood does not account for the amount of gas detected as venous gas emboli.

Secondly, what has not been established is the link between venous gas emboli, possible micronuclei, and bubbles in critical tissues. Any such correlations of venous gas emboli with tissue micronuclei would unquestionably require considerable first-hand knowledge of nuclei size distributions, sites, and tissue thermodynamic properties. Recent Doppler studies and correlations by Powell and Rogers, Eckenhoff, and Sawatzky and Nishi do hint that the variability in gas phase formation, however, is probably less than the variability in symptom generation. Whatever the origin of venous gas emboli, procedures and protocols which reduce gas phases in the venous circulation deserve attention, for that matter, anywhere else in the body. The moving Doppler bubble may not be the bends bubble, but perhaps the difference may only be the present site. The propensity of venous gas emboli may reflect the state of critical tissues where decompression sickness does occur. Studies and tests based on Doppler detection of venous gas emboli are still the only viable means of monitoring free phases in the body.

## STOPS AND ASCENT RATES

Safety stops and slower ascent rates, in the context of dissolved gas models, are consistent with bubble mechanics, actually reducing bubble growth rate and free gas buildup because of greater effective pressure at the end of the dive. That is strong endorsement for the practice. Additionally, some regard safety stops, slower ascent rates, and increased off-gassing pressures as consistent treatment for separated (free) gas phases, particularly near the surface where further pressure reduction enhances growth. And gas nucleation theory and experiment tell us that on any given dive (compression-decompression), families of micronuclei larger than a critical (minimum) size are excited into bubble growth, so we must pay attention to free phase development throughout the dive. Experiments and calculations suggest that shallow, short stops and slow ascent rates not only have beneficial impact on reducing free phase buildup, but also reduce dissolved gas in the faster tissues. And that is important for deeper diving. Reasons are rooted in nucleation and bubble mechanics, as described, but some studies deserve mention before we finish with some illustrative phase model calculations.

Utilitarian procedures, entirely consistent with phase mechanics and bubble dissolution time scales, have been developed under duress, and with trauma, by Australian pearl divers and Hawaiian diving fishermen, for both deep and repetitive diving with possible in-water recompression for hits. While the science behind such procedures was not initially clear, the operational effectiveness was always noteworthy and could not be discounted easily. Later, the rationale, essentially recounted in the foregoing, became clearer.

Pearling fleets, operating in the deep tidal waters off northern Australia, employed Okinawan divers who regularly journeyed to depths of 300 *fsw*





for as long as one hour, two times a day, six days per week, and ten months out of the year. Driven by economics, and not science, these divers developed optimized decompression schedules empirically. As reported by LeMessurier and Hills, deeper decompression stops, but shorter decompression times than required by Haldane theory, were characteristics of their profiles. Such protocols are entirely consistent with minimizing bubble growth and the excitation of nuclei through the application of increased pressure, as are shallow safety stops and slow ascent rates. With higher incidence of surface decompression sickness, as might be expected, these Australians devised a simple, but very effective, in-water recompression procedure. The stricken diver is taken back down to 30 *fsw* on oxygen for roughly 30 *minutes* in mild cases, or longer in severe cases. Increased pressures help to constrict bubbles, while breathing pure oxygen maximizes inert gas washout (elimination).

Similar schedules and procedures have evolved in Hawaii, among diving fishermen, according to Farm, Hayashi, and Beckman. Harvesting the oceans for food and profit, Hawaiian divers make between 8 and 12 dives a day to depths beyond 350 *fsw*. Profit incentives induce divers to take risks relative to bottom time in conventional tables. Three repetitive dives are usually necessary to net a school of fish. Consistent with bubble and nucleation theory, these divers make their deep dive first, followed by shallower excursions. A typical series might start with a dive to 220 *fsw*, followed by 2 dives to 120 *fsw*, and culminate in 3 or 4 more excursions to less than 60 *fsw*. Often, very short or zero surface intervals are clocked between dives. Such types of profiles literally clobber Haldane tables, but, with proper reckoning of bubble and phase mechanics, acquire some credibility. With ascending profiles and suitable application of pressure, gas seed excitation and any bubble growth are constrained within the body's capacity to eliminate free and dissolved gas phases. In a broad sense, the final shallow dives have been tagged as prolonged safety stops, and the effectiveness of these procedures has been substantiated *in vivo* (dogs) by Kunkle and Beckman.

While the above practices developed by trial-and-error, albeit with seeming principle, venous gas emboli measurements, performed off Catalina by Pilmanis on divers making shallow safety stops, fall into a more scientific category. Contrasting bubble counts following bounce exposures near 100 *fsw*, with and without zonal stops in the 10-20 *fsw* range, marked reductions (factors of 4 to 5) in venous gas emboli were noted when stops were made. If, as some suggest, venous gas emboli in bounce diving correlate with bubbles in sites such as tendons and ligaments, then safety stops probably minimize bubble growth in such extravascular locations. In these tests, the sample population was small, but similar studies were also conducted by Neuman, Hall, and Linaweaver.

Smith and Stayton, in goat studies, have shown that the incidence of precordial bubbles was greatly reduced when ascent rates were cut from 60 *fsw/min* to 30 *fsw/min*. Across a variety of decompression profiles, venous bubbles were greatly reduced by slower ascent rates and deeper initial decompression stops than required by the US Navy tables. Venous bubbles eliminated during short, deeper stops probably originate in fast tissues, so eliminating these bubbles earlier in the decompression could allow more-slowly-exchanging tissues to desaturate safely, while also minimizing numbers of arterial emboli possibly remaining after intracardial shunting, or transpulmonary escape, of venous gas emboli.

## PHASE CALCULATIONS

Theoretically, growth minimization and free phase elimination also favor slow ascents. Figure 11 plots the surfacing radius of an initially small bubble ($r$ = 0.36 *microns*), held in both fast (5 *minute*) and slow (120 *minute*) saturated compartments at a depth of 120 *fsw*, as a function of constant ascent rate, employing a bubble growth equation. Results plotted are also typical for recreational bounce, multi-level, and repetitive diving profiles, and underscore growth minimization with slow ascent due to increased ambient pressure on the average.

Using tissue bubble growth equations, Gernhardt, Lambertsen, Miller, and Hopkins have correlated bubble sizes with statistical risk of decompression sickness. One result of that analysis is a risk curve increasing with surfacing bubble radius, pointing to the efficacy of slow ascent rates and safety stops, which reduce surfacing bubble radii as seen in Figure 11.

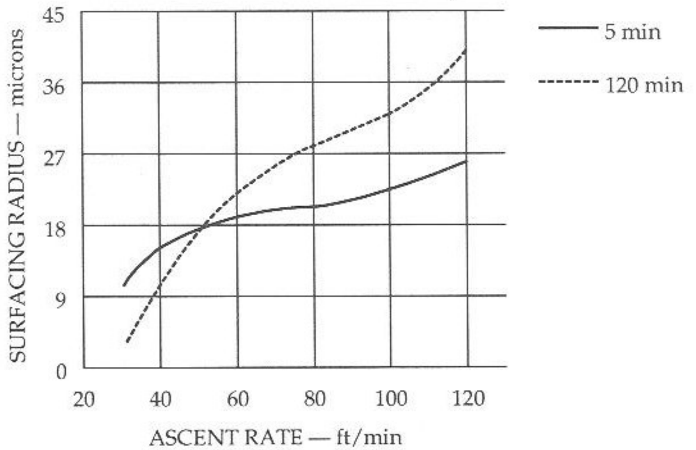
As mentioned, discussions at the American Academy Of Underwater Sciences ascent workshop, recorded by Lang and Egstrom, suggested discretionary safety stops for 2-4 *minutes* in the 10-20 *fsw* zone. Supporting calculations, recorded by Wienke, and summarized in Table 7, underscore the bases of the suggestions for a number of reasons. Relative changes in three computed trigger points, tissue tension, separated phase volume, and bubble





radius, are listed for six compartments following a nominal bounce dive to 120 *fsw* for 12 *minutes*, with and without a safety stop at 15 *fsw* for 3 *minutes*.

**FIGURE 11. BUBBLE GROWTH WITH VARYING ASCENT RATE**




The rate at which bubbles grow on ascent depends on their size and surface tension, and the average difference between tissue tension and ambient pressure. For bubbles larger than a certain critical (cutoff) radius, faster ascents in the presence of elevated gas tensions in surrounding tissue sites support growth, because average ambient pressure, P, is lessened by fast ascent. Increasing ambient pressure always restricts bubble growth, since internal bubble pressure is always greater than ambient pressure by the surface tension pressure, $2\gamma / r$. In this simple calculation, $2\gamma = 8.3$ fsw-micron, and unit solubility, concentration, and diffusivity are employed for simplicity. One notes that the growth rate in the 5 minute compartment is less than in the 120 minute compartment. Ostensibly, the faster compartment off-gases more rapidly during any ascent, presenting a lower average tension and weaker diffusion gradient for growth than the slower compartment. Larger surfacing radii for bubbles in both compartments result with increasing ascent rate, due to reduced ambient pressure on the average.

Stop procedures markedly restrict bubble and phase volume growth and dissolved gas buildup in the faster tissue compartments, while only supporting insignificant dissolved gas buildup in the slow tissues. The reduction in growth parameters far outstrips any dissolved gas buildup in slow compartments, and faster compartments naturally eliminate dissolved gases and bubbles during the stop, important for deeper diving.

| τ (min) half-time | tissue tension relative change | critical volume relative change | bubble radius relative change |
|---|---|---|---|
| 5 | -21% | -34% | -68% |
| 10 | -11% | -24% | -39% |
| 20 | -6% | -11% | -24% |
| 40 | -2% | -8% | -18% |
| 80 | 1% | 3% | -2% |
| 120 | 2% | 4% | 1% |

**TABLE 7. RELATIVE CHANGES IN CRITICAL PARAMETERS AFTER SAFETY STOP.**

Safety stop time can be added to bottom time for additional conservatism, but the effect of neglecting stop time is also small. A stop at 15 *fsw* for 2 *minutes* is roughly equivalent to more than halving the standard ascent rate at depths in excess of 120 *fsw*. Procedures such as this, as well as conservative non-stop time limits, appear beneficial in multi-day, multi-level, and repetitive diving. A safety stop near 15 *fsw* is easier than 10 *fsw* in adverse water conditions, such as surge and surface disturbances. Slower ascent rates afford additional advantages, but safety stops in the 2-4 *minute* range are easier and more efficient. Ascent rates slower than 60 *fsw/min* and safety stops in the 10-20 *fsw* zone are becoming routine in the regimens of recreational and scientific divers.

Bubble growth and excitation are compounded at altitude because of reduced pressure. Bubbles grow faster as they get bigger, and as ambient pressure drops. At altitude, bubble mechanics theoretically exacerbate decompression risk. Point to be made here is simple. Increased off-gassing pressures most likely reduce bubble growth rates dramatically in shallow zones, while impacting dissolved gas buildup in the slowest compartments minimally. Fast compartments also off-load gas and bubbles during slow ascents and safety stops, important for deep diving. Stops and slow ascent rates are always advisable, and particularly at altitude and in multi-diving activities.



# SUMMARY

In the foregoing, we have attempted to discuss and link a number of topics relating to:

1. Gas transport and phase dynamics
2. Nucleation and bubbles
3. Table and meter algorithms
4. Thermodynamics and pressure mechanics
5. Breathing gas mixtures
6. Data validation and testing
7. Physiological impacts of reduced pressure
8. Diving protocols at altitude

The underwater environment, with its rapidly changing ambient pressures, already presents pathophysiologic conditions potentiating a variety of afflictions, among them barotrauma, nitrogen narcosis, high pressure nervous syndrome, oxygen toxicity, and decompression sickness. Reduced surface pressures may compound these problems, while potentiating a few altitude specific afflictions. Conservative diving protocols thus seem prudent and well advised, and especially since altitude procedures have not been tested as extensively as sea level procedures.

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# APPENDIX

The Appendix details mathematical aspects mentioned, but not developed, in the text. Topics are included for completeness, and directed toward the more inclined and interested reader. Gas transport, critical tensions, altitude extrapolation, controlling tissues, gas mixtures, buoyancy, gauges, and consumption rates at elevation are treated.

## IDEAL GAS KINETICS

Most gases at room temperature obey a simple law relating pressure, $P$, volume, $V$, and temperature, $T$, of the form

$$P\,V = n\,R\,T \quad (1)$$

with $n$ the number of moles of gas, and $R$ the universal gas constant (8.317 *joule/mole*·°*K*). Temperature is measured in absolute, or Kelvin, degrees (°*K*). If the gases are non-reactive ($n$ is constant), changes in the state variables, $P$, $V$, and $T$, are linked to each other by the simple relationship

$$\frac{PV}{T} = nR = \gamma \quad (2)$$

with $\gamma$ constant. This is the ideal gas law in general form. If each of the variables is in turn held fixed, Eq. (2) then yields three well known ideal gas law corollaries:

$$PV = \gamma_T \quad \text{(Boyle's law)}$$





$$\frac{P}{T} = \gamma_V \quad \text{(Amonton's law)}$$

$$(3)$$

$$\frac{V}{T} = \gamma_P \quad \text{(Charles' law)}$$

with $\gamma_T = \gamma\,T$, $\gamma_V = \gamma\,/\,V$, and $\gamma_P = \gamma\,/\,P$ constants linked to $\gamma$, but not important here. Equations (3) connect any number of arbitrary changes of state for constant temperature, volume, or pressure. In a mixture of ideal gases, the total pressure is the sum of component gas partial pressures.

Temperatures are measured in degrees Centigrade (°C), Fahrenheit (°F), Kelvin (°K), and Rankine (°R), related by

$$°F = 1.8 \cdot °C + 32°$$

$$°K = °C + 273°$$

$$°R = °F + 460° \quad (4)$$

Rankine temperatures, °R, can also be used in the ideal gas equations with impunity.

## DISSOLVED GAS TRANSFER

All gases dissolve in all liquids, but actual solubilities range over many orders of magnitude. Considering inert gases at room temperature, for illustration, the solubility of xenon in *n*-octane, a hydrocarbon liquid, is 470 times that of helium in water. Gas solubilities can vary much more for complex solutes and solvents. The solubility of the anesthetic gas halothane in olive oil is more than $10^6$ times the solubility of common gases in liquid mercury. Inert *nitrogen* is readily soluble in tissues and blood, and its solubility forms the basis for dissolved gas model treatments of decompression.

Exchange of dissolved tissue and blood gas, controlled by blood flow rates across regions of varying concentration, is driven by the local gradient, that is, the difference between the arterial blood tension, $p_a$, and the instantaneous tissue tension, $p$. Such behavior is modeled in time, $t$, by simple classes of exponential response functions, bounded by $p_a$ and the initial value of $p$, denoted $p_i$. These multi-tissue functions satisfy a differential perfusion rate equation

$$\frac{\partial p}{\partial t} = -\lambda(p - p_a) \qquad (5)$$

and take the form, tracking both dissolved gas buildup and elimination symmetrically,

$$p - p_a = (p_i - p_a)\exp(-\lambda t)$$

where

$$\lambda = \frac{.6931}{\tau} = \frac{\ln 2}{\tau} \qquad (6)$$

with perfusion constant, $\lambda$, defined by the tissue half-time, $\tau$. Compartments with 1, 2.5, 5, 10, 20, 40, 80, 120, 180, 240, 360, 480, and 720 minute half-times, $\tau$, are employed, and half-times are independent of pressure.

In a series of dives or multiple stages, $p_i$ and $p_a$ represent extremes for each stage, or more precisely, the initial tension and the arterial tension at the beginning of the next stage. Stages are treated sequentially, with finishing tensions at one step representing initial tensions for the next step, and so on.

## CRITICAL TENSIONS

To maximize the rate of uptake or elimination of dissolved gases the *gradient*, simply the difference between $p_i$ and $p_a$, is maximized by pulling the diver as close to the surface as possible. Exposures are limited by requiring that the tissue tensions, $p$, never exceed criticality, $M$, written for each tissue compartment, $\tau$,

$$M = M_0 + \Delta M d \qquad (7)$$

as a function of depth, $d$, for $\Delta M$, the change per unit depth. A set of $M_0$ and $\Delta M$ are listed in Table 1, varying approximately as $\tau^{-1/4}$. In absolute pressure units, the corresponding critical gradient, $G$, is given by





$$G = \frac{M}{0.79} - P = 1.27\,M - P \qquad (8)$$

with $P$ ambient pressure, and $M$ critical nitrogen pressure. In bubble theories, supersaturation is limited by the critical gradient, $G$. In decompressed gel experiments, Strauss suggested that $G \cong 20$ *fsw* at ambient pressures less than a few atmospheres. Other studies suggest $14 \le G \le 30$ *fsw*, as a range of critical gradients ($G$-values).

## ALTITUDE SIMILARITY

At altitude, some critical tensions have been correlated with actual testing, in which case, the depth, $d$, is defined in terms of the absolute pressure

$$d = P - 33 \qquad (9)$$

with atmospheric pressure, $P_h$, at altitude, $h$, given by (*fsw*),

$$P_h = 33\exp(-0.0381h) = \frac{33}{\alpha}$$

$$\alpha = \exp(0.0381h) \qquad (10)$$

and $h$ in multiples of 1,000 *ft*. However, in those cases where critical tensions have not been tested nor extended to altitude, an exponentially decreasing extrapolation scheme, called *similarity*, has been employed. Extrapolations of critical tensions, below $P$ = 33 *fsw*, then fall off more rapidly then in the linear case, Eq. (9). The similarity extrapolation holds the ratio, $R = M/P$, constant at altitude. Denoting a *sea level equivalent depth*, $\delta$, at altitude, $h$, one has for an excursion to actual depth, $d$,

$$\frac{M(d)}{d + 33\alpha^{-1}} = \frac{M(\delta)}{\delta + 33} \qquad (11)$$

so that the equality is satisfied when

$$\delta = \alpha d$$

$$M(\delta) = \alpha M(d) \qquad (12)$$

Considering minimum bubble surface tension pressures (8 *fsw*), employed in computational modeling, as a limit point, the similarity extrapolation should be limited to 10,000 *ft* in elevation, and neither for decompression, nor heavy repetitive diving.

## CONTROLLING TISSUES

Blood rich, well-perfused, aqueous tissues are usually thought to be *fast* (small $\tau$), while blood poorer, scarcely-perfused, lipid tissues are thought to be *slow* (large $\tau$), though the spectrum of half-times is not correlated with actual perfusion rates in critical tissues. As reflected in Table 1, critical parameters are obviously larger for faster tissues. The range of variation with compartment and depth is not small, as noted in Figure 1. Fast compartments control short deep exposures, while slow compartments control long shallow, decompression, and saturation exposures.

Surfacing values are principal concerns in dissolved gas staging regimens, dictated by the necessity to maximize gradients through upward excursion. Phase models focus on the amount of separated gas, with corresponding pressure balance requiring gradients for bubble elimination to *increase* with depth, directly opposite to dissolved gas elimination gradients which *decrease* with depth. Then decompression becomes a playoff between dissolved gas buildup and free phase growth, tempered by body ability to eliminate both.

As is well known, bounce exposures are often limited by a depth-time law of the form

$$dt_{ns}^{1/2} = C \qquad (13)$$

with $t_{ns}$ the non-stop time limit, and $400 \leq C \leq 500$ $fsw{\cdot}min^{1/2}$. One can obtain the corresponding tissue constant, $\lambda$, controlling the exposure at depth $d$, for non-stop time $t_{ns}$, by differentiating Eq. (6) with respect to depth, $d$, and setting the result to zero.





With $p_a = 0.79\,(d + 33)$ at sea level, there results

$$1 - \exp(-\lambda t_{ns})(1 + 2\lambda t_{ns}) = 0 \qquad (14)$$

Corresponding critical tensions, $M$, are then easily obtained from Eq. (6) using $d$, $\lambda$, and $t_{ns}$. In the above case, the transcendental equation is satisfied when

$$\lambda t_{ns} = 1.25 \qquad (15)$$

## TIME REMAINING

Time remaining before a stop, time at a stop, or surface interval before flying can all be obtained by inverting Eq. (6). Denoting the appropriate critical tension at some desired stage, $M$, and the instantaneous tension at that time, $p$, at stage, $p_a$, the time remaining, $t_{rem}$, follows from

$$t_{rem} = \frac{1}{\lambda} \ln \left[ \frac{p - p_a}{M - p_a} \right] \qquad (16)$$

for each compartment, $\lambda$. Obviously, the smallest $t_{rem}$ controls the ascent.

## GAS MIXTURES

In the case of mixtures of gases (nitrogen, helium, hydrogen), the foregoing is generalized in a straightforward manner, using the set of nitrogen critical tensions, $M$, and half-times, $\tau$, as the bases. Denoting gas species, $k = N_2$, $He$, $H_2$; atomic masses, $A_k$; and partial pressures, $p_k$; each component satisfies a Haldane tissue equation, with rate modified coefficient, $\lambda_k$, given by

$$p_k - p_{ak} = (p_{ik} - p_{ak}) \exp(-\lambda_k t) \qquad (17)$$

for $p_{ak}$ and $p_{ik}$ ambient and initial partial pressures of the $k^{th}$ species, and with decay constant, $\lambda_k$, related by Graham's law to the nitrogen coefficient, $\lambda_{N_2} = \lambda$, by

$$\lambda_k = \left[\frac{A_{N_2}}{A_k}\right]^{1/2} \lambda \qquad (18)$$

Thus, for instance, one has

$$\lambda_{He} = 2.7\lambda$$

and

$$\lambda_{H_2} = 3.7\lambda \qquad (19)$$

For an arbitrary mixture of $K$ inert gases, the decompression requirement is simply

$$\sum_{k=1}^{K} p_k \leq M \qquad (20)$$

for all exposures. Denoting ambient partial pressures, $p_{ak}$, as a fraction, $f_k$, of total pressure, $P$, that is,

$$p_{ak} = f_k P \qquad (21)$$

it follows that

$$f_{O_2} + \sum_{k=1}^{K} f_k = 1 \qquad (22)$$

neglecting any carbon dioxide or water vapor in the mixture, of course. For 75/25 (enriched) nitrox, $f_{N2} = 0.75$, for 90/10 heliox, $f_{He} = 0.90$, for 75/10/15 trimix, $f_{He} = 0.75$, $f_{N2} = 0\ .10$, while for 95/5 hydrox, $f_{H2} = 0.95$. For pure air, obviously $f_{N2} = 0.79$, as the common case. Clearly the treatment of breathing mixtures assumes a single critical tension, $M$, for each compartment, $\tau$, in this case, extracted from the nitrogen data.

With enriched nitrox ($f_{N2} < 0.79$), it is clear that the nitrogen decompression requirements are reduced when using the same set of $M$, that is, the air set of $M$ are assumed to apply equally to both air and other nitrogen mixtures. The procedure has been applied to heliox, trimix, and hydrox mixtures in similar vein. One important constraint in any mixture is the





oxygen content. Partial pressures of oxygen must be kept below 52.8 *fsw* (1.6 *atm*) to prevent toxicity, and above 5.3 *fsw* (0.16 *atm*) to prevent hypoxia. Balancing diver mobility within this window at increasing depth is a delicate procedure at times.

## BUOYANCY CHANGES

Wetsuits expand at elevation, while fresh water is less dense than salt water. Both affect diver buoyancy because of Archimedes principle and Boyle's law. Consider the wetsuit effect at altitude first.

## WETSUIT

Gas bubbles in wetsuits are subject to Boyle's law as external pressure changes, though the response is something less than 55% of the volume change predicted by the gas law. To estimate the buoyancy increase due to wetsuit expansion at elevation, we compute the effect using Archimedes' principle and Boyle's law directly, and then scale the result by the factor 0.55, as a figure of merit. Denoting the volume of the wetsuit on the surface at sea level, $v_0$, and the corresponding volume at altitude, $v_h$, we have by the gas law,

$$33 v_0 = P_h v_h \qquad (23)$$

with $P_h$ surface pressure at altitude. The theoretical buoyancy change (gain), $\Delta B_{alt}$, at altitude is given by

$$\Delta B_{alt} = \rho(v_h - v_0) \qquad (24)$$

with ρ the actual water density. Using Eq. (23), it follows that

$$\Delta B_{alt} = \rho v \left[\frac{33}{P_h} - 1\right] \qquad (25)$$

Making the assumption that the wetsuit offsets the weight belt, somewhere near 10% of diver body weight, $w$,

$$\rho v = 0.10w \tag{26}$$

and that the expansion of the wetsuit is some 55% of maximum, Eq. (25) reduces to

$$\Delta B_{alt} = 0.055w\left[\frac{33}{P_h} - 1\right] \tag{27}$$

Approximating ambient pressure at altitude,

$$P_h = \frac{33}{\alpha} \approx 33(1 - 0.038h) \tag{28}$$

with $h$ the elevation in multiples of 1,000 *ft*, we find

$$\Delta B_{alt} = 0.0019wh \tag{29}$$

as the approximate buoyancy gain, good to few percent up to 7,000 *ft*.

## FRESH AND SALT WATER

Application of Archimedes' principle directly to a diver submerged in fresh and salt water at sea level yields the fresh water buoyancy loss, $\Delta B_{sea}$. Denoting total diver plus gear weight, $w$, and the corresponding volume of water displaced at sea level in salt water, $v$, we have for neutral buoyancy,

$$W = \rho v \tag{30}$$

with $\rho$ sea water density. The difference in buoyant forces acting upon an object of displaced volume, $v$, in fresh water and salt water is the buoyancy change (loss)

$$\Delta B_{sea} = \rho v(\eta - 1) = W(\eta - 1) \tag{31}$$





with $\eta$ the fresh water *specific* density (ratio of fresh water to salt water density). Taking $\eta = 0.975$, there results

$$\Delta B_{sea} = -0.025W \tag{32}$$

with the minus sign denoting a buoyancy loss.

## GAUGE CALIBRATIONS

Capillary gauges employ pressure ratios to register depths, using a sea level ratio calibration point, while bourdon and oil filled gauges measure direct pressure and subtract off sea level atmospheric pressure to register depths. The mechanics are seen as follows, taking the capillary gauge first.

## CAPILLARY GAUGES

In any fluid, capillary gauge readings are dependent on the volume of compressed air in the tube. Out of the fluid, at atmospheric pressure, $P_h$, the volume of the tube occupied by air, $v_{max}$, is maximum. At actual depth, $d$, the volume of the tube, $v$, occupied by air is less (because of compression). At depth, $d$, the total pressure, $P$, is simply

$$P = P_h + \eta d \tag{33}$$

with $\eta$ the fluid specific density. By Boyle's law, the volumes are related by

$$(p_h + \eta d)\, v = P_h v_{max} \tag{34}$$

for any specific density, $\eta$, and any surface pressure $P_h$. Capillary gauges are calibrated for sea level atmospheric pressure, $P_0 = 33$ *fsw*, and in salt water, $\eta = 1$, at some depth, $\delta$, so that the volume ratio reduces

$$\frac{v_{max}}{v} = \left[\frac{33 + \delta}{33}\right] \tag{35}$$

In any other fluid, at actual depth, $d$, the corresponding gauge reading, $\delta$, can be obtained by substituting the calibration relationship into Eq. (34) and simplifying, with the result

$$\delta = \left[\frac{33}{P_h}\right]\eta d \tag{36}$$

For fresh water, $\eta = 0.975$, as noted, and atmospheric pressure, $P_h$, at elevation, $h$, is given by Eq. (10).

## BOURDON AND OIL FILLED GAUGES

Other gauges measure absolute ambient pressure and mechanically subtract off surface pressure to give a reading. Thus, at depth, $d$, a bourdon or oil filled gauge in fluid of specific density, $\eta$, senses ambient pressure, $P$, subtracts off a constant, $X$, and registers a mechanical response, $Y$,

$$Y = \eta d + P_h - X \tag{37}$$

If calibrated at depth, $\delta$, in salt water, $\eta = 1$, for sea level atmospheric pressure, $P_0 = 33\ fsw$, then

$$Y = \delta + 33 - X \tag{38}$$

Substituting Eq. (38) into Eq. (37) yields the gauge reading, $\delta$, in any fluid, $\eta$, at actual depth, $d$, for any surface pressure, $P_h$,

$$\delta = \eta d + P_h - 33 \tag{39}$$

in analogy to Eq. (36) for a capillary gauge.

## AIR CONSUMPTION RATES

Denoting the altitude surface consumption rate, $\chi_h$, the consumption rate, $\chi$, at depth, $d$, and implied elevation, $\alpha$, scales directly with the pressure; that is, neglecting the 3% density difference between salt and fresh water for simplicity,





$$\chi = \chi_h \left[1 + \frac{d\alpha}{33}\right] \tag{40}$$

The total pressure, $P$, satisfies a similar relationship in terms of surface pressure, $P_h$,

$$P = P_h + d = \frac{33}{\alpha} + d = \frac{33}{\alpha}\left[1 + \frac{\alpha d}{33}\right] \tag{41}$$

At any altitude, consumption rates increase rapidly with depth, offsetting reduced surface rates. The surface rate at altitude, $\chi_h$, is related to the surface rate at sea level, $\chi_0$, by the relationship

$$\chi_h = \frac{\chi_0}{\alpha} \approx \chi_0(1 - 0.038h) \tag{42}$$

for $h$ the usual elevation in multiples of 1,000 *ft*.

## SAMPLE ALTITUDE EXERCISE

Putting all of the foregoing together, consider a diver who leaves a site at 80 *ft* elevation, makes two dives at 4895 *ft* elevation using an oil filled gauge, and then plans on a destination site at 10,755 *ft* elevation. The diver weighs 148 *lbs* and his gear weighs an additional 46 *lbs*. Gearing up at the dive site takes 80 *minutes*. The first dive is to 51 *fsw* (on the gauge) for 25 *minutes*, and the second dive, separated by a 215 *minute* surface interval, registers 27 *fsw* for 65 *minutes*. Using the US Navy tables and Table 2 directly, the worksheet below summarizes all pertinent altitude calculations and decompression table manipulations impacting the diver, that is, buoyancy changes, gauge corrections, ascent and descent rate, altitude correction factor, equivalent depths, actual depths, arrival and destination groups, and profile.

## SAMPLE ALTITUDE EXERCISE WORKSHEET

Diver Weight *148 lbs.*

Gear Weight *46 lbs.*

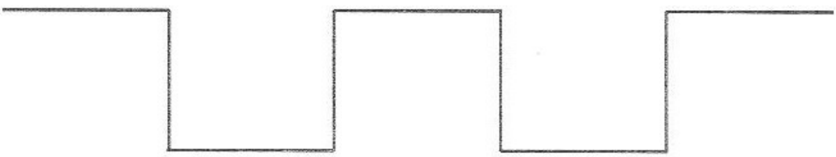
$\Delta B_{alt}$ *1.3 lbs*

$\Delta B_{sea}$ *– 4.9 lbs.*

| | | | |
|---|---|---|---|
| Embarkation Altitude | *80 feet* | | |
| Dive Site Altitude | *4895 feet* | | |
| Correction Factor | *1.20* | Destination Altitude | *10755 feet* |
| Arrival Group | *D* | Permissible Group | *G* |

Ascent Rate *50 ft./min.*

D → 1:20 → C H → 3:35 → C I → 3:35 → G



| | | | |
|---|---|---|---|
| Gauge Depth/Time | *51/25* | Gauge Depth/Time | *27/65* |
| Correction/Residual Time | *+6.5/15* | Correction/Residual Time | *+5.8/25* |
| Actual Depth/Time | *57.5/40* | Actual Depth/Time | *32.8/90* |
| Sea Level Depth/Time | *69/40* | Sea Level Depth/Time | *39.4/90* |