TECHNICAL DIVING PRIMER AND WORKBOOK

RGBM Technical Series 7

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FORWARD

As land dwelling, air breathing creatures, we have evolved perceptions, behaviors, practices, and procedures for living in an air atmosphere. Venturing into the underwater world, many things change. A number of important physical changes affect this underwater world and are important to us as technical and commercial divers. This monograph discusses these changes and suggests application problems that will help to quantify underlying physical principles affecting underwater activities.

Technical diving used to be the pervue of just commercial and military divers. Today, highly motivated and well trained recreational divers are pushing diving to new depths, on mixed gases, with sophisticated electronic sensors and dive computers, using modern rebreathers, wearing special exposure suits, in the oceans, lakes, and at high altitude. This new breed of diver receives training from any one of a number of new technical agencies, like the National Association of Underwater Instructors (NAUI), Technical Diving International (TDI), International Association Of Nitrox And Technical Divers (IANTD), and Association Of Nitrox Diving Instructors (ANDI), as well as the older recreational agencies, such as PADI, YMCA, SSI, and NASDS. For the technical diver and working commercial diver, this monograph is hopefully both a training tool and extended reference.

Technical diving encompasses a wide spectrum of related disciplines, from geophysics to biophysics, atmospherics physics to hydrodynamics, medical physics to engineering physics, and mathematical physics to statistical analysis. The scope is immense, and so any monograph has to be selective, and probably not in depth as possible. And diving physics can be a tedious exercise for readers. Obviously, physiology is an even more complicated mix of physics, chemistry, and biology. Like comments apply to decompression theory, a combination of biophysics, physiology, and biochemistry in a much cloudier picture within perfused and metabolic tissue and blood. Biological systems are so complex, beyond even the fastest and biggest supercomputers for modeling analysis. Often, the tedium relates to a proliferation of equations and deduced results.

So, selectivity without mathematical complexity is the direction we take here in narrative. Mathematical equations are kept at definitional level to facilitate description. The hope is to better encapsulate a large body of underlying physical principle in very readible form. Sample problems, with solutions, are included to enhance quantitative description and understanding. Topics are fundamental and chosen in their relevance to technical diving. Bibliographies do offer full blown treatments of all principles detailed for diving. For highlight, Figures include mathematical definitions for completeness, with the intended purpose of extending discourse. Problems (101) employ quantitative relationships detailed in the text, using data and information from Tables and Figures.

Many thanks to our mutual and separate friends and colleagues, collaborators in the industrial, medical, and diving sectors, and to technical and commercial divers who posed many nitty questions about diving. Their queries prompted this monograph on diving physics, physiology, geophysics, marine phenomenon, biophysics, decompression models, algorithms, tables, and related topics.

Special thanks to Luzanne and Diane for being spectacular women in all ways, and to Hillary and Seana for reminding us that adults have much to learn from children.

Good reading, and good diving always.

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Pages - 100, Figures - 15, References - 115, Problems - 101

LEARNING OBJECTIVES

Hopefully by the end of this monograph, you will be able to:

- understand concepts presented in headings and subsections;
- discuss English and metric systems of units, and be able to easily convert back and forth between the systems;
- describe the basic mechanical laws of nature;
- describe how light, heat, and sound transmission are affected by water;
- describe the simple gas laws in diving, and associated phase dynamics;
- discuss breathing gas mixtures and impact on diving activity;
- describe the basic thermodynamic laws of nature;
- discuss temperature scales and their relationships;
- describe how pressure and density changes affect the diver underwater;
- describe how pressure and density changes affect diver equipment underwater;
- describe how dive tables amd meter algorithms limit diving activities;
- describe common diving maladies in a cursory fashion;
- work sample technical diving problems.

OVERVIEW AND UNITS

The physics, biology, engineering, physiology, medicine, and chemistry of diving center on pressure, and pressure changes. The average individual is subjected to atmospheric pressure swings of 3% at sea level, as much as 20% a mile in elevation, more at higher altitudes, and all usually over time spans of hours to days. Divers and their equipment can experience compressions and decompressions orders of magnitude greater, and within considerably shorter time scales. While the effects of pressure change are readily quantified in physics, chemistry, and engineering applications, the physiology, medicine, and biology of pressure changes in living systems are much more complicated. Caution is needed in transposing biological principles from one pressure range to another. Incomplete knowledge and mathematical complexities often prevent extensions of even simple causal relationships in biological science. Causal relationships between observables are, of course, the pervue of physics, and that difficult process in living systems is biophysics. In the underwater realm, *diving physics* is collectively the quantification of pressure related natural phenomena, and that certainly includes elements of geophysics, oceanography, astrophysics, and geology, as well.

With such understanding, this primer focuses on diving physics and associated mathematical relationships. Basic principles are presented, and practical applications and results are detailed. Topics discussed are related to diver, diving protocols, and operational procedures. Topics include the usual energy and matter interactions, particle and wave mechanics, heat, light, sound, gas kinetics, thermodynamics, phase dynamics, temperature, nucleation and and cavitation, gas mixtures, hydrostatics, and their coupling in diving. Standard (SI) and English 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) and meters of sea water (msw), with 1 atm = 33 fsw = 10 msw to very good approximation.

Units And Equivalences

Notation for units are also abbreviated according to standard convention, otherwise spelled out. The abbreviated units include second (sec), minute (min), hour (hr), meter (m), millimeter (mm), centimeter (cm), micrometer ($micron$), nanometer (nm), kilometer (km), gram (g), kilogram (kg), pound (lb), inch (in), foot (ft), yard (yd), miles per hour (mph), liter (l), milliliter (ml), quart (qt), calorie (cal), pounds per square inch (psi), newton (nt), dyne (dyn), atmosphere (atm), British thermal unit (btu), horsepower (hp), gram molecular weight ($gmole$), atomic mass unit (amu), electrostatic unit (esu), coulomb ($coul$), ampere (amp), feet of sea water (fsw), and meters of sea water (msw).

Units are easily converted using the *chain rule* or *equivalence ratio*, that is, simple multiplication of a measurement, or unit count, by the conversion ratio. For instance, to convert 3 *nautical mile* to *kilometers*, one merely multiplies 3 *nautical mile* by the ratio, $1.85\ km/nautical\ mile$, and cancels units to get the answer in *kilometers*, $3\ nautical\ mile \times 1.85\ km/nautical\ mile = 5.55\ km$. Multiple equivalence ratios can also be chained to give conversions. To convert 230 *cal* to *ergs*, one might use, $230\ cal \times 4.19\ j/cal \times\ 10^7\ ergs/j = 963.7 \times 10^7\ ergs$, or any one of a number of other equivalence chains. Table 1 equivalences SI, English, and other units. Each equivalence can be cast as conversion ratio.

Table 1. Equivalences And Unit Conversions.

Time

$$\begin{aligned} 60\ sec &= 1\ min \\ 1\ megahertz &= 10^6\ sec^{-1} \end{aligned}$$

Length

$$\begin{aligned} 1\ cm &= .39\ in \\ 1\ m &= 3.28\ ft \\ &= 1.09\ yd \\ 1\ micron &= 10^{-6}\ m \\ 1\ km &= .62\ mile \\ 1\ fathom &= 6\ ft \\ 1\ nautical\ mile &= 6,080\ ft \\ &= 1.15\ mile \\ &= 1.85\ km \\ 1\ light\ year &= 9.46 \times 10^{12}\ km \\ &= 5.88 \times 10^{12}\ mile \end{aligned}$$

Speed

$$\begin{aligned} 1\ km/hr &= 27.77\ cm/sec \\ 1\ mph &= 5280\ ft/sec \\ 1\ knot &= 1.15\ mph \\ &= 51.48\ cm/sec \end{aligned}$$

Volume

$$\begin{aligned} 1\ cm^3 &= .06\ in^3 \\ 1\ m^3 &= 35.32\ ft^3 \\ &= 1.31\ yd^3 \\ 1\ l &= 10^3\ cm^3 \\ &= .04\ ft^3 \\ &= .91\ qt \end{aligned}$$

Mass and Density

$$\begin{aligned}
1\ g &= .04\ oz \\
1\ kg &= 32.27\ oz \\
&= 2.20\ lb \\
1\ g/cm^3 &= .57\ oz/in^3 \\
1\ kg/m^3 &= .06\ lb/ft^3
\end{aligned}$$

Force and Pressure

$$\begin{aligned}
1\ nt &= 10^5\ dyne \\
&= .22\ lb \\
1\ g/cm^2 &= .23\ oz/in^2 \\
1\ kg/m^2 &= .20\ lb/ft^2 \\
1\ atm &= 33\ fsw \\
&= 10\ msw \\
&= 10.1\ nt/cm^2 \\
&= 14.69\ lb/in^2
\end{aligned}$$

Energy and Power

$$\begin{aligned}
1\ cal &= 4.19\ j \\
&= 3.96 \times 10^{-3}\ btu \\
&= 3.09\ ft\ lb \\
1\ j &= 10^7\ ergs \\
&= .74 ft\ lb \\
1\ keV &= 10^3\ eV \\
&= 1.60 \times 10^{-16}\ j \\
1\ amu &= 1.66 \times 10^{-24} g \\
1\ watt &= 1\ j/sec \\
&= 3.41\ btu/hr \\
&= 1.34 \times 10^{-3}\ hp
\end{aligned}$$

Electricity and Magnetism

$$\begin{aligned}
1\ coul &= 2.99 \times 10^9\ esu \\
1\ amp &= 1\ coul/sec \\
&= 1\ volt/ohm \\
1\ volt &= 1\ nt\ coul\ m \\
&= 1\ j/coul
\end{aligned}$$

Breathold diving dates as far back as Xerxes (519 *BC*) and Alexander the Great (356 *BC*), and was chronicled by the Greek historian, Herodotus, some 500 years before Christ. Reed breathing tubes were employed by ambushing Roman Legions, and primitive diving bells also date *BC*. The inverted receptacles, utilizing Boyle's law compressed air as breathing mixture, gained renown in the 1600s. Persians also carried air in goatskins underwater. Today, some Korean and Japanese breathold divers still gather pearls and sponges in the same old way.

As early as 1880, Fleuss developed and tested the first closed circuit, oxygen rebreathing system. At that time, of course, oxygen toxicity was not completely understood, though the effects of breathing pure oxygen were coupled to excitability and fever. In ensuing years, the apparatus was refined considerably, and was used by underwater combatants in World War II. During the 1950s, recreational divers used oxygen rebreathers. However, by the late 1950s, recreational divers switched to the popular open circuit device developed by Cousteau and Gagnan, thereby trading oxygen toxicity and caustic carbon dioxide concerns for decompression sickness and nitrogen narcosis. Today, rebreathers are witnessing a rebirth among technical divers. And, US Navy Underwater Demolition (UDT) and Sea Air Land (SEAL) Teams have continuously employed rebreathers for tactical operations.

Surface supplied air and demand regulators were employed in hard hat diving by the 1800s, with the first demand regulator, patented by Rouquayrol in 1866, supplied by hand bellows. The first case of nitrogen narcosis was reported by Junod in 1835. Full diving suits, in which air escapes through a one way exhaust valve, were invented in 1840, and a few are still around. Quietly, the revolutionary *aqua lung* of Cousteau, a refinement of the Rouquayrol surface supplied demand regulator, ushered the modern era of SCUBA in wartime Europe in 1943. Diving would never be the same afterward. Freed from surface umbilical, the open and closed circuit units provided an element of stealth to tactical underwater operations to be sure, but the impact on non military diving was orders of magnitude greater. Coupled to high pressure compressed air in tanks, SCUBA offered the means to explore the underwater world for fun and profit.

Commercial availability of the demand regulator in 1947 initiated sport diving and a fledgling equipment industry. Serious diver training and certifying agencies, such as the YMCA, National Association of Underwater Instructors (NAUI), and Professional Association of Diving Instructors (PADI), strong and still vital today, organized in the late 1950s and 1960s. In the mid 1950s, the Royal Navy (RN) released their bulk diffusion decompression tables, while a little later, in 1958, the US Navy (USN) compiled their modified Haldane tables with six perfusion limited compartments. Both would acquire biblical status over the next 25 years, or so. In the mid to late 1950s, Fredrickson in the USA and Alinari in Italy designed and released the first analog decompression meters, or computers, emulating tissue gas uptake and elimination with pressure gauges, porous plugs, and distensible gas bags. The first digital computers, designed by DCIEM in Canada, appeared in the mid 1950s. Employed by the Canadian Navy (CN), they were based on a four compartment analog model of Kidd and Stubbs. Following introduction of a twelve compartment Haldanian device, linked to Doppler technolgy, by Barshinger and Huggins in 1983, decompression computers reached a point of maturation and acceptance. Flexible, more reliable to use, and able to emulate almost any mathematical model, digital computers rapidly replaced pneumatic devices in the 1980s. Their timely functionality and widespread use heralded the present era of hi-tech diving, with requirments for comprehensive decompression models across a full spectrum of activity. Computer usage statistics, gathered in the 1990s, point to an enviable track record of diver safety, with an underlying decompression sickness (DCS) incidence below 0.05% roughly.

Diver mobility concerns ultimately fostered development of the modern SCUBA unit, and the quest to go deeper led to exotic gas breathing mixtures. High pressure cylinders and compressors similarly expedited deeper diving and prolonged exposure time. The world record dives of Keller to 1,000 feet of sea water, in 1960, not only popularized multiple gas mixtures, but also witnessed the first use of computers to generate decompression schedules. Saturation diving and underwater habitats followed soon after, spurred by a world thirst for oil. Both multiple gas mixtures and saturation diving became a way of life for some commercial divers by the 1970s, particularly after the oil embargo. Oil concerns still drive the commercial diving industry today.

Cochrane in England invented the high pressure caisson in 1830. Shortly afterward, the first use of a caisson in 1841 in France by Triger also witnessed the first case of decompression sickness, aptly termed the bends because of the position assumed by victims to alleviate the pain. Some fifty years later, in 1889, the first medical lock was employed by Moir to treat bends during construction of the Hudson River Tunnel. Since that time many divers and caisson workers have been treated in hyperbaric chambers. Indeed, the operational requirements of diving over the years have provided the incentives to study hyperbaric physiology and its relationship to decompression sickness, and impetus for describing fundamental biophysics. Similarly, limitations of nitrogen mixtures at depth, because of narcotic reactivity, prompted recent study and application of helium, nitrogen, hydrogen, and oxygen breathing mixtures at depth, especially in the commercial sector.

Increases in pressure with increasing depth underwater impose many of the limitations in diving, applying equally well to the design of equipment used in this environment. Early divers relied on their breathholding ability, while later divers used diving bells. Surface supplied air and SCUBA are rather recent innovations. With increasing depth and exposure time, divers encountered a number of physiological and medical problems constraining activity, with decompression sickness perhaps the most restrictive. By the 1800s, bubbles were noted in animals subject to pressure reduction. In the 1900s, they were postulated as the cause of decompression sickness in caisson workers and divers. Within that postulate, and driven by a need to both optimize diver safety and time underwater, decompression modeling has consolidated early rudimentary schedules into present more sophisticated tables and meters. As knowledge and understanding of decompression sickness increase, so should the validity, reliability, and range of applicability of models.

Modern Diving

A concensus of opinions, and for a variety of reasons, suggests that modern diving began in the early 1960s. Technological achievements, laboratory programs, military priorities, safety concerns, commercial diving requirements, and international business spurred diving activity and scope of operation. Diving bells, hot water heating, mixed gases, saturation, deep diving, expanded wet testing, computers, and efficient decompression algorithms signaled the modern diving era. Equipment advances in open and closed circuit breathing devices, wet and dry suits, gear weight, mask and fin design, high pressure compressors, flotation and buoyancy control vests, communications links, gauges and meters, lights, underwater tools (cutting, welding, drilling, explosives), surface supplied air, and photographic systems paced technological advances. Training and certification requirements for divers, in military, commercial, sport, and scientific sectors, took definition with growing concern for underwater safety and well being.

In the conquest and exploration of the oceans, saturation diving gained prominence in the 1960s, permitting exploitation of the continental shelf impossible with the short exposure times allowed by conventional diving. Spurred by both industrial and military interests in the ability of men to work underwater for long periods of time, notable *habitat* experiments, such as Sealab, Conshelf, Man In Sea, Gulf Task, Tektite, and Diogene, demonstrated the feasibility of living and working underwater for long periods of time. These efforts followed proof of principle validation, by Bond and coworkers (USN) in 1958, of saturation diving. Saturation exposure programs and tests have been conducted from 35 fsw to 2,000 fsw.

The development and use of underwater support platforms, such as habitats, bell diving systems, lockout and free flooded submersibles, and diver propulsion units also accelerated in the 1960s and 1970s, for reasons of science and economics. Support platforms extended both diver usefulness and bottom time, by permitting him to live underwater, reducing descent and ascent time, expanding mobility, and lessing physical activity. Today, themselves operating from underwater platforms, remotely operated vehicles (ROVs) scan the ocean depths at 6,000 fsw for minerals and oil.

Around 1972, strategies for diving in excess of 1,000 fsw received serious scrutiny, driven by a commercial quest for oil and petroleum products, and the needs of the commercial diving industry to service that quest. Questions concerning pharmacological additives, absolute pressure limits, thermal exchange, therapy, compression-decompression procedures, effective combinations of mixed breathing gases, and equipment functionality addressed many fundamental issues, unknown or only partially understood. By the early 1980s, it became clear that open sea water work in the 1,000 fsw to 2,000 fsw range was entirely practical, and many of the problems, at least from an operational point of view, could be solved. Today, the need for continued deep diving remains, with demands that cannot be answered with remote, or 1 atm, diver systems. Heliox and trimix have become standards for deep excursion breathing gases, with heliox the choice for shallower exposures, and trimix the choice for deeper exposures in the field.

Yet, despite tremendous advances in deep diving technology, most of the ocean floor is outside human reach. Breathing mixtures that are compressible are limiting. Breathing mixtures that are not compressible offer interesting alternatives. In the 1960s, serious attention was given to liquid breathing mixtures, physiological saline solutions. Acting as inert respiratory gas diluents, oxygenated fluids have been used as breathing mixtures, thereby eliminating decompression requirements. Some synthetic fluids, such as fluorocarbon (FX^{80}), exhibit enormous oxygen dissolution properties.

MATTER

Matter is anything that occupies space, usually in solid, liquid, or gaseous state Matter has definite mass and volume, can change form and phase, and consists of tiny atoms and molecules. A gram molecular weight ($gmole$) of substance, that is, an amount of substance in grams equal to its atomic weight, A, possesses Avogadro's number, N_0, of atoms or molecules, some 6.025×10^{23} constituents. At standard temperature and pressure (STP), a gram mole of ideal gas occupies 22.4 l, that is, at 0 C^o and 1 atm pressure. Molecules of a gas are in constant motion. Liquid molecules are free to move and slide over each other, while loosely bound. Molecules in a solid are relatively fixed, but can oscillate about their lattice points. Elements are collections of all the same atoms. They are the building blocks of nature, and number somewhere over 100 in natural occuring abundance.

Matter cannot be created nor destroyed, but it can be transformed by chemical and nuclear reactions. In the most general sense, matter and energy are equivalent. For instance, the nuclear and chemical binding energies of molecules and atoms result from very small mass reductions in constituent particles (mass defect) when in bound states. The postulate of the conservation of mass-energy is fundamental, and cannot be derived from any other principle. Stated simply, mass-energy can neither be created nor destroyed. All of observable science is based on this premise.

Atomistics And Elementals

The concept that one or a few elementary substances could interact to form matter was originated by Greek philosophers in the Sixth Century, BC. The atomic hypotheses, indispensable to our understanding of chemical elements, originated with the philosopher Leucippus and follower Democritus in the Fifth Century, BC. These two interacting concepts of elements and atoms are unsurpassed in their importance to the development of science and technology.

Aristotle accepted from earlier philosophers that air, water, earth, and fire were elements, and he added a fifth, the ether, representing the heavenly bodies. Although all matter was formulated from these elements, the elements themselves represented qualities and were nonmaterial. Centuries later, as alchemists found new transformations, three more were added to the list, namely, sulfur, mercury, and salt. These were thought to represent the quantities of combustibility, volatility, and incombustibility. This view prevailed for about 2000 yr.

In 1661, on the heels of Democritus, Robert Boyle developed a chemical atomic theory, giving definition to chemical elements as certain primitive and simply unmingling bodies. Boyle also deduced the ideal gas law from experiments in the laboratory. A century later, Lavoisier composed a list of elements based on experimentally verifiable definition, that is, a chemical substance is one that cannot be decomposed into simpler structures by chemical means. The list was some 30 elements long, and was based on some careful studies of decomposition and recombination. The list included some stable compounds, such as silica and alumina, which defied decomposition with existent technology, and also heat and light. The Greek notion was still lingering.

Continued work by Lavoisier led to the law of definite proportions, which states that in any given compound, the elements always occur in the same proportions by weight no matter how the compound is synthesized. This was generalized to the law of equivalent weights, or that weight which will combine with or replace a unit of standard weight from a standard element, such as hydrogen.

Two centuries later, in 1808, John Dalton postulated an atomic theory that incorporated atomic weight as distinguished from equivalent weight (but including equivalent weight as a supercase) and was capable of explaining empirically derived and observed laws of chemical combination. Dalton postulated:

1. all atoms of a given element are identical but different from the atoms of another element
2. compounds are formed from these elemental atoms;

3. chemical reactions result from the atoms being arranged in new ways;
4. if only one compound can be formed from X and Y, then that compound contains one X and one Y atom.

The fourth assumption (incorrect as we know) suggested that nature is more simple than real. Lussac, Avogadro, and Cannizzaro later corrected Dalton's fourth assumption, merely by interjecting nX and mY atoms in the chemical reaction stream. Mendeleev, in 1865, using these assumptions constructed the first Periodic Chart, with 65 elements in the list.

Mendeleev made an important discovery while looking for relationships among these elements. The properties of the elements are periodic functions of their atomic weights. This periodic law allows the arrangement of elements in the table in order of increasing weight, such that the table contains columns and rows of elements with similar properties, by row and/or column (Periodic Table). For the first time in history, it was shown that the chemical elements form an entity in their interrelationships, and seemingly undiscovered elements with predictable properties could be sought to fill holes in the table. Today, the Periodic Table has been filled, so to speak, for $Z \leq 94$ in the natural world. However, particle accelerators and cosmic probes continue the search for *superheavies*, with a number of short lived elements already added to the Table (californium, einsteinium, fermium, rutherfordium, hahnium, nobelium, curium, berkelium, and others).

Clearly pressure and density are fundamental concepts at the lowest level of description. Both stem from Feynman's conjecture that the *atomic hypothesis*, namely all things are made of atoms moving in perpetual motion, is the most succint statement we can make about scientific knowledge. Atoms have mass, occupy space, collide with each other, and can repel or attract each other. That atoms have mass, occupy space, and move in collisional paths is a microscopic statement that matter has density, exerts pressure, and links temperature to measure collisional speeds. Macroscopically, such a fundamental conception exhibits itself in the equation of state of a solid, liquid, or gas. The equation of state relates pressure, density, and temperature in one relationship. That atoms attract or repel one another is the basis of chemical, atomic, and elementary particle reaction kinetics.

Atoms may certainly stick together (attract into bound states), forming larger molecules that also have mass, occupy space, and move in collisional paths. Molecules may also attract or repel other atoms and molecules. Or they may directly interact producing new species after binding or colliding. And the process continues along the same path to larger fundamental blocks. Molecules, may synthesize into macromolecules, and so on. Soon the process results in matter on perceivable state and scale (liquid, gas, or solid). The atomistics view is totally compatible with our level of perception and we can measure down to the atomistic level.

But, if we lived in a smaller world (subatomic), we might point to the substructure of electrons, neutrons, and protons comprising atoms. And then we would suggest that quarks, partons, and gluons, thought to be the building blocks of subatomic particles are the objects of the succint statement applied to atoms. And then the structure of these components might be further divided.

Both pressure and density are intuitive, fundamental concepts, elucidated and measured at early times in our scientific history by the Greeks, Romans, Babylonians, Egyptians, and probably others, well before atomic hypotheses. Pressure, P, is simply the force, F, per unit area, A, that is,

$$P = \frac{F}{A} \tag{1}$$

and is equal in all directions (scalar quantity, while force itself is formally a vector quantity). As seen, pressure in gases results from molecular collisions with surroundings. Pressure from extended matter results from the collective forces applied across boundaries of fluids and solids.

Density

The concepts of mass and corresponding occupied volume are fundamental perceptions. The mass, m, in unit volume, V, is the mass density, ρ,

$$\rho = \frac{m}{V} \ , \tag{2}$$

and gases are usually the least dense, followed by fluids, and then solids. Weight density is often used, simply the weight, w, in unit volume, V. Table 2 lists densities of the naturally occuring elements. The three states of the same matter usually have much different densities. The interactions of the macroscopic states of matter are generically termed mechanics. The specific density, η, of a liquid is its density divided by the density of seawater, a convenient quantity in diving circles.

MECHANICAL INTERACTIONS

Mechanics itself is concerned with the effects of forces to produce or retard motion (kinetic energy), change position, induce material deformation, or cause chemical and nuclear reactions (potential energy). Forces may be gravitational, nuclear, or electromagnetic in origin. Mechanical properties describe the change in shape of matter when external forces are applied. Examples include the simple bending of a beam, the propagation of sound waves, the permanent deformation of metals into useful shapes, and the flow of liquids and gases around obstacles. For matter in the liquid and gaseous state, the usual force is the hydrostatic pressure, and deformation is a change in volume. For matter in the solid state, both tensile and shearing forces come into play to produce deformations, such as elongations and shear distortions.

Force And Momentum

Force is a push or a pull. Newton's first law states that a body in motion tends to stay in motion unless acted upon by an unbalanced force. Forces, F, acting upon bodies of mass, m, produce accelerations, a, linked by Newton's second law,

$$F = ma \quad , \tag{3}$$

with acceleration, a, velocity, v, and displacement, s, all measured over time, t,

$$v = \frac{ds}{dt} \quad , \tag{4}$$

$$a = \frac{dv}{dt} \tag{5}$$

with dv, ds, and dt instantaneous changes in the same quantities, and with t the time. The most general representation of force, however, is the time rate of change of momentum, p,

$$p = mv \quad , \tag{6}$$

that is,

$$F = \frac{dp}{dt} \quad , \tag{7}$$

with dp and dt instantaneous changes in momentum and time.

Newton's third law states that for every action, there is an equal and opposite reaction. Stated another way, for every applied force, there is an equal and opposite reaction force, a stipulation requiring the conservation of momentum in all directions. A diver, propelling himself through the water also pushes the water away from hi,self with the same momentum.

A force applied across an element of surface area, perpendicular to the surface element, generates a pressure, P, given by,

$$P = \frac{F}{A} \quad , \tag{8}$$

with F and A the elements of force and surface area. Pressure at a point is equal in all directions, and is not a specifically directed (vector) quantity.

Table 2. Densities Of Elements.

element	Z	A	ρ (g/cm^3)	element	Z	A	ρ (g/cm^3)
H	1	1.008	.0009	*Cd*	48	112.41	8.65
He	2	4.003	.0017	*In*	49	114.82	7.28
Li	3	6.940	.53	*Sn*	50	118.70	6.52
Be	4	9.013	1.85	*Sb*	51	121.76	6.69
B	5	10.82	2.45	*Te*	52	127.61	6.24
C	6	12.01	1.62	*I*	53	126.91	4.93
N	7	14.08	.0013	*Xe*	54	131.30	.0059
O	8	16.00	.0014	*Cs*	55	132.91	1.87
F	9	19.00	.0017	*Ba*	56	137.36	5.52
Ne	10	20.18	.0009	*La*	57	138.92	6.19
Na	11	22.99	.971	*Ce*	58	140.13	6.78
Mg	12	24.32	1.74	*Pr*	59	140.92	6.78
Al	13	26.98	2.70	*Nd*	60	144.27	6.95
Si	14	28.09	2.42	*Pm*	61	145.01	7.23
P	15	30.98	1.82	*Sm*	62	150.35	7.70
S	16	32.06	2.07	*Eu*	63	152.08	5.22
Cl	17	35.46	.0032	*Gd*	64	157.26	7.95
Ar	18	39.94	.0018	*Tb*	65	158.93	8.33
K	19	39.10	.87	*Dy*	66	162.51	8.56
Ca	20	40.08	1.55	*Ho*	67	164.94	8.76
Sc	21	44.96	2.52	*Er*	68	167.27	9.16
Ti	22	47.90	4.58	*Tm*	69	168.94	9.35
V	23	50.95	5.96	*Yb*	70	173.04	7.01
Cr	24	52.01	7.10	*Lu*	71	174.99	9.74
Mn	25	54.94	7.22	*Hf*	72	178.53	13.32
Fe	26	55.85	7.86	*Ta*	73	180.95	16.62
Co	27	58.94	8.91	*W*	74	183.86	19.28
Ni	28	58.71	8.86	*Re*	75	186.22	20.53
Cu	29	63.54	8.94	*Os*	76	190.24	22.48
Zn	30	65.38	7.14	*Ir*	77	192.18	22.42
Ga	31	69.72	5.91	*Pt*	78	195.09	21.37
Ge	32	72.60	5.36	*Au*	79	197.02	19.39
As	33	74.91	5.73	*Hg*	80	200.61	13.55
Se	34	78.96	4.79	*Ti*	81	204.39	11.85
Br	35	79.92	3.12	*Pb*	82	207.21	11.35
Kr	36	83.82	.0037	*Bi*	83	209.03	9.75
Rb	37	85.48	1.53	*Po*	84	210.06	9.24
Sr	38	87.63	2.54	*At*	85	211.12	10.24
Y	39	88.92	5.52	*Rn*	86	222.13	.0010
Zr	40	91.22	6.43	*Fr*	87	223.09	
Nb	41	92.91	6.45	*Ra*	88	226.05	5.04
Mo	42	95.95	10.21	*Ac*	89	227.13	
Tc	43	98.02		*Th*	90	232.09	11.32
Ru	44	101.12	12.23	*Pa*	91	231.12	15.43
Rh	45	102.91	12.53	*U*	92	238.07	18.91
Pd	46	106.42	12.22	*Np*	93	237.52	
Ag	47	107.88	10.52	*Pu*	94	239.12	19.73

Energy And Work

Energy in simplest terms is the ability to do work. Or equivalently, the ability to do work requires an interchange of energy between a system and its surroundings. Energy takes two main forms, kinetic and potential. Kinetic energy is the energy associated with motion. Potential energy is the energy associated with position in a force field. Binding energy is the energy associated with changes in both kinetic and potential energies in bound composite systems, undergoing chemical, nuclear, or molecular interactions. Electromagnetic and acoustical energies are kinetic and potential energies associated with light and pressure waves. Heat energy can be kinetic energy associated with random molecular translations, vibrations, and rotations, or potential energy of frictional surface distortions and stress fatigue, nuclear and chemical reactions, and phase transformations. In all processes known to man, mass-energy is conserved, which is to say that mass can be converted to energy, and vice versa.

The kinetic, K, and potential, U, energy of particle depend on its mass, m, and speed, v, and position, h, in a gravitational field (or any other force field for that matter),

$$K = \frac{1}{2} m v^2 \quad , \tag{9}$$

$$U = mgh \quad , \tag{10}$$

with g the acceleration of gravity (32 ft/sec^2). Kinetic and potential are easily exchanged in physical processes. The total energy, H, is the sum of the kinetic and potential energy,

$$H = K + U \quad , \tag{11}$$

and, in the ideal case, is a constant of motion, with potential and kinetic energy freely exchanging, but always summing to the same H.

In the general (relativistic) sense, mass and energy are equivalent, as mentioned, which follows as a consequence of the constancy of the speed of light in any inertial frame. An inertial frame is a frame of reference moving with constant velocity (no acceleration). Einstein postulated that the laws of physics are identical for two observers moving with constant velocity with respect to each other, the first law of relativity, and that the speed of light, c, is a constant independent of relative motion between reference frames, the second law of relativity. Accordingly, the energy, E, associated with a moving particle of rest mass, m, is given by,

$$E = \gamma m c^2 \quad , \tag{12}$$

for c the speed of light, and,

$$\gamma = (1 - v^2 \, / \, c^2)^{-1/2} \quad , \tag{13}$$

with v the particle speed. The corresponding kinetic energy of motion, K, is written,

$$K = (\gamma - 1) \, m c^2 \quad , \tag{14}$$

while the momentum, p, takes the form,

$$p = \gamma m v \quad , \tag{15}$$

Power

Power, W is simply the rate of energy change, that is,

$$W = \frac{dH}{dt} \tag{16}$$

with dH the energy change in time dt. Power obviously measures how fast energy is being consumed, exchanged, generated, or dissipated in physical interactions.

The interactions of matter and energy are sometimes broken down into light, heat, and sound. Macroscopically, this is a classical division, suitably splitting mechanics into major observable categories, but with the understanding that each is a detailed science by itself.

Light

Light is energy in the form of radiation, equivalently regarded as photons (particles) or electromagnetic packets (waves). Light, regarded as photons in the energy range, $2.5 \times 10^{-19}\ j$ up to $5.2 \times 10^{-19}\ j$, or electromagnetic waves in the wavelength range, 380 up to 800 *nm*, causes sensation of vision. Solar radiation reaching the Earth's surface is peaked in this same spectral range, a range where humans and animals possess sensitive receptors. Light forms a small part of the continuous spectrum of electromagnetic radiation, which encompasses radio waves and infrared radiation at wavelengths longer than light, and ultraviolet, x-ray, gamma ray, and cosmic ray radiation at progressively shorter wavelenghts. Treated as photons, light possess particle energy, ε, associated with wave frequency, f,

$$\varepsilon = hf \tag{17}$$

for h Planck's constant ($6.625 \times 10^{-34}\ j\ sec$). The *colors* of light, namely red, orange, yellow, blue, indigo, and violet, span a frequency range, $3 \times 10^{14}\ sec^{-1}$ up to $8 \times 10^{14}\ sec^{-1}$ with red the least energetic and violet the most energetic component. The combination of all colors together is white light, that is, what our eyes see as sunlight on the Earth.

In a vacuum, light (waves or photons) travels at constant speed, c, but in a material medium, however, photons are absorbed and re-emitted by molecules, slowing down the speed of propagation in the medium. This retardation is represented by an index of refraction, n. Refractive index, n, is really a function of wavelength, so that two light beams of different color (wavelength) propagate through materials at different speeds. Across the visible spectrum, differences in refractive indices are small. In glass, 0.009 is the difference between blue and red light indices of refraction. Table 3 lists refractive indices of a few materials.

Table 3. Refractive Indices.

media	refractive index n	media speed of light c/n (m/sec)
vacuum	1.0000	2.99 x 10^8
air	1.0003	2.98 x 10^8
glass	1.4832	2.02 x 10^8
quartz	1.4564	2.05 x 10^8
steam	1.3178	2.27 x 10^8
salt water	1.3340	2.24 x 10^8
pure water	1.3321	2.24 x 10^8

When light passes from one medium to another, it is refracted and reflected according to the refractive indices of the media. Figure 1 depicts the the relationships between angles of incidence, ϕ, refraction, $\phi^{'}$, reflection, $\phi^{''}$, and the indices of refraction, n and $n^{'}$, assuming $n^{'} > n$. In terms of refractive indices, we have because of phase equality of incident, reflected, and refracted waves,

$$n \sin \phi = n^{'} \sin \phi^{'} = n \sin \phi^{''} \ . \tag{18}$$

Therefore, the angle of incidence equals the angle of reflection,

$$\phi = \phi^{''} \ , \tag{19}$$

and the refracted angle, $\phi^{'}$, satisfies Snell's law,

$$n \sin \phi = n^{'} \sin \phi^{'} \ . \tag{20}$$

Figure 1. Incidence, Reflection, And Refraction Of Light

Plane electromagnetic waves, such as light, striking the surface between two transmitting media, with refractive indices, n and n'*, experience reflection and refraction according to Snell's law,*

$$\phi = \phi''$$

$$n \sin \phi = n' \sin \phi'$$

with the case drawn for $n' > n$*.*

The most general form for waves propagating across interfaces supporting different propagation speeds is written,

$$\frac{sin\ \phi}{v} = \frac{sin\ \phi^{'}}{v^{'}} \ \ , \tag{21}$$

with v and $v^{'}$ the propagation velocities. Such bending (refraction) occurs with electromagnetic, acoustical, thermal, plasma, and shock wave propagation. As a limiting case in the less dense optical media (smallest refractive indices), with incident rays approaching and angle of incidence of 90^o (grazing incidence), the refracted ray approaches a critical value, $\phi^{'}_c$, beyond which no refracted light is possible,

$$sin\ \phi^{'}_c = \frac{n}{n^{'}} \ \leq \ 1 \ \ . \tag{22}$$

Water is transparent to light. Although a glass of water seems to allow all the light to pass through, it is obvious that as one goes deeper underwater, it gets darker. In the ocean, with so much water available, the amount of light energy absorbed becomes important. Water clarity and lack of turbidity are also primary factors in determining light penetration in different regions, or layers. Thus, it is difficult to determine at what depth water becomes dark. Some indication of light penetration is the depth at which microscopic plants exist underwater, because marine plants, like land plants, require light for photosynthesis. The vertical region in the ocean where light exists is called the *euphotic* zone, existing from the surface down to where only 1% of the light remains. The lower limit varies from 45 fsw along the coasts, down to as much as 500 fsw in the clear tropical zones. As one descends, white sunlight is selectively absorbed, starting with the red part of the spectrum, and then continuing to the green and blue parts. Colors, such as red, perceived in fish and other creatures underwater, do not come from surface light. Pigments in these creatures absorb the remaining blue-green light, and then remit the light as red. At a depth of 33 fsw, little or no color distinction is possible. There are no shadows, and light seems to be coming from all around. At 330 fsw, visibility is limited to a few feet. At 950 fsw, all is quite dark.

Unlike sound waves encountering density interfaces, light transmission through opaque liquid interfaces is only slightly attenuated, with energy passing easily from one media to the other. Because of refraction, however, perceived images of source objects differ across the interface separating the two media. Such refractive phenomena change image size and relative position, the study of which is called optics.

Optics

Optics deals with ray phenomena that are not dependent in any way on the wave or quantum behavior of light. In geometrical optics, light travels along straight lines, or rays, in homogeneous media, which are bent at the interfaces separating media, or curved in media with variable refractive indices. At any point along a fan of rays emitted by an object point source of light, there is a surface everywhere perpendicular to the rays, called the wave front. The wave front is the locus of points reached by light after a given time along all possible ray paths. If the wave front emerging from a lens or other optical interface is a true sphere, a perfect image will be formed. Any departure from a true sphere represents the presence of optical aberrations, or, more simply, image distortions. An optical system consists of an assembly of mirrors, lenses, prisms, and apertures, usually with spherical surfaces to facilitate precise image formation. The human eye is an optical system consisting of lenses, apertures, and image forming planes.

Each ray from an object point, after passing through an optical system (such as the eye), strikes a specified image plane at a single point, with all such points for all possible rays passing through the system constituting the geometrical image of the source as formed by the optical system. While the number of rays are infinite, only a few rays, strategically chosen with regard to the optical system, are actually traced in an image assembly called a spot diagram. The spot diagram represents an outline picture of the image produced by the optical system, but lacking fine structure caused by light wave interference and diffraction. In spite of microstructural limitations, the simple ray tracing technique can quantify gross relationships between souce and image sizes, distances, focal lengths, and refractive indices of optical media.

Refraction of paraxial rays (very nearly normally incident), as shown in Figure 2 is a good example of the power of ray tracing techniques in optical applications. The ratio of image to object distance, σ, is termed *shortening*, while the ratio of image to object height, μ, is the *lateral magnification*. For paraxial bundles of rays, the dispersion is small and the bundle is clustered at near normal incidence. Under these conditions,

Figure 2. Virtual Images And Refraction At Plane Surfaces

Objects viewed through a plane surface separating media of refractive indices, n and n'*, are seen clearly, but not necessarily in their true position nor size. As virtual images, they appear closer or farther away, smaller or larger, depending on the indices of refraction. The actual distance, s, in media, n, and the apparent distance,* s'*, in media,* n'*, are related through the paraxial relationship (near normal incidence),*

$$s' = \frac{n'}{n} s$$

When looking into water from air, an object underwater is foreshortened by a factor of 3/4, the ratio of air to water refractive indices, and magnified by the reciprocal, 4/3.

$$\sigma = \frac{n'}{n} \quad , \tag{23}$$

$$\mu = \frac{n}{n'} \quad . \tag{24}$$

Objects underwater, viewed at the surface, appear larger and closer than their actual size and position. The shortening is 3/4, while the lateral magnification is 4/3, taking $n = 4/3$ for water, and $n' = 1$ for air. The opposite occurs underwater, when viewing an object above the surface. Underwater viewing of surface objects is also limited by the critical angle, ϕ_c. Outside the viewing cone, limited by ϕ_c underwater, no surface images can be transmitted through the water to the eyes.

The eyes focus using paraxial rays. The ability to accommodate angular spread in the paraxial bundle is called peripheral vision. The greater the ability to accommodate angular dispersion in rays striking the eye, the greater is the corresponding peripheral vision. Cutting off the most widely dispersed rays in the bundle reaching the eyes, for instance, with a mask underwater, causes tunnel vision, or the perception of a brightly illuminated foreground, and dark peripheral background

The refraction and focusing of overhead sunlight by wave motion produces the pattern of light ripples often seen on sandy bottoms below shallow, clear water. Wave crests act like converging lenses, focusing light rays into spatial regions of higher intensity, while the troughs act like diverging lenses, defocusing light rays into spatial regions of lesser intensity.

Sound

Any change in stress or pressure leading to a local change in density, or displacement from equilibrium, in an elastic medium can generate an acoustical wave. Acoustics is concerned with fluctuations in mechanical properties characterizing the state of matter, such as pressure, temperature, density, stress, and displacement. Primary acoustical measurements determine the magnitude and wave structure of one of these mechanical properties, whereas secondary measurements characterize the propagation speed and the rate of dissipation of acoustical energy. Table 4 lists sound speeds in various media.

Sound propagation is but one aspect of acoustics. When we speak, we utter sound. Someone nearby hears the sound. In studying the production and reception of sound, and transmission through media, acoustics is a discipline of physics, but speech and hearing obviously invoke biological elements and processes. When speaking, a slight disturbance is produced in the air in front of the mouth, a compression resulting in a change in air pressure near 1 $dyne/cm^2$. Since air is an elastic medium, it does not stay compressed and expands again passing on the disturbance to its neighbor. That neighbor in turn passes the disturbance on to its next neighbor, and so on, resulting in a pressure fluctuation that moves through the air column in the form of a sound (acoustical) wave. Reaching the ear of an observer, the disturbance moves the eardrum, which in turn displaces the little bones in the middle ear, communicating motion to the hair cells in the cochlea, with the ultimate biophysical interpretation of the hearing of the sound by the brain. Underwater, of course, sound travels faster than in air, and the signals received confuse our brain. The end result is that we hear sound, but can't localize sound underwater. The near and far ears, serving as differential signal sensors, receive signals too closely spaced in time to separate.

A great bulk of data gathered about the ocean bottom, and other underwater objects, uses sound navigation and ranging, or *sonar*. Sonar may be active or passive. Passive sonar is equipment that listens to noises underwater, and can determine presence and relative direction of sound sources. Active sonar, or echo sounding, acts like radar, sending out an acoustical signal which is reflected back to a receiver. If sounding from the bottom, the depth is equal to 1/2 the time for the signal to leave and return, multiplied by the speed of sound in water, about 4,950 ft/sec. Ships tracing out prescribed paths can continuously map the bottom with sonar.

Table 4. Sound Speeds At Standard Temperature And Pressure.

media	sound speed u (m/sec)
vacuum	0
air	333
steel	5302
copper	3292
parafin	1305
wood	2984
salt water	1452
pure water	1461

Acoustical waves are readily reflected at air-water interfaces, and very little is transmitted. For an air-water interface, we have transmission and reflection factors, T and R, given by,

$$T = .0081 \ , \tag{25}$$

$$R = .9919 \ , \tag{26}$$

in approximately both cases (air-water, or water-air propagation), using nominal values of water and air densities, and acoustical speeds. These results parallel electromagnetic wave propagation across a metallic-dielectric (conducting-nonconducting) interface.

Heat

In thermodynamics, heat denotes the quantity of energy exchanged by thermal interaction of any system with its environment. For example, if a flame is applied to a cool metal plate, the energy content of the plate increases, as evidenced by its temperature increase, and we say that heat has passed from the flame to the plate. If energy losses to the surrounding air can be ignored, the heat transferred from the flame is equal to the energy gain of the plate. In more complex processes, involving mechanical as well as thermal interactions, the heat transferred is more difficult to identify. Thermodynamics focuses on the controlled and slow evolution of heat, energy, and entropy, and the distinctions between them in mechanical systems. While heat is a tenuous concept, linked to observables such as internal energy change and external work, we often deal with systems at different temperatures, exchanging heat in the absence of mechanical interactions, or external forces.

Heat, then, is the energy exchanged between parts of mechanical systems at different temperatures. Three fundamental and well known mechanisms include convection, conduction, and radiation. In practical situations, near standard temperatures and pressures, heat exchange usually involves the first two, conduction and convection. Radiative transfer underscores fairly high temperatures.

Heat conduction is the exchange of heat from one body at a given temperature to another body at a lower temperature with which it is in contact. Transfer of molecular kinetic energy occurs directly by molecular impacts or collisions. Heat conduction is governed by Fourier's law,

$$\phi = -K \frac{dT}{dx} \tag{27}$$

with heat flux, ϕ, conductivity, K, and dT the temperature drop across the region dx.

Heat convection is a special case of conduction that occurs when a fluid or gas flows past the outer boundary of a system. Then the determination of K involves solving the fluid equations of a viscous, heat conducting fluid or gas, coupled to the heat flow equations in the system. Table 5 summarizes specific heats, conductivities, and corresponding densities for a cross section of materials.

Radiative transfer is a different mechanism completely from conduction and convection. The mechanism is electromagnetic wave emission from a heated surface, with the spectrum of wavelengths a complex function of surface temperature. For a point (idealized) source at temperature, T, the radial (isotropic) heat flux, ϕ, is given by the Stefan-Boltzmann relationship,

$$\phi = \sigma_0 T^4 \ , \tag{28}$$

with T the temperature, and $\sigma_0 = 5.67 \times 10^{-8}\ watt/m^2\ K^{o4}$.

The most complex heat transfer phenomena are those in which extended physical systems interact by combinations of the above, in addition to phase transformations such as boiling, condensation, or solidification.

Table 5. Specific Heats, Conductivities, And Densities.

material	specific heat c_P $(cal/g\ C^o)$	conductivity K $(cal/sec\ cm\ C^o)$	density ρ (g/cm^3)
air	.242	.0001	.00024
iron	.121	.0858	16.623
aluminum	.207	.5375	2.721
polyethylene	.912	.6939	.925
neoprene	.381	.0004	.189
glass	.135	.0025	2.312
salt water	.949	.0013	1.025
pure water	1.00	.0014	1.000
alcohol	.653	.0010	.791

Radiation is absorbed in passing through matter, and the fraction absorbed is characteristic of the material. The ratio of absorbed to incident radiation at a certain wavelength is called the absorptivity, α, and depends on the wavelength. A body with absorptivity equal to one is called a *black* body. Perfect black bodies do not exist in nature, but there are many approximate black bodies, especially in the infrared, or long wavelength, region. Of the incident radiation that is not absorbed, part is reflected and part is transmitted. The ratio of reflected to incident radiation is called the reflectivity, ρ, and the ratio of transmitted to incident radiation is called the transmissivity, τ. Obviously, the three quantities are related by,

$$\alpha + \rho + \tau = 1 \ . \tag{29}$$

For a black body, $\rho = \tau = 0$, and $\alpha = 1$. A molecule which absorbs radiation at a particular wavelength is also able to emit radiation at the same wavelength.

Equation Of State

The relationship between pressure, volume, and temperature for any substance is called the equation of state (EOS). In the case of solids and liquids, equations of state are typically quite complicated, mainly because molecular interactions in solids and liquids are extended (long range). Gases, however, present a simpler situation. Interactions of gas molecules are localized (short range), compared to solids and liquids, and the corresponding equation of state reflects the point nature of interactions.

Long before kinetic theory and statistical mechanics provided the molecular basis for gas laws, chemists (and probably alchemists) deduced that, under pressure, P, volume, V, and temperature, T, changes, to good order of the day,

$$\frac{PV}{nT} = R \ , \tag{30}$$

for n the number of moles of the gas, with R a constant, and temperature, T, measured on an absolute (K^o) scale. Obviously, their range of investigation was limited in phase space, but it is still interesting to note that all gas laws reduce to the simple form in the limit of low pressure, for any temperature. Specific volume, v, is the molal volume,

$$v = \frac{V}{n} \ , \tag{31}$$

so that we write,

$$\frac{Pv}{T} = R \ . \tag{32}$$

In terms of the number of molecules of the gas, N, and Avogadro's number, N_0, we also have,

$$n = \frac{N}{N_0} \quad . \tag{33}$$

With this subset of definitions, the relationship between pressure, volume, temperature, and number of moles of gas is called the *ideal gas law*, and R is the *universal gas constant* ($8.317 \ j/gmole \ K^o$).

If the temperature is kept constant, the pressure increases linearly with inverse specific volume. If the pressure is kept constant, the specific volume varies linearly with temperature, or, if the volume is kept constant, the pressure increases linearly with temperature. The fact that real gases approximate this behavior has been known for centuries, in fact, the quantifications are often called the laws of Boyle, Charles and Gay-Lussac, after the eighteenth century investigating chemists.

Many equations have been proposed quantifying gas behavior more accurately than the ideal gas law. Some are empirical, while others derive from fundamental molecular assumptions. In the latter 1800s, van der Waals proposed the following equation of state,

$$\left(P + \frac{a}{v^2}\right) \ (v - b) = RT \quad , \tag{34}$$

with a and b constants, arising from the presence of intermolecular forces and the actual volume occupied by the gas molecule itself. A range of values for light gases like hydrogen and helium is,

$$50 \ \le \ a \ \le \ 3000 \, nt \ m/kgmole^2 \quad , \tag{35}$$

$$0.020 \ \le \ b \ \le \ 0.032 \, m^3/kgmole \quad . \tag{36}$$

In the limit of large specific volumes, a/v^2 is small compared with P, and b becomes negligible compared to v. The van der Waals equation then goes over to the ideal gas law, as do other equations of state at large specific volumes.

In compressed gas diving applications, use of the ideal gas law is usually correct to a few percent in detailing gas behavior, with deviations occuring only at very high pressures.

Wave Motion

All waves transport energy, no matter how complex the interaction with matter. Wave motion pervades all mechanical interaction. Waves can be *transverse*, in which case they oscillate in directions perpendicular to the direction of energy transport, or they can be *longitudinal*, in which case they oscillate in direction of energy transport. Electromagnetic waves in a vacuum are transverse, while acoustical waves in a frictionless media are longitudinal. Water waves are combination of both, possessing tranverse and longitudinal components.

Waves are *linear* or *nonlinear*. Amplitudes of oscillation of linear waves are usually scalar quantities, so that the waves can be added, or *superposed*, linearly. Amplitudes of oscillation of nonlinear waves are often vector quantities, so that waves cannot be added, or superposed, linearly. Acoustical waves are linear, while water and electromagnetic waves are nonlinear.

Media supporting wave propagation are *dispersive* or *nondispersive*. Wave speeds, u, in nondispersive media are independent of frequency, f, or wavelength, λ, with,

$$u = f\lambda \quad . \tag{37}$$

Wave speeds in dispersive media depend on wavelength in complicated fashion. Water and plasma waves exhibit dispersion, while light waves in a vacuum and acoustical waves in air exhibit nondispersion.

Interference phenomena, or the interaction of different waves, are common to all wave motion, whether linear or nonlinear, tranverse or longitudinal, dispersive or nondispersive. When two waves waves interact, a third forms wave by superposition (addition). The addition process is not simple arithmetic, however, rather a process of adding time vary sinusoids together. The resultant wave exhibits classical interference patterns of reinforcement and cancellation in time and space. All waves, dispersive or nondispersive, linear or nonlinear, transverse or longitudinal, exhibit similar interference patterns of reinforcement and cancellation (*constructive* or *destructive* interference), but with more complicated dependence on time, position, wavenumber, and frequency.

If two sinusoids of the same amplitude and frequency, but travelling in opposite directions, interfere, the resultant wave is called a *standing* wave, because the interference pattern has fixed nodes (zero points of oscillation) Waves propagating continuously (without breakup and reformation) in a media generate interference patterns described above. If waves breakup, reform, and propagate anew, the interference pattern is more complicated, and the process is termed *diffraction*.

Diffraction refers collectively to the scattering of a wave train into many small wavelets, and the subsequent recombination of the wavelets into a new wave train. Passage of a wave train through a small aperture, through a scored grating, or by a knife edge falls into this category. Propagation of waves into regions of geometrical shadow is another example. The passage of water waves past a narrow breakwater, light through a ruled lens, and X-rays off crystalline lattices is diffractive.

Holography, or wave front reconstruction, is one of the more important applications of optical diffraction. Holographic photography differs from regular photography in that holographic cameras record light reflected from every point on the object, not just the light forming an image on the photographic plane. The hologram consists of a hodgepodge of specks, blobs, blurs, and whorls, bearing no resemblance to the object. Nevertheless, the hologram contains in special code, and decipherable only upon application of diffraction theory, all the information about an object that would be contained in a regular photograph, plus other information that cannot be recorded in a photograph. Applications of holography span information storage, image processing, metrology, and biomedical analysis.

RHEOLOGY

Rheology is the interdisciplinary study of the deformation and flow of material under internal and external forces. Rheology tries to correlate macroscopic response and flow of solids, liquids, and gases with constitutive equations spanning atomic, molecular, intermolecular, and broader domain scales. Irreversible processes, such as macroscopic flow, heat generated by internal friction, mechanical aging, fatigue, solid deformation, shearing, and stressing can be collectively quantized through constitutive equations. The mechanical relationships, describing the change in shape or flow of matter under internal and external forces, are also called the *material* properties.

Deformation

A solid is *elastic* if the amount of deformation is directly proportional to the applied force, implying that the deformation process is reversible and independent of the way the force is applied. A solid is *inelastic* if the displacement depends on the rate, or direction, of the applied force. Interest in the elastic and inelastic properties of matter date back to Galileo.

For most metals and ceramics, the rate dependent effects are small, but play an important role in the dissipation of oscillational energy, causing damping of vibrations in machines and oscillating mechanical systems. In plastics and rubbers, inelastic contributions to deformations are large, and these types of materials are termed *viscoelastic*. The categorization, *plastic* solid, or plastic deformation, is appropriate for materials in which deformation is a nonlinear, irreversible function of the applied force. Examples include the permanent deformation of metals by large forces, the response of organic polymers, and glass at high temperature. Deformations are part of a class of destructive forces called dissipative.

Friction and viscosity are also dissipative forces, tending to convert kinetic energy into mostly heat and potential energy that is not recoverable. Frictional and viscous forces impart irreversibility to physical processes, contributing to overall increase in entropy. Perpetual motion machines, indefinite oscillations, and perfect multi-directionality of physical phenomena are precluded because of dissipative mechanisms. Yet, without frictional and viscous forces, we could not walk on the Earth, drive cars, nor swim underwater with fins.

Friction

Friction is the tangential force necessary to overcome resistance in sliding contacting surfaces against each other, under a normal force pressing the surfaces together. Friction is mainly a surface phenomenon, depending primarily on conditions at the interfacial surfaces. By definition, friction is the ratio of the magnitudes of the required moving force, F, to the normal (load) force, N, and takes the form,

$$\mu = \frac{F}{N} \ , \tag{38}$$

with the coefficient of friction, μ, ranging from small to large values. For lubricated surfaces, μ ranges from 0.001 to 0.2, for dry surfaces, μ, varies between 0.1 and 2.0, while for ultraclean surfaces, μ becomes very large. For ultrasmooth surfaces, μ is large because of large cohesive forces, while for very rough surfaces, μ is large because of high asperity interlocking.

The maximum value of frictional force required to start sliding is known as *static* friction, while the amount of frictional force necessary to maintain sliding is known as *kinetic* friction. Static friction is always slightly greater than kinetic friction. Some static coefficients of friction for metals are listed in Table 6 below. Kinetic coefficients are no more than 5% to 10% less.

Table 6. Coefficients Of Static Friction

metal	against itself	against steel
aluminum	1.3	0.6
brass	1.4	0.5
bronze	1.2	0.4
copper	1.3	0.8
iron	0.4	0.4

Contact between surfaces that are dry, and ordinarily rough, usually involves the tips of tall asperities. thus, total contact area is only a small fraction of the entire interfacial area. Tips adhere to opposing surfaces, and must be sheared if motion is to occur. Total force requisite to shear these junctions is roughly the product of the shear strength of the materials times the area of all junctions at the onset of sliding.

Wear (*tribology*), concerned with the loss or transfer of material in contact, results from many interactive frictional forces, including adhesion, abrasion, corrosion, fatique, and worse, combinations of all. The volume of wear (material lost), w, is proportional to the applied normal load, N, distance moved or slid, x, and inversely proportional to the material hardness, β, so that,

$$w = k \left(\frac{Nx}{\beta} \right) \ , \tag{39}$$

with k the proportionality constant, obviously a function of many variables. Lubrication attempts to mitigate wear by imposing films of foreign substances between contacting bodies, with films solid (graphite), fluid (oil), or chemically active substances. Elastohydrodynamic lubrication occurs in highly loaded assemblies with changes in fluid viscosities under high pressure and temperature, seen, for instance, in multiple viscosity oil for car engines and compressors.

Viscosity

Fluid flow is invariably accompanied by drag, that is, mechanical work is expended to keep the fluid in motion, and is then converted into heat. The effect is linked to *viscosity*, or internal fluid friction as it is termed in analogy to material properties. Viscosity arises in fluids and gases as a result of momentum transfer between adjacent layers of molecules, simply, shear forces resulting from velocity differences between molecules in interacting layers. Velocity differences can arise through applied forces, temperature differences, boundary effects, or local turbulence and mixing. Like friction, viscosity is dissipative, tending to resist motion, or changes in motion.

In gases, viscosity is proportional to the square root of absolute temperature, and is essentially independent of pressure. For actual gases, viscosity is indeed constant over a wide range of pressures, somewhere in the range of 0.01 *atm* up to 10 *atm*. In liquids, on the other hand, viscosity falls off rapidly with increasing temperature. Additionally, viscosity in liquids has a short range, intermolecular force component.

Measurement of viscosity is simple, conceptually. Two plates of cross sectional area, A, separated by a distance, dx, are placed in a fluid. The force, F, required to induce a small velocity change, dv, with respect to the other, in parallel direction, defines the viscosity, X, through the relationship,

$$F = XA \left(\frac{dv}{dx} \right) \quad . \tag{40}$$

The statement above assumes that the shear process does not alter the gas or fluid structure. Certainly for gases this poses no problems, but for fluids, this may not always be true. For instance, within polymers, the shearing and flow result in partial alignment of elongated molecules.

Shocks

Shocks are wave disturbances propagating at supersonic speeds in materials, characterized by rapid rise in local pressure, density, and temperature in frontal regions. Shock waves are generated by the sudden release of large amounts of energy in a small region, for instance, detonations in high explosives, passage of supersonic aircraft in the atmosphere, or discharges of lightning bolts in a narrow air channel. Shock waves, not sustained in propagation, lose energy through viscous dissipation, reducing to ordinary sound (acoustical) waves.

Detonation waves are special types of self-sustaining shock waves, in which exothermal reactions move with supersonic speed into the undetonated material, compressing, heating, and igniting chemical reactions that sustain shock propagation. The detonation process usually requires a shock wave to initiate reactions. Deflagrations, or flames, differ from shocks and detonation waves because deflagrations propagate at subsonic speeds.

A unique feature of shock wave propagation in gases is the high shock temperatures attainable, near 15,000 K^o. Such high temperatures are very useful for the study and application of shock tubes to measurements of reaction rate processes in science and aeronautics. Measurements of chemical reaction, vibrational relaxation, dissociation, and ionization rates have been effected with shock tubes, over large temperature ranges. Modified shock tubes can be used as short duration wind tunnels, so to speak, producing high Mach number ($\mu = 16$), high temperature ($T = 6,000\ K^o$) environments replicating the gas dynamics encountered by missiles and reentry vehicles (RVs). Conventional wind tunnels are constrained by Mach numbers approximately half shock tube Mach numbers.

The shock equation of state, simply the relationship between pressure and volume for given shock speed, has been established for many materials, and up to pressures of 10 $Mbar$. Pressures and densities attained in shock compressed geologic material are comparable to those found in the Earth, and have provided valuable data for geophysical analysis. Volcanism, plate faulting, and marine disturbances generate geological shocks of enormous potential destructive force, and an accurate assessment of their propagation characteristics in the Earth is an important component of seismology and geophysics.

THERMAL INTERACTIONS

Thermodynamics, like rheology, deals with macroscopic properties of extended matter, such as density and pressure, where temperature is a significant variable. Thermodynamics provides a complete description of these properties under conditions of equilibrium, and offers a starting point for investigation of nonequilibrium phenomena such as hydrodynamics, transport, and chemical reactions. Collectively, thermodynamics relates mechanics to heat and temperature changes, assigns directionality to physical processes, and serves as the basis for descriptions of macroscopic interactions. Thermodynamics grew naturally out of early studies of temperature.

Temperature

Temperature is a measure of hotness or coldness. But more particularly, temperature is a measure of the average kinetic energy of the molecular ensemble comprising the object, also called the internal energy. For an ideal gas, the mean molecular kinetic energy, $\bar{\varepsilon}$, satisfies the Boltzmann relationship,

$$\bar{\varepsilon} = \frac{3}{2}\, kT \quad , \tag{41}$$

with k Boltzmann's constant $(1.38 \times 10^{-23}\ j/gmole\ K^o)$, and T the absolute temperature. The first temperature measuring devices, employing displaced air volumes to define hotness of coldness according to the pronunciations of the instrument maker, were called thermometers in the 1600s. The liquid sealed in glass thermometers, based on thermal expansion and contraction, appeared in the latter half of the 1600s.

Use of temperature as a measurement of hotness or coldness is based on two requirements, that is, a universal agreement on calibration and scale, and technology sufficient to produce reliable instruments giving identical readings under the same conditions. Wide adoption of the Fahrenheit scale, F^o, was promoted by the trusty mercury (in glass) thermometers constructed in Danzig, by Fahrenheit, in the early 1700s. The scale was based on two fixed points, namely, the melting point of ice and the temperature of a healthy human body (later replaced by the boiling point of water). Celsius, at Uppsala, around the mid 1700s, introduced the Celsius (Centigrade) scale, C^o, on which the degree was $1/100$ of the interval between the freezing and boiling points of water. Later, in the 1800s, Kelvin introduced the absolute scale, K^o, based on the second law of thermodynamics and entropy, ultimately linked by statistical mechanics to an absolute zero, that is, a temperature at which random molecular motion ceases. By 1887, the international community adopted the constant volume hydrogen gas thermometer as defining measurements on the Kelvin scale.

While thermometry is concerned with heat measurements and fixed calibration points for instruments, some indicated in Table 7 below, what thermometers measure is the average kinetic energy, εbar, of the molecular ensemble, the essence of temperature. Typically, thermometers employ linear or logarithmic scales, most often using two (sometimes three) calibration points, T_a and T_b. General forms include,

$$\frac{T - T_a}{T_b - T_a} = \frac{X - X_a}{X_b - X_a} \ , \tag{42}$$

$$\frac{T - T_a}{T_b - T_a} = \frac{ln\, X/X_a}{ln\, X_b/X_a} \ , \tag{43}$$

with X, X_a, and X_b values of measured properties, such as electrical resistance, length of a mercury in a tube, electrical potential, and radiant power. Combinations of the above are also employed for different temperature ranges of the same measuring device.

In the 1,000 K^o to 5,000 K^o temperature range, at 1 atm pressure, all condensed phases (solid and liquid) are unstable against the gaseous phase. There are no known stable solids above 4,200 K^o, the approximate melting point of a mixture of tantalum carbide and hafnium carbide. Stable liquids do exist over the entire range, although not extensively studied. The normal boiling point of tungsten, for example, is about 6,200 K^o. Although intermolecular forces responsible for the stability of solids and liquids begin to weaken as temperature is increased from 1,000 to 5,000 K^o, chemical valence binding is still of considerable importance in the gas phase. Molecular species that are unstable at room temperatures are sometimes found in conditions of equilibrium in high temperature vapors. In the 5,000 to 10,000 K^o range, no stable molecules can exist in the gas phase. At temperatures near 10,000 K^o, atoms and ions can exist together, while above 10,000 K^o appreciable numbers of free electrons are present. At 50,000 K^o, mostly electrons and bare nuclei persist. In the 100,000,000 K^o region, like charged ions in a plasma possess sufficiently high collisional energy to overcome mutual Coulomb repulsion, supporting, in the case of deuterium and tritium, fusion.

Table 7. Temperature Calibration Points.

calibration point	Kelvin (K^o)	Fahrenheit (F^o)	Centigrade (C^o)
absolute zero	0	-460	-273
hydrogen triple	14	-434	-259
neon boiling	27	-410	-246
oxygen boiling	90	-297	-183
water triple	273	32	0
water boiling	373	212	100
sulfur boiling	717	831	444
gold freezing	1336	1945	1063

Kelvin (K^o), Centigrade (C^o), Rankine (R^o), and Fahrenheit (F^o) temperatures are defined on linear scales, and can be easily related,

$$F^o = \frac{9}{5} C^o + 32 \ , \tag{44}$$

$$K^o = C^o + 273 \ , \tag{45}$$

$$R^o = F^o + 460 \ . \tag{46}$$

Kelvin and Rankine temperatures are employed in the gas laws.

First Law

The first law of thermodynamics is really a statement of conservation of energy in any system. Denoting the internal energy of the system, U, the net heat flow into the system, Q, and the work, W, done on the system, the first law requires that infinitesimal changes dQ, dU, and dW satisfy,

$$dU = dQ - dW \ . \tag{47}$$

The internal energy of an ideal gas is only dependent on temperature, and that is a good approximation in most other real gases near standard temperature and pressure. (32 F^o, and 1 atm). Denoting the number of molecules of the gas, N, and the number of moles, n, with R the gas constant and k Boltzmann's constant, we have

$$dU = N\bar{\varepsilon}dT = \frac{3}{2} NkdT = \frac{3}{2} nRdT \ , \tag{48}$$

as a measure of the internal energy change, dU, for temperature change, dT. Heat flow, dQ, into or out of the system occurs through conduction, convection, or radiation. Mechanical work, dW, performed on, or by, the system is associated with volume change, dV, under pressure, P,

$$dW = PdV \ , \tag{49}$$

so that,

$$dU = dQ - PdV \ , \tag{50}$$

in a mechanical system. We do not live in a reversible world, that is to say, processes usually proceed in only one direction. Collectively, the directionality ascribed to physical processes is termed *entropy*.

Second Law

From experience, we know that some processes satisfying the first law (conservation of energy) never occur. For instance, a piece of rock resting on the floor will never cool itself down and jump up to the ceiling, thereby converting heat energy into potential energy. The second law defines a state *directional* variable, S, called the entropy, so that for any process, the heat transferred, dQ, is given by,

$$dQ = TdS \tag{51}$$

$$dS \geq 0 \ . \tag{52}$$

The requirement that the entropy change, dS, associated with the process must be greater than or equal to zero imparts directionality to the process, or the process is forbidden. Put another way by Kelvin, there exist no thermodynamic processes, nor transformations, that extract heat from a reservoir and convert it entirely into work. Dissipative mechanisms, such as friction and viscosity, prevent a reduction in system entropy for any process. Processes for which the entropy change is zero,

$$dS = 0 \ , \tag{53}$$

are termed reversible, or *isentropic*, represent an idealization of physical reality. Processes in which no heat is exchanged by the system are called *adiabatic*, that is,

$$dQ = 0 \ . \tag{54}$$

Combining the first and second laws, and considering only mechanical work,

$$dW = PdV \ , \tag{55}$$

we see that,

$$dU = TdS - PdV \tag{56}$$

Simple energy considerations applied to the steady flow of a fluid (gas or liquid) in system able to exchange heat and do external work, such as a steam engine, refrigerator, turbine, compressor, and scuba regulator, provide a simple means to relate temperature, internal energy, kinetic and potential energy, and pressure changes to external work and heat. The simple, yet powerful, relationships detailed above can be applied to air and fluid flows in diving systems, such as regulators, compressors, tanks, hoses, and gauges to yield rough estimates of pressures, temperatures, heat, and work. Actual flow patterns can be extremely complicated, requiring numerical solution on high speed computers, especially high pressure flows.

Regulators and compressors move gases from one reservoir to another at different pressure, and often, temperature. Regulators simply reduce gases at high pressure to low pressure, and compressors elevate gases at low pressure to high pressure. In both cases, gas flows involve high pressures and turbulent flows, for which steady state dynamics are a low order approximation, particularly as time scales decrease. The essence of regulator and compressor flow dynamics can be extracted from a simple high pressure flow model, namely, a fixed reservoir with connecting flow, treating the air as an ideal gas. In zero order, for abiabatic flow, and in the absence of shaft work and elevation changes, the flow temperature change, dT, and velocity change, dv, are related,

$$\frac{dv}{dT} = \frac{1}{v} \frac{\gamma R}{1-\gamma} \ , \tag{57}$$

with universal gas constant, R, and $\gamma = 5/3$.

High Pressure Cylinders

High pressure cylinders are mostly made from steel and aluminum, although prototypes of stainless steel and fiber wound composites have appeared. Carbon steel, used in early tanks, has been replaced with chrome molybdenum steel. Aluminum is alloyed with other metals, such as magnesium and titanium. Steel tanks were introduced in the late 1940s, and aluminum tanks became popular in the 1970s, though the first were imported from France in 1950. Cylinders carry compressed gases for underwater breathing, and are rated according to maximum working pressure, and the corresponding volume occupied by the breathing gas at 1

atm. Table 8 summarizes tank characteristics for a number of rated steel and aluminum cylinders. Steel tanks are generally heavier and exhibit negative buoyancy when filled with air. Aluminum tanks are lighter and tend to exhibit positive buoyancy before all tank air is depleted. To recover the buoyancy characteristics of steel tanks, aluminum tanks of the same size must have thicker walls, thus increasing their weight, but not their displacement.

Table 8. Cylinder Specifications.

material	volume (ft^3)	pressure (lb/in^2)	length (in)	diameter (in)	weight (lbs)	buoyancy (lbs)
steel	15	3300	13.80	4.00	7.5	-1.30
aluminum	14	2015	16.60	4.40	5.4	3.22
aluminum	50	3000	19.00	6.90	21.5	2.25
steel	50	1980	22.50	6.80	20.8	2.43
steel	72	2475	25.00	6.80	29.5	3.48
aluminum	72	3000	26.00	6.90	28.5	3.60
aluminum	80	3000	26.40	7.25	33.3	4.00
aluminum	80	3000	27.00	7.25	34.5	4.12
steel	95	3300	25.00	7.00	39.1	-6.11

Pressures in a cylinder increase as temperatures increase, and decrease as temperatures decrease. Denoting the initial pressure and temperature, P_0 and T_0, and the final pressure and temperature, P and T, we have, assuming an ideal gas,

$$\frac{P_0}{T_0} = \frac{P}{T} \ , \tag{58}$$

or,

$$P = \frac{T}{T_0} P_0 \ , \tag{59}$$

Phase Transformations

Every substance obeys an equation of state, some fundamental relationship between pressure, temperature, and volume. That of ideal gases is a simple example. Real substances can exist in the gas phase only at sufficiently high temperatures. At low temperature and high pressures, transitions occur to the liquid and solid phases. Figure 3 depicts the phase diagram for a substance like carbon dioxide that contracts on freezing. Inspection of the figure shows that there exist regions in which the substance can exist only in a single phase, regions labeled solid, liquid, vapor, and gas. A vapor is just the gas phase in equilibrium with its liquid phase. In other regions, labelled solid-vapor, solid-liquid, and liquid-vapor, both phases exist simultaneously. Along a line called the triple line, all three phases coexist.

Liquids tend to evaporate, or vaporize, by releasing molecules into the space above their free surfaces. If this is a confined space, the partial pressure exerted by released molecules increases until the rate at which molecules return to the liquid equals the rate at which they leave the liquid surface. At this equilibrium point, the vapor pressure is known as the saturation pressure.

Molecular evaporation increases with increasing temperature, hence the saturation pressure increases with temperature. At any one temperature, the pressure on the liquid surface may be higher than this value, but it cannot be lower. Any slight reduction below saturation pressure induces the very rapid rate of evaporation called boiling.

Saturation vapor pressures of known liquids vary widely. Table 9 lists saturation vapor pressures for a number of liquids. At 70 F^o, vapor pressures of mercury and gasoline are seen to differ by a factor of 10^5 approximately.

Figure 3. Phase Surfaces For Carbon Dioxide

An equation of state (EOS) is a relationship between temperature, pressure, and volume (or density) for any substance. All possible states lie on a surface, as portrayed below for carbon dioxide. In certain regimes, only the gas, solid, or liquid phases are possible. In other regions, two phases can exist, solid-liquid, solid vapor, or liquid vapor. A vapor is a gas in equilibrium with its liquid phase. Along the triple point, all three phases can coexist. For instance, water vapor, ice, and water coexist at $0.0098\,C^o$*, typical during the winter.*

Table 9. Saturated Vapor Pressures.

liquid	temperature (F^o)	vapor pressure (lb/in^2)
mercury	70	0.000025
mercury	320	0.081
water	200	7.510
water	70	0.363
water	32	0.089
kerosene	70	0.492
alcohol	70	1.965
gasoline	70	4.439
ammonia	200	794.778
ammonia	50	89.190
ammonia	-100	1.238

PRESSURE AND DENSITY EFFECTS

Probably little need be said about pressure. Of all underwater diving variables, pressure is the only predictable one. For each 33 fsw of depth, the pressure increases 1 atm, or 14.7 lb/in^2, the same pressure exerted by the air column, some 80 $miles$ high, on the surface of the Earth. At the deepest part of the ocean, about 7 $miles$, the pressure is almost 1,000 times greater than atmospheric pressure, near 7 ton/in^2. Such pressure is tremendous. A pressure of roughly $1,350$ lb/in^2 would compress a block of wood to half its size, and, as such, it would sink. Pressure is the biggest reason man has not explored the deep ocean in submarines. In 1960, the Trieste (USN) descended to the bottom of the Challenger Deep in the Mariana Trench, some 36,000 fsw. The trip took nearly 5 hrs. But, ships like the Trieste are not capable of sustained activity under such pressures. Scuba divers can descend to 550 fsw, but their working depth is closer to 200 fsw as a maximum. Early submarines were restricted to 300 fsw operationally, but submarines today operate at 3 times that depth.

Pressure

Pressure is simply force per unit area. In terms of incremental elements, pressure, P, is given by,

$$P = \frac{dF}{dA} \quad , \tag{60}$$

with dF and dA the differential force and area. Pressure is assumed to act equally in all directions at the point of application of the force, hence the scalar representation and definition. In fluids, such a representation is unequivocal. In a gas or water column, the weight of the gas or water above any point in the column exerts a force on the rest of the column below it. Pressure on the fluid or gas at any point is equal in all directions, else the material would move by itself under pressure imbalance. The pressure, P, at any point depends on the density, ρ, of the material, the vertical position (depth) in the column, d, and the acceleration of gravity, g,

$$P = \rho\, g\, d \quad , \tag{61}$$

with the density, ρ, given by,

$$\rho = \frac{m}{V} \quad , \tag{62}$$

for material mass, m, in volume, V.

Barometer Equation

Atmospheric pressure falls off exponentially with altitude. Near elevation of 18,000 ft, atmospheric pressure is half (16.5 fsw) of sea level pressure. If air were incompressible, like water, a simple linear dependence on altitude could be employed to estimate altitude ambient pressure, P_h, with h denoting the elevation. Since air is compressible, simple linear pressure relationships, such as those to compute water pressure, are not generally applicable, though a linear approximation to P_h is good approximation over low altitude range.

Assuming a uniform atmosphere, behavior of P_h with elevation, h, is seen for the temperature case of 300 K^o (80 F^o) in Figure 4. Roughly, linear to about 7,000 ft, atmospheric pressure falls off exponentially. Direct altitude measurements of pressure correlate with the barometer equation. Seasonal and geographical variations near 7% are not uncommon. To good order, for surface ambient pressure, P_0, we have,

$$P_h = P_0 \; exp \; (-0.0381 \, h) \;\; , \tag{63}$$

with h measured in multiples of 1,000 ft elevation. For small values of the argument,

$$P_h \approx P_0 \; (1 - 0.0381 \, h) \;\; , \tag{64}$$

exhibiting the linear behavior for low altitude, that is, for $0.0381h << 1$. The exponential term, α in operational protocols, is an altitude scaling factor, simply the ratio of sea level pressure over ambient pressure,

$$\alpha = exp \; (0.038h) = \frac{P_0}{P_h} \;\; . \tag{65}$$

Air Consumption

Regulator function exploits air compressibility to deliver air to the lungs at any ambient pressure. Filled with compressed air at ambient pressure, the lungs can function underwater in the same manner as on the surface, inflating and deflating normally. However, underwater, assuming the same metabolic consumption rate for given activity, the diver uses more air to fill the lungs than on the surface, because the air is compressed. At sea level, we consume air at a rate, χ_0. Relative to χ_0, the underwater rate is greater. At elevation, the surface consumption is less than χ_0.

More specifically, denoting the altitude surface consumption rate, χ_h, the consumption rate, χ, at depth, d, and implied elevation, α, scales directly with the pressure, that is,

$$\chi = \chi_h \; \left(1 + \frac{d \eta \alpha}{P_0} \right) \;\; . \tag{66}$$

with η the specific density of the water. The total pressure, P, satisfies a similar relationship in terms of surface pressure, P_h,

$$P = P_h + \eta d = \frac{P_0}{\alpha} + \eta d \;\; . \tag{67}$$

At any altitude, consumption rates increase rapidly with depth, offsetting reduced surface rates. The surface rate at altitude, χ_h , is related to the surface rate at sea level, χ_0, by the relationship,

$$\chi_h = \frac{\chi_0}{\alpha} \approx \chi_0 \; (1 - 0.038 \, h \,) \;\; , \tag{68}$$

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

Variation in consumption rate with ambient pressure is a gas density effect (regulator function), while variation in rate with activity is a metabolic effect (oxygen requirement). Figure 5 graphs surface consumption rates at altitude for corresponding sea level consumption rates. Table 10 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.

Table 10. Activities Air Consumption Rates At Sea Level.

Land/Water Activity	Sea Level Consumption Rate χ_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

Compared to the sea level surface consumption rate, the altitude surface consumption rate is reduced by the ratio of ambient pressure to sea level pressure, α. 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 bouyancy with increasing pressure.

GAUGES

Underwater gauges sense pressure, or pressure ratios, to give depth readings. Submersible tank gauges measure tank pressure directly. 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, seen as follows.

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,

$$P = P_h + \eta \, d \quad , \tag{69}$$

with η the fluid specific density. By Boyle's law, the volumes are related,

$$(P_h + \eta \, d) \, v = P_h \, v_{max} \quad , \tag{70}$$

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

$$\frac{v_{max}}{v} = \left(\frac{P_0 + \delta}{P_0} \right) \quad . \tag{71}$$

In any other fluid, at actual depth, d, the corresponding gauge reading, δ, can be obtained by substituting the calibration relationship into the above, and simplifying, with the result,

$$\delta = \left(\frac{P_0}{P_h} \right) \eta \, d \quad . \tag{72}$$

For fresh water, $\eta = .975$, as noted, and atmospheric pressure, P_h, at elevation, h, decreases exponentially. Figure 6 depicts capillary gauge reading as a function of actual depth at various elevations.

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, η, senses ambient pressure, P, subtracts off a constant, X, and registers a mechanical response, Y,

$$Y = \eta \, d + P_h - X \quad , \tag{73}$$

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

$$Y = \delta + P_0 - X \tag{74}$$

Substituting equations yields the gauge reading, δ, in any fluid, η, at actual depth, d, for any surface pressure, P_h,

$$\delta = \eta\, d + P_h - P_0 \quad , \tag{75}$$

in analogy to a capillary gauge. Figure 7 plots Bourdon and oil filled gauge readings at altitude as a function of actual depth.

Capillary, diaphragm, and bourdon depth gauges are usually calibrated at sea level for salt water. Fresh versus salt water reading errors alone, as with bouyancy changes, are small (near 3%), but all register increasing error with altitude. Diaphram 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.

Submersible Tank Gauges

Submersible gauges read tank pressure directly. Knowing the rated tank pressure, P_r, and rated gas volume, V_r, permits rapid estimation of air remaining in the tank for breathing. The rated tank pressure is the maximum recommended pressure for the tank upon filling. The rated tank volume is the amount of gas, initially at standard temperature and pressure, compressed to the rated tank pressure. For instance, the standard steel 72 ft^3 tank, is rated at 2475 lb/in^2, meaning that, $V_r = 72\ ft^3$, and that, $P_r = 2475\ lb/in^2$.

From Boyle's law, we can write for any tank pressure, P, and remaining breathing volume, V, denoting the actual tank volume, V_t, and standard pressure, P_0, usually 1 atm,

$$PV_t = P_0 V \quad , \tag{76}$$

and we also know at rated pressure, P_r, and volume, V_r,

$$P_r V_t = P_0 V_r \quad . \tag{77}$$

Dividing the above two equations yields the ratio,

$$\frac{P}{P_r} = \frac{V}{V_r} \quad , \tag{78}$$

which permits direct estimation of remaining air volume, V, for submersible gauge reading, P, and specified P_r and V_r. The ratio, P_r/V_r is called the *tank constant*, using any convenient set of units.

HYDROSTATICS

Objects denser than a fluid will sink in that fluid, and objects less dense than a fluid will float. Sinking objects have negative buoyancy, while floating objects have positive buoyancy. Objects with the same density as the fluid are neutrally buoyant, and can be moved about without sinking or rising. Relative buoyancy obviously depends on fluid and object densities.

Solids and fluids possess essentially fixed density under nominal pressure changes, but gases, and flexible objects containing gases, change density rapidly under pressure change. Relative buoyancy also changes rapidly as object density varies. For contained gases, density and buoyancy changes result from changes in volume.

The body itself and equipment worn by divers contain air spaces that can expand and contract under pressure changes. The lungs, wet and dry suit, and buoyancy compensator (BC), for instance, respond readily to pressure change, inducing commensurate buoyancy change. Since salt water is denser than freshwater, it exerts a greater buoyant force than fresh water. Buoyancy changes in fresh and salt water thus differ as object density changes.

Buoyancy changes occur when divers descend and ascend, move between fresh and salt water and/or different elevations. Buoyancy is lost relative to the surface when wet suit divers descend. 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 can be quantified by Archimedes' and Boyle's laws. In all cases, effects ultimately relate to the densities of constituent fluid media.

Archimedes Principle

According to Archimedes many centuries ago, any object displacing a volume, V, of fluid of density, ρ, is buoyed upward by a force, B, equal to the weight of the displaced fluid. From what we know about pressure in a fluid, this fact can be deduced easily by imagining a uniform block of height, h, and cross sectional surface area, A, with volume, $V = Ah$. Submerging the block in a fluid of density, ρ, in an upright position, we can add up all the pressures on the block to determine the buoyant upward force, B. The sum total of all pressures on faces is zero, since every force on every face is balanced by an equal force on the opposite face. At the top of the block, a downward force, $F_d = \rho gAd$, is exerted by the fluid. On the bottom, an upward force, $F_u = \rho gA(h+d)$, is exerted by the fluid. The difference of the two forces is the buoyant (upward) force, B,

$$B = F_u - F_d = \rho gAh = \rho gV \quad , \tag{79}$$

or Archimedes' principle. This simple law has far reaching implications for diving, essentially dictating functionality of weight belts, wet suits, drysuits, and BCs for underwater activities.

Wetsuits, BCs, and drysuits expand and compress, 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 first, and then salt versus fresh water buoyancy.

Wetsuit Expansion And Compression

Gas bubbles in wetsuits are subject to Boyle's law as external pressure changes, though the response is something less than 50% of the volume change predicted by the gas law. To estimate the buoyancy increase due to expansion or compression, we compute the effect using Archimedes' principle and Boyle's law directly, and then scale the result by the factor 0.50, as a figure of merit.

At depth, d, the buoyancy loss, Δw, due to wetsuit compression can be written, assuming the weight belt is 15% of diver weight, w,

$$\Delta w = -.075\, w \left(\frac{\eta d}{P_0 + \eta d} \right) \quad , \tag{80}$$

with η the specific density of water. Wetsuit buoyancy loss per multiple of 100 *lbs* of diver weight, as a specific function of depth, is plotted in Figure 8 for various altitudes. The altitude effect on underwater buoyancy loss is seen to be small.

Similarly, the surface buoyancy increase due to wetsuit expansion, following increase in elevation, h, can be written,

$$\Delta w \approx .0029\, wh \quad , \tag{81}$$

as the approximate buoyancy gain, good to few percent up to 7,000 ft. Each multiple of 1,000 ft elevation increases diver buoyancy by .3% of body weight.

Altitude environments are usually sufficiently cold that wetsuits are required (and more often drysuits today). The increased wetsuit buoyancy is mostly of concern near the surface, since increased water pressure will compress the suit rapidly at moderate depth. Figure 9 charts surface wetsuit buoyancy gains at various altitudes as a function of body weight.

Fresh And Salt Water Buoyancy

Application of Archimedes' principle directly to a diver submerged in fresh and salt water at sea level yields the fresh water buoyancy loss, ΔW. 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,

$$W = \rho g v \ , \tag{82}$$

with ρ 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 loss,

$$\Delta W = \rho g v (\eta - 1) = W(\eta - 1) \ , \tag{83}$$

with η the fresh water specific density (ratio of fresh water to salt water density). Taking $\eta = .975$, there results,

$$\Delta W = -.025\, W \ , \tag{84}$$

with the minus sign denoting a buoyancy loss.

As seen, application of Archimedes' principle to a body submerged in salt and fresh water (displacing equal volumes), yields a buoyancy change that depends on the ratio of densities and the total (body plus gear) diver weight. This simple correction for fresh water relative to sea water amounts to buoyancy reduction near 2.5% of total diver weight. Figure 10 depicts fresh water buoyancy loss against diver body weight.

GAS AND FLUID KINETICS

The behavior of materials under pressure, volume, and temperature changes was first deduced phenomenologically, that is, from correlation of assumed behavior with experiment (data fits). And certainly such fits are useful. And while thermodynamic principles can predict many relations between the properties of matter, such as heat capacities and variations with pressure and temperature, it is not possible to derive from thermodynamic considerations alone the absolute magnitude of heat capacities, nor the equation of state of a substance.

We go beyond the limitations of pure thermodynamics only by making hypotheses regarding the nature of matter. And by far, the most fruitful, as well as one of the oldest, is that matter is not continuous in structure, but is composed of molecules. In the case of gases, the molecules are in constant linear motion, and collide with themselves and the walls of any container, generating pressure. Not all gas molecules have the same velocity, but the sum total of all their kinetic energies is the internal energy of the molecular ensemble, a true measure of temperature.

Ideal And Real Gases

Air is a mixture of inert and metabolic gases, composed of hydrogen and oxygen mainly, with variable amounts of carbon dioxide, water vapor, ozone, sulfur dioxide, and nitrogen dioxide, and fixed trace amounts of xenon, helium, krypton, argon, methane, nitrous oxide, hydrogen, and neon. By volume, air is 78.1% nitrogen, 20.9% oxygen, and 1% everything else. Over nominal pressure and temperature ranges encountered in the Earth's atmosphere, air can be treated as an *ideal*, or dilute, gas.

Ideal gas molecules occupy no space, do not interact, scatter elastically from each other, and cannot be distorted upon collision, in short, act as vanishingly small, perfectly elastic, hard spheres in constant random motion from collisions. Real gases, in the limit of very large confining volumes, all behave like ideal gases, as well as over select ranges of pressure, temperature, and density. Simple monatomic (one atom molecules) and diatomic (two atom molecules) gases and mixtures, such as air at room temperatures and atmospheric pressures, are considered ideal, and satisfy an $equation\ of\ state$ (EOS) relating pressure P, volume, V, and and temperature, T, of the form,

$$P\,V = n\,R\,T \ , \tag{85}$$

with n the number of moles of gas, and R the universal gas constant ($8.317\ j/gmole\ K^o$), related to Boltzmann's constant, k, and Avogadro's number, N_0, through,

$$R = N_0\,k \ , \tag{86}$$

bridging thermodynamics and statistical mechanics. Temperature is measured in absolute, or Kelvin (K^o), units. In conservative processes, n is constant and changes in the state variables, P, V, and T, are linked to each other by the $P-V-T$ relationship. If each variable is alternatively held fixed, we get three well known ideal gas law corollaries (Boyle, Guy-Lussac, and Charles principles),

$$P\,V = \gamma_T \ \ , \tag{87}$$

$$\frac{P}{T} = \gamma_V \ \ , \tag{88}$$

$$\frac{V}{T} = \gamma_P \ \ , \tag{89}$$

with $\gamma_T = nRT$, $\gamma_V = nR/V$, and $\gamma_P = nR/P$ all constant. The relationships connect any number of arbitrary changes of state for constant temperature, volume, or pressure, respectively.

In a mixture of ideal gases, the total pressure is the sum of component gas partial pressures, intuitively obvious, but also known as Dalton's law. Denoting gas partial pressures, p, the total pressure, P, is given by,

$$P = \sum_{j=1}^{J} p_j \ \ , \tag{90}$$

with p_j the partial pressure of the j^{th} gas species in a J component mixture.

All gas molecules occupy space, exert short-ranged forces on each other, scatter inelastically at times, and possibly distort with collision, in short, act as non ideal gas molecules. Then equations-of-state need include such effects, particulary in appropriate pressure, temperature, and density regimes. yhe most general form of the equation of state can be cast in *virial* form, in terms of the molal specfic volume, $v = V/n$

$$P\,v = \left(a + \frac{b}{v} + \frac{c}{v^2} + \frac{d}{v^3} + ...\right) \ \ , \tag{91}$$

with a, b, c, and d functions mostly of temperature, possibly specific volume. For ideal gases, $b = c = d = 0$, but in general these virial constants are non zero.

Certainly as the specific volume, v, or real volume, V, gets large, the virial expansion collapses to the ideal case. The virial expansion and coefficients can be fitted to sets of experimental data for gases. Such fits to even very complicated gas behavior all have one feature in common. The quantity, pv/T, always approaches the universal gas constant, R, as temperatures, T, approach absolute zero (-273 C^o, or -460 F^o).

Water Waves

Waves interact with matter in many complex ways. Consider a floating block of wood, and surface water waves incident upon it. The block is set into vertical oscillations by the passage of the wave, and the vertical oscillations produce a circular wave traveling outward from the block in concentric circles. One describes the phenomena as isotropic scattering of incident energy. If the block is very small, or the wave very long, the block rises and falls with the surface of the water, and little energy is scattered. If the block is very large, or the waves very short, the block is motionless, and the wave is reflected. Reflection, however, is clearly a special case of scattering. For a particular block, energy scattered might be considered a function of wavelength, and then, total energy scattered in all directions reaches a maximum for a particular *resonant* wavelength. These observations pervade all types of wave motion and interactions with matter, be they acoustical, electromagnetic, gravitational, thermal, plasma, or water waves.

Surface water waves result from the interaction of gravity, surface tension, and applied impulse. Neglecting the viscosity and compressibility of water, gravity and surface tension act as restoring forces, wanting to maintain the fluid surface flat in the presence of any applied disturbance. Such simplifications provide a linear basis for analysis of water motion, requiring wave slopes that are smaller than unity. Under simple impulse, such as the wind, fluid particles trace elliptical orbits, approaching nearly horizontal motion at horizontal boundaries, and circular motion far from them. Amplitudes for such fluid oscillations decrease exponentially at depth, d.

Shallow waves (long wavelengths) ultimately break on a beach, while deep waves (short wavelengths) are dispersive, compared to shallow waves, and become shallow waves before they break on a beach. Shallow water waves occur in depths less than one half their wavelength, while deep water waves occur in depths greater than one half their wavelength.

Fluidization

Fluidization of solids by liquids is a process intermediate between the flow of solids through fluids, and the flow of fluids through solids. When a fluid is passed upward through a bed of granular solids, such as surf or surge through rock and coral debris, a pressure drop accompanies the flow across the bed. When this pressure drop approaches the weight of the bed per unit cross sectional area, the individual granules become disengaged from one another, and the bed begins to resemble a liquid in the state of boiling. It appears that the bed has been *fluidized*. When the particles remain mostly localized, the granular system is a fixed bed. In a moving bed, the particles remain in contact but move as a whole. In a turbulent bed, particles of different size continually mix and change relative position.

PHASE DYNAMICS

Solubility is an old subject, although most early interest and study centered on the solubility of solids in water, still an important area of research and application. Aristotle knew that the evaporation of seawater uncovered dissolved salts, and there are records of systematic studies by Pliny the Elder of the relative solubilities of many solids in water. Today, we understand the thermodynamics and statistical mechanics of solubility fairly well, but it is difficult to make quantitative predictions of solubility for real systems on first principles. Of course, similar comments apply to bubble formation in the presence of dissolved gases.

Dissolved Phases

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 gases such as helium and nitrogen are readily soluble in tissue and blood, and their solubility can fuel bubble growth with reduction in ambient pressure, a concern for decompressing divers.

Denoting the ambient partial pressure of a gas, p, and its solubility, S, in a liquid, the relative concentration of the dissolved gas component, c, is given by Henry's law,

$$c = S\,p \quad . \tag{92}$$

The corresponding *tension*, or dissolved gas partial pressure, is also p at equilibrium. By convention, partial pressures usually refer to the free gas phase, while tensions refer to the dissolved gas phase, though some folks use them interchangeably. When there exist differences, or *gradients*, between gas partial pressures and/or tensions across regions of varying concentration or solubility, gases will diffuse until partial pressures are equal, in short, move from regions of higher partial pressures to regions of lower partial pressures, regardless of the phases (free or dissolved) of the components. Some gas solubilities, S, are listed in Table 11 for water and oil.

Table 11. Henry Coefficients.

	$S\ (atm^{-1})$	$S\ (atm^{-1})$
gas	water	oil
H_2	.014	.050
He	.008	.016
Ne	.009	.021
N_2	.012	.067
Ar	.025	.150
O_2	.023	.122

In divers, gas soulubility and transfer from blood to tissue, and back, is important. Gas is driven across the tissue-blood interface by the gradient, but the rate at which bulk tissue transfers gas also depends on the blood flow rate and the degree of vascularity. Then both blood perfusion rate and gas diffusion rate contribute to the overall transfer process.

Perfusion And Diffusion Transport

Exchange of dissolved tissue and blood gas, controlled by blood flow rates across regions of varying concentration or solubility, is driven by the local tissue-blood gradient, that is, the difference between the arterial blood tension, p_a, and the instantaneous tissue tension, p, assuming that blood flow rates are considerably slower than gas diffusion rates across the regions. 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 multitissue functions satisfy a differential $perfusion$ rate equation and are the bases for dive table and meter algorithms. Exchange of dissolved tissue and blood gas, controlled by diffusion across regions of varying concentration or solubility, is also driven by the local tissue-blood gradient, but solutions to the diffusion equation control transport. Diffusion equations have also been employed to build dive tables.

Free Phases

Henry's law tells us that a gas will tend to separate from solution (pass from the dissolved state to the free state) if the tension of the gas in the dissolved state exceeds its partial pressure in the adjacent free state. And the opposite holds true if the gradient is reversed. Phase separation can be delayed if some remnant of a free phase does not already exist in the liquid, providing a pathway for the dissolved gas to $dump$ over into the free state, rendering the dissolved gas $metastable$ during the delay. The challenge in tracking phase separation is the presence and quantification of free phase precursors, or seeds, that facilitate gas transfer in a process called $nucleation$.

Nucleation

Metastable states are unstable thermodynamic states lying close to stable configurations, that is, separated by relatively small energy differences. A substance in a metastable state will eventually transition into a stable state. For instance, a supercooled vapor will eventually condense into a liquid, a supercooled liquid will eventually become solid, and a superheated liquid will eventually evaporate into a gas. Bubble formation can be a process in which a gas, or vapor, phase is initially formed from a metastable liquid environment, one that is usually superswith dissolved gas.

Metastable phase transitions deposit an unstable phase onto a stable phase, with aggregates in the stable phase serving as *nuclei* for the transition. Liquid drops in a supercooled vapor, if sufficiently large, become centers of condensation of the vapor, for example. Nuclei will form in both phases because of statistical fluctuations, but the nuclei in the metastable phase will disappear in time, while those in the stable phase will remain. Such nuclei form statistically as a result of thermal fluctuations in the interior of the media, with a certain (small) number reaching $critical$ radius for growth. If large enough, nuclei in the stable phase seed the continuing process of phase transitions from the metastable state. For each metastable state, there is a minimum size which nuclei in the stable phase must possess to afford more stability than the metastable state. This size is called the critical radius, r_c. Nuclei smaller than the critical radius will not support phase transitions from the metastable state, and will also disappear in time. In assigning a critical radius to nuclei, spherical aggregate symmetry is assumed, and is requisite to minimize surface energy.

While theories of heterogeneous and homogeneous nucleation work well for a number of liquids, the application of the heterogeneous model to water with impurities is not able to reduce the tensile strength to observable values. The homogeneous theory of nucleation predicts a tensile strength of water near 1,400 atm, the heterogeneous theory, with a variety of solid impurities, drops the tensile strength down to 1,000 atm, and the measured value for water is approximately 270 atm.

In any solution, gas nuclei can be deactivated (crushed) by the application of large hydrostatic pressures. The process of *crushing* is also termed $denucleation$. When denucleated solutions are decompressed in supersaturated states, much higher degrees of supersaturation are requisite to induce bubble formation. In diving, denucleation has been suggested as a mechanism for acclimatization. If denucleation is size selective, that is, greater hydrostatic pressures crush smaller and smaller nuclei, and if number distributions of nuclei increase with decreasing radius (suggested by some experiments), than a conservative deep dive, followed by sufficient surface interval, should in principle afford a margin of safety, by effectively crushing many nuclei and reducing the numbers of nuclei potentially excited into growth under compression-decompression.

The mechanisms of nucleation in the body are obscure. Though nucleation most probably is the precursor to bubble growth, formation and persistence time scales, sites, and size distributions of nuclei remain open questions. Given the complexity and number of substances maintained in tissues and blood, heterogeneous nucleation would appear a probable mechanism.

Cavitation

Simply, *cavitation* is the process of vapor phase formation of a liquid when pressure is reduced. A liquid cavitates when vapor bubbles are formed and observed to grow as consequence of pressure reduction. When the phase transition results from pressure change in hydrodynamic flow, a two phase stream consisting of vapor and liquid results, called a cavitating flow. The addition of heat, or heat transfer in a fluid, may also produce cavitation nuclei in the process called boiling. From the physico-chemical perspective, cavitation by pressure reduction and cavitation by heat addition represent the same phenomena, vapor formation and bubble growth in the presence of seed nuclei. Depending on the rate and magnitude of pressure reduction, a bubble may grow slowly or rapidly. A bubble that grows very rapidly (explosively) contains the vapor phase of the liquid mostly, because the diffusion time is too short for any significant increase in entrained gas volume. The process is called vaporous cavitation, and depends on evaporation of liquid into the bubble. A bubble may also grow more slowly by diffusion of gas into the nucleus, and contain mostly a gas component. In this case, the liquid degasses in what is called gaseous cavitation, the mode observed in the application of ultrasound signals to the liquid. For vaporous cavitation to occur, pressure drops below vapor pressure are necessary. For gaseous cavitation to occur, pressure drops may be less than, or greater than, vapor pressure, depending on nuclei size and degree of liquid saturation. In supersaturated ocean surfaces, for instance, vaporous cavitation occurs very nearly vapor pressure, while gaseous cavitation occurs above vapor pressure.

In gaseous cavitation processes, the inception of growth in nuclei depends little on the duration of the pressure reduction, but the maximum size of the bubble produced does depend upon the time of pressure reduction. In most applications, the maximum size depends only slightly on the initial size of the seed nucleus. Under vaporous cavitation, the maximum size of the bubble produced is essentially independent of the dissolved gas content of the liquid. This obviously suggests different cavitation mechanisms for pressure (reduction) related bubble trauma in diving. Slowly developing bubble problems, such as limb bends many hours after exposure, might be linked to gaseous cavitation mechanisms, while rapid bubble problems, like central nervous system hits and and embolism immediately after surfacing, might link to vaporous cavitation.

Today we know that the inception of cavitation in liquids involves the growth of submicroscopic nuclei containing vapor, gas, or both, which are present within the liquid, in crevices, on suspended matter or impurities, or on bounding layers. The need for cavitating nuclei at vapor pressures is well established in the laboratory. There is some difficulty, however, in accounting for their presence and persistence. For a given difference between ambient and gas-vapor pressure, only one radius is stable. Changes in ambient, gas, or vapor pressures will cause the nuclei to either grow, or contract. But even if stable hydrostatically, bubbles and nuclei, because of constricting surface tension, will eventually collapse as gas and vapor diffuse out of the assembly. For instance, an air bubble of radius 10^{-3} cm will dissolve in saturated water in about 6 sec, and even faster if the water is undersaturated or the bubble is smaller. In saturated solutions, bubbles will grow by diffusion, and then tend to be quickly lost at free surfaces as buoyant forces raise them up. A 10^{-2} cm air bubble rises at the rate of 1.5 cm/sec in water. If nuclei are to persist in water, or for that matter, any liquid media, some mechanism must prevent their dissolution or buoyant exit.

A number of possibilities have been suggested to account for the presence of persistent, or stabilized, nuclei in undersaturated liquids, liquids that have been boiled, or denucleated. Crevices in the liquid, or surrounding boundary, may exert mechanical pressure on gas nuclei, holding them in place. Microscopic dust, or other impurities, on which gas and vapor are deposited, are stabilized already. Surface activated molecules, (such as hydrogen and hydroxyl ions in water), or surface activated skins formed from impurities may surround the nuclei and act as rigid spheres, offsetting constrictive surface tension, preventing diffusion of gas out of the nuclei and collapse. In all cases, the end result is a family, or group of families, of persistent nuclei. Time scales for stabilization and persistence of nuclei would obviously equate to the strength and persistence of stabilizing mechanism. Experimentally, trying to differentiate stabilization modes is very difficult, because (eventual) growth patterns of nuclei are the same in all cases. The ulimate crumbling of surrounding shells, release of crevice mechanical pressure, removal of dust and impurity nucleation centers, and deactivation of surface chemicals leads to the onset of cavitation and bubble growth.

BUBBLE MECHANICS

To satisfy thermodynamic laws, bubbles assume spherical shapes in the absence of external or mechanical (distortion) pressures. Bubbles entrain free gases because of a thin film, exerting surface tension pressure on the gas, of magnitude, $2\gamma/r$, with γ the Laplacian surface tension and r the bubble radius. Hydrostatic pressure balance requires that the pressure inside the bubble exceed ambient pressure by the surface tension pressure, $2\gamma/r$. Figure 11 depicts the pressure balance in a spherical bubble of radius, r. At small radii, surface tension pressure is greatest, and at large radii, surface tension pressure is least. In watery tissue, $\gamma = 50\ dyn/cm$, roughly.

Gases will also diffuse into or out of a bubble according to differences in gas partial pressures inside and outside the bubble, whether in free or dissolved phases outside the bubble. In the former case, the gradient is termed $free - free$, while in the latter case, the gradient is termed $free - dissolved$. Unless the surface tension, γ, is identically zero, there is always a gradient tending to force gas out of the bubble, thus making the bubble collapse on itself because of surface tension pressure. If surrounding external pressures on bubbles change in time, however, bubbles may grow or contract. Figure 12 sketches bubble gas diffusion under instantaneous hydrostatic equilibrium (γ nonzero).

Surfactants

Water, gasoline, glycerin, and salad oil are clearly liquids. Pancake syrup, paster, eggwhite, silly putty, paint, glue, and soap are also liquids, that is, they flow on the application of stress, but border on classification otherwise. In mechanical response, the latter class differs from each other as much as they differ from solids. And the response is variable in time. Syrup becomes sticky as it dries. Dishwashing soap often dries into light flakes. Silly putty flows on tilt, but shatters on sudden impact. Airplane glue is springy and rubbery.

Substances in the latter category are called structured fluids, owing their distinctive and unusual properties to large polyatomic composites, many times the size of a water molecule. Fluids containing polyatomic structures manifest a wide variety of mechanical response and self organization. Body tissues and fluids host an uncountable variety of organic and inorganic matter, with many biochemical substances falling into structured fluid category. Among the structured fluids, a class of self assemblies, called surfactants, are very interesting, possessing properties which can stabilize microbubbles in various stages of evolution by offsetting surface tension.

A surfactant is a structured fluid which is *ambiphillic*, incorporating parts that assume preferential orientations at water-oil (immisicible) interfaces. A surfactant molecule usually consists of a bulky ion at one end, and a counter ion at the other. Isolated molecules cannot usually exist in one media type, or the other, but instead orient themselves into *micelles*, configurations in which like parts clump together, that is head in one substance and tail in the other. Micelles typically possess diameters near 10^{-3} *microns*, and render the interfaces unlike anything measured in the components. Lipid-aqueous tissue interfaces potentially present favorable environments for surfactants.

Under certain conditions, a surfactant can reduce interfacial surface tension, allowing the interface to grow and wrap around itself. The result is a microbundle full of alternating surfaces and interfaces, spherical in structure to minimize thermodynamic energy constraints. Many substances may be bound up in the microbundle. If small gas nuclei, but typically much larger than a micelle, are in contact with the interfaces, or surfactants directly, a spherical gas micronucleus-microemulsion can develop, varying in size and surfactant content. The assembly is stable when the effective surface tension is zero, when surfactant skin pressure just balances mechanical (Laplace) surface tension. If the effective surface tension of the microbubble, γ, is not zero, the collection will grow or contract until stable, or disassemble. In the case of gas microemulsions, the surfactant is thought to coat the inside boundary layer mostly, with free gas in the interior. The actual picture is probably more complex, but such a picture can be drawn for computational simplicity. Surfactant stabilized micronuclei may theoretically destabilize under compression-decompression processes in diving, perhaps spawning bubble growth fueled by high gas tension in surrounding media. Microbubbles may remain at the interfaces, but probably migrate. Sources of initial gas nuclei, surfactant composition, and tissue sites await description.

Doppler Bubbles

A change in the observed frequency of sound, light, and other waves, caused by relative source-observer motion, is known as the Doppler effect. One example is a change in train whistle pitch upon approach and retreat. The observed frequency, $f^{'}$, is higher than the source frequency, f, as source and observer approach each other, and lower as source and observer retreat from each other.

For sound waves that propagate with characteristic velocity, u, in a medium (air, water, tissue), the Doppler shift depends on both source velocity, v_s, and observer velocity, v_o. The number of sound waves per second arriving at the observer can be estimated by simply counting the waves emitted per second by the source, and the change per second in the number of waves in flight from source to observer,

$$f^{'} = f \, \frac{u - v_o}{u - v_s} \quad , \tag{93}$$

with source and observer velocities measured along the direction from source to observer (longitudinal component). If the observer is at rest, obviously,

$$\Delta f = f^{'} - f = f \, \frac{v_s}{u - v_s} \quad , \tag{94}$$

as the usual case. If the observer is moving, and the source is at rest,

$$\Delta f = f^{'} - f = - f \, \frac{v_o}{u} \quad . \tag{95}$$

Doppler devices used to monitor bubbles in the circulation, or trap speeders with radar detectors, are simple. High frequency waves, emitted by a sending crystal of a Doppler probe, easily travel through body tissue, with a portion reflected back towards a receiving crystal. Tissue moving toward or away from the sending unit will reflect part of the source signal with a frequency shift determined by the velocity of the reflecting medium. Integrated Doppler systems discard the unshifted portion of the reflected signal, and only analyze the shifted portion. Shifted signals fall within the human audibility range. In the veins, bubbles reflect more of the signal than flowing blood, with chirps and pops superimposed on continuous flowing blood background sounds. Detected bubbles are graded from 0 to 4, roughly no bubbles to 1,000 or more per minute.

Doppler probes are inserted into leg and arm veins, pulmonary arteries (heart to lung), and even the heart ventricles. Bubbles detected in veins or ventricles are traveling from tissues to the lungs. They may, or may not, be associated with free phases at joints, or in the spinal column, causing DCS at these sites. Doppler prediction of DCS falls in the 10% to 15% success range, even for high grade bubbles (3-4 Doppler grade). While less than totally predictive, the preponderance of high Doppler grade bubbles for a dive profile renders the profile suspect at least. Following a typical nonstop dive to the limits, Doppler bubble levels tend to peak in an hour, or two. Recent studies by the Divers Alert Network (DAN) at Duke University reported that some 18% of recreational dives produced some level of Doppler bubbling, on tables or decompression meters.

Acoustical signals in the *megahertz* frequency range are typically employed in Doppler analysis. The size and velocity of reflecting bubbles in the flowing media are crucial factors in the reflected return signals. Where flow rates are the highest, the smallest bubbles can be detected with Doppler technology. Roughly, entrained bubbles in the 20 - 40 *micron* diameter range are detectable in flows ranging 50 -60 cm/sec, as depicted in Figure 13, according to bubble flow experiments employing 5 *megahertz* acoustical signals.

Micronuclei And Gel Experiments

Internal pressures in bubbles exceed ambient pressures by amounts equal to the effective surface tensions of the bubbles, as seen in Figure 11. To eliminate bubbles, or reduce growth, increasing ambient pressure is requisite not only to restrict size, but also to drive the gas by diffusion out of the bubble and across the tissue-bubble interface, according to Figure 12. The shorter the desired time of elimination, the greater must be the ambient pressure. Experiments conducted in decompressed gels are illuminating, as described in Figure 14 depicting dissolution time against bubble size. The smaller the bubble, the shorter the dissolution time. Here implication for diving is suggestive. In the presence of asymptomatic free phases, increased offgassing pressure is prudent, With any overpressure, the length of time required to dissolve bubbles of 250 *micron* diameter is significantly shorter than that required to dissolve larger bubbles. Immediate recompression within less than 5 *minutes* is adequate treatment for bubbles less than 100 *microns* in diameter, and this supports the practice of underwater recompression for divers on general principles. Of course, gels and body tissue are different, and gels are neither metabolic nor perfused by blood.

Bubbles, which are unstable, are thought to grow from micron size, gas nuclei which resist collapse due to elastic skins of surface activated molecules (surfactants), or possibly reduction in surface tension at tissue interfaces or crevices. If families of these micronuclei persist, they vary in size and surfactant content. Large pressures (somewhere near 10 *atm*) are necessary to crush them. Micronuclei are small enough to pass through the pulmonary filters, yet dense enough not to float to the surfaces of their environments, with which they are in both hydrostatic (pressure) and diffusion (gas flow) equilibrium. When nuclei are stabilized, and not activated to growth or contraction by external pressure changes, the skin (surfactant) tension offsets both the Laplacian (film) tension and any mechanical help from surrounding tissue. Then all pressures and gas tensions are equal. However, on decompression, the seed pockets are surrounded by dissolved gases at high tension and can subsequently grow (bubbles) as surrounding gas diffuses into them. The rate at which bubbles grow, or contract, depends directly on the difference between tissue tension and local ambient pressure, effectively the bubble pressure gradient, denoted G. At some point in time, a critical volume of bubbles, or separated gas, is established and bends symptoms become statistically more probable. On compression, the micronuclei are crunched down to smaller sizes across families, apparently stabilizing at new reduced size. Bubbles are also crunched by increasing pressure because of Boyle's law, and then additionally shrink if gas diffuses out of them. As bubbles get smaller and smaller, they probably restabilize as micronuclei.

Under compression-decompression, gas nuclei may grow as bubbles, depending on their effective bubble radius. Below a certain critical radius, r_c, listed in Table 12. as a function of pressure according to a bubble model (varying permeability), as fitted to gel experiments, bubbles tend to collapse on themselves, while at larger equilibrium radius, they grow as gas diffuses into them. Stabilized nuclei evolve into unstable bubbles when their effective surface tension is greater than zero, or a sufficient diffusion gradient exists to drive gas into, or out of, the nucleus. At sea level, the model excitation radius is near .8 *microns*, smaller than living cells, having dimensions starting at a few microns.

Table 12. Micronuclei Excitation Radii.

pressure P (fsw)	excitation radius r $(microns)$	pressure P (fsw)	excitation radius r $(microns)$
13	.89	153	.49
33	.80	173	.46
53	.72	193	.44
73	.66	213	.41
93	.61	233	.39
113	.57	253	.37
133	.53	273	.36

Micronuclei can be broadly classified as *homogeneous* or *heterogeneous*, depending upon their composition and that of the surrounding media. If the composition of both micronuclei and parent media are essentially the same, the nucleation process is termed homogeneous. If the composition of micronuclei and parent media differ, the nucleation process is termed heterogeneous. Spontaneously bubble formation in pure supersaturated liquids under explosive decompression is mainly homogeneous, while bubble formation on dust particles in supersaturated fluids is mostly heterogeneous. Homogeneous nucleation and bubble formation usually require large decompressions (many tens of atmospheres), while heterogeneous nucleation and bubble formation processes transpire with very small decompressions (tenths of atmospheres). Homogeneous nucleation in body tissue under nominal and controlled conditions of decompression appears much less likely than heterogeneous nucleation, considering pressure change and host of organic and inorganic body sustances.

Nucleation theory is consistent with a number of diving observations. Divers can significantly increase tolerance against bubble formation, and therefore bends, by following three simple practices:

1. make the first dive a deep, short (crush) dive, thereby constricting micronuclei down to smaller, safer size;

2. make succeeding dives progressively more shallow, thus diving within crush limits of the first dive and minimizing excitation of smaller micronuclei;
3. make frequent dives (like every other day), thus depleting the number of micronuclei available to form troublesome bubbles.

An underlying point can be made here. If nucleation sites are extinguished, reduced in number, or ill-disposed to excitation, bubble formation and risk are commensurately reduced. Regeneration times for classes of micronuclei are estimated to be near a week, underscoring physiological adaptation to recurring pressure environments. The mechanics of nucleation, stabilization, and bubble growth are fairly complex, with stabilization mechanisms only recently quantified. Source and generation mechanisms before stabilization are not well understood. Some candidates include cosmic radiation and charged particles, dissolved gases in fluids we drink, lymph draining tissues into veins, collisional coalescence, blood turbulence and vorticity, exercise, the stomach, and the thin air-blood endothelium in the lungs. Once formed, micronuclei must stabilize very rapidly with surfactant material. Passing through the pulmonary filters of the lungs, only sub-micron sizes might survive. If nuclei are persistent, it is not clear that they populate all tissue sites, nor possess the same size distributions. Some can argue that gel findings are not relevant because biological fluids are formed, and contained, in a sealed environment (the body), but studies confirm the existence of preformed gas micronuclei in serum and egg albumin. Nuclei seem to pervade all manner of fluids.

Abandoning preformed nuclei, other methods of instantaneous bubble formation are certainly possible. Cavitation, produced by the rapid tearing, or moving apart, of tissue interfaces, is a candidate, as well as surface friction (tribonucleation). Crevices in tissues may form or trap gas phases, with later potential for release. Vorticity in blood flow patterns might cause small microbubbles. Stable, or unstable, the copious presence of microbubbles in the venous circulation would impact dissolved gas elimination adversely, also possibly impairing the lungs or the arterial network. The presence of bubbles in the arterial circulation might result in embolism. Bubble clogging of the pulmonary circulation is thought to relate to the *chokes*, a serious form of decompression sickness, while cerebral decompression sickness is believed due to emboli. Microbubbles in the venous circulation would render gas uptake and elimination asymmetric, with uptake faster than elimination. Displacing blood, microbubbles would reduce the effective area and volume for tissue-blood gas exchange.

Bends

Clinical manifestations of decompression sickness, or decompression illness (DCI), can be categorized as pulmonary, neurological, joint, and skin DCI. All cases are linked to bubbles resulting from pressure reduction, with embolism also included in the categorization. Pulmonary DCI manifests itself as a sore throat with paroxysmal cough upon deep inspiration, followed by severe chest pain, and difficult respiration, a condition collectively called the *chokes*. Chokes is seen often in severe high altitude exposures. Neurological DCI affects the heart, brain, and spinal cord, through arterial gas emboli, venous gas emboli, shunted venous gas emboli (VGE that pass through the pulmonary circulation and enter the arterial circulation), and stationary, extravascular (*autochthonous*) bubbles. Joint DCI is the most common form of mild bends, affecting the nervous (*neurogenic*), bone marrow (*medullar*), and joint (*articular*) assemblies. Neurogenic pain is localized at remote limb sites, usually without apparent cerebral or spinal involvment. Bubbles in the bone have been proposed as the cause of both dull aching pain and bone death. Expanding extravascular bubbles have been implicated in the mechanical distortion of sensory nerve endings. Skin DCI manifests itself as itching, rash, and a sense of localized heat. Skin DCI is not considered serious enough for hyperbaric treatment, but local pain can persist for a few days. Blotchy purple patching of the skin has been noted to precede serious DCI, especially the chokes.

Reiterating, most believe that bends symptoms follow formation of bubbles, or the gas phase, after decompression. Yet, the biophysical evolution of the gas phase is incompletely understood. Doppler bubble and other detection technologies suggest that:

1. moving and stationary bubbles do occur following decompression;
2. the risk of decompression sickness increases with the magnitude of detected bubbles and emboli;

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.

Gas phase formation is the single most important element in understanding decompression sickness, and is also a crucial element in preventative analysis.

Treatment of decompression sickness is an involved process, requiring a recompression chamber and various hyperbaric treatment schedules depending on the severity of the symptoms, location, and initiating circumstance. Recompression is usually performed in a double lock hyperbaric chamber, with the patient taken to a series of levels to mitigate pain, first, and then possibly as deep as 165 *fsw* for treatment. Depending on the depth of the treatment schedule, oxygen may, or may not, be administered to washout inert gas and facilitate breathing. Treatment of air embolism follows similar schedules.

MIXED BREATHING GASES

Air is a usual breathing mixture for diving, composed of 79% nitrogen, 20% oxygen, and some 1% of trace gases like neon, carbon dioxide, argon, and others. Other mixtures, across a spectrum of activities, have been utilized very successfully, notably mixtures of nitrogen, helium, and oxygen differing from pure air, and lately those with higher oxygen content than air (*enriched*) which can be employed efficiently in shallow diving. Non-enriched mixtures of nitrogen/oxygen (nitrox), helium/oxygen (heliox), and helium/nitrogen/oxygen (trimix), of course, have been employed commercially in deep and saturation diving. Recently, mixtures of hydrogen/oxygen (hydrox) have also been tested. A closer look at these inert gases in a range of diving applications is illuminating, particularly gas properties, advantages and disadvantages, and interplay.

Biological Reactivity

Low pressure oxygen toxicity can occur if a gas mixture with 60% oxygen is breathed at 1 *atm* for 12 *hours* or more. Pulmonary damage, irritation, and coughing are manifestations (pulmonary toxicity). High pressure oxygen toxicity can occur when breathing pure oxygen at pressures greater than 1 *atm* for periods of minutes to hours, the lower the oxygen pressure the longer the time for symptoms to develop, and vice versa. Twitching, convulsions, and dizziness are the symptoms (nervous system toxicity). On the other, if oxygen pressures fall below .16 *atm*, unconsciousness may result. Low levels of oxygen inhibit tissue cell metabolic function (hypoxia). Confusion and difficulty in maintaining coordination are milder symptoms. Severe hypoxia requires medical attention.

Clearly a constraint in mixed gas diving is the oxygen partial pressure. Inspired partial pressures of oxygen must remain below 1.6 *atm* (52.8 *fsw*) to prevent central nervous system (CNS) toxicity, and above .16 *atm* (5.3 *fsw*) to prevent hypoxia. This window, so to speak, is confining, some 1.44 *atm* (47.5 *fsw*). Denoting the mole fraction of oxygen, f_{O_2}, the upper and lower limits of this window, d_{max} and d_{min}, can be written (*fsw*),

$$\eta d_{max} = \frac{52.8}{f_{O_2}} - P_h \ , \tag{96}$$

$$\eta d_{min} = \frac{5.3}{f_{O_2}} - P_h \ , \tag{97}$$

$$\eta d_{max} - \eta d_{min} = \frac{47.5}{f_{O_2}} \ , \tag{98}$$

with working depths, d, limited by d_{max} and d_{min},

$$d_{min} \ \leq \ d \ \leq \ d_{max} \ . \tag{99}$$

Certainly up to about 7,000 *ft* elevation, the lower limit, d_{min}, is no real constraint, with the surface accessible as the limit.

Another factor inhibiting performance underwater is inert gas narcosis, particularly at increasing ambient pressure. Although the common gases nitrogen and helium associated with diving are physiologically inert under normal atmospheric conditions, they both exhibit anesthetic properties as their partial pressures increase. The mechanism is not completely understood, but impaired carbon dioxide diffusion in the lungs, increased oxygen tension, fear, and related chemical reactions have all been implicated in the past. With 80/20 mixtures, symptom onset fon nitrogen is near 100 fsw, and very much deeper on helium, in the 1,000 fsw range. Symptoms range from light headedness to unconsciousness at the extreme.

Comparative Properties

Nitrogen is limited as an inert gas for diving. Increased pressures of nitrogen beyond 200 fsw lead to excessive euphoria, and reduced mental and physical functional ability, while beyond 600 fsw loss of consciousness results. Individual tolerances vary widely, often depending on activity. Symptoms can be marked at the beginning of a deep dive, gradually decreasing with time. Flow resistance and the onset of turbulence in the airways of the body increase with higher breathing gas pressure, considerably reducing ventilation with nitrogen-rich breathing mixtures during deep diving. Oxygen is also limited at depth for the usual toxicity reasons. Dives beyond 300 fsw requiring bottom times of hours need employ lighter, more weakly reacting, and less narcotic gases than nitrogen, and all coupled to reduced oxygen partial pressures.

A number of inert gas replacements have been tested, such as hydrogen, neon, argon, and helium, with only helium and hydrogen performing satisfactorily on all counts. Because it is the lightest, hydrogen has elimination speed advantages over helium, but, because of the high explosive risk in mixing hydrogen, helium has emerged as the best all-around inert gas for deep and saturation diving. Helium can be breathed for months without tissue damage. Argon is highly soluble and heavier than nitrogen, and thus a very poor choice. Neon is not much lighter than nitrogen, but is only slightly more soluble than helium. Of the five, helium is the least and argon the most narcotic inert gas under pressure.

Saturation and desaturation speeds of inert gases are inversely proportional to the square root of their atomic masses. Hydrogen will saturate and desaturate approximately 3.7 times faster than nitrogen, and helium will saturate and desaturate some 2.7 times faster than nitrogen. Differences between neon, argon, and nitrogen are not significant for diving. Comparative properties for hydrogen, helium, neon, nitrogen, argon, and oxygen are listed in Table 14 below. Solubilities, S, are quoted in atm^{-1}, weights, A, in *atomic mass units*, and relative narcotic potencies, ν, are dimensionless (referenced to nitrogen in observed effect). Least potent gases have the highest index, ν.

Table 13. Inert Gas And Oxygen Molecular Weights, Solubilities, and Narcotic Potency.

	H_2	He	Ne	N_2	Ar	O_2
$A\ (amu)$	2.02	4.00	20.18	28.02	39.44	32.00
$S\ \ (atm^{-1})$						
blood	.0149	.0087	.0093	.0122	.0260	.0241
oil	.0502	.0150	.0199	.0670	.1480	.1220
ν	1.83	4.26	3.58	1.00	0.43	

The size of bubbles formed with various inert gases depends upon the amount of gas dissolved, and hence the solubilities. Higher gas solubilities promote bigger bubbles. Thus, helium is preferable to hydrogen as a light gas, while nitrogen is perferable to argon as a heavy gas. Neon solubility roughly equals nitrogen solubility. Narcotic potency correlates with lipid (fatty tissue) solubility, with the least narcotic gases the least soluble.

Different uptake and elimination speeds suggest optimal means for reducing decompression time using helium and nitrogen mixtures. Following deep dives beyond 300 fsw breathing helium, switching to nitrogen is without risk, while helium elimination is accelerated because the helium tissue-blood gradient is increased when breathing an air mixture. By gradually increasing the oxygen content after substituting nitrogen for helium, the nitrogen uptake can also be kept low. Workable combinations of gas switching depend upon the exposure and the tissue compartment controlling the ascent. In deep saturation diving, *normoxic* breathing mixtures of gases are often advantageously employed to address oxygen concerns. A normoxic breathing mixture, helium or nitrogen, reduces the oxygen percentage so that the partial pressure of oxygen at the working depth is the same as at sea level, the obvious concerns, again, hypoxia and toxicity. Helium (normal 80/20 mixture) nonstop time limits are shorter than nitrogen, and follow a $t^{1/2}$ law similar to nitrogen, that is, depth times the square root of the nonstop time limit is approximately constant. Using standard techniques of extracting critical tensions from the nonstop time limits, fast compartment critical tensions can be assigned for applications. Modern bubble models, such as the varying permeability model, have also been used strategically in helium diving.

Today, the three mixtures (nitrox, heliox, trimix) are employed for deep and saturation diving, with a tendency towards usage of enriched oxygen mixtures in shallow (recreational) diving. The use of enriched oxygen mixtures by recreational divers is aptly concerned with diver safety. Breathing mixture purity, accurate assessment of component gas ratios, oxygen toxicity, and appropriate decompression procedures are valid concerns for the mixed gas diver. Care, in the use of breathing mixtures, is to be underscored. Too little, or too much, oxygen can be a problem. The fourth hydrogen mixture (hydrox) is much less commonplace.

Nitrox

Mixtures of oxygen and nitrogen with less oxygen than 21% (pure air) offer protection from oxygen toxicity in moderately deep and saturation diving. Moderately deep here means no more than a few hundred feet. Hypoxia is a concern with mixtures containing as much as 15% oxygen in this range. Saturation diving on oxygen-scarce nitrox mixtures is a carefully planned exposure. The narcotic effects of nitrogen in the 100 fsw to 200 fsw depth range mitigate against nitrox for deep diving.

Diving on enriched nitrox mixtures need be carefully planned exposures, but for opposite reason, that is, oxygen toxicity. Mixtures of 30% more of oxygen significantly reduce partial pressures of nitrogen to the point of down loading tissue tensions compared to air diving. If standard air decompression procedures are employed, enriched nitrox affords a diving safety margin. However, because of elevated oxygen partial pressures, a maximum permissible depth (floor) needs be assigned to any enriched oxygen mixture. Taking 1.6 atm (52.8 fsw) as the oxygen partial pressure limit, the floor for any mixture is easily computed. Enriched nitrox with 32% oxygen is floored at a depth of 130 fsw for diving, also called the oxygen limit point. Higher enrichments raise that floor proportionately.

Decompression requirements on enriched nitrox are less stringent than air, simply because the nitrogen content is reduced below 79%. Many equivalent means to schedule enriched nitrox diving exist, based on the standard Haldane critical tension approach. Air critical tensions can be employed with exponential buildup and elimination equations tracking the (reduced) nitrogen tissue gas exchange, or equivalent air depths (always less than the actual depths on enriched nitrox) can be used with air tables. The latter procedure ultimately relates inspired nitrogen pressure on a nitrox mixture to that of air at shallower depth (equivalent air depth). For instance, a 74/26 nitrox mixture at a depth of 140 fsw has an equivalent air depth of 130 fsw for table entry. Closed breathing circuit divers have employed the equivalent air depth approach for many years.

Heliox

The narcotic effects of nitrogen in the several hundred feet range prompted researchers to find a less reactive breathing gas for deeper diving. Tests, correlating narcotic effects and lipid solubility, affirm helium as the least narcotic of breathing gases, some 4 times less narcotic than nitrogen, as summarized in Table 13. Deep saturation and extended habitat diving, conducted at depths of 1,000 ft or more on helium/oxygen mixtures by the US Navy, ultimately ushered in the era of heliox diving. For very deep and saturation diving above 700 fsw or so, heliox remains a popular, though expensive, breathing mixture.

Helium uptake and elimination can also be tracked with the standard Haldane exponential expressions employed for nitrogen, but with a notable exception. Corresponding helium halftimes are some 2.7 times faster than nitrogen for the same hypothetical tissue compartment. Thus, at saturation, a 180 $minute$ helium compartment behaves like a 480 $minute$ nitrogen compartment. All the computational machinery in place for nitrogen diving can be ported over to helium nicely, with the 2.7 scaling of halftimes expedient in fitting most helium data.

When diving on heliox, particularly for deep and long exposures, it is advantageous to switch to nitrox on ascent to optimize decompression time, as discussed earlier. The higher the helium saturation in the slow tissue compartments, the later the change to a nitrogen breathing environment. Progressive increases of nitrogen partial pressure enhance helium washout, but also minimize nitrogen absorption in those same compartments. Similarly, progressive increases in oxygen partial pressures aid washout of all inert gases, while also addressing concerns of hypoxia.

An amusing problem in helium breathing environments is the high-pitched voice change, often requiring electronic voice encoding to facilitate diver communication. Helium is also very penetrating, often damaging vacuum tubes, gauges, and electronic components not usually affected by nitrogen. Though helium remains a choice for deep diving, some nitrogen facilitates decompression, ameliorates the voice problem, and helps to keep the diver warm.

Trimix

Diving much below 1400 fsw on heliox is not only impractical, but also marginally hazardous. High pressure nervous syndrome (HPNS) is a major problem on descent in very deep diving, and is quite complex. The addition of nitrogen to helium breathing mixtures (trimix), is beneficial in ameliorating HPNS. Trimix is a useful breathing mixture at depths ranging from 500 fsw to 2,000 fsw, with nitrogen percentages usually below 10% in operational diving, because of narcotic effect.

Decompression concerns on trimix can be addressed with traditional techniques. Uptake and elimination of both helium and nitrogen can be limited by critical tensions. Using a basic set of nitrogen halftimes and critical tensions, and a corresponding set of helium halftimes approximately 3 times faster for the same nitrogen compartment, total inert gas uptake and elimination can be assumed to be the sum of fractional nitrogen and helium in the trimix breathing medium, using the usual exponential expressions for each inert gas component. Such approaches to trimix decompression were tested by researchers years ago, and many others after them.

Hydrox

Since hydrogen is the lightest of gases, it is reasonably expected to offer the lowest breathing resistance in a smooth flow system, promoting rapid transfer of oxygen and carbon dioxide within the lungs at depth. Considering solubility and diffusivity, nitrogen uptake and elimination rates in blood and tissue should be more rapid than nitrogen, and even helium. In actuality, the performance of hydrogen falls between nitrogen and helium as an inert breathing gas for diving.

Despite any potential advantages of hydrogen/oxygen breathing mixtures, users have been discouraged from experimenting with hydrox because of the explosive and flammable nature of most mixtures. Work in the early 1950s by the Bureau of Mines, however, established that oxygen percentages below the 3%-4% level provide a safety margin against explosive and flammability risks. A 97/3 mixture of hydrogen and oxygen could be utilized at depths as shallow as 200 fsw, where oxygen partial pressure equals sea level partial pressure. Experiments with mice also indicate that the narcotic potency of hydrogen is less than nitrogen, but greater than helium. Unlike helium, hydrogen is also relatively plentiful, and inexpensive.

Equivalent Air Depth

In extending air tables to other breathing mixtures, an extrapolation based on the foregoing forms the basis of the *equivalent air depth* method. The equivalent air depth method for table use derives from the imposed equality of mixture and inert gas partial pressures, and is very similar to the altitude equivalent depth method, but is not the same. For instance, with nitrox mixtures, the usual case, the equivalent air depth, δ, is related to the effective depth, d, by imposing the equality of nitrogen partial pressures,

$$f_{N_2}\ (P_h + d) = .79\ (P_h + \delta)\ \ , \tag{100}$$

with P_h surface ambient pressure. Simplifying, we get,

$$\delta = \frac{f_{N_2}}{.79}\ (P_h + d) - P_h\ \ . \tag{101}$$

At altitude, the effective depth, d, is the sea level equivalent depth described earlier. At sea level, the actual depth and effective depth are the same.

With enriched mixtures ($f_{N_2} < .79$), it is clear that the equivalent air depth, δ, is less than the effective depth, d, so that nitrogen decompression requirements are reduced when using δ to enter any set of air tables. Obviously. the same set of M are assumed to apply equally to both air and other mixture in the approach. At sea level, the above reduces to the form,

$$\delta = \frac{f_{N_2}}{.79}\ (33 + d) - 33\ \ , \tag{102}$$

with d the actual depth, and has been utlilized extensively in ocean diving.

The same procedure can be applied to arbitrary heliox, trimix, and hydrox mixtures in theory, basically an extrapolation from a reference (standard) table with the same gas components (helium, nitrogen, or hydrogen with oxygen). Denoting the inert gas molar fraction in the standard (table) mixture, f_{ks}, with $k = N_2$, He, and H_2, and its molar fraction in the arbitrary mixture, f_k, we have,

$$\delta = \frac{f_k}{f_{ks}}\ (P_h + d) - P_h\ \ . \tag{103}$$

Oxygen Rebreathing

In closed circuit systems, exhaled gas is kept in the apparatus, scrubbed of carbon dioxide by chemical absorbents, and then returned to the diver. No gas is released into the water (no bubbles). Gas consumption is related only to the physiological consumption of oxygen. Only a small amount of oxygen is required for extended exposures. Oxygen is taken directly from a breathing bag, and exhaled gas passes separately through an alkaline, absorbent material, where it is scrubbed of carbon dioxide. A typical reduction process involves water vapor, sodium and potassium hydroxide, and carbon dioxide in the reaction chain,

$$CO_2 + H_2 + O \rightarrow H_2 + CO_3, \tag{104}$$

$$2H_2 + CO_3 + 2NaOH + 2KOH \rightarrow Na_2 + CO_3 + K_2 + CO_3 + 4H_2 + O, \tag{105}$$

$$Na_2 + CO_3 + K_2 + CO_3 + 2Ca(OH)_2 \rightarrow 2CaCO_3 + 2NaOH + 2KOH. \tag{106}$$

Rebreathers today last about 3 hr, using approximately 6 m^3 of oxygen and 4 lbs of absorbent. Because of oxygen toxicity, depth is a limitation for oxygen rebreathing. Depth limitation for pure oxygen rebreathing is near 20 fsw. Today, closed circuit mixed gas rebreathers blend inert gases with oxygen (lowering oxygen partial pressure) to extend depth limitations. Two cylinders, one oxygen and the other inert gas (or a premixed cylinder), are employed, and the mixture is scrubbed of carbon dioxide before return to the breathing bag.

Closed circuit oxygen scuba takes advantage of gas conservation, but is limited in dive depth and duration by oxygen toxicity effects. Open circuit scuba offers greater depth flexibility, but is limited in depth and duration by the inefficiency of gas utilization. To bridge this gap, semi-closed circuit mixed gas rebreathers were developed. The semi-closed circuit rebreather operates much like the closed circuit rebreather, but requires a continuous, or frequent, purge to prevent toxic inert gas buildup. Two cylinders of oxygen and inert gas (or one premixed), are charged with safe levels of both, usually corresponding to safe oxygen partial pressure at the maximum operating depth. Gas flow from the high pressure cylinders the breathing circuit is controlled by a regulator and nozzle, admitting a continuous and constant mass flow of gas determined by oxygen consumption requirements. The diver inhales the mixture from the breathing bag and exhales it into the exhalation bag. Pressure in the exhalation bag forces the gas mixture through the carbon dioxide scrubber, and from the scrubber back into the breathing bag for diver consumption. When gas pressure in the breathing circuit reaches a preset limit, a relief valve opens in the exhalation bag, purging excess gas into the water.

Crucial to the operation of rebreathers is a constant and continuous mass flow of breathing gas, subject to oxygen metabolic requirements and depth. Mass balance simply requires that the flow into the breathing bag equals the amount used by the body plus that exhaled into the breathing bag or exhalation bag. Denoting the breathing gas flow rate, F, the metabolic oxygen (consumption) rate, m, the source oxygen fraction, f_{O_2}, and inspired (breathing bag) oxygen fraction, i_{O_2}, mass balance is written,

$$f_{O_2}F = i_{O_2}F + (1 - i_{O_2})m \tag{107}$$

The source flow rate, F, and oxygen fraction, f_{O_2}, depend on nozzle and mixture. The metabolic rate, m, depends on workload, and the inspired fraction, i_{O_2}, is uniquely determined with the other three specified.

Or, for requisite inspired fraction, i_{O_2}, and metabolic rate, m, the source rate, F, and oxygen source fraction, f_{O_2}, can be fixed within limits. Workload rates, m, range, 0.5 - 20.5 l/min, while source flows, F, depend on depth, cylinder and nozzle, with typical values, 5 - 16 l/min. As seen, the source oxygen fraction, f_{O_2}, is uniquely determined by the maximum depth, d_{max}, and maximum oxygen pressure (typically 1.6 - 1.4 atm). Always, inspired oxygen partial pressures are kept between hyperoxic and hypoxic limits, roughly, 0.16 - 1.6 atm.

Oxygen rebreathing at high partial pressures can lead to central nervous system (or pulmonary) oxygen poisoning. It is thought that high pressure oxygen increases the production of oxygen free radicals disrupting cell function. The US Navy conducted research into safe depths and durations for oxygen diving, and concluded that there is very little risk of central nervous system oxygen toxicity when partial pressures of oxygen are maintained below 1.6 atm. Additionally, risk only increases slightly when oxygen partial pressures are maintained below 1.8 atm.

ELECTROMAGNETIC INTERACTIONS

Electrodynamics is the study of charged particles and their associated electrical and magnetic field interactions. The word was coined by Ampere in 1850 to describe all electromagnetic phenomena. The comprehensive description of all electromagnetic phenomena, embodied in Maxwell's equations, is another crowning achievement in science.

The coupling of thermodynamics and electrodynamics is the basis of plasma physics, the study of high temperature matter composed of charged particles. Stellar and interstellar matter is mostly in the plasma state, as is matter in the upper atmosphere (magnetosphere, ionosphere), flames, chemical and nuclear explosions, and electrical discharges. Matter in a controlled thermonuclear reactor would also be in a plasma state, and the study of fusion as a source of energy and power has led to extensive knowledge and advances in plasma physics. In terms of gross properties, plasmas differ from nonionized gases because of their high electrical and thermal conductivity, unusual dielectric and refractive properties, their emission of electromagnetic radiation, collective, long range particle interactions due to the Coulomb force, and very high temperatures.

Electrodynamics is generically the study of charges in motion, the associated electric and magnetic fields fields produced, and their interaction with, and in, matter. The fundamental entity is electrical charge, and only electrical charge, since corresponding magnetic poles have not been found to date. Electrodynamics describes moving charges and time varying fields, while electrostatics and magnetostatics are concerned with stationary charges and constant fields in time, obviously a subcase.

Coulomb And Ampere Laws

Electrical charge is a property of matter, first observed in ancient Greece in materials we now call dielectrics. Centuries ago, it was noted that amber, upon being rubbed, attracts bits of straw and lighter objects. The Greek word for amber is *electron*. That electrified bodies attract and repel was noted by Cabeo in the early 1700s, while du Fay and Franklin denoted these two types of electricities, *positive* and *negative*, a convention still holding today, and established the notion that charge can be neither created nor destroyed (conservation of charge) in physical processes. These deductions were based on the early work of Coulomb and Ampere.

Coulomb noted from extensive laboratory experiments in the 1800s that two electrical point charges, q and e, at distance, r, apart, experience a mutual force, F, inversely varying as the separation squared,

$$F = \frac{qe}{4\pi\varepsilon r^2} \ , \tag{108}$$

with ε the electric permittivity, and the force directed along the line joining them $(1/4\pi\varepsilon = 8.91 \times 10^9 \ m/farad)$. The universal graviational law takes the same form, with the gravitational constant, $G = 6.67 \times 10^{-11} nt \ m^2/kg^2$, replacing $1/4\pi\varepsilon$, and masses, m and M, replacing q and e. Ampere deduced that two charges, q and e, moving with constant velocities, v and u, experience a magnetic force, F, in addition to the Coulomb force, given by,

$$F = \frac{\mu q e v u}{4\pi r^2} \ , \tag{109}$$

with μ the magnetic permeability, and r the separation $(\mu/4\pi = 1 \times 10^{-7} \ henry/m)$.

Magnetic materials have traditionally been considered as elements, alloys, or compounds permitting ordered arrangements, or correlations, among electron magnetic moments or spins. Net magnetic polarization can be ferromagnetic, in which all spins are aligned parallel, antiferromagnetic, in which neighboring spins are aligned antiparallel, or ferrimagnetic, in which spins of two dissimilar atoms are aligned antiparallel. Metals such as iron, cobalt, and nickel are ferromagnetic, while manganese and chromium are antiferromagnetic. The temperature necessary to induce a phase transition from an unordered magnetic state to a magnetically ordered state is the Curie temperature, whether ferrromagnetic or antiferromagnetic in the final state. The permanent properties of such materials are useful in magnetic devices, such as computers and transformers.

An essential difference between electric and magnetic interactions appears in the direction of the force. The electrical force acts in the direction of motion, while the magnetic force acts normal to the direction of motion. Hence the magnetic force can only change direction of the moving charge, but cannot do work on it. Interestingly, both the Coulomb and Ampere laws exhibit an inverse square dependence on the separation of source and field point, just like the gravitational law.

Plasmas

Plasma physics is the physics of ionized gases, and is a relatively new science. Not until development of the electrical power industry were controlled experiments on ionized gases possible, so plasma physics is some 100 *years* old. Studies at the turn of the century of gas discharges and radio propagation off the ionosphere, along with impetus for controlled thermonuclear reaction programs in the 1950s, fueled study of the complex mechanisms attending plasma interactions. The discovery of the solar wind and Van Allen radiation belts in the 1960s provided much data for integration of plasma theory and experiment. Plasmas are complex, exhibiting fluid turbulence and collective motion, linear and nonlinear behavior, and wave and particle motions.

Plasmas exhibit a state of matter in which a significant number, if not all, of the electrons are free, not bound to an atom or molecule. Practically speaking, matter is in the plasma state if there are enough free electrons to provide a significant electrical conductivity, σ. Usually, only a small fraction of electrons need be free to meet this criterion. Collisional ionization, caused by energetic thermal motions of atoms at high temperature, is the source of large numbers of free electrons in matter. Large densities of free electrons are also found in metals at solid densities, independent of the temperature, accounting for the electrical conductivity of metals ar room temperatures and lower. Most terrestrial plasmas, excepting metals which are not plasmas, are very hot and not very dense. The plasma state is the highest temperature state of matter, occuring certainly at much higher temperatures than the gaseous state. Plasmas are hot, ionized gases. Plasmas in discharge tubes, for instance, have subatmospheric densities on the whole. On the cosmological scale, most of the matter in the universe is thought to reside in stellar interiors, where the density is so high that it is called a stellar plasma independent of its temperature. Of course, the temperature is also so high that only the plasma phase could exist. In describing plasmas quantitatively, one must consider the collective motion of the free electrons. By comparison, the charge balancing ions are heavy and sluggish compared to the electrons, and their motion can be neglected. When the density of negative electrons in a region exceeds, or is less than, the density of positive ions, resulting in charge imbalance, electric fields spontaneously develop restoring neutrality. However, the inertia of the electrons causes this balancing procedure to be oscillatory, with frequency, ω. The frequency is a limiting frequency, in that it represents a cutoff for any oscillatory electromagnetic wave, or disturbance, propagation in the plasma. Frequencies below the plasma frequency are not supported by the plasma, and waves cannot propagate. Waves incident on plasmas in which they cannot propagate are reflected, as seen in the reflection of radio waves, for instance, off the ionosphere.

Plasmas are quite luminous. Of the light sources in the universe, most are plasmas. Free electrons in a plasma emit photons when they collide with ions, in a process called *bremsstrahlung*. The spectrum of bremsstrahlung radiation produced spans the infrared to the ultraviolet, and into the X-ray regime, that is, wavelength, λ, spread,

$$1 \le \lambda \le 1{,}000 \, microns \ . \tag{110}$$

Plasmas exhibit collisionless behavior, oddly enough, as temperatures increase. This results from the collective nature of plasma interactions. The binary collisional frequency falls off with temperature, like $T^{-3/2}$, and when it drops below the plasma frequency, other higher frequency processes become more important with the collisional frequency suffering cutoff.

In the laboratory, much research interest centers on economical means to exploit plasmas for energy production. One focus is fusion energy production in thermonuclear fuels, such as deuterium and tritium.

Fusion Energy

Fusion processes in the solar plasma are responsible for energy radiated to the Earth. For the past four decades, scientists have pursued the dream of controlled thermonuclear fusion. The attraction of this pursuit is the enormous energy potentially available in fusion fuels, and the widely held view of fusion as a safe and clean energy source. The fusion reaction with the highest cross mechanism,

$$D+T -> n+He \ , \tag{111}$$

releasing some 17.6 MeV of energy, denoting deuterium, D, tritium, T, neutron, n, and helium, He. To produce fusion reactions in a deuterium-tritium plasma, very high collisional temperatures are necessary to overcome the Coulomb repulsion between interacting nuclei, and the plasma must be confined for long time scales so that many fusion collision reactions can take place to make the process economically feasible. Temperatures near 3 keV ($3.47 \times 10^7 \ K^o$) are necessary for plasma ignition and sustained thermonuclear burn.

Development of an economically viable fusion reactor would literally give us the energy equivalent of oceans of oil. Because seawater contains about 40 g of deuterium and 0.1 g of lithium per ton, every barrel of seawater contains the energy equivalent of almost 30 barrels of oil in deuterium fuel, and about 1/5 barrel of oil in tritium fuel (with tritium produced, or *bred*, from neutron capture on lithium). A volume of seawater equal to the top meter of the oceans would yield enough fuel to power electrical generators for thousands of years at the present consumption rate.

Two methods for producing controlled fusion are popular today, certainly areas of investigation, called magnetic confinement fusion (MCF) and inertial confinement fusion (ICF). Magnetic fusion uses very intense magnetic fields to squeeze a DT plasma to high enough temperatures and densities to ignite and sustain fusion burn. Inertial fusion attempts the same by imploding small pellets, containing DT, with high energy light, ion, or electron beams focused across the pellet. Both are tough problems technologically. With DT fuel, both processes require fuel temperatures in excess of $10^8 \tilde{K}^o$, and fuel particle densities, n, and confinement times, τ, such that,

$$n\tau \ \geq \ 10^{15} \ sec/cm^3 \ \ . \tag{112}$$

Magnetic fusion operates in a regime, $\tau \approx 1$ sec, and therefore, $n \approx 10^{15}$ cm^{-3}. For magnetic confinement fusion, the density is limited by the maximum magnetic field strength that can be generated, often determined by the material strength of the confining vessel. Inertial fusion relies on the mass of the imploding target to provide confinement. For inertial fusion, $\tau \approx 10^{-10}$ sec, so that, $n \approx 10^{25}$ cm^{-3}. Again, these are tough technological constraints in the Earth laboratory, but minor operational limitations in the interior furnace of the sun, which keeps bathing the Earth with direct solar energy from fusion processes, some 2 $cal/min \ cm^2$.

Stellar Evolution

The sun is a star with nuclear furnace, like countless others in the universe. The evolution of nominal stars is detailed by four differential equations in space and time, much like the equations of hydrodynamics. Star birth occurs following a gravitational instability in interstellar dust clouds, that is, a dynamical contraction phase due to gravity against a counteracting pressure gradient. At sufficiently high densities and temperatures in the keV range, thermonuclear reactions occur, releasing of large amounts of energy. In such simplified approach, the star is assumed to be a gaseous sphere, subjected to its own gravity while maintaining spherical symmetry throughout its evolution, from a contracting protostar in interstellar dust, to a very hot, and dense, radiating plasma, to a fuel depleted, dying orb. External forces, magnetic fields, and stellar rotation are not included.

Most stars follow four steps of evolution, namely, gravitational contraction until thermonuclear ignition, expansion due to fusion burn of light elements (hydrogen), lesser expansion due to fusion burn of heavier elements (helium), and final contraction (death) into a white dwarf, neutron star, or black hole (depending on stellar mass) as thermonuclear fuel is depleted, or sometimes enormous explosion (nova). Lightweight stars, with masses less than 4 times the solar mass, usually die as white dwarfs (including the sun). Middleweight stars, up to about 8 solar masses, because they are thought to burn carbon later in their evolution, may die as white dwarfs, or possibly explode as nova and supernova. Heavyweight stars, beyond 8 solar masses, may also explode, but can degenerate (burn) into cold neutron stars or black holes. Neutron stars are very dense objects, essentially compressed neutrons, supported against gravitational collapse by neutron degeneracy (quantum exclusion limit) pressure, while black holes are collapsed gravitational fields, so strong that light emerging from within is completely trapped by gravity, acccording to general relativity. Matter densities in such stellar objects are enormous, on the order of $tons/cm^3$.

Elementary Particle Interactions

Stellar interactions of enormous proportions are driven mainly by gravity. While such interactions on the cosmological scale are beyond imagination, there exist interactions that are up to 10^36 stronger than the *gravitational* forces compressing massive stellar objects, the so called *strong*, *weak*, and *electromagnetic* forces. Elementary particle physics deals with all four at a fundamental level, but a modern focus has been the latter three, namely, strong, weak, and electromagnetic interactions.

The past 40 years have witnessed an explosion of experimental particle data, gathered from high energy accelerators and outer space. Information has been integrated in a consistent picture of elementary particle interactions. Particles are classified in distinct categories. Particles of spin 1/2, with weak and electromagnetic interactions, are called *leptons*. Leptons include electrons, muons, neutrinos, and their antiparticles. Masses typically range from .511 MeV (electron) possibly up to 1,800 MeV (τ lepton). Neutrinos are massless. Particles with strong interactions, including weak and electromagnetic, are called *hadrons*. Integer spin hadrons are *mesons*, while half integer spin hadrons are *baryons*. Masses of hadrons range from 135 MeV (pion) up to as high as 10,200 Mev (short lived resonances). Baryon numbers are conserved in all interactions. Meson numbers are not. Hadrons include protons, neutrons, pions, kaons, short lived resonances, and their antiparticles.

The long range forces of gravity and electromagnetism account for large scale macroscopic phenomena, like planetary attraction and charged particle scattering. The short range strong and weak forces account for microscopic phenomena, such as nucleon binding, radioactive nuclear transmutation, and hadron decay into leptons and photons. Strengths of the fundamental forces inversely as their ranges, in order, strong, weak, electromagnetic, and gravitational, and roughly in the ratio, $10^{36} : 10^{22} : 10^{10} : 1$.

DIVE TABLES AND METERS

Decompression sickness results from excessive changes in ambient pressure over a particular period of time. With simple decompression sickness, 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, more recently encoded into digital underwater computers.

Haldane Model

Haldane models limit degrees of tissue supersaturation, assuming gas exchange is controlled by perfusion (blood flow rate) 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.

$$\frac{\partial(p - p_a)}{\partial t} = -\lambda(p - p_a) \tag{113}$$

with perfusion limited solutions,

$$p - p_a = (p_i - p_a) \; exp \; (-\lambda t) \tag{114}$$

$$\lambda = \frac{.693}{\tau} \qquad (115)$$

for p, p_a, and p_i the instantaneous, arterial, and initial tensions, and τ the assumed tissue halftime. Compartments with 2, 5, 10, 20, 40, 80, 120, 240, 360, and 480 *min* halftimes, τ, are employed in applications today, and halftimes are assumed to be independent of pressure. A one-to-one correspondence between compartments and specific anatomical entities is neither established, nor implied. For large values of τ, tissue uptake and elimination of inert gas is relatively slow according to the response function. For small values of τ, inert gas uptake and elimination proceed much more rapidly. 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.

Decay constants for different gases, λ_i and λ_j, are related by Graham's law,

$$\lambda_j A_j^{1/2} = \lambda_i A_i^{1/2} \qquad (116)$$

with, A_i and A_j, atomic mass numbers. Decay constants for lighter gases are thus greater than those for heavier gases, simply a mobility effect. In this way, sets of critical tensions for nitrogen can be employed for other gases directly, using nitrogen constants (tissue halftimes) scaled by the above.

The rate of uptake and elimination of inert gas is symmetric the same set of tissue halftimes 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, halftimes for uptake are then theoretically shorter than halftimes for elimination.

Critical Tensions

Haldane theory limits degrees of dissolved gas buildup, hypothetically absolute compartment supersaturation, by critical values, M, having a range, $122 \leq M \leq 36$ fsw, notably of American origin. Equivalently, critical ratios, R, and critical gradients, G are also employed, with the $R = M/P$ and $G = M - P$, for P ambient pressure. 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. Critical tensions extracted by Workman and Buhlmann for arbitrary compartments are well known, and, along with previously mentioned exponential tissue functions, are the essential elements of the Haldane approach.

Critical tensions, M, generally increase linearly with depth, d, according to,

$$M = M_0 + \Delta M d \qquad (117)$$

for surfacing critical tension, M_0, and change per depth, ΔM. The USN set are retabulated in Table 14 under appropriate headings.

Table 14. Classical US Navy Surfacing Ratios And Critical Tensions.

halftime τ (min)	critical ratio R_0	critical tension M_0 (fsw)	tension change ΔM
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

The above set (Table 14) can be approximated by the fit relationship,

$$M = 152.7\tau^{-1/4} + 3.25\tau^{-1/4} d \qquad (118)$$

with d the depth (fsw).

Decompression studies developed separately above and below sea level, referenced as aerial and underwater decompression, also by the adjectives, hypobaric and hyperbaric. Hypobaric (aerial) decompression differs from routine hyperbaric (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 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.

Table And Meter Algorithms

Considering only dissolved gases, 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 updated 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 *min* compartment (the slowest) controlling repetitive activity. A set of US Navy Tables, with reduced nonstop limits, appears in Figure 15. Standard US Navy Tables provide safe procedures for dives up to 190 fsw for 60 *min*. Dives between 200 and 300 fsw were tested and reported in the exceptional exposure US Navy tables, including a 240 *min* 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, 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 *min* 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

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 a very low incidence rate of decompression sickness, below 0.01% according to some reports.

Altitude Procedures

Present diving schedules are based to large extent on the model discussed in the foregoing, constraining activities so that M, or R and G, are never compromised. An approach to altitude diving, that is more conservative than some of the linear M extrapolations of the recent past, 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. Recent analyses of high altitude aviator experiments also support the concept of constant tissue ratios for permissible decompressions, and so the approach is not without basis.

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, β, called altitude correction factors, which are just the ratios, α, of sea level atmospheric pressure to altitude atmospheric pressure, multiplied by the specific density of fresh water,

$$\beta = \eta \frac{P_0}{P_h} = \eta\alpha \qquad (119)$$

with operational neglect of the specific density scaling by .975 a conservative convenience, and one of minimal impact on these factors. Today, wrist altimeters facilitate rapid, precise estimation of α on site. They can also be estimated from the barometer equation, and are always greater than one. Table 15 lists altitude factors at various altitudes, z, ranging to 10,000 ft. Up to about 7,000 ft elevation, $\alpha \approx 1 + .0381\,h$, with h measured in multiples of 1,000 ft, that is, $z = 1000\,h$. The higher one ascends to dive, the deeper is his relative exposure in terms of sea level equivalent depth. As described and seen in Table 4, P and α are reciprocally related, inverses actually. Again, time is measured directly, that is, correction factors are only applied to underwater depths, ascent rates, and stops.

Table 15. Altitude Correction Factors And US Navy Altitude Groups.

altitude, or change z (ft)	atmospheric pressure P_h (fsw)	correction factor α	penalty group on arrival at altitude	permissible group for ascension to altitude
0	33.0	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

The similarity rule for altitude table modification, applying correction factors to depths, is straightforward. Convert depths at altitude to sea level equivalent depths through multiplication by β. Convert all table sea level stops and ascent rates back to actual altitude through division by β. 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 $\beta = 1.2$. 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. 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. Whenever salt water tables are used directly in fresh water at sea level, the density difference is usually neglected.

Computing technology has made incredible progress in the past 50 years. In 1945, there were no stored program computers. Today, a few thousand dollars will purchase a desktop personal computer with more performance, more memory, and more disk storage than a million dollar computer in 1965. This rapid rate of improvement has come from advances in technology used to build the computer and from innovation in computer design. Increases in performance of computers are sketched in Figure 14, in terms of a nominal 1965 minicomputer. Performance growth rates for supercomputers, minicomputers, and mainframes are near 20% per year, while performance growth rate for microcomputers is closer to 35% per year. Supercomputers are the most expensive, ranging from one to tens of millions of dollars, while microprocessors are the least expensive, ranging from a few to tens of thousands of dollars. Supercomputers and mainframes are usually employed in high end, general purpose, compute intensive applications. Minicomputers and microprocessors address the same functionality, but often in more diverse roles and applications. The latter class of computers is usually more portable, because they are generally smaller in size.

The label supercomputer usually refers to the fastest, biggest, and most powerful computer in existence at any time. In the 1940s, supercomputers were employed in the design of nuclear weapons (as still today), In the 1950s, supercomputers were first used in weather forecasting, while in the 1960s, computational fluid dynamics problems in the aerospace industry were solved on supercomputers. In the 1970s, 1980s, and 1990s seismological data processing, oil reservoir simulation, structural analysis of buildings and vehicles, quantum field theory, circuit layout, econometric modeling, materials and drug design, brain tomography and imaging, molecular dynamics, global climate and ocean circulation modeling, and semiconductor fabrication joined the supercomputing revolution. Very few areas in science and engineering have not been impacted by supercomputers. Diving is still on the fringes of supercomputing, but applications are growing, particularly in the areas dive profile analysis, statistics, data management, and biomodeling. Smaller and less powerful computers are now employed for monitoring, controlling, directing, and analyzing dives, divers, equipment, and environments.

Over the past four decades, the computer industry has experienced four generations of development, physically marked by the rapid changing of building blocks from relays and vacuum tubes (40s and 50s), to discrete diodes and transistors (50s and 60s), to small and medium scale integrated (SSI/MSI) circuits (60s and 70s), to large and very large scale integrated (LSI/VSLI) devices (70s and beyond). Increases in device speed and reliability, and reductions in hardware cost and physical size, have greatly enhanced computer performance. But device hardware is not the sole factor contributing to high performance computing. Efficient structuring of all the components (platform) supporting computing, such as memories, interconnecting networks, compilers, operating systems, communications channels, user interfaces, software, database banks, graphics servers, and peripheral devices, is an essential ingredient in modern systems.

Today, supercomputers process data and perform calculations at rates of 10^9 floating point operations per second $(gigaflops)$, that is, 10^9 adds, subtracts, multiplies, or divides per second. In the not distant future, 10^{12} floating point operations per second ($teraflops$) will be reached, opening yet another age in computational science. These machines will probably be massively parallel computers, involving thousands of processors processing trillions of data points. To support these raw computing speeds, networks transmitting data at gigabits per second, and fast storage exchanging terabytes of information over simulation times are also requisite. Ultrafast, high resolution graphics servers, able to process voluminous amounts of information, offer an expeditious means to assess output data. Differences in raw processing speeds between various components in a high performance computing environment can degrade overall throughput, conditions termed latencies, or simply, manifest time delays in processing data. Latencies are parasitic to sustained computing performance. Latencies develop at the nodes connecting various computer, storage, network, terminal, and graphics devices, simply because of impedance mismatch in data handling capabilities.

Computers today are categorized as complex instruction set computers (CISC), or reduced instruction set computers (RISC). Reducing memory requirements in storing computer programs is a prime CISC concern, while faster instruction execution is the RISC concern. Larger mainframes usually employ CISC technology, while more recent workstations employ RISC technology. Notable advances in reduced instruction set computer technology, along ith substantial decrease in disk and memory costs, have led many to consider workstation clusters for running parallel programs. Workstation clusters and mainframe parallel computers have significantly different network characteristics. Clusters are limited by slower interconnection speeds and higher message latencies. Studies of clusters suggest minimal latencies in the few millisecond range. Mainframe parallel processors exhibit substantially better message passing capabilities, in the few microsecond range. Choice of cluster or mainframe is often an economic decision by the computer consumer.

Serial And Parallel Processors

Obviously, computers work on processing information, doing calculations, and fetching and storing data in steps. A set of operations, performed in sequential fashion by one processor, is termed serial. A set of operations performed in any fashion, by any number of processors, is roughly termed parallel. Serial computing architectures, once the standard, are now being replaced by parallel computing architectures, with anywhere from tens to thousands of central processing units (CPUs). Processors themselves can be scalar, or vector, that is, operating on a single entity, or group of entities (numbers).

The architectural feature associated with supercomputers in the 1970s was vector processing. Vector processing allowed large groups of numbers, or vectors, to be processed in parallel, resulting in performance speedups by factors of ten or more (compared to generational improvements on the order of 2 or 3). In the early 1980s, parallel supercomputing was introduced, allowing multiple processors to work concurrently on a single problem. By the end of the century, significantly greater computing parallelism (combining tens of thousands of processing units perhaps), and architectures that integrate modalities, such as numeric and symbolic processing, may be possible. As in the past, software developments on future state of the art supercomputers will probably trail hardware advances, perhaps with increasing distance due to increasingly more complex superparallel systems.

Networks And Storage

Networks are the backbone of modern computer systems. Supercomputers without high speed communications and network interfaces are degraded in application processing speed, limited by the slowest component in the computing platform. Gigaflop computers need $gigabit/sec$ network transmission speeds to expedite the flow of information.

Today, data, voice, image, and full motion video can be digitally encoded, and sent across a variety of physical media, including wire, fiber optics, microwaves, and satellites. The assumption is that all information transmitted will be digital. The greater the number of systems, people, and processes that need to transmit information to one another, the greater the speeds and bandwidths required. Like water in a pipe, to get more information through a network, one can increase the rate of flow (speed), and/or increase the amount that can flow through cross sectional area (bandwidth). Applications under development today presage the needs to transfer data very quickly tomorrow.

To perform as a utility, that is, usefully communicate anything, anytime, anywhere, a network must possess four attributes:

1. connectivity – ability to move information regardless of the diversity of the media;
2. interoperability – ability of diverse intelligent devices to communicate with one another;
3. manageability – ability to be monitored, and to change with applications and devices;
4. distributed applications and connective services – ability to provide easy access to tools, data, and resources across different computing platforms, or organizations.

Advances in massively parallel, large memory computers, and high speed networks have created computing platforms allowing researchers to execute supercodes that generate enormous amounts of data. A typical large application will generate from tens of gigabytes up to several terabytes of data. Such requirements are one to two orders of magnitude greater than the capacities of present generation storage devices. New high performance data systems (HPDS) are needed to meet the very large data storage and data handling Systems consist of fast, large capacity storage devices that are directly connected to a high speed network, and managed by software distributed across workstations. Disk devices are used to meet high speed and fast access requirements, while tape devices are employed to meet high speed and high capacity requirements. Storage devices usually have a dedicated workstation for storage and device management, and to oversee data transfer.

Computer systems use a hierarchy to manage information storage:

1. primary storage – fast, solid state memory contained in the processor;
2. direct access storage – magnetic or optical disks, connected to the processor, providing fast access;
3. sequential access storage – magnetic tape cassettes or microfilm, providing large capacity.

Moving down the hierarchy, access time goes up, storage capacity increases, and costs decrease.

Grand Challenge Problems

Grand Challenge problems are computational problems requiring the fastest computers, networks, and storage devices in existence, and problems whose solutions will have tremendous impact on the economic well being of the United States. Vortices in combustion engines, porous flow in oil bearing substrates, fluid turbulence, three dimensional seismic imaging, ductile and brittle fracture of materials under stress, materials by computer design, global convection of tectonic plates, geomagnetic field generation, ocean and atmospheric circulation, high impact deformation and flow, air and groundwater pollution, global climate modeling, elastic-plastic flow, brain tomography, HIV correlations, and many others are just such problems.

The scale of computational effort for nominal Grand Challenge problems can be gleaned from Table 16, listing floating point operations, computer memory, and data storage requirements. As a reference point, the 6 million volumes in the Library Of Congress represent some 6 terabytes of information. The simulations listed in Table 6 run for a week on the CM5, the Thinking Machines Corporation (TMC) massively parallel supercomputer. On future generation supercomputers, simulation times are expected to drop to hours.

Table 16. Grand Challenge Computing Requirements.

problem	description	operations $(gigaflops)$	memory $(terabytes)$	storage $(terabytes)$
porous media	3D immisicible flow	10^9	1	4
ductile material	3D molecular dynamics	10^9	.30	3
	3D material hydro	10^9	1	20
plasma physics	numerical tokamak	10^9	1	100
global ocean	century circulation	10^8	4	20
brain topology	3D rendering	10^6	.015	.001
quantum dynamics	lattice QCD	10^9	.008	.008

Monte Carlo Methods

Monte Carlo calculations explicitly employ random variates, coupled to statistical sampling, to simulate physical processes and perform numerical integrations. In computational science, Monte Carlo methods play a special role because of their combination of immediacy, power, and breadth of application. The computational speed and memory capacity of supercomputers have expedited solutions of difficult physical and mathematical problems with Monte Carlo statistical trials. Although Monte Carlo is typically used to simulate a random process, it is frequently applied to problems without immediate probabilistic interpretation, thus serving as a useful computation tool in all areas of scientific endeavor.

The Monte Carlo method is different than other techniques in numerical analysis, because of the use of random sampling to obtain solutions to mathematical and physical problems. A stochastic model, which may or may not be immediately obvious, is constructed, and, by sampling from appropriate probability distributions, numerical solution estimates are obtained. Monte Carlo calculations are then performed by simulating the physics at each point in an event sequence. All that is required for the simulation of the cumulative history is a probabilistic description of what happens at each point in the history. This generally includes a description of the geometrical boundaries of regions, a description of material composition within each region, and the relative probability function for an event.

With high speed computers, millions of events can be generated rapidily to provide simulation of the processes defined by the probability function. Statistically, the accuracy of the simulation, measured by the variance, increases with number of events generated. In actual simulations, the true mean is usually unknown, but the central limit theorem tells us that, as the number of sample sizes increases, the distribution of sample means itself is normally distributed about the true mean. In addition to large number, and rapid, event generation, supercomputers, in the absence of analytic means, can economically invert the probability integral relating event and probability.

Sampling schemes often employ biasing to reduce variance. Biasing means sampling the most important region of a problem, affixing a weight factor to any event to correct for distortion in the sampling scheme. Popular techniques are splitting and Russian roulette. In entering regions very important to physical simulations, particles are split into μ identical particles, and assigned weights, w/μ, with w the weight of the incoming particles. Weight is clearly preserved by the process, and the statistics are improved, because the numbers of events increase and the variance is reduced. In complex geometries, each cell of a geometric region can be assigned an importance, I. When a particle of weight, w, enters the region, $n+1$, from region, n, the importance ratio, I_{n+1}/I_n, is examined. If the ratio is is greater than one, the particle is entering a cell of greater importance, and the particle is split into $\mu = I_{n+1}/I_n$ identical particles, each with weight, w/μ. When the importance decreases, that is, the ratio is less than one, Russian roulette is employed. Particles either survive with probability, μ, or are destroyed with probability, $1-\mu$, with, of course, $\mu = I_{n+1}/I_n < 1$. When splitting and Russian roulette are combined, than particles in a region of importance, I, tend to acquire the same weights, helpful in estimating the variance of scored quantities. Simple to use, and hard to abuse, splitting and Russian roulette are widely used variance reduction schemes.

Another approach, coupled to increasing the numbers of particles and adjusting weights in regions of increasing importance, is seen in the exponential transformation. The importance of a region is assigned the value, $I = exp\ (\alpha x)$, with x the penetration distance, assumed to increase monotonically with penetration. The constant, α, is adjusted to bias events which reduce variance, while reflecting possible exponential physical behavior as well. In the limit of infinitely many splitting boundaries, Russian roulette and splitting (together) are a special case of exponential biasing.

Monte Carlo methods can be applied to generate bubbles in tissue and blood using the thermodynamical Gibbs free energy, G. as a sampling probability. Cavitation nuclei are generated from the instantaneous Gibbs probability, dG, as a function of nuclei radius, r, via,

$$dG = \frac{8\pi\gamma}{3kT} r\ exp\ (-4\pi\gamma r^2/3kT) dr, \tag{120}$$

with γ the liquid-vapor surface tension, and T the temperature. A random variable on the interval, $0 \leq \zeta \leq 1$, permits the instantaneous probability function to be sampled easily,

$$\zeta = \frac{8\pi\gamma}{3kT} \int_0^r x\ exp\ (-4\pi\gamma x^2/3kT) dx \tag{121}$$

when inverted analytically, or numerically, for bubble radius, r, in terms of the random variable, ζ. Surrounded by dissolved gas at tension, p, for ambient pressure, P, bubbles can be generated and tracked through growth and collapse cycles in time, allowed to move with surrounding fluid, coalesced with each other on collision, and removed at external boundaries. Such cavitation simulations can be applied to multiphase flow in reactor vessels, cavitation around ship propellors, bubbles in tissue and blood, cloud condensation processes in the atmosphere, cosmic ray tracking in detector chambers, and boiling processes in general.

Diving has its own brand of medical complications, linked to ambient pressure changes. For brief consideration, a few of the common medical problems associated with compression-decompression and diving follow. The bubble problem has been long discussed, but we can start off by summarizing a few concensus opinions concerning decompression sickness. A cursory discussion of some maladies and drugs then follows.

Bends

Clinical manifestations of decompression sickness, or decompression illness (DCI), can be categorized as pulmonary, neurological, joint, and skin DCI, as summarized by Vann. All are linked to bubbles upon pressure reduction, with embolism also included in the categorization. Pulmonary DCI manifests itself as a sore throat with paroxysmal cough upon deep inspiration, followed by severe chest pain, and difficult respiration, a condition collectively called the *chokes*. Chokes is seen often in severe high altitude exposures. Neurological DCI affects the heart, brain, and spinal cord, through arterial gas emboli, venous gas emboli, shunted venous gas emboli (VGE that pass through the pulmonary circulation and enter the arterial circulation), and stationary, extravascular (*autochthonous*) bubbles. Joint DCI is a common form of mild bends, affecting the nervous (*neurogenic*), bone marrow (*medullar*), and joint (*articular*) assemblies. Neurogenic pain is localized at remote limb sites, usually without apparent cerebral or spinal involvment. Bubbles in the bone have been proposed as the cause of both dull aching pain and bone death. Expanding extravascular bubbles have been implicated in the mechanical distortion of sensory nerve endings. Skin DCI manifests itself as itching, rash, and a sense of localized heat. Skin DCI is not considered serious enough for hyperbaric treatment, but local pain can persist for a few days. Blotchy purple patching of the skin has been noted to precede serious DCI, especially the chokes.

Most believe that bends symptoms follow formation of bubbles, or the gas phase, after decompression. Yet, the biophysical evolution of the gas phase is incompletely understood. Doppler bubble and other detection technologies suggest that:

1. moving and stationary bubbles do occur following decompression;
2. the risk of decompression sickness increases with the magnitude of detected bubbles and emboli;
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.

Gas phase formation is the single most important element in understanding decompression sickness, and is also a crucial element in preventative analysis.

Treatment of decompression sickness is an involved process, requiring a recompression chamber and various hyperbaric treatment schedules depending on the severity of the symptoms, location, and initiating circumstance. Recompression is usually performed in a double lock hyperbaric chamber, with the patient taken to a series of levels to mitigate pain, first, and then possibly as deep as 165 fsw for treatment. Depending on the depth of the treatment schedule, oxygen may, or may not, be administered to washout inert gas and facilitate breathing. Treatment of air embolism follows similar schedules.

High Pressure Nervous Syndrome

Hydrostatic pressure changes, particularly in the several hundred atm range, are capable of affecting, though usually reversibly, central nervous system activity. Rapidly compressed divers, say 120 fsw/min to 600 fsw, breathing helium, experience coarse tremors and other neurological disorders termed *high pressure nervous syndrome* (HPNS). At greater depths, near 800 fsw, cramps, dizziness, nausea, and vomiting often accompany the tremor. Although HPNS can be avoided by slowing the compression rate, the rate needs to be substantially reduced for compressions below 1,100 fsw.

While the underlying mechanisms of HPNS are not well understood, like so many other pressure related afflictions, the use of pharmacological agents, some nitrogen in the breathing mixture, staged compressions, alcohol, and warming have been useful in ameliorating HPNS in operational deep diving.

Gas induced osmosis has been implicated as partially causative in high pressure nervous syndrome. Water, the major constituent of the body, shifting between different tissue compartments, can cause a number of disorders. Mechanical disruption, plasma loss, hemoconcentration, and bubbles are some. Under rapid pressure changes, gas concentrations across blood and tissue interfaces may not have sufficient time to equilibrate, inducing balancing, but counter, fluid pressure gradients (osmotic gradients). The strength of the osmotic gradient is proportional to the absolute pressure change, temperature, and gas solubility.

Inert Gas Narcosis

It is well known that men and animals exposed to hyperbaric environments exhibit symptoms of intoxication, simply called *narcosis*. The narcosis was first noticed in subjects breathing compressed air as earlier as 1835. The effect, however, is not isolated to air mixtures (nitrogen and oxygen). Both helium and hydrogen, as well as the noble (rare) gases such as xenon, krypton, argon, and neon, cause the same signs and symptoms, though varying in their potency and threshold hyperbaric pressures. The signs and symptoms of inert gas narcosis have manifest similarity with alcohol, hypoxia (low oxygen tension), and anesthesia. Exposure to depths greater than 300 fsw may result in loss of consciousness, and at sufficiently great pressure, air has been used as an anesthetic. Individual susceptibility to narcosis varies widely from individual to individual. Other factors besides pressure potentiate symptoms, such as alcohol, work level, apprehension, and carbon dioxide levels. Frequent exposure to depth with a breathing mixture, as with DCS, affords some level of adaptation.

Many factors are thought contributory to narcosis. Combinations of elevated pressure, high oxygen tensions, high inert gas tensions, carbon dioxide retention, anesthetically blocked ion exchange at the cellular interface, reduced alveolar function, and reduced hemoglobin capacity have all been indicted as culprits. But, still today, the actual mechanism and underlying sequence is unknown.

The anesthetic aspects of narcosis are unquestioned in most medical circles. Anesthesia can be induced by a wide variety of chemically passive substances, ranging from inert gases to chloroform and ether. These substances depress central nervous system activity in a manner altogether different from centrally active drugs. Anesthetics have no real chemical structure associated with their potency, and act on all neural pathways, like a bulk phase. Physicochemical theories of anesthetics divide in two. One hypothesis envisions anesthetics interacting with hydrophobic surfaces and interfaces of lipid tissue. The other postulates anesthetic action in the aqueous phases of the central nervous system. The potency and latency of both relate to the stability of gas hydrates composing most anesthetics. The biochemistry of anesthetics and narcosis in divers has not, obviously, been unraveled.

Hyperoxia And Hypoxia

Elevated oxygen tensions (*hyperoxia*), similar to elevated inert gas tensions, can have a deleterious effect on divers, aviators, and those undergoing hyperbaric oxygen treatment. The condition is known as oxygen toxicity, and was first observed, in two forms, in the final quarter of the 1800s. Low pressure pressure oxygen toxicity (Lorraine Smith effect) occurs when roughly a 50% oxygen mixture is breathed for many hours near 1 atm, producing lung irritation and inflammation. At higher partial pressures, convulsions develop in high pressure oxygen toxicity (Bert effect), with latency time inversely proportional to pressure above 1 atm. Factors contributing to the onset of symptoms are degree of exertion, amount of carbon dioxde retained and inspired, and individual susceptibility. Early symptoms of oxygen poisioning include muscualr twitching (face and lips), nausea, tunnel vision, difficulty hearing and ringing, difficulty breathing and taking deep breaths, confusion, fatigue, and coordination problems. Convulsions are the most serious manifestation of oxygen poisioning, followed ultimtely by unconsciousness. Oxygen toxicity is not a problem whenever the oxygen partial pressures drop below .5 atm.

Oxygen toxicity portends another very complex biochemical condition. Elevated oxygen levels interfere with the enzyme chemistry linked to cell metabolism, especially in the central nervous system. Reduced metabolic and electrolytic transport across neuronal membranes has been implicated as a causative mechanism The role of carbon dioxide, while contributory to the chain of reactions according to measurements, is not understood, just as with inert gas narcosis. On the other hand, it has been noted that only small increases in brain carbon dioxide correlate with severe symptoms of oxygen toxicity. Carbon dioxide seems to play an important, though subtle, part in almost all compression-decompression afflictions.

Breathing air at atmospheric pressure after the onset of oxygen toxicity symptoms can restore balance, depending on severity of symptoms. Deep breathing and hyperventilation can also forestall convulsions if initiated at the earliest sign of symptoms.

When the tissues fail to receive enough oxygen, a tissue debt (*hypoxia*) develops, with varying impact and latency time on body tissue types. Hypoxia can result with any interruption of oxygen transport to the tissues. Although the nervous system itself represents less than 3% of body weight, it consumes some 20% of the oxygen inspired. When oxygen supply is cut, consciousness can be lost in 30 *seconds* or less, respiratory failure follows in about a *minute*, and irreparable damage to the brain and higher centers usually occurs in about 4 *minutes*. Obviously, the brain is impacted the most. The victim of hypoxia may be unaware of the problem, while euphoria, drowsiness, weakness, and unconsciousness progress. Blueness of the lips and skin results, as blood is unable to absorp enough oxygen to maintain its red color. When oyxgen partial pressures drop below .10 *atm*, unconsciousness is extremely rapid.

Hypoxia is a severe, life threatening condition. However, if fresh air is breathed, recovery is equally as rapid, providing breathing has not stopped. If breathing has stopped, but cardiac function continues, artificial respiration can stimulate the breathing control centers to functionality. Cardiopulmonary resuscitation can be equally successful when both breathing and heart action have ceased.

Hypercapnia And Hypocapnia

Tissue carbon dioxide excess (*hypercapnia*) can result from inadequate ventilation, excess in the breathing mixtures, or altered diver metabolic function. All tissues are affected by high levels of carbon dioxide, but the brain, again, is the most susceptible. The air we breathed contains only some .03% carbon dioxide. As partial pressures of carbon dioxide approach .10 *atm*, symptoms of hypercapnia become severe, starting with confusion and drowsiness, followed by muscle spasms, rigidity, and unconsciousness. Carbon dioxide at .02 *atm* pressure will increase breathing rate, and carbon dioxide at .05 *atm* pressure induces an uncomfortable sensation of shortness of breath. Factors which increase the likelihood and severity of hypercapnia include corresponding high partial pressure of oxygen, high gas densities, breathing dead spaces, and high breathing resistance.

Any process which lowers carbon dioxide levels in the body below normal (*hypocapnia*), can produce weakness, faintness, headache, blurring of vision, and, in the extreme case, unconsciousness. Hypocapnia often results from hyperventilation. The respiratory system monitors both carbon dioxide and oxygen levels to stimulate breathing. Rising carbon dioxide tensions and falling oxygen tesnions trigger the breathing response mechanism. Hyperventilation (rapid and deep breathing) lowers the carbon dioxide levels, leading to hypocapnia.

Extended breathholding after hyperventilation can lead to a condition known as shallow water blackout. Following hyperventilation and during a longer breathholding dive, oxygen tensions can fall to a very low level before a diver returns to the surface and resumes breathing. Oxygen levels are lowered because exertion causes oxygen to be used up faster, but also the sensitivity to carbon dioxide drops as oxygen tension drops, permitting oxygen levels to drop even further. Upon ascension, the drop in the partial pressure of oxygen in the lungs may be sufficient to stop the uptake of oxygen completely, and, with the commensurate drop in carbon dioxide tension, the urge to breathe may also be suppressed.

While the short term effects of both hypercapnia and hypocapnia can be disastrous in the water, drowning if consciousness is lost, the long term effects following revival are inconsequential. Treatment in both cases is breathing standard air normally. Residual effects are minor, such as headache, dizziness, nausea, and sore chest muscles.

Carbon dioxide seems to be a factor in nearly every other compression-decompression malady, including decompression sickness, narcosis, hyperoxia, and hypoxia. It is a direct product of metabolic processes, with about 1 l of carbon dioxide produced for every 1 l of oxygen consumed. Carbon dioxide affects the metabolic rate, and many other associated biochemical reactions. The physical chemistry of carbon dioxide uptake and elimination is much more complex than that of inert gases, such as nitrogen and helium. Transfer of inert gases follows simple laws of solubility (Henry's law) in relation to partial pressures. Carbon dioxide transport depends on three factors, namely, gas solubility, chemical combination with alkaline buffers, and diffusion between the cellular and plasma systems. Only relatively small changes in partial pressures of carbon dioxide can induce chain reactions in the three mechanisms, and larger scale biological impact on gas exchange and related chemistry.

Barotrauma

With pressure decrease, air contained in body cavities expands. Usually, this expanding air vents freely and naturally, and there are no problems. If obstructions to air passage exist, or the expanding air is retained, overexpansion problems, collectively called barotrauma, can occur. One very serious overexpansion problem occurs in the lungs. The lungs can accommodate overexpansion to just a certain point, after which continued overpressurization produces progressive distention, and then rupture, of the alveoli (air exchange sacs). Problems with lung overexpansion can occur with pressure differentials as small as 5 fsw. This distention can be exacerbated by breathholding on ascent or inadequate ventilation, and partial obstruction of the bronchial passageways.

The most serious affliction of pulmonary overpressure is the dispersion of air from the alveoli into the pulmonary venous circulation (arterial embolism), thence, into the heart, systemic circulation, and possibly lodging in the coronary and cerebral arterioles. Continuing to expand with further decrease in pressure, these emboli (bubbles) can block blood flow to vital areas. Clinical features of arterial gas embolism develop rapidly, including dizziness, headache, and anxiety first, followed by unconsciousness, cyanosis, shock, and convulsions. Death can result from coronary or cerebral occlusion, inducing cardiac arrhythmia, shock, and circulatory and respiratory failure. The only treatment for air embolism is recompression in a hyperbaric chamber, with the intent of shrinking emboli in size, and driving the air out of the emboli into solution.

Gas from ruptured alveoli may pass into the membrane lining the chest, the parietal pleura, and also rupture the lining (*pneumothorax*). Trapped in the intrapleural lining, the gas may further expand on ascent, and push against the heart, lungs, and other organs. Often the lungs collapse under the pressure. Symptoms of pneumothorax include sudden chest pain, breathing difficulty, and coughing of frothy blood. Recompression is the indicated treatment for a concomitant condition, along with thoracentesis.

Gas trapped in the tissues about the heart and blood vessels, and the trachea (*mediastinal emphysema*), can adversely impact the circulation, particularly, the venous flow. Symptoms include pain in the sternum, shortness of breath, and sometimes fainting. The condition is exacerbated on ascent as gas trapped in tissues expands. In severe cases, hyperbaric treatment is utilized.

If the bubbles migrate to the tissues beneath the skin (*subcutaneous emphysema*), often a case accompanying mediastinal emphysema, their presence causes a swelling of neck tissue and enhanced local pressure. Feeling of fullness, and change of voice are associated with subcutaneous emphysema. Treatment consists of oxygen breathing, which accelerates tissue absorption of the air trapped in the neck region.

Pressure increases and decreases can be tolerated by the body when they are distributed uniformly, that is, no local pressure differentials exist. When pressure differentials exist, outside pressure greater than inside pressure locally, and vice versa, distortion of the shape of the local site supporting the pressure difference is the outcome. Burst alveoli are one serious manifestation of the problem. Other areas may suffer similar damage, for instance, the ears, sinuses, teeth, confined skin under a wetsuit, and the intestines. Though such complications can be very painful, they are usually not life threatening. When local pressure differentials develop because of inside and outside pressure imbalances, blood vessels will rupture in attempt to equalize pressure. The amount of rupture and degree of bleeding is directly proportional to the pressure imbalance.

Pressures in air spaces in the sinuses, middle air, and teeth fillings are often imbalanced during compression-decompression. To accommodate equalization when diving, air must have free access into and out of these spaces during descent and ascent. Failure to accommodate equalization on descent is termed a squeeze, with outside pressure greater than inside (air space) pressure, while failure to accommodate equalization on ascent is called a reverse block, with inside pressure (air space) greater than ambient pressure. In the case of the ear, it is the eustachian tube which does not permit air passage from the throat to the middle ear. The sinuses have very small openings which close under congestive circumstance, inhibiting air exchange. Similarly, small openings in and around teeth fillings complicate equalization of the air space under the filling (usually a bad filling). In all cases, slow descents and ascents are beneficial in ameliorating squeeze and reverse block problems.

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.

Acclimimatization 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) can affect nonacclimatized 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, evidence of cough, shortness of breath, or tightness serves as a warning. Rapid treatment, including lower altitude, hospitalization, and appropriate therapy, is recommended.

Hypothermia And Hyperthermia

Exposure to cold results in heat loss, called *hypothermia*, 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 a feeling of being very cold are first symptoms of hypothermia, and the situation gets worse fast. 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.

Inadequate ventilation and body heat loss, called *hyperthermia*, 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 life threatening.

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.

Dysbaric Osteonecrosis

Bone rot (*dysbaric osteonecrosis*) is an insidious disease of the long bones associated with repeated high pressure and saturation exposures. Deep and saturation diving portend problems with temperature control in environmental suits, habitats, respiration and surface monitoring, compression and decompression, inert gas reactivity, communication, oxygen levels, and many others, all falling into an operational control category, that is, problems which can be ameliorated through suitable application of sets of established diving protocols. But aseptic bone necrosis is a chronic complication about which we know little.

Affecting the long bones as secondary arthritis or collapsed surface joints, lesions, detected as altered bone density upon radiography, are the suspected cause. Statistics compiled in the early 1980s by the US Navy, Royal Navy, Medical Research Council, and commercial diving industry suggest that some 8% of all divers exposed to pressures in the 300 fsw range exhibited bone damage, some 357 out of 4,463 examined divers. No lesions were seen in divers whose exposures were limited to 100 fsw. Some feel that very high partial pressures of oxygen for prolonged periods is the ultimate culprit for bone lesions, leading to fat cell enlargement in more closed regions of the bone core, a condition that reduces blood flow rate and probably increases local vulnerability to bubble growth. The facts, however, are still not clear. And commercial divers continue to be at higher risk of osteonecrosis.

Drugs

Very few studies have systematized the overall effects of drugs underwater. Drug utilization by divers is connected with medication used to ameliorate diving problems, medication used to treat illness, and recreational drugs. Recent studies suggest that drug effects are compounded at increasing depth, having been described as potentiating, antagonizing, and unpredictable as far as altered behavior with increasing pressure. Side effects can be subtle and also variable, possibly exacerbated by other risk factors such as cold water, oxygen, or nitrogen concentrations. Many different types of drugs are utilized.

Among the more common drugs used by divers are decongestants, taken for ear and sinus relief. These drug products are typically *antihistamines*, providing relief by constricting blood vessels, reducing tissue swelling, and opening passages between sinuses and middle ear for air exchange. Antihistamines often produce drowsiness and decreased mental acuity. Another decongestant, with trade name terfenadine, has no sedative effects. Drugs addressing motion sickness may lead to functional motor impairment. Antihistamines, particularly *meclizine* and *dimenhydrate* are often employed for motion sickness, additionally causing sedation. The skin patch drug, *scopolamine*, also possesses sedative properties, with some additional side effects of blurred vision and dry mouth. Individual reactions vary widely.

Sedative and pain agents also alter mental function. Anti-anxiety drugs, such as *valium*, *halcion*, and *dalmane*, are strong agents, producing significant changes in mental outlook. Muscle relaxants, such as *flexiril* and *robaxin*, induce drowsiness. Analgesics containing *propoxyphene*, *codein*, *oxycodone*, or *hydrocodone* reduce mental and physical exercise capacity. Agents used in the treatment of depression or psychosis cause sedation, and have been noted to induce cardiac dysfunction. Tradename drugs in this category, *elavil*, *haldol*, and *sinequan*, impair cognitive abilities.

Hypertension drugs can limit diving performance. Diuretics, like *lasix* and *hydrochlorothiazide*, cause fluid loss, possibly compounding dehydration and electrolytic imbalance. Agents affecting heart rate and peripheral vasculature may cause drowsiness and reduce blood flow capacity. These drugs include *metoprolol*, *hytrin*, *tenex*, and others. Bronchodilators, used in the treatment of asthma, include *theophylline* and *steroids*. In the former category, tradename drugs, such as *theodur*, *uniphyl*, *metaprel*, and *ventolin* can cause cardiac dysrhythmias and CNS impairment. Gastrointestinal drugs containing *histamines* can also affect the central nervous system, causing drowsiness and headache. Antacids seem to have no noted adverse effects on divers.

According to the diving medical community at large, the bottom line on drugs underwater is caution, since little is known about many, particularly newer ones. Narcotics and hallucinogens, alcohol, and heavy doses of caffeine have been linked to reduced mental and physical acuity, sedation, vasodilatation, diuresis, and dehydration on the mild side, and extreme neurological, respiratory, and cardiovascular stress on the more severe side.

TECHNICAL DIVING PROBLEMS

Problems are based on the material presented, using Tables and Figures for data. Units are used interchangeably, and the simple equivalence ratios nested in Table 1 can be employed to convert back and forth across units. The (modified) USN Tables in Figure 15 should be employed for table applications.

1. Convert depth, $d = 38\ fsw$, to ft (fresh water).

$$38\ fsw \times \frac{1\ ft}{.975\ fsw} \ =\ 38.9\ ft$$

2. Convert ascent rate, $r = 60\ fsw/min$, to msw/sec.

$$r\ =\ 60\ fsw/min \times \frac{msw}{3.28\ fsw} \times \frac{min}{60\ sec} \ =\ .305\ msw/sec$$

3. Convert volume, $V = 6.2\ m^3$, to ft^3.

$$V\ =\ 62\ m^3 \times \frac{3532\ ft^3}{m^3} \ =\ 2189\ ft^3$$

4. Convert pressure, $P = 5.3\ kg/m^2$, to lb/in^2.

$$P \ = \ 5.3\, kg/m^2 \times \frac{.20\ lb/ft^2}{1\ kg/m^2} \times \frac{1\ ft^2}{144\ in^2} \ = \ .0074\, lb/in^2$$

5. Convert acceleration, $g = 32\ ft/sec^2$, to m/sec^2.

$$g \ = \ 32\ ft/sec^2 \times \frac{1\ m}{3.28\ ft} \ = \ 9.8\, m/sec^2$$

6. What does a wrist thermometer of mass, $m = 10\ g$, weigh, w?

$$w \ = \ mg$$

$$w \ = \ 10 \times 980\, dynes \ = \ 9.8 \times 10^3\ dynes$$

What does a 1.5 lb abalone iron weigh, w?

$$w \ = \ 1.5\, lb$$

7. What is the density of fresh water, ρ, of weight, $w = 31.2\ lbs$, occupying $.5\ ft^3$?

$$\rho \ = \ \frac{w}{V} \ = \ \frac{31.2}{.5}\ lb/ft^3 \ = \ 62.4\, lb/ft^3$$

8. What is the density of salt water, ρ, of mass, $m = 2050\ kg$, occupying $2.0\ m^3$?

$$\rho \ = \ \frac{m}{V} \ = \ \frac{2050.}{2.0}\ kg/m^3 \ = \ 1025\, kg/m^3$$

9. What is the mass, m, of 1500 cm^3 of iron (Fe)?

$$\rho_{Fe} \ = \ 7.86\, g/cm^3 \ \ , \ \ m \ = \ \rho_{Fe}V \ = \ 7.86 \times 1500\, g \ = \ 11.8kg$$

10. What volume, V, does 600 g of calcium (Ca) occupy?

$$\rho_{Ca} \ = \ 1.55\, g/cm^3 \ \ , \ \ V \ = \ \frac{m}{\rho_{Ca}} \ = \ \frac{600}{1.55}\ cm^3 \ = \ 387\ cm^3$$

11. What is the gram molecular weight, G, of osmium (Os), and density, ρ_{Os}?

$$A_{Os} \ = \ 190.24 \ \ , \ \ G \ = \ A_{Os}\, g \ = \ 190.24\, g \ \ , \ \ \rho_{Os} \ = \ 22.48\, g/cm^3$$

12. What is the specific density, η, of mercury (Hg) with respect to seawater?

$$\rho_{Hg} \ = \ 13.55\, g/cm^3 \ \ , \ \ \rho_{seawater} \ = \ 1.026\, gm/cm^3$$

$$\eta \ = \ \frac{\rho_{Hg}}{\rho_{seawater}} \ = \ \frac{13.55}{1.026} \ = \ 13.21$$

13. A spear gun propels a lock tip shaft at speed, $v = 34\ ft/sec$? How long before the shaft impales a target grouper 9 ft away?

$$v \ = \ \frac{ds}{dt} \ \ , \ \ dt \ = \ \frac{ds}{v} \ = \ \frac{9}{34}\ sec \ = \ .26\, sec$$

14. What is the average speed of a Zodiac covering distance, $ds = 23\ miles$, in time, $dt = 30\ min$?

$$v \ = \ \frac{ds}{dt} \ = \ \frac{23}{.5}\, mph \ = \ 46\, mph$$

Docking, the Zodiac stops in time, $dt = 5.6\ sec$. What is the magnitude of the deceleration, a?

$$a \ = \ \frac{dv}{dt} \ = \ \frac{-46}{5.6} \times \frac{5280}{3600}\ ft/sec^2 \ = \ -12\ ft/sec$$

15. What is the change in speed, dv, of a hydroplane accelerating for time, $dt = 6\ sec$, with acceleration, $a = 24\ ft/sec^2$?

$$dv \ = \ adt \ = \ 24 \times 6\ ft/sec \ = \ 144\ ft/sec$$

16. A diver surfacing from 150 fsw covers the first 90 fsw in 90 sec, and the remaining 60 fsw in 30 sec. What is the average ascent rate, r?

$$r \ = \ \frac{ds}{dt} \ = \ \frac{150}{90+30}\ fsw/sec \ = \ 1.25\ fsw/sec$$

17. A submersible of mass, m, moves underwater with speed, v. If the speed is doubled, with is the increase in kinetic energy, ΔK, of the submersible?

$$\Delta K \ = \ \frac{1}{2}m(2v)^2 - \frac{1}{2}mv^2 \ = \ \frac{3}{2}mv^2$$

If the speed is tripled, what is the change in momentum, Δp?

$$\Delta p \ = \ 3mv - mv \ = \ 2mv$$

18. A pearl diver plus all gear weigh 128 lbs, and are buoyed up in the water with a force of 124 lbs. What does the pearl diver weigh, ΔW, in the water?

$$\Delta W \ = \ 128 - 124\, lbs \ = \ 4\ lbs$$

If a BC provides lift, how much additional lift, ΔB, is necessary to float the pearl diver at neutral buoyancy?

$$\Delta B = \Delta W \ = \ 4\ lbs$$

19. What are the momentum, p, and kinetic energy, K, of a light diver propulsion vehicle (DPV), $m = 32\ kg$, moving with velocity, $v = 6\ m/sec$?

$$p \ = \ mv \ = \ 32 \times 6\, kg\ m/sec \ = \ 192\ kg\ m/sec$$

$$K \ = \ \frac{1}{2}mv^2 \ = \ \frac{1}{2} \times 32 \times 36\, kg\ m^2/sec^2 \ = \ 1.15\ \times 10^3\ j$$

What is the force, F, required to stop it in 8 sec?

$$dp \ = \ 192\, kg\ m/sec \ \ , \ \ dt \ = \ 8\, sec$$

$$F \ = \ \frac{dp}{dt} \ = \ \frac{192}{8}\ kg\ m/sec^2 \ = \ 24\, nt$$

20. What is the increase in potential energy, U, for a diver of weight, $mg = 150\ lbs$, who ascends from 60 fsw to the surface?

$$U \ = \ mgh \ = \ 150 \times 60 \ ft \ lb \ = \ 9 \times 10^3 \ ft \ lb$$

21. An 80 kg diver giant strides from the deck of a boat into the water 2.7 m below, taking .74 sec to hit the surface. What is the power, W, generated by the fall?

$$W \ = \ \frac{dH}{dt} \ , \ dH \ = \ mgh \ , \ dt \ = \ .74\, sec$$

$$dH \ = \ 80 \times 9.8 \times 2.7\, kg\ m^2/sec^2 \ = \ 2.13 \times 10^3 \ j$$

$$W \ = \ \frac{2.13 \times 10^3}{.74} \ j/sec \ = \ 2.86 \times 10^3\, watt$$

What is the kinetic energy, K, on impact, neglecting air resistance?

$$v \ = \ gt \ = \ 9.8 \times .74\, m/sec \ = \ 7.3\, m/sec$$

$$K \ = \ \frac{1}{2} mv^2 \ = \ \frac{1}{2} \times 80 \times 53.3\ j \ = \ 2.13 \times 10^3 \ j$$

22. A UDT paradiver jumps from a USN Seawolf helicopter with initial potential energy, $U_i \ = \ 12 \times 10^3 \ j$, and zero kinetic energy, $K_i \ = \ 0 \ j$ (all relative to the surface of the Earth). What is the kinetic energy, K_f, when the paradiver hits the water (neglecting air resistance) in the Gulf of Tonkin?

$$E_i \ = \ K_i + U_i \ = \ E_f \ = \ K_f + U_f$$

$$U_i \ = \ 12 \times 10^3 \ j \ , \ U_f \ = \ 0 \ j \ , \ K_i \ = \ 0 \ j$$

$$K_f \ = \ E_f - U_f \ = \ E_i - U_f \ = \ K_i + U_i - U_f \ = \ 0 + 12 \times 10^3 + 0 \ j \ = \ 12 \times 10^3 \ j$$

At some point in the drop, the paradiver gains kinetic energy, $K = 9 \times 10^3 \ j$. What is the corresponding potential energy, U?

$$E \ = \ K + U \ = \ E_i \ = \ E_f \ = \ 12 \times 10^3 \ j$$

$$U \ = \ E - K \ = \ 12 \times 10^3 - 9 \times 10^3 \ j \ = \ 3 \times 10^3 \ j$$

23. What is the energy, ε, of a photon moving at the speed of light, c, and frequency, $f = 8.2 \times 10^{14}\ sec^{-1}$?

$$h \ = \ 6.625 \times 10^{-34} \ j\ sec \ , \ f \ = \ 8.2 \times 10^{14} \ sec^{-1}$$

$$\varepsilon \ = \ hf \ = \ 6.625 \times 8.2 \times 10^{-20} \ j \ = \ 5.4 \times 10^{-19} \ j \ = \ 3.39 \times 10^{-3} \ keV$$

What is the corresponding photon wavelength, λ?

$$c \ = \ 2.99 \times 10^{10} \ cm/sec$$

$$\lambda \ = \ \frac{c}{f} \ = \ \frac{2.99 \times 10^{10}}{8.2 \times 10^{14}} \ cm \ = \ 3.6 \times 10^{-5} \ cm$$

24. What is the energy, E, of a lead weight, $m = 1\ kg$, moving at velocity, $v/c = .85$, aboard the Starship Enterprize initiating warp acceleration?

$$c \ = \ 2.99 \times 10^8\ m/sec \ \ , \ \ m \ = \ 1\ kg$$

$$E \ = \ \frac{mc^2}{(1-v^2/c^2)^{1/2}} \ = \ \frac{1 \times (2.99 \times 10^8)^2}{(1-.85^2)^{1/2}} kg\ m^2/sec^2 \ = \ 1.72 \times 10^{17}\ j$$

What is the corresponding kinetic energy, K?

$$\gamma \ = \ (1-v^2/c^2)^{-1/2} \ = \ .52^{-1/2} \ = \ 1.39$$

$$K \ = \ (\gamma - 1)mc^2 \ = \ .39 \times 1 \times (2.99 \times 10^8)^2\ kg\ m^2/sec^2 \ = \ 3.49 \times 10^{16}\ j$$

25. What is the critical angle, ϕ_c, at the air-water interface, that is, in taking, $n_{air} = 1.0$, and, $n_{water} = 1.33$?

$$sin\ \phi_c \ = \ \frac{n_{air}}{n_{water}} \ = \ \frac{1}{1.33} \ = \ .75$$

$$\phi_c \ = \ sin^{-1}\ (.75) \ = \ 48.5^o$$

26. What is the magnification, μ, and foreshortening, σ, across the quartz-air interface for an object in quartz, viewed in air?

$$\mu \ = \ \frac{n_{quartz}}{n_{air}} \ \ , \ \ \sigma \ = \ \frac{n_{air}}{n_{quartz}}$$

$$\mu \ = \ \frac{1.456}{1.000} \ = \ 1.456 \ \ , \ \ \sigma \ = \ \frac{1.000}{1.456} \ = \ .687$$

27. What is the magnification, μ, and foreshortening, σ, for an object in air, viewed in quartz?

$$\mu \ = \ \frac{n_{air}}{n_{quartz}} \ \ , \ \ \sigma \ = \ \frac{n_{quartz}}{n_{air}}$$

$$\mu \ = \ .687 \ \ , \ \ \sigma \ = \ 1.456$$

28. A coral head appears, $h_{wat} = 8\ ft$, tall, and, $s_{wat} = 6\ ft$, in Truk Lagoon. What are the actual height, h, and distance, s?

$$\mu \ = \ 1.33 \ \ , \ \ \sigma \ = \ .75$$

$$h \ = \ \frac{h_{wat}}{\mu} \ = \ \frac{8}{\mu}\ ft \ = \ 6\ ft$$

$$s \ = \ \frac{s_{wat}}{\sigma} \ = \ \frac{6}{.75}\ ft \ = \ 8\ ft$$

29. How long, dt, does it take a sound wave to propagate a distance, $d = 10,604\ m$, in steel?

$$u \ = \ 5032\ m/sec \ \ , \ \ dt \ = \ \frac{ds}{u} \ = \ \frac{10604}{5302}\ sec \ = \ 2\ sec$$

30. A surface tender screams at a diver underwater with acoustical energy, $\varepsilon = 4.1\ btu$. What is the energy, ε_R, reflected from the surface, and energy, ε_T, transmitted at the surface (absorbed in less than a *cm*)?

$$\varepsilon_R \ = \ R\varepsilon \ \ , \ \ \varepsilon_T \ = \ T\varepsilon$$

$$\varepsilon_R \ = \ .9919 \times 4.1\ btu \ = \ 4.066\ btu \ \ , \ \ \varepsilon_T \ = \ .0081 \times 4.1\ btu \ = \ .034\ btu$$

31. What is the heat flux, ϕ, across a neoprene wetsuit of thickness, $dx = .64\ cm$, for body temperature of $22.7\ C^o$ and water temperature of $4.1\ C^o$?

$$\phi \ = \ -K\, \frac{dT}{dx}$$

$$K \ = \ .0004\ cal/cm\, C^o\ sec \ \ , \ \ dx \ = \ .64\ cm \ \ , \ \ dT \ = \ 22.7 - 4.1\, C^o \ = \ 18.6\, C^o$$

$$\phi \ = \ .0004 \times \frac{18.6}{.64}\ cal/cm^2\ sec \ = \ 1.16 \times 10^{-2}\ cal/cm^2\ sec$$

32. What heat flux, ϕ, does a *light stick* at $298\ K^o$ emit underwater, and what is the Centigrade temperature, (C^o), of the chemical candle?

$$\phi \ = \ \sigma_0 T^4$$

$$T \ = \ 298\ K^o \ \ , \ \ \sigma_0 \ = \ 5.67 \times 10^{-8}\ watts/m^2\ K^{o4}$$

$$\phi \ = \ 5.67 \times 10^{-8} \times 298^4 watts/m^2 \ = \ 447.1\ watts/m^2$$

$$C^o \ = \ K^o - 273 \ = \ 298 - 273 \ = \ 25^o$$

33. An welding thermometer is constructed using changes in resistance to measure temperature changes. If the thermometer is logarthmic in response, what is the temperature, T, at resistance, $X = 60\ ohms$, for fixed points, $T_f = 500\ C^o$, $X_f = 80\ ohms$, and $T_i = 100\ C^o$, $X_i = 20\ ohms$?

$$T - T_i \ = \ (T_f - T_i)\ \left(\frac{ln\ X/X_i}{ln\ X_f/X_i} \right)$$

$$T \ = \ 400 \times \left(\frac{ln\ 60/20}{ln\ 80/20} \right) + 100\ C^o \ = \ 417\ C^o$$

34. Sunlight striking the shallow azure water off the coast of Cozumel delivers, $\Gamma = 2\ cal/m^2$, to the surface. If, $\rho = .02$, is reflected, and, $\tau = .04$, is transmitted, what fraction, α, is absorbed?

$$\rho \ = \ .02 \ \ , \ \ \tau \ = \ .04$$

$$\rho + \tau + \alpha \ = \ 1 \ \ , \ \ \alpha \ = \ 1 - \tau - \rho$$

$$\alpha \ = \ 1 - .04 - .02 \ = \ .95$$

What is the magnitude, Γ_r, of the reflected radiation?

$$\Gamma_r \ = \ \rho\Gamma \ \ , \ \ \Gamma_r = .02 \times 2\ cal/m^2 \ = \ .04\ cal/m^2$$

35. What is the magnitude of the gravitational force, F, between a hard hat diver of mass, $m = 60\ kg$, and surface platform of mass, $M = 6000\ kg$, separated a distance, $r = 30\ m$, underwater?

$$m\ =\ 60\, kg\ \ ,\ \ M\ =\ 6000\, kg\ \ ,\ \ r\ =\ 30\, m$$

$$G\ =\ 6.67 \times 10^{-11}\ nt\ m^2/kg^2$$

$$F\ =\ G\,\frac{mM}{r^2}\ =\ 6.67 \times 10^{-11} \times \frac{60 \times 6000}{30^2}\ nt\ =\ 2.67 \times 10^{-6}\ nt$$

What is the magnitude of the gravitational force, F, between the Earth and the hard hat diver?

$$m\ =\ 60\ kg\ \ ,\ \ g\ =\ 9.8\ m/sec^2$$

$$F\ =\ mg\ =\ 60 \times 9.8\ kg\ m/sec^2\ =\ 588\ nt$$

36. What is the speed of a shallow water wave, $v_{shallow}$, propagating in depth, $d = 10\ fsw$, across the Oso Bay flats at Corpus Christi (Texas)?

$$v_{shallow}\ =\ (gd)^{1/2}\ =\ (32 \times 10)^{1/2}\ ft/sec\ =\ 17.9\ ft/sec$$

37. What is the speed of a deep water wave, v_{deep}, propagating with wavelength, $\lambda = 10\ m$, in the South China Sea?

$$v_{deep}\ =\ (g\lambda/2\pi)^{1/2}\ =\ (9.8 \times 10/6.28)^{1/2}\ m/sec\ =\ 9.9\ m/sec$$

38. What is the speed, u, of a *tsunami* (tidal wave), wavelength, $\lambda = 150\ miles$, and frequency, $f = .31\ hr^{-1}$, slamming into Guam?

$$u\ =\ \lambda f\ =\ 150 \times .31\ mile/hr\ =\ 465\ mph$$

39. What is the horizontal force, F, necessary to drag a 16.5 kg scuba tank across a flat iron plate at a fill station?

$$\mu\ =\ .4\ \ ,\ \ N\ =\ mg$$

$$F\ =\ \mu N\ =\ .4 \times 16.5 \times 9.8\ kg\ m/sec^2\ =\ 64.7\ nt$$

How much work, dH, is done in moving the tank a distance, $ds = 12\ m$?

$$dH\ =\ F ds\ =\ 64.7 \times 12\ j\ =\ 776.4\ j$$

40. Convert 37 C^o to Fahrenheit (F^o), and then to Rankine (R^o) temperatures.

$$F^o\ =\ \frac{9}{5}\, C^o + 32 = \frac{9}{5} \times 37 + 32\ =\ 98.6^o$$

$$R^o\ =\ F^o + 460\ =\ 98.6 + 460\ =\ 558.6^o$$

41. Convert 80 F^o to Centigrade (C^o), and then to Kelvin (K^o) temperatures.

$$C^o\ =\ \frac{5}{9}\,(F^o - 32)\ =\ \frac{5}{9}\,(80 - 32)\ =\ 26.6^o$$

$$K^o\ =\ C^o + 273\ =\ 26.6 + 273\ =\ 299.6^o$$

42. What is the pressure of a column of seawater, $d = 33\ fsw$, assuming density, $\rho = 64\ lbs/ft^3$?

$$P \ = \ \rho d \ = \ 64 \times 33\ lbs/ft^2 \ = \ 2112\ lbs/ft^2 \ = \ 14.6\ lbs/in^2$$

43. What is the pressure of a column of fresh water, $d = 34\ ft$, assuming density, $\rho \ = \ 62.4\ lbs/ft^3$?

$$P \ = \ \rho d \ = \ 62.4 \times 34\ lbs/ft^2 \ = \ 2121\ lbs/ft^2 \ = \ 14.7\ lbs/in^2$$

44. What are the composite partial pressures, p, in a 80/10/10 trimix breathing gas at an ocean depth of 400 fsw (that is, $f_{He} = .80$, $f_{O_2} = .10$, and $f_{N_2} = .05$)?

$$p_i \ = \ f_i\ (33 + 400)\ fsw \quad (i = He, O_2, N_2)$$

$$p_{He} = .80 \times 433\ fsw \ = \ 346.4\ fsw$$

$$p_{O_2} \ = \ .10 \times 433\ fsw \ = \ 43.3\ fsw$$

$$p_{N_2} \ = \ .10 \times 433\ fsw \ = \ 43.3\ fsw$$

45. A diver inflates his BC at depth, $d = 10\ msw$, to approximately $.015\ m^3$. How much work, dW, does the diver do?

$$dW \ = \ PdV$$

$$dW \ = \ 20.2 \times 10^4 \times .015\ kg\ m^2/sec^2 \ = \ 3.03\ \times 10^3\ j$$

46. A mole of air in a tank at $300\ K^o$ is released to the atmosphere and registers an average temperature drop of $30\ K^o$. What is the mean square speed change, vdv of the exiting gas?

$$\frac{dv}{dT} \ = \ \frac{1}{v}\frac{R\gamma}{1-\gamma}$$

$$\gamma \ = \ \frac{5}{3} \ , \ R \ = \ 8.317\ j/gmole\ K^o \ , \ dT \ = \ -30\ K^o$$

$$vdv \ = \ dT\left(\frac{R\gamma}{1-\gamma}\right) \ = \ 30 \times \left(\frac{8.317 \times 5/3}{2/3}\right)\ m^2/sec^2 \ = \ 623.7\ m^2/sec^2$$

If the mean square speed change is roughly half the velocity squared of the exiting gas, what is the average velocity, v?

$$\frac{v^2}{2} \ = \ vdv \ = \ 623.7\ m^2/sec^2$$

$$v \ = \ (2vdv)^{1/2} \ = \ (2 \times 623.7)^{1/2}\ m/sec \ = \ 35.3\ m/sec$$

47. A tank initially at standard temperature and pressure, $P_i = 1\ atm$, and, $T_i = 273\ K^o$, is heated to $313\ K^o$ by the sun. What is the pressure, P, in the tank?

$$P \ = \ \frac{T}{T_i}\ P_i \ = \ \frac{313}{273} \times 1\ atm \ = \ 1.146\ atm$$

48. The air in a dry suit at ambient sea level pressure, $P_0 = 33\ fsw$, occupies volume, $V_0 = .3\ ft^3$, at temperature, $T = 300\ K^o$. What is volume, V, occupied at depth, $P = 50\ fsw$, and temperature, $T = 280\ K^o$?

$$\frac{P_0 V_0}{T_0} = \frac{PV}{T}$$

$$V = V_0 \frac{P_0 T}{P T_0} = .3 \times \frac{33 \times 280}{50 \times 300}\ ft^3 = .185\ ft^3$$

49. What volume, V, does a *gmole* of an ideal gas occupy at standard temperature and pressure?

$$p = 10.1\ nt/cm^2 \ , \ T = 273\ K^o \ , \ R = 8.317\ j/gmole\ K^o$$

$$PV = nRT \ , \ V = \frac{nRT}{P}$$

$$V = \frac{8.317 \times 273}{.101}\ cm^3 = 22.48 \times 10^3\ cm^3 = 22.48\ l$$

50. What is ambient pressure, P_h, at an elevation of $6,500\ ft$?

$$P_h = P_0\ exp\ (-0.038h) \ , \ P_0 = 33\ fsw \ , \ h = 6.5$$

$$P_{6.5} = 33\ exp\ (-0.038 \times 6.5)\ fsw = 33 \times .78\ fsw = 25.7\ fsw$$

51. What is the temperature, T, of a *kgmole* van der Waals gas at pressure, $P = 500\ nt/m^2$, and a specific volume, $v = 2\ m^3/kgmole$, taking the viral coefficients, $a = 100\ nt\ m/kgmole$, and $b = .03\ m^3/kgmole$?

$$RT = \left(P + \frac{a}{v^2}\right)(v - b)$$

$$T = \left(500 + \frac{100}{4}\right) \times (2 - .03) \times \frac{1}{8.31 \times 10^{-3}} = 124.5 \times 10^3\ K^o$$

52. What is the altitude scaling factor, α, for depth, and what is the sea level equivalent depth, δ, for actual depth, $d = 78\ ft$?

$$\alpha = exp\ (0.038h) = exp\ (0.038 \times 6.5) = 1.28$$

$$\delta = \eta\alpha d = .975 \times 1.28 \times 78\ fsw = 97.5\ fsw$$

If a decompression stop is required at $20\ fsw$ according to the USN Tables, what is the actual depth, d, of the stop at 6,500 ft elevation?

$$\delta = 20\ fsw \ , \ d = \frac{\delta}{\eta\alpha} = \frac{20}{.975 \times 1.28}\ ft = 16\ ft$$

53. The air pressure in a scuba tank drops from 2475 lbs/in^2 to 1500 lbs/in^2 in 8 *min*? What is the air consumption rate, χ?

$$\chi = \frac{2475 - 1500}{8}\ lbs/in^2\ min = 121.9\ lbs/in^2\ min$$

If the tank is rated at 72 ft^3, what is the consumption rate, χ, in ft^3/min?

$$121.9\ lbs/in^2\ min \times \frac{72\ ft^3}{2475\ lbs/in^2} = 3.5\ ft^3/min$$

54. How long, t, will a tank containing, $V = 34\ ft^3$, of air last at 33 fsw for an EOD specialist swimming against a 6 *knot* very cold current in the ocean?

$$P_0 \ = \ 33\ fsw \ \ , \ \ \chi_0 \ = \ 2\ ft^3/min \ \ , \ \ \chi \ = \ \chi_0 \left(1 + \frac{d}{P_0}\right)$$

$$\chi \ = \ 2 \left(1 + \frac{33}{33}\right) \ ft^3/min \ = \ 4\ ft^3/min$$

$$t \ = \ \frac{V}{\chi} \ = \ \frac{34}{4}\ min \ = \ 8.5\ min$$

55. What is the air consumption rate, χ, at depth, $d = 46\ ft$, and elevation, $z = 6,500\ ft$, for sea level surface consumption rate, $\chi_0 = .95\ ft^3/min$? in fresh water?

$$\chi \ = \ \frac{\chi_0}{\alpha} \left(1 + \frac{d\eta\alpha}{P_0}\right)$$

$$\chi \ = \ \frac{.95}{1.28} \times \left(1 + \frac{46 \ \times \ .975 \times 1.28}{33}\right) \ ft^3/min \ = \ 2.03\ ft^3/min$$

56. If a hookah unit pumps a surface rate, $\chi_0 = 5\ ft^3/min$, of air , what rate, χ, will it deliver at depth, $d = 20 fsw$, on a reef?

$$\chi \ = \ \chi_0 \ \frac{P_0}{P_0 + d} \ = \ 5 \times \frac{33}{53}\ ft^3/min \ = \ 3.13\ ft^3/min$$

57. What fill rate at 9,000 ft elevation will a high speed compressor deliver if its rated output is 10 ft^3/min at sea level?

$$\chi_0 \ = \ 10\ ft^3/min \ \ , \ \ h \ = \ 9$$

$$\alpha \ = \ exp\ (-0.038 \times 9) \ = \ 1.41$$

$$\chi \ = \ \frac{\chi_0}{\alpha} \ = \ \frac{10}{1.41}\ ft^3/min \ = \ 7.09 ft^3/min$$

58. At an altitude, $z = 1,300\ m$, what reading, δ, will a capillary gauge register at actual depth, $d = 18\ m$, in fresh water?

$$\delta \ = \ \alpha\eta d \ \ , \ \ h \ = \ \frac{1300}{1000} \ \times 3.28 \ = \ 4.26$$

$$\alpha \ = \ exp\ (-0.038 \times 4.26) \ = \ 1.19 \ \ , \ \ \delta \ = \ 1.19 \times .975 \times 18\, msw \ = \ 20.3\, msw$$

59. What does a bourdon (oil) gauge read, δ, at 1,300 m elevation and depth, $d = 18\ m$?

$$P_0 \ = \ 10\, msw \ \ , \ \ P_{4.26} \ = \ 8.4\, msw$$

$$\delta \ = \ \eta d + P_h - P_0 \ = \ .975 \times 18 + 8.4 - 10.\, msw \ = \ 15.9\, msw$$

60. A tank rated 80 ft^3 at 3000 lb/in^2, registers a pressure, $P = 1420\ lb/in^2$ on a sub gauge. What is the remaining air volume, V?

$$V = V_r \frac{P}{P_r}$$

$$V = 80 \times \frac{1420}{3000}\ ft^3 = 37.8\ ft^3$$

What is the tank constant, κ?

$$\kappa = \frac{P_r}{V_r} = \frac{3000}{80}\ lb/in^2\ ft^3 = 37.5\ lb/in^2\ ft^3$$

61. How much fresh water, V, does a 200 lb lift bag displace?

$$\rho = 62.4\ lbs/ft^3 \ ,\ W = 200\ lbs$$

$$V = \frac{W}{\rho} = \frac{200}{62.4}\ ft^3 = 3.2\ ft^3$$

62. A 10 qt plastic container is submerged to 100 ft in Lake Michigan. What is its volume, V?

$$P_i = 33\ fsw \ ,\ P = 33 + .975 \times 100\ fsw = 130.5\ fsw$$

$$P_i V_i = PV \ ,\ V = V_i \frac{P_i}{P}$$

$$V = 10 \times \frac{33}{130.5}\ qt = 10 \times .253\ qt = 2.53\ qt$$

63. A weather balloon is partially inflated at 50 fsw to 20 ft^3, and allowed to drift to the ocean surface slowly. What is the volume, V_f, at 20 fsw?

$$P_i = 33 + 50\ fsw = 83\ fsw \ ,\ P_f = 33 + 20\ fsw = 53\ fsw \ ,\ V_i = 20\ ft^3$$

$$P_i V_i = P_f V_f$$

$$V_f = V_i \frac{P_i}{P_f} = 20 \times \frac{83}{53}\ ft^3 = 31.3\ ft^3$$

64. A fully inflated BC displaces, $V = .78\ ft^3$, of sea water. What is the lift, B, provided by the BC?

$$B = \rho V$$

$$B = 64 \times .78\ lb = 49.9\ lb$$

65. A fully clad diver displaces, $V = 3.5\ ft^3$, of fresh water. What is the buoyant force, B, on diver and gear?

$$B = \rho V$$

$$B = 62.4 \times 3.5\ lb = 218\ lb$$

If diver plus gear weigh, $W = 200\ lb$, how much add additional weigh, ΔW, must be added to the belt for neutral buoyancy?

$$\Delta W = B - W = (218 - 200)\ lb = 18\ lb$$

66. What is the relative buoyancy, ΔB, of an empty 95 ft^3 steel tank, rated at 3300 lbs/in^2?

$$\Delta B \ = \ -6.11 \ lbs$$

What is the approximate tank volume, V?

$$r \ = \ \frac{d}{2} \ , \ d \ = \ 7 \ in \ , \ l \ = \ 25 \ in$$

$$V \ = \ \pi r^2 l \ = \ \frac{\pi d^2 l}{4} \ = \ \frac{3.14 \times 49 \times 25}{4} \ in^3 \ = \ 962 \ in^3 \ = \ .56 \ ft^3$$

What does the tank weigh, w?

$$V \ = \ .56 \ ft^3 \ , \ \rho \ = \ 64 \ lbs^3/ft \ , \ \Delta B \ = \ -6.11 \ lbs$$

$$w \ = \ \rho V - \Delta B \ = \ 64 \times .56 + 6.11 \ lbs \ = \ 42.5 \ lbs$$

67. A 448 lb winch gear, displacing a volume, $V = 2 \ ft^3$, rests on a hard sea bottom at 99 fsw. What surface volume of air, V_{sur}, is needed to inflate lift bags to bring the gear to the surface?

$$d = 99 \ fsw \ , \ \rho \ = \ 64 \ lbs/ft^3 \ , \ w \ = \ 448 \ lbs$$

$$V_{lift} \ = \ \frac{w}{\rho} \ = \ \frac{448}{64} \ ft^3 \ = \ 7 \ ft^3$$

$$V_{sur} \ = \ V_{lift} \left(1 + \frac{d}{33}\right) \ = \ 4 \times 7 \ ft^3 \ = \ 28 \ ft^3$$

68. A buoy weighing 48 lbs occupies, $V = 3 ft^3$. What fraction, ξ, of its volume will float above water?

$$V \ = \ 3 \ ft^3 \ , \ \xi \ = \ \frac{V - V_{dis}}{V}$$

$$V_{dis} \ = \ \frac{w}{\rho} \ = \ \frac{48}{64} \ ft^3 \ = \ .75 \ ft^3$$

$$\xi \ = \ \frac{3 - .75}{3} \ = \ .75$$

69. A 75 kg diver journeys to a mountain lake at $1,830$ m. What is the surface wetsuit buoyancy, Δw, increase?

$$\Delta w \ = \ .0029 wh \ , \ h \ = \ \frac{1830}{1000} \times 3.28 \ = \ 6 \ , \ w \ = \ mg$$

$$\Delta w \ = \ .0029 \ \times 75 \times 9.8 \times 6 \ nt \ = \ 12.7 \ nt$$

70. What is the salt water to fresh water buoyancy loss, ΔW, for a salvage diver plus gear of mass, $m = 90 \ kg$?

$$W \ = \ mg$$

$$\Delta W \ = \ -.025 \ W \ = \ -.025 \times 90 \times 9.8 \ nt \ = \ -22.5 \ nt$$

71. A skin diver with lung volume of 6 qt descends to a depth, $d = 85\ fsw$. Assuming his lung tissues are 40% air space, what is his compressed lung volume, V?

$$V_i = .4 \times 6\ qt = 2.4\ qt \ , \ V_{tis} = .6 \times 6\ qt = 3.6\ qt$$

$$P_i = 33\ fsw \ , \ P = 33 + d = 33 + 85\ fsw = 118\ fsw$$

$$P_i V_i = P V_f$$

$$V_f = V_i \frac{P_i}{P} = 2.4 \frac{33}{118}\ qt = .67\ qt$$

$$V = V_f + V_{tis} = .67 + 3.6\ qt = 4.27\ qt$$

72. A helium-oxygen gas mixture at pressure, $P_i = 225\ atm$, occupying, $V_i = 1.2\ ft^3$, and at temperature, $T_i = 293\ K^o$, is released to a larger tank with volume, $V = 4.5\ ft^3$. Upon expansion, the mixture, drops to a temperature, $T = 283\ K^o$. What is the new pressure, P?

$$\frac{P_i\ V_i}{T_i} = \frac{P\ V}{T}$$

$$P = P_i \frac{V_i}{V} \frac{T}{T_i} = 225 \times \frac{1.2}{4.5} \times \frac{283}{293}\ atm = 51.6\ atm$$

73. What is the change in internal energy, dU, of air in a compressor heated an amount, $dQ = 100\ cal$, while doing piston expansion work, $dW = 165\ j$?

$$dQ = 100 \times 4.19\ j = 419\ j \ , \ dW = 165\ j$$

$$dU = dQ - dW = 419 - 165\ j = 254\ j$$

74. What is the mean molecular energy, $\bar{\epsilon}$, of 1 $gmole$ ideal gas at temperature, $T = 900\ K^o$?

$$\bar{\epsilon} = \frac{3}{2} kT$$

$$\bar{\epsilon} = \frac{3}{2} \times 1.38 \times 10^{-23} \times 900\ j = 1.24 \times 10^{-20}\ j$$

75. What is the relative concentration, c, of neon dissolved in oil at a partial pressure $p = 9.8\ atm$?

$$c = Sp = .009 \times 9.8 = .0882$$

76. What is the ratio, ζ, of relative solubilities of neon in water and oil?

$$\zeta = \frac{S_{water}}{S_{oil}} = \frac{.009}{.021} = .43$$

How many more times, ξ, is nitrogen soluble in oil versus water?

$$\xi = \frac{S_{oil}}{S_{water}} = \frac{.067}{.012} = 5.6$$

77. What is the (Doppler) frequency shift, Δf, of a boat horn, $f = 32.5$ *hertz*, moving toward a stationary snorkeler at speed of $v_s = 6$ *knots*?

$$\Delta f \ = \ f \ \frac{v_s}{u - v_s}$$

$$u \ = \ 333 \, m/sec \ \ , \ \ v_s \ = \ 6 \times .514 \, m/sec \ = \ 3.08 \, m/sec$$

$$\Delta f \ = \ 32.5 \times \frac{3.08}{333 + 3.08} \, hertz \ = \ .0314 \, hertz$$

78. What is the total pressure, P_t, inside a bubble lodged in an arteriole of diameter, $2r = 10 \ \mu m$, if ambient pressure, $P = 45 \ fsw$, and assuming a watery surface tension, $\gamma = 50 \ dyne/cm$?

$$P \ = \ \frac{45}{33} \times 10.1 \, nt/cm^2 \ = \ 13.77 \, nt/cm^2$$

$$\frac{2\gamma}{r} \ = \ \frac{100}{5 \times 10^{-6}} \, dyne/cm^2 \ = \ 2 \, nt/cm^2$$

$$P_t \ = \ P + \frac{2\gamma}{r} \ = \ 13.77 + 2 \, nt/cm^2 \ = \ 15.77 \, nt/cm^2$$

79. For ambient pressure, $P = 28 \ fsw$, what is the watery critical bubble radius, r_c, at total bubble internal pressure, $P_t = 20 \ nt/cm^2$?

$$2\gamma \ = \ 1.0 \times 10^{-3} \, nt/cm^2$$

$$P_t \ = \ 20 \, nt/cm^2 \ \ , \ \ P \ = \ \frac{28}{33} \times 10.1 \, nt/cm^2 \ = \ 8.56 \, nt/cm^2$$

$$r_c \ = \ \frac{2\gamma}{P_t - P} \ = \ \frac{1.0 \times 10^{-3}}{20 - 8.56} \, cm \ = \ 1.14 \, \mu m$$

80. At elevation, $z = 3{,}800 \ m$, what are the working depths, d_{max} and d_{min}, for a 74/26 nitrox mixture, assuming 1.6 *atm* and .16 *atm* as the upper and lower oxygen partial pressure limits?

$$f_{N_2} \ = \ .74 \ \ , \ \ \eta \ = \ .975$$

$$h \ = \ 3800 \times \frac{3.28}{1000} \ = \ 12.46 \ \ , \ \ P_{12.46} \ = \ 33 \times exp\,(-.038 \ \times 12.46) \ fsw \ = \ 20.55 \ fsw$$

$$\eta d_{max} \ = \ \frac{52.8}{f_{O_2}} - P_h \ fsw \ \ , \ \ \eta d_{min} \ = \ \frac{5.3}{f_{O_2}} - P_h \ fsw$$

$$\eta d_{max} \ = \ \frac{52.8}{.26} - 20.55 \ fsw \ = \ 182.5 \ fsw$$

$$d_{max} \ = \ \frac{182.5}{\eta} \ \ ft \ = \ 187.2 \ ft$$

$$\eta d_{min} \ = \ \frac{5.3}{.26} - 20.55 \ fsw \ = \ -.2 \ fsw \ (means \ surface \ is \ OK)$$

$$d_{min} \ = \ -\frac{.2}{\eta} \ ft \ = \ -.21 \ ft$$

81. What is the equivalent air depth, δ, at ocean depth, $d = 98\ fsw$, for enriched 74/26 nitrox?

$$f_{N_2} = .74$$

$$\delta = \frac{f_{N_2}}{.79}(33+d) - 33 = \frac{.74}{.79} \times (33+98) - 33\ fsw = 89.7\ fsw$$

82. What is the nitrogen fraction, f_{N_2}, for an equivalent air depth, $\delta = 110\ fsw$, at ocean depth, $d = 125\ fsw$?

$$f_{N_2} = \frac{.79(\delta+33)}{(d+33)} = \frac{.79 \times 143}{158} = .72$$

What is the corresponding oxygen floor, d_{max}?

$$f_{O_2} = .28\ ,\ P_0 = 33\ fsw$$

$$d_{max} = \frac{52.8}{f_{O_2}} - P_0\ fsw = \frac{52.8}{.28} - 33 = 156\ fsw$$

83. What is the inspired oxygen fraction, i_{O_2}, for a rebreather delivering 7.6 l/min of 50/50 nitrox to a Navy SEAL needing 1 l/min oxygen for metabolic consumption 3 miles off the coast of Kuwait?

$$i_{O_2} = \frac{f_{O_2}F - m}{F - m}$$

$$f_{O_2} = .50\ ,\ F = 7.6\ l/min\ ,\ m = 1.0\ l/min$$

$$i_{O_2} = \frac{.5 \times 7.6 - 1.0}{7.6 - 1.0} = \frac{2.8}{6.6} = .42$$

If ambient pressure doubles, what is the nozzle flow, F_d, and inspired oxygen fraction, i_{O_2}?

$$F_d = F\,\frac{P}{2P} = \frac{7.6}{2}\ l/min = 3.8\ l/min$$

$$i_{O_2} = \frac{.5 \times 3.8 - 1.0}{3.8 - 1.0} = \frac{.9}{2.8} = .32$$

84. What is the instantaneous nitrogen pressure, p, in the 15 min tissue compartment of a Maine scallop diver at 67 fsw for 38 min, assuming initial sea level equilibration?

$$\tau = 15\ min\ ,\ f_{N_2} = .79$$

$$p_i = 33 \times .79\ fsw = 26.1\ fsw$$

$$p_a = f_{N_2}(P_0 + d) = (33+67) \times .79\ fsw = 79\ fsw$$

$$\lambda = \frac{.693}{15}\ min^{-1} = .046\ min^{-1}$$

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

$$p = 79 + (26.1 - 79) \times .174\ fsw = 69.7\ fsw$$

What is the tension in the 240 *min* compartment?

$$\lambda = \frac{.693}{240}\ min^{-1} = .0029\ min^{-1}$$

$$p = 79 + (26.1 - 79) \times .896\ fsw = 31.6\ fsw$$

85. What is the critical tension, M, at a nominal depth of 10 fsw for the 15 *min* tissue compartment?

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

$$M = 152.7 \times .51 + 3.25 \times .51 \times 10\ fsw = 94.4\ fsw$$

What is the corresponding critical ratio, R,?

$$R = \frac{M}{P} = \frac{94.4}{43} = 2.19$$

86. According to Graham, what roughly is the ratio, ψ, of molecular diffusion speeds of hydrogen to oxygen?

$$\psi = \left(\frac{A_{O_2}}{A_{H_2}}\right)^{1/2} = \left(\frac{32}{2}\right)^{1/2} = 4$$

87. How long does it take for the 80 *min* tissue compartment to approach its critical surfacing tension, $M = M_0 = 52\ fsw$, at a depth of 140 fsw, assuming initial nitrogen tension of 45 fsw?

$$p_i = 45\ fsw\ ,\ p_a = f_{N_2}(33 + d)$$

$$p_a = .79 \times (33 + 140)\ fsw = 136.6\ fsw$$

$$\lambda = \frac{.693}{80}\ min^{-1} = .0087\ min\ ,\ M = 52\ fsw$$

$$t = \frac{1}{\lambda}\ ln\ \frac{p_i - p_a}{M - p_a} = 114.9 \times ln\ \frac{91.6}{84.6}\ min = 9.1\ min$$

What is the nonstop limit, t, for the 80 *min* tissue at this depth?

$$t = 9.1\ min$$

88. If the nonstop time limit at depth, $d = 90\ fsw$, is, $t = 22\ min$, what is the surfacing critical tension, M_0, assuming that the 5 *min* compartment controls the exposure (has largest computed tissue tension at this depth)?

$$\lambda = \frac{.693}{5}\ min^{-1} = .1386\ min^{-1}$$

$$p_i = .79 \times 33\ fsw = 26.1\ fsw$$

$$p_a = .79 \times (33 + 90) = 97.1\ fsw$$

$$M_0 = p_a + (p_i - p_a)\ exp\ (-\lambda t)$$

$$M_0 = 97.1 - 78.2\ exp\ (-.1386 \times 22)\ fsw = 94\ fsw$$

89. A commercial diving operation is constructing a set of helium proprietary tables using the popular DCIEM nitrogen tables as a basis before testing. If the spectrum of tissues, τ, in the DCIEM nitrogen tables is (2.5, 5, 10, 20, 40, 80, 160, 320 *min*), what are the corresponding set for the helium tables, assuming the same critical tensions, M, as the nitrogen tables?

$$\tau_{He} = \left(\frac{A_{He}}{A_{N_2}}\right)^{1/2} \tau_{N_2} = \left(\frac{4}{28}\right)^{1/2} \tau_{N_2} = .38 \times \tau_{N_2}$$

$$\tau_{He} = (.94,\ 1.89,\ 3.78,\ 7.56,\ 15.12,\ 30.24,\ 60.48,\ 120.96)\ min$$

90. An oil rig diver is saturated at a depth of 300 fsw in the North Sea on heliox. For critical helium gradient (absolute), $G = M - P = 40\ fsw$, what is the minimum depth (ceiling), d, accessible to the platform diver?

$$M = 333\ fsw\ ,\ P = M - G = (333 - 40)\ fsw = 293\ fsw$$

$$d = (P - 33)\ fsw = (293 - 33)\ fsw = 260\ fsw$$

91. What is the ratio, ζ, of narcotic potency of helium to argon?

$$\zeta = \frac{\nu_{He}}{\nu_{Ar}} = \frac{4.26}{.43} = 9.9$$

Which is the least potent?

$$Least\ Potent\ Gas = helium$$

92. What is the critical tension, M, at depth, $d = 34\ fsw$, for the helium tissue compartment, $\tau = 7.56\ min$?

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

$$M = 152.7 \times .603 + 3.25 \times .603 \times 34\ fsw = 158.7\ fsw$$

93. A Group F diver sustains what overpressure, ΔP, in nitrogen loading (absolute) in the 120 *min* compartment?

$$\Delta P = 6 \times 2\ fsw = 12\ fsw$$

94. After 6 halftimes, $t = 6\tau$, what is the ratio, ω, of tissue saturation, $(p - p_a)$, to initial tissue saturation, $(p - p_i)$?

$$\omega = \frac{p - p_a}{p_i - p_a} = exp\ (-\lambda t) = exp\ (-.693 \times 6) = .016$$

95. What is the nitrogen tension, p, in the 120 *min* compartment of a surface F diver after 160 *min*?

$$\Delta P = 12\ fsw\ ,\ p_i - p_a = f_{N_2}\Delta P = .79 \times 12\ fsw = 9.48\ fsw$$

$$\lambda = \frac{.693}{120}\ min^{-1} = .0058\ min^{-1}$$

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

$$p \;=\; 26.1 + 9.48 \times exp\,(-.0058 \times 160) \;=\; 29.8\; fsw$$

Into what Group does the diver now fall?

$$\Delta P \;=\; \frac{(p - p_a)}{f_{N_2}} \;=\; \frac{(29.8 - 26.1)}{.79} \;=\; 4.68\; fsw$$

$$Group \;=\; C$$

96. What is the surface oxygen partial pressure, p_0, for a normoxic breathing mixture at 450 fsw?

$$p \;=\; .21\, atm \;\; (normoxic) \;\; , \;\; P_0 \;=\; 33\; fsw \;\; , \;\; P \;=\; 450 + 33\; fsw \;=\; 483\; fsw$$

$$p_0 \;=\; \frac{P_0}{P}\; p \;=\; \;=\; \frac{33}{483} \times .2\, atm \;=\; .0137\, atm$$

97. If a Park Ranger lugs his dive gear to Lake Catherine above Santa Fe (New Mexico) at an elevation of 9,560 ft and plans a dive to 40 ft, what is the altitude correction factor, β, and what is the sea level equivalent depth for the dive?

$$\beta \;=\; \eta\; exp\,(0.038h) \;=\; .975 \times exp\,(0.038 \times 9.65) \;=\; 1.40$$

$$\delta \;=\; \beta d \;=\; 1.40 \times 40\; fsw \;=\; 56.2\; fsw$$

If the ascent rate, r_0, in the Tables at sea level is 60 fsw/min, what is the altitude rate, r,

$$r \;=\; \frac{r_0}{\beta} \;=\; \frac{60}{1.4}\; ft/min \;=\; 42.8\; ft/min$$

If the excursion to Lake Catherine is launched from Sante Fe, elevation 6,860 ft, taking 15 min, what Group should the Ranger diver assign to the start of the dive?

$$\Delta z \;=\; 9650 - 6860\; ft \;=\; 2790\; ft$$

$$Altitude\; Group \;=\; B$$

If the dive lasts 20 min, in what group does the diver surface?

$$Group\; B\; Penalty\; Time\; (60\; fsw) \;=\; 11\; min$$

$$Total\; Dive\; Time \;=\; 20 + 11\; min \;=\; 31\; min$$

$$Surfacing\; Group \;=\; G$$

As a Group G diver, what is the maximum change in altitude permitted?

$$Permitted\; Altitude\; Change \;=\; 6000\; ft$$

How long before a mountain Group G diver drops into Group A?

$$Surface\; Interval\; Time \;=\; 7.6\; hr$$

How long before a Group G diver can ascend 7,000 ft in elevation, according to the 24 hr rule?

$$Surface\; Interval\; Time \;=\; 3.7\; hr$$

98. According to the USN Tables at sea level, the nonstop limit at 100 fsw is 22 min. What is the nonstop limit, t, at mountain elevation of 5,600 ft, using the similarity method?

$$\beta \ = \ \eta \ exp \ (0.038h) \ = \ .975 \times exp \ (0.038 \times 5.6)$$

$$\beta \ = \ .975 \times 1.23 \ = \ 1.20$$

$$\delta \ = \ 100 \times 1.20 \ fsw \ = \ 120 \ fsw$$

$$t \ = \ 12 \ min$$

99. A reef ecologist at depth, $d = 35$ fsw, on a dive computer registers a spectrum of nitrogen tensions, $p = (50, 48, 43, 41, 40, 42, 44)$ fsw, in tissues, $\tau = (5, 10, 20, 40, 80, 120, 240)$ min. What are the corresponding tissue gradients, $g = p - p_a$?

$$g \ = \ p - p_a \ \ , \ \ P \ = \ 33 + 35 \ fsw \ = \ 68 \ fsw \ \ , \ \ p_a \ = \ .79 \ P \ = \ 53.7 \ fsw$$

$$g \ = \ (-3.7, -5.7, -10.7, -12.7, -13.7, -11.7, -9.7) \ fsw$$

Since tissue gradients are inward (all negative), what is the implication for the present dive?

Present Dive Has Been Short And Shallow

What might higher tissue tensions in the two slowest compartments, relative to faster middle compartments, suggest?

Repetitive Diving Within 12 − 24 *hrs*

100. What is the exact USN critical tension, M, in the 80 min tissue compartment at a depth, $d \ = \ 80 \ fsw$?

$$M_0 \ = \ 52 \ fsw \ \ , \ \ \Delta M \ = \ 1.26$$

$$M \ = \ M_0 + \Delta M d$$

$$M \ = \ 52 + 1.26 \times 80 \ fsw \ = \ 152.8 \ fsw$$

What is the critical ratio, R?

$$R \ = \ \frac{M}{P} \ \ , \ \ P \ = \ 80 + 33 \ fsw \ = \ 113 \ fsw$$

$$R \ = \ \frac{152.8}{113} \ = \ 1.35$$

What is the critical gradient, G?

$$G \ = \ M - P \ = \ 152.8 - 113 \ fsw \ = \ 39.8 \ fsw$$

101. Construct a set of critical surfacing ratios at 7,000 ft elevation using the standard USN set, R_0, at sea level, and altitude similarity (downscaling) through the correction factor, α.

$$\alpha = exp\,(0.0381h) \ , \ h = 7$$

$$R_h = \frac{R_0}{\alpha} = R_0\, exp\,(-0.0381h)$$

$$R_0 = (3.15, 2.67, 2.18, 1.76, 1.58, 1.55)$$

$$R_7 = R_0\, exp\,(-0.0381 \times 7) = .77\, R_0$$

$$R_7 = (2.43, 2.05, 1.67, 1.35, 1.20, 1.19)$$

SUMMARY

Underwater experiences are unique and fascinating to our perceptions. Behavior and sensations seem very different underwater than on the surface. Divers often have trouble interpreting the feedback underwater. Yet, despite these vagaries, the same physical laws apply. The only real difference is pressure and the water surrounding the diver. Understanding pressure effects and the impact of a totally liquid environment surrounding the diver is the essence of technical diving.

Theory, applications and problems have been discussed with an eye towards increasing diver awareness of the physical laws impacting the underwater environment. The exposition has attempted to walk a line between highly technical and mathematical physics and extended dialogue with more prose. Topics developed and discussed draw upon basic mechanics, thermodynamics, electrodynamics, optics, hydrodynamics, and gas phase dynamics. The targeted audience is the technical diver, commercial diver, table designer, hyperbaric technician, underwater researcher, and instructor.

Hope it has met your technical diving needs.

ADDITIONAL READING

References span a wide spectra of technical diving material and details, broaching historical to modern developments. Entries are alphabetically and chronologically listed, completing or extending related reading at the end of each Part.

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Bruce Wienke is a Program Manager in the Nuclear Weapons Technology/ Simulation And Computing Office at the Los Alamos National Laboratory (LANL), with interests in computational decompression and models, gas transport, and phase mechanics. He authored *Physics, Physiology And Decompression Theory For The Technical And Commercial Diver, High Altitude Diving, Basic Diving Physics And Applications, Diving Above Sea Level, Basic Decompression Theory And Application*, and some 200 technical journal articles. Diving environs include the Caribbean, South Pacific, Asia, inland and coastal United States, Hawaii, and polar Arctic and Antarctic in various technical, scientific, military, and recreational activities. He functions on the LANL Nuclear Emergency Strategy Team (NEST), in exercises often involving Special Operations Units, above and underwater. He heads Southwest Enterprises, a consulting company for computer research and applications in wide areas of applied science and simulation.

He is an Instructor Trainer with the National Association Of Underwater Instructors (NAUI), has served on the Board Of Directors (Vice Chairman for Technical Diving, Technical and Decompression Review Board Member), is a Master Instructor with the Professional Association Of Diving Instructors (PADI) in various capacities (Instructor Review Committee), is an Institute Director with the YMCA, and is an Instructor Trainer with Scuba Diving International/Technical Diving International (SDI/TDI).

Wienke, a former dive shop owner in Santa Fe, presently works with DAN on applications of high performance computing and communications to diving, and is a Regional Data Coordinator for Project Dive Safety. SCUBAPRO, SUUNTO, ABYSMAL DIVING, and ATOMICS engage (or have) him as Consultant for meter algorithms. He is the developer of the Reduced Gradient Bubble Model (RGBM), a dual phase approach to staging diver ascents over an extended range of diving applications (altitude, nonstop, decompression, multiday, repetitive, multilevel, mixed gas, and saturation). The SUUNTO VYPER dive computer incorporates the

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