CHAPTER 2

Underwater Physics

2-1 INTRODUCTION

2-1.1 **Purpose.** This chapter describes the laws of physics as they affect humans in the water.

2-1.2 **Scope.** A thorough understanding of the principles outlined in this chapter is essential to safe and effective diving performance.

2-2 PHYSICS

Humans readily function within the narrow atmospheric envelope present at the earth's surface and are seldom concerned with survival requirements. Outside the boundaries of the envelope, the environment is hostile and our existence depends on our ability to counteract threatening forces. To function safely, divers must understand the characteristics of the subsea environment and the techniques that can be used to modify its effects. To accomplish this, a diver must have a basic knowledge of physics—the science of matter and energy. Of particular importance to a diver are the behavior of gases, the principles of buoyancy, and the properties of heat, light, and sound.

2-3 MATTER

Matter is anything that occupies space and has mass, and is the building block of the physical world. Energy is required to cause matter to change course or speed. The diver, the diver's air supply, everything that supports him or her, and the surrounding environment is composed of matter.

2-3.1 **Elements.** An *element* is the simplest form of matter that exhibits distinct physical and chemical properties. An element cannot be broken down by chemical means into other, more basic forms. Scientists have identified more than 100 elements in the physical universe. Elements combine to form the more than four million substances known to man.

2-3.2 **Atoms.** The *atom* is the smallest particle of matter that carries the specific properties of an element. Atoms are made up of electrically charged particles known as protons, neutrons, and electrons. Protons have a positive charge, neutrons have a neutral charge, and electrons have a negative charge.

2-3.3 **Molecules.** *Molecules* are formed when atoms group together (Figure 2-1). Molecules usually exhibit properties different from any of the contributing atoms. For example, when two hydrogen atoms combine with one oxygen atom, a new substance—water—is formed. Some molecules are active and try to combine with many of the other molecules that surround them. Other molecules are inert and do not naturally combine with other substances. The presence of inert elements in

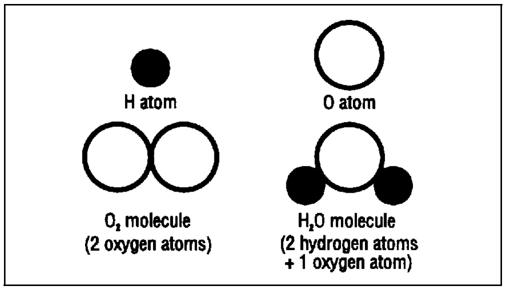

Figure 2-1. Molecules. Two similar atoms combine to form an oxygen molecule while the atoms of two different elements, hydrogen and oxygen, combine to form a water molecule.

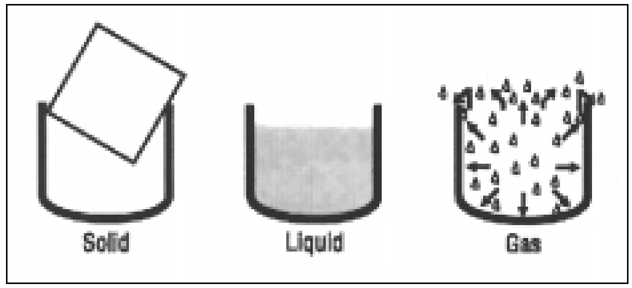

Figure 2-2. The Three States of Matter.

breathing mixtures is important when calculating a diver's decompression obligations.

2-3.4 **The Three States of Matter.** Matter can exist in one of three natural states: solid, liquid, or gas (Figure 2-2). A solid has a definite size and shape. A liquid has a definite volume, but takes the shape of the container. Gas has neither definite shape nor volume, but will expand to fill a container. Gases and liquids are collectively referred to as fluids.

The physical state of a substance depends primarily upon temperature and partially upon pressure. A solid is the coolest of the three states, with its molecules rigidly aligned in fixed patterns. The molecules move, but their motion is like a constant vibration. As heat is added the molecules increase their motion, slip apart from each other and move around; the solid becomes a liquid. A few of the molecules will spontaneously leave the surface of the liquid and become a gas. When the substance reaches its boiling point, the molecules are moving very rapidly in all directions and the liquid is quickly transformed into a gas. Lowering the temperature reverses the sequence. As the gas molecules cool, their motion is reduced and the gas condenses into a liquid. As the temperature continues to fall, the liquid reaches the freezing point and transforms to a solid state.

2-4 MEASUREMENT

Physics relies heavily upon standards of comparison of one state of matter or energy to another. To apply the principles of physics, divers must be able to employ a variety of units of measurement.

2-4.1 **Measurement Systems.** Two systems of measurement are widely used throughout the world. Although the English System is commonly used in the United States, the most common system of measurement in the world is the International System of Units. The International System of Units, or *SI* system, is a modernized metric system designated in 1960 by the General Conference on Weights and Measures. The SI system is decimal based with all its units related, so that it is not necessary to use calculations to change from one unit to another. The

SI system changes one of its units of measurement to another by moving the decimal point, rather than by the lengthy calculations necessary in the English System. Because measurements are often reported in units of the English system, it is important to be able to convert them to SI units. Measurements can be converted from one system to another by using the conversion factors in Tables 2-10 through 2-18.

2-4.2 **Temperature Measurements.** While the English System of weights and measures uses the Fahrenheit (°F) temperature scale, the Celsius (°C) scale is the one most commonly used in scientific work. Both scales are based upon the freezing and boiling points of water. The freezing point of water is 32°F or 0°C; the boiling point of water is 212°F or 100°C. Temperature conversion formulas and charts are found in Table 2-18.

Absolute temperature values are used when employing the ideal gas laws. The absolute temperature scales are based upon absolute zero. Absolute zero is the lowest temperature that could possibly be reached at which all molecular motion would cease (Figure 2-3).

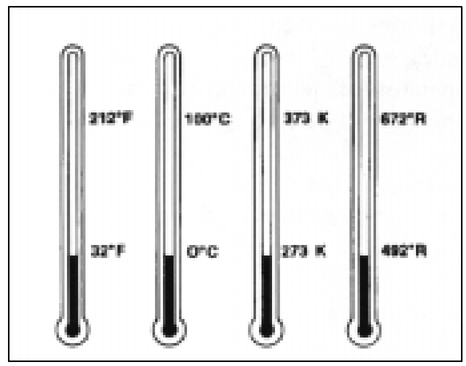

Figure 2-3. Tempera ture Scales. Fahrenheit, Celsius, Kelvin, and Rankine temperature scales showing the freezing and boiling points of

2-4.2.1 **Kelvin Scale.** One example of an absolute temperature scale is the Kelvin scale, which has the same size degrees as the Celsius scale. The freezing point of water is 273°K and boiling point of water is 373°K. Use this formula to convert from Celsius to absolute temperature (Kelvin):

Kelvin (K) = °C + 273

2-4.2.2 **Rankine Scale.** The Rankine scale is another absolute temperature scale, which has the same size degrees as the Fahrenheit scale. The freezing point of water is 492°R and the boiling point of water is 672°R. Use this formula to convert from Fahrenheit to absolute temperature (degrees Rankine, °R):

°R = °F + 460

2-4.3 **Gas Measurements.** When measuring gas, actual cubic feet (acf) of a gas refers to the quantity of a gas at ambient conditions. The most common unit of measurement for gas in the United States is standard cubic feet (scf). Standard cubic feet relates the quantity measurement of a gas under pressure to a specific condition. The specific condition is a common basis for comparison. For air, the standard cubic foot is measured at 60°F and 14.696 psia.

2-5 ENERGY

Energy is the capacity to do work. The six basic types of energy are mechanical, heat, light, chemical, electromagnetic, and nuclear, and may appear in a variety of forms (Figure 2-4). Energy is a vast and complex aspect of physics beyond the scope of this manual. Consequently, this chapter only covers a few aspects of light, heat, and mechanical energy because of their unusual effects underwater and their impact on diving.

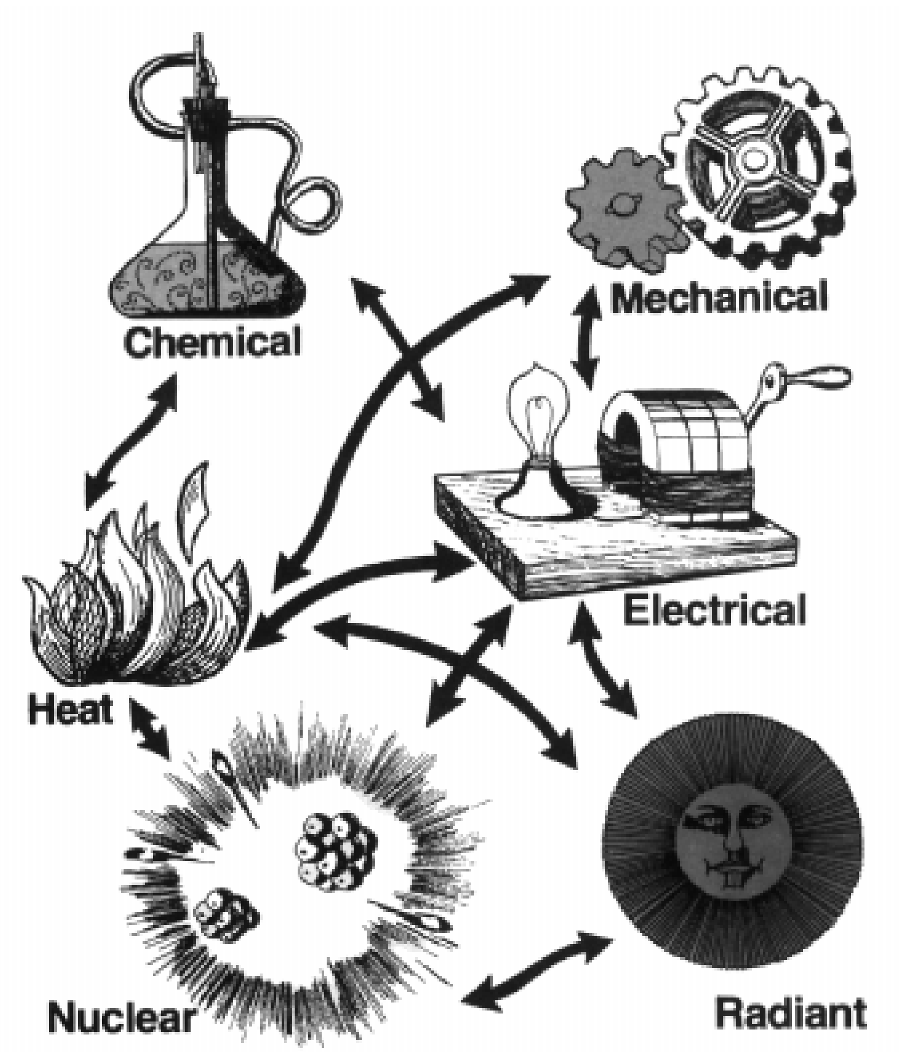

Figure 2-4. The Six Form of Energy.

2-5.1 **Conservation of Energy.** The Law of the Conservation of Energy, formulated in the 1840s, states that energy in the universe can neither be created nor destroyed. Energy can be changed, however, from one form to another.

2-5.2 **Classifications of Energy.** The two general classifications of energy are potential energy and kinetic energy. Potential energy is due to position. An automobile parked on a hill with its brakes set possesses potential energy. Kinetic energy is energy of motion. An automobile rolling on a flat road possesses kinetic energy while it is moving.

2-6 LIGHT ENERGY IN DIVING

Refraction, turbidity of the water, salinity, and pollution all contribute to the distance, size, shape, and color perception of underwater objects. Divers must understand the factors affecting underwater visual perception, and must realize that distance perception is very likely to be inaccurate.

2-6.1 **Refraction.** Light passing from an object bends as it passes through the diver's faceplate and the air in his mask (Figure 2-5). This phenomenon is called refraction, and occurs because light travels faster in air than in water. Although the refraction that occurs between the water and the air in the diver's face mask produces undesirable perceptual inaccuracies, air is essential for vision. When a diver loses his face mask, his eyes are immersed in water, which has about the same refractive index as the eye. Consequently, the light is not focused normally and the diver's vision is reduced to a level that would be classified as legally blind on the surface.

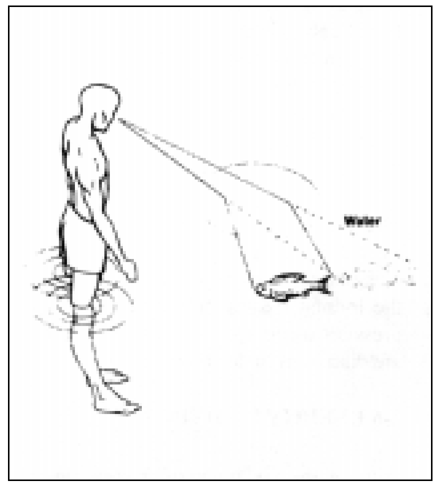

Figure 2-5. Objects Underwater Appear Closer.

Refraction can make objects appear closer than they really are. A distant object will appear to be approximately three-quarters of its actual distance. At greater distances, the effects of refraction may be reversed, making objects appear farther away than they actually are. Reduced brightness and contrast combine with refraction to affect visual distance relationships.

Refraction can also affect perception of size and shape. Generally, underwater objects appear to be about 30 percent larger than they actually are. Refraction effects are greater for objects off to the side in the field of view. This distortion interferes with hand-eye coordination, and explains why grasping objects underwater is sometimes difficult for a diver. Experience and training can help a diver learn to compensate for the misinterpretation of size, distance, and shape caused by refraction.

2-6.2 Turbidity of Water. Water turbidity can also profoundly influence underwater vision and distance perception. The more turbid the water, the shorter the distance at which the reversal from underestimation to overestimation occurs. For example, in highly turbid water, the distance of objects at 3 or 4 feet may be overestimated; in moderately turbid water, the change might occur at 20 to 25 feet and in very clear water, objects as far away as 50 to 70 feet might appear closer than they actually are. Generally speaking, the closer the object, the more it will appear to be too close, and the more turbid the water, the greater the tendency to see it as too far away.

2-6.3 Diffusion. Light scattering is intensified underwater. Light rays are diffused and scattered by the water molecules and particulate matter. At times diffusion is helpful because it scatters light into areas that otherwise would be in shadow or have no illumination. Normally, however, diffusion interferes with vision and underwater photography because the backscatter reduces the contrast between an object and its background. The loss of contrast is the major reason why vision underwater is so much more restricted than it is in air. Similar degrees of scattering occur in air only in unusual conditions such as heavy fog or smoke.

2-6.4 Color Visibility. Object size and distance are not the only characteristics distorted underwater. A variety of factors may combine to alter a diver's color perception. Painting objects different colors is an obvious means of changing their visibility by enhancing their contrast with the surroundings, or by camouflaging them to merge with the background. Determining the most and least visible colors is much more complicated underwater than in air.

Colors are filtered out of light as it enters the water and travels to depth. Red light is filtered out at relatively shallow depths. Orange is filtered out next, followed by yellow, green, and then blue. Water depth is not the only factor effecting the filtering of colors. Salinity, turbidity, size of the particles suspended in the water, and pollution all effect the color-filtering properties of water. Color changes vary from one body of water to another, and become more pronounced as the amount of water between the observer and the object increases.

The components of any underwater scene, such as weeds, rocks, and encrusting animals, generally appear to be the same color as the depth or viewing range increases. Objects become distinguishable only by differences in brightness and not color. Contrast becomes the most important factor in visibility; even very large objects may be undetectable if their brightness is similar to that of the background.

2-7 MECHANICAL ENERGY IN DIVING

Mechanical energy mostly affects divers in the form of sound. Sound is a periodic motion or pressure change transmitted through a gas, a liquid, or a solid. Because liquid is denser than gas, more energy is required to disturb its equilibrium. Once this disturbance takes place, sound travels farther and faster in the denser medium. Several aspects of sound underwater are of interest to the working diver.

2-7.1 **Water Temperature and Sound.** In any body of water, there may be two or more distinct contiguous layers of water at different temperatures; these layers are known as thermoclines. The colder a layer of water, the greater its density. As the difference in density between layers increases, the sound energy transmitted between them decreases. This means that a sound heard 50 meters from its source within one layer may be inaudible a few meters from its source if the diver is in another layer.

2-7.2 **Water Depth and Sound.** In shallow water or in enclosed spaces, reflections and reverberations from the air/water and object/water interfaces produce anomalies in the sound field, such as echoes, dead spots, and sound nodes. When swimming in shallow water, among coral heads, or in enclosed spaces, a diver can expect periodic losses in acoustic communication signals and disruption of acoustic navigation beacons. The problem becomes more pronounced as the frequency of the signal increases.

Because sound travels so quickly underwater (4,921 feet per second), human ears cannot detect the difference in time of arrival of a sound between each ear. Consequently, a diver cannot always locate the direction of a sound source. This disadvantage can have serious consequences for a diver or swimmer trying to locate an object or a source of danger, such as a powerboat.

2-7.2.1 **Diver Work and Noise.** Open-circuit scuba affects sound reception by producing high noise levels at the diver's head and by creating a screen of bubbles that reduces the effective sound pressure level (SPL). When several divers are working in the same area, the noise and bubbles affect communication signals more for some divers than for others, depending on the position of the divers in relation to the communicator and to each other.

A neoprene wet suit is an effective barrier to sound above 1,000 Hz and it becomes more of a barrier as frequency increases. This problem can be overcome by exposing a small area of the head either by cutting holes at the ears of the suit or by folding a small flap away from the surface.

2-7.2.2 **Pressure Waves.** Sound is transmitted through water as a series of pressure waves. High-intensity sound is transmitted by correspondingly high-intensity pressure waves. A high-pressure wave transmitted from the water surrounding a diver to the open spaces within the body (ears, sinuses, lungs) may increase the pressure within these open spaces, causing injury. Underwater explosions and sonar can create high-intensity sound or pressure waves. Low intensity sonar, such as depth finders and fish finders, do not produce pressure waves intense enough to endanger divers. However, anti-submarine sonar-equipped ships do pulse dangerous, high-intensity pressure waves.

It is prudent to suspend diving operations if a high-powered sonar transponder is being operated in the area. When using a diver-held pinger system, divers are advised to wear the standard ¼-inch neoprene hood for ear protection. Experiments have shown that such a hood offers adequate protection when the ultrasonic pulses are of 4-millisecond duration, repeated once per second for acoustic source levels up to 100 watts, at head-to-source distances as short as 0.5 feet (Pence and Sparks, 1978).

2-7.3 **Underwater Explosions.** An underwater explosion creates a series of waves that are transmitted as hydraulic shock waves in the water, and as seismic waves in the seabed. The hydraulic shock wave of an underwater explosion consists of an initial wave followed by further pressure waves of diminishing intensity. The initial high-intensity shock wave is the result of the violent creation and liberation of a large volume of gas, in the form of a gas pocket, at high pressure and temperature. Subsequent pressure waves are caused by rapid gas expansion in a non-compressible environment, causing a sequence of contractions and expansions as the gas pocket rises to the surface.

The initial high-intensity shock wave is the most dangerous; as it travels outward from the source of the explosion, it loses its intensity. Less severe pressure waves closely follow the initial shock wave. Considerable turbulence and movement of the water in the area of the explosion are evident for an extended time after the detonation.

2-7.3.1 **Type of Explosive and Size of the Charge.** Some explosives have characteristics of high brisance (shattering power in the immediate vicinity of the explosion) with less power at long range, while the brisance of others is reduced to increase their power over a greater area. Those with high brisance generally are used for cutting or shattering purposes, while high-power, low-brisance explosives are used in depth charges and sea mines where the target may not be in immediate contact and the ability to inflict damage over a greater area is an advantage. The high-brisance explosives create a high-level shock and pressure waves of short duration over a limited area. Low brisance explosives create a less intense shock and pressure waves of long duration over a greater area.

2-7.3.2 **Characteristics of the Seabed.** Aside from the fact that rock or other bottom debris may be propelled through the water or into the air with shallow-placed charges, bottom conditions can affect an explosion's pressure waves. A soft bottom tends to dampen reflected shock and pressure waves, while a hard, rock bottom may amplify the effect. Rock strata, ridges and other topographical features of the seabed may affect the direction of the shock and pressure waves, and may also produce secondary reflecting waves.

2-7.3.3 **Location of the Explosive Charge.** Research has indicated that the magnitude of shock and pressure waves generated from charges freely suspended in water is considerably greater than that from charges placed in drill holes in rock or coral.

2-7.3.4 **Water Depth.** At great depth, the shock and pressure waves are drawn out by the greater water volume and are thus reduced in intensity. An explosion near the surface is not weakened to the same degree.

2-7.3.5 **Distance from the Explosion.** In general, the farther away from the explosion, the greater the attenuation of the shock and pressure waves and the less the intensity. This factor must be considered in the context of bottom conditions, depth of water, and reflection of shock and pressure waves from underwater structures and topographical features.

2-7.3.6 **Degree of Submersion of the Diver.** A fully submerged diver receives the total effect of the shock and pressure waves passing over the body. A partially submerged diver whose head and upper body are out of the water, may experience a reduced effect of the shock and pressure waves on the lungs, ears, and sinuses. However, air will transmit some portion of the explosive shock and pressure waves. The head, lungs, and intestines are the parts of the body most vulnerable to the pressure effects of an explosion. A pressure wave of 500 pounds per square inch is sufficient to cause serious injury to the lungs and intestinal tract, and one greater than 2,000 pounds per square inch will cause certain death. Even a pressure wave of 500 pounds per square inch could cause fatal injury under certain circumstances.

2-7.3.7 **Estimating Explosion Pressure on a Diver.** There are various formulas for estimating the pressure wave resulting from an explosion of TNT. The equations vary in format and the results illustrate that the technique for estimation is only an approximation. Moreover, these formulas relate to TNT and are not applicable to other types of explosives.

The formula below (Greenbaum and Hoff, 1966) is one method of estimating the pressure on a diver resulting from an explosion of tetryl or TNT.

$$P = \frac{13,000\sqrt[3]{W}}{r}$$

Where:

P	=	pressure on the diver in pounds per square inch
W	=	weight of the explosive (TNT) in pounds
r	=	range of the diver from the explosion in feet

Sample Problem. Determine the pressure exerted by a 45-pound charge at a distance of 80 feet.

1. Substitute the known values.

$$P = \frac{13,000\sqrt[3]{45}}{80}$$

2. Solve for the pressure exerted.

$$P = \frac{13,000\sqrt[3]{45}}{80}$$

$$= \frac{13,000 \times 3.56}{80}$$

$$= 578.5$$

Round up to 579 psi.

A 45-pound charge exerts a pressure of 579 pounds per square inch at a distance of 80 feet.

2-7.3.8 **Minimizing the Effects of an Explosion.** When expecting an underwater blast, the diver shall get out of the water and out of range of the blast whenever possible. If the diver must be in the water, it is prudent to limit the pressure he experiences from the explosion to less than 50 pounds per square inch. To minimize the effects, the diver can position himself with feet pointing toward and head directly away from the explosion. The head and upper section of the body should be out of the water or the diver should float on his back with his head out of the water.

2-8 HEAT ENERGY IN DIVING

Heat is crucial to man's environmental balance. The human body functions within only a very narrow range of internal temperature and contains delicate mechanisms to control that temperature.

Heat is a form of energy associated with and proportional to the molecular motion of a substance. It is closely related to temperature, but must be distinguished from temperature because different substances do not necessarily contain the same heat energy even though their temperatures are the same.

Heat is generated in many ways. Burning fuels, chemical reactions, friction, and electricity all generate heat. Heat is transmitted from one place to another by conduction, convection, and radiation.

2-8.1 **Conduction, Convection, and Radiation.** *Conduction* is the transmission of heat by direct contact. Because water is an excellent heat conductor, an unprotected diver can lose a great deal of body heat to the surrounding water by direct conduction.

Convection is the transfer of heat by the movement of heated fluids. Most home heating systems operate on the principle of convection, setting up a flow of air currents based on the natural tendency of warm air to rise and cool air to fall. A diver seated on the bottom of a tank of water in a cold room can lose heat not only by direct conduction to the water, but also by convection currents in the water. The warmed water next to his body will rise and be replaced by colder water passing along the walls of the tank. Upon reaching the surface, the warmed water will lose heat to the cooler surroundings. Once cooled, the water will sink only to be warmed again as part of a continuing cycle.

Radiation is heat transmission by electromagnetic waves of energy. Every warm object gives off waves of electromagnetic energy, which is absorbed by cool objects. Heat from the sun, electric heaters, and fireplaces is primarily radiant heat.

2-8.2 **Heat Transfer Rate.** To divers, conduction is the most significant means of transmitting heat. The rate at which heat is transferred by conduction depends on two basic factors:

- The difference in temperature between the warmer and cooler material
- The thermal conductivity of the materials

Not all substances conduct heat at the same rate. Iron, helium, and water are excellent heat conductors while air is a very poor conductor. Placing a poor heat conductor between a source of heat and another substance insulates the substance and slows the transfer of heat. Materials such as wool and foam rubber insulate the human body and are effective because they contain thousands of pockets of trapped air. The air pockets are too small to be subject to convective currents, but block conductive transfer of heat.

2-8.3 **Diver Body Temperature.** A diver will start to become chilled when the water temperature falls below a seemingly comfortable 70°F (21°C). Below 70°F, a diver wearing only a swimming suit loses heat to the water faster than his body can replace it. Unless he is provided some protection or insulation, he may quickly experience difficulties. A chilled diver cannot work efficiently or think clearly, and is more susceptible to decompression sickness.

Suit compression, increased gas density, thermal conductivity of breathing gases, and respiratory heat loss are contributory factors in maintaining a diver’s body temperature. Cellular neoprene wet suits lose a major portion of their insulating properties as depth increases and the material compresses. As a consequence, it is often necessary to employ a thicker suit, a dry suit, or a hot water suit for extended exposures to cold water.

The heat transmission characteristics of an individual gas are directly proportional to its density. Therefore, the heat lost through gas insulating barriers and respiratory heat lost to the surrounding areas increase with depth. The heat loss is further aggravated when high thermal conductivity gases, such as helium-oxygen, are used for breathing. The respiratory heat loss alone increases from 10 percent of the body’s heat generating capacity at one ata, to 28 percent at 7 ata, to 50 percent at 21 ata when breathing helium-oxygen. Under these circumstances, standard insulating materials are insufficient to maintain body temperatures and supplementary heat must be supplied to the body surface and respiratory gas.

2-9 PRESSURE IN DIVING

Pressure is defined as a force acting upon a particular area of matter. It is typically measured in pounds per square inch (psi) in the English system and Newton per square centimeter (N/cm^2) in the System International (SI). Underwater pressure is a result of the weight of the water above the diver and the weight of the atmosphere over the water. There is one concept that must be remembered at all times—any diver, at any depth, must be in pressure balance with the forces at that depth. The body can only function normally when the pressure difference between the forces acting inside of the diver's body and forces acting outside is very small. Pressure, whether of the atmosphere, seawater, or the diver's breathing gases, must always be thought of in terms of maintaining pressure balance.

2-9.1 Atmospheric Pressure. Given that one atmosphere is equal to 33 feet of sea water or 14.7 psi, 14.7 psi divided by 33 feet equals 0.445 psi per foot. Thus, for every foot of sea water, the total pressure is increased by 0.445 psi. Atmospheric pressure is constant at sea level; minor fluctuations caused by the weather are usually ignored. Atmospheric pressure acts on all things in all directions.

Most pressure gauges measure differential pressure between the inside and outside of the gauge. Thus, the atmospheric pressure does not register on the pressure gauge of a cylinder of compressed air. The initial air in the cylinder and the gauge are already under a base pressure of one atmosphere (14.7 psi or $10N/cm^2$). The gauge measures the pressure difference between the atmosphere and the increased air pressure in the tank. This reading is called *gauge pressure* and for most purposes it is sufficient.

In diving, however, it is important to include atmospheric pressure in computations. This total pressure is called *absolute pressure* and is normally expressed in units of atmospheres. The distinction is important and pressure must be identified as either gauge (psig) or absolute (psia). When the type of pressure is identified only as psi, it refers to gauge pressure. Table 2-10 contains conversion factors for pressure measurement units.

2-9.2 Terms Used to Describe Gas Pressure. Four terms are used to describe gas pressure:

- **Atmospheric**. Standard atmosphere, usually expressed as $10N/cm^2$, 14.7 psi, or one atmosphere absolute (1 ata).
- **Barometric**. Essentially the same as atmospheric but varying with the weather and expressed in terms of the height of a column of mercury. Standard pressure is equal to 29.92 inches of mercury, 760 millimeters of mercury, or 1013 millibars.
- **Gauge**. Indicates the difference between atmospheric pressure and the pressure being measured.

- **Absolute**. The total pressure being exerted, i.e., gauge pressure plus atmospheric pressure.

2-9.3 **Hydrostatic Pressure.** The water on the surface pushes down on the water below and so on down to the bottom where, at the greatest depths of the ocean (approximately 36,000 fsw), the pressure is more than 8 tons per square inch (1,100 ata). The pressure due to the weight of a water column is referred to as hydrostatic pressure.

The pressure of seawater at a depth of 33 feet equals one atmosphere. The absolute pressure, which is a combination of atmospheric and water pressure for that depth, is two atmospheres. For every additional 33 feet of depth, another atmosphere of pressure (14.7 psi) is encountered. Thus, at 99 feet, the absolute pressure is equal to four atmospheres. Table 2-1 shows how pressure increases with depth.

Table 2-1. *Pressure Chart.*

Depth Gauge Pressure	Atmospheric Pressure	Absolute Pressure
0	One Atmosphere	1 ata (14.7 psia)
33 fsw	+ One Atmosphere	2 ata (29.4 psia)
66 fsw	+ One Atmosphere	3 ata (44.1 psia)
99 fsw	+ One Atmosphere	4 ata (58.8 psia)

The change in pressure with depth is so pronounced that the feet of a 6-foot tall person standing underwater is exposed to pressure that is almost 3 pounds per square inch greater than that exerted at his head.

2-9.4 **Buoyancy.** Buoyancy is the force that makes objects float. It was first defined by the Greek mathematician Archimedes, who established that “Any object wholly or partly immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced by the object.” This is known as Archimedes’ Principle and applies to all objects and all fluids.

2-9.4.1 **Archimedes’ Principle.** According to Archimedes’ Principle, the buoyancy of a submerged body can be established by subtracting the weight of the submerged body from the weight of the displaced liquid. If the total displacement (the weight of the displaced liquid) is greater than the weight of the submerged body, the buoyancy is positive and the body will float or be buoyed upward. If the weight of the body is equal to that of the displaced liquid, the buoyancy is neutral and the body will remain suspended in the liquid. If the weight of the submerged body is greater than that of the displaced liquid, the buoyancy is negative and the body will sink.

The buoyant force on an object is dependent upon the density of the substance it is immersed in (weight per unit volume). Fresh water has a density of 62.4 pounds per cubic foot. Sea water is heavier, having a density of 64.0 pounds per cubic foot. Thus an object is buoyed up by a greater force in seawater than in fresh water, making it easier to float in the ocean than in a fresh water lake.

2-9.4.2 **Diver Buoyancy.** Lung capacity has a significant effect on buoyancy of a diver. A diver with full lungs displaces a greater volume of water and, therefore, is more buoyant than with deflated lungs. Individual differences that may affect the buoyancy of a diver include bone structure, bone weight, and body fat. These differences explain why some individuals float easily while others do not.

A diver can vary his buoyancy in several ways. By adding weight to his gear, he can cause himself to sink. When wearing a variable volume dry suit, he can increase or decrease the amount of air in his suit, thus changing his displacement and thereby his buoyancy. Divers usually seek a condition of neutral to slightly negative buoyancy. Negative buoyancy gives a diver in a helmet and dress a better foothold on the bottom. Neutral buoyancy enhances a scuba diver's ability to swim easily, change depth, and hover.

2-10 GASES IN DIVING

Knowledge of the properties and behavior of gases, especially those used for breathing, is vitally important to divers.

2-10.1 **Atmospheric Air.** The most common gas used in diving is atmospheric air, the composition of which is shown in Table 2-2. Any gases found in concentrations different than those in Table 2-2 or that are not listed in Table 2-2 are considered contaminants. Depending on weather and location, many industrial pollutants may be found in air. Carbon monoxide is the most commonly encountered and is often present around air compressor engine exhaust. Care must be taken to exclude the pollutants from the divers' compressed air by appropriate filtering, inlet location, and compressor maintenance. Water vapor in varying quantities is present in compressed air and its concentration is important in certain instances.

For most purposes and computations, diving air may be assumed to be composed of 79 percent nitrogen and 21 percent oxygen. Besides air, varying mixtures of oxygen, nitrogen, and helium are commonly used in diving. While these gases are discussed separately, the gases themselves are almost always used in some mixture. Air is a naturally occurring mixture of most of them. In certain types of diving applications, special mixtures may be blended using one or more of the gases with oxygen.

2-10.2 **Oxygen.** Oxygen (O_2) is the most important of all gases and is one of the most abundant elements on earth. Fire cannot burn without oxygen and people cannot survive without oxygen. Atmospheric air contains approximately 21 percent oxygen, which exists freely in a diatomic state (two atoms paired off to make one molecule). This colorless, odorless, tasteless, and active gas readily combines with other elements. From the air we breathe, only oxygen is actually used by the body. The other 79 percent of the air serves to dilute the oxygen. Pure 100 percent oxygen is often used for breathing in hospitals, aircraft, and hyperbaric medical

Table 2-2. Components of Dry Atmospheric Air.

Component	Concentration: Percent by Volume	Concentration: Parts per Million (ppm)
Nitrogen	78.084	
Oxygen	20.946	
Carbon Dioxide	0.033	
Argon	0.0934	
Neon		18.18
Helium		5.24
Krypton		1.14
Xenon		0.08
Hydrogen		0.5
Methane		2.0
Nitrous Oxide		0.5

treatment facilities. Sometimes 100 percent oxygen is used in shallow diving operations and certain phases of mixed-gas diving operations. However, breathing pure oxygen under pressure may induce the serious problems of oxygen toxicity.

2-10.3 **Nitrogen.** Like oxygen, nitrogen (N_2) is diatomic, colorless, odorless, and tasteless, and is a component of all living organisms. Unlike oxygen, it will not support life or aid combustion and it does not combine easily with other elements. Nitrogen in the air is inert in the free state. For diving, nitrogen may be used to dilute oxygen. Nitrogen is not the only gas that can be used for this purpose and under some conditions it has severe disadvantages as compared to other gases. Nitrogen narcosis, a disorder resulting from the anesthetic properties of nitrogen breathed under pressure, can result in a loss of orientation and judgment by the diver. For this reason, compressed air, with its high nitrogen content, is not used below a specified depth in diving operations.

2-10.4 **Helium.** Helium (He) is a colorless, odorless, and tasteless gas, but it is monatomic (exists as a single atom in its free state). It is totally inert. Helium is a rare element, found in air only as a trace element of about 5 parts per million (ppm). Helium coexists with natural gas in certain wells in the southwestern United States, Canada, and Russia. These wells provide the world's supply. When used in diving to dilute oxygen in the breathing mixture, helium does not cause the same problems associated with nitrogen narcosis, but it does have unique disadvantages. Among these is the distortion of speech which takes place in a helium atmosphere. The "Donald Duck" effect is caused by the acoustic properties of helium and it impairs voice communications in deep diving. Another negative characteristic of helium is its high thermal conductivity which can cause rapid loss of body and respiratory heat.

2-10.5 Hydrogen. Hydrogen (H_2) is diatomic, colorless, odorless, and tasteless, and is so active that it is rarely found in a free state on earth. It is, however, the most abundant element in the visible universe. The sun and stars are almost pure hydrogen. Pure hydrogen is violently explosive when mixed with air in proportions that include a presence of more than 5.3 percent oxygen. Hydrogen has been used in diving (replacing nitrogen for the same reasons as helium) but the hazards have limited this to little more than experimentation.

2-10.6 Neon. Neon (Ne) is inert, monatomic, colorless, odorless, and tasteless, and is found in minute quantities in the atmosphere. It is a heavy gas and does not exhibit the narcotic properties of nitrogen when used as a breathing medium. Because it does not cause the speech distortion problem associated with helium and has superior thermal insulating properties, it has been the subject of some experimental diving research.

2-10.7 Carbon Dioxide. Carbon dioxide (CO_2) is colorless, odorless, and tasteless when found in small percentages in the air. In greater concentrations it has an acid taste and odor. Carbon dioxide is a natural by-product of animal and human respiration, and is formed by the oxidation of carbon in food to produce energy. For divers, the two major concerns with carbon dioxide are control of the quantity in the breathing supply and removal of the exhaust after breathing. While some carbon dioxide is essential, unconsciousness can result when it is breathed at increased partial pressure. In high concentrations the gas can be extremely toxic. In the case of closed and semiclosed breathing apparatus, the removal of excess carbon dioxide generated by breathing is essential to safety.

2-10.8 Carbon Monoxide. Carbon monoxide (CO) is a colorless, odorless, tasteless, and poisonous gas whose presence is difficult to detect. Carbon monoxide is formed as a product of incomplete fuel combustion, and is most commonly found in the exhaust of internal combustion engines. A diver’s air supply can be contaminated by carbon monoxide when the compressor intake is placed too close to the compressor’s engine exhaust. The exhaust gases are sucked in with the air and sent on to the diver, with potentially disastrous results. Carbon monoxide seriously interferes with the blood’s ability to carry the oxygen required for the body to function normally. The affinity of carbon monoxide for hemoglobin is approximately 210 times that of oxygen. Carbon monoxide dissociates from hemoglobin at a much slower rate than oxygen.

2-10.9 Kinetic Theory of Gases. On the surface of the earth the constancy of the atmosphere’s pressure and composition tend to be accepted without concern. To the diver, however, the nature of the high pressure or hyperbaric, gaseous environment assumes great importance. The basic explanation of the behavior of gases under all variations of temperature and pressure is known as the kinetic theory of gases.

The kinetic theory of gases states: “The kinetic energy of any gas at a given temperature is the same as the kinetic energy of any other gas at the same temperature.” Consequently, the measurable pressures of all gases resulting from kinetic activity are affected by the same factors.

The kinetic energy of a gas is related to the speed at which the molecules are moving and the mass of the gas. Speed is a function of temperature and mass is a function of gas type. At a given temperature, molecules of heavier gases move at a slower speed than those of lighter gases, but their combination of mass and speed results in the same kinetic energy level and impact force. The measured impact force, or pressure, is representative of the kinetic energy of the gas. This is illustrated in Figure 2-6.

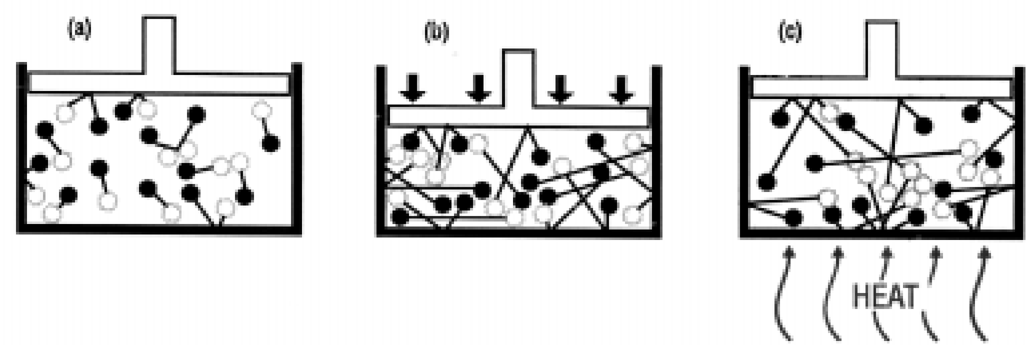

Figure 2-6. Kinetic Energy. The kinetic energy of the molecules inside the container (a) produces a constant pressure on the internal surfaces. As the container volume is decreased (b), the molecules per unit volume (density) increase and so does the pressure. As the energy level of the molecules increases from the addition of thermal energy (heat), so does the pressure (c).

2-11 GAS LAWS

Gases are subject to three closely interrelated factors—temperature, pressure, and volume. As the kinetic theory of gases points out, a change in one of these factors must result in some measurable change in the other factors. Further, the theory indicates that the kinetic behavior of any one gas is the same for all gases or mixtures of gases. Consequently, basic laws have been established to help predict the changes that will be reflected in one factor as the conditions of one or both of the other factors change. A diver needs to know how changing pressure will effect the air in his suit and lungs as he moves up and down in the water. He must be able to determine whether an air compressor can deliver an adequate supply of air to a proposed operating depth. He also needs to be able to interpret the reading on the pressure gauge of his tanks under varying conditions of temperature and pressure. The answers to such questions are calculated using a set of rules called the gas laws. This section explains the gas laws of direct concern to divers.

2-11.1 **Boyle’s Law.** Boyle’s law states that at constant temperature, the absolute pressure and the volume of gas are inversely proportional. As pressure increases the gas volume is reduced; as the pressure is reduced the gas volume increases. Boyle’s law is important to divers because it relates to change in the volume of a gas caused by the change in pressure, due to depth, which defines the relationship of pressure and volume in breathing gas supplies.

The formula for Boyle's law is: $C = P \times V$

Where:

C	=	a constant
P	=	absolute pressure
V	=	volume

Boyle's law can also be expressed as: $P_1V_1 = P_2V_2$

Where:

P_1	=	initial pressure
V_1	=	initial volume
P_2	=	final pressure
V_2	=	final volume

When working with Boyle's law, pressure may be measured in atmospheres absolute. To calculate pressure using atmospheres absolute:

$$P_{ata} = \frac{\text{Depth fsw} + 33\text{ fsw}}{33\text{ fsw}} \quad \text{or} \quad P_{ata} = \frac{\text{psig} + 14.7\text{psi}}{14.7\text{psi}}$$

Sample Problem 1. An open diving bell with a volume of 24 cubic feet is to be lowered into the sea from a support craft. No air is supplied to or lost from the bell. Calculate the volume of the air in the bell at 99 fsw.

1. Rearrange the formula for Boyle's law to find the final volume (V_2):

$$V_2 = \frac{P_1V_1}{P_2}$$

2. Calculate the final pressure (P_2) at 99 fsw:

$$P_2 = \frac{99\text{ fsw} + 33\text{ fsw}}{33\text{ fsw}}$$

$$= 4\text{ata}$$

3. Substitute known values to find the final volume:

$$V_2 = \frac{1\text{ata} \times 24\text{ft}^3}{4\text{ata}}$$

$$= 6\text{ft}^3$$

The volume of air in the open bell has been compressed to 6 ft.^3 at 99 fsw.

2-11.2 Charles'/Gay-Lussac's Law. When working with Boyle's law, the temperature of the gas is a constant value. However, temperature significantly affects the pressure and volume of a gas. Charles'/Gay-Lussac's law describes the physical relationships of temperature upon volume and pressure. Charles'/Gay-Lussac's law states that at a constant pressure, the volume of a gas is directly proportional to the change in the absolute temperature. If the pressure is kept constant and the absolute temperature is doubled, the volume will double. If the temperature decreases, volume decreases. If volume instead of pressure is kept constant (i.e., heating in a rigid container), then the absolute pressure will change in proportion to the absolute temperature.

The formulas for expressing Charles'/Gay-Lussac's law are as follows.

For the relationship between volume and temperature:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Where: Pressure is constant

T_1 = initial temperature (absolute)
T_2 = final temperature (absolute)
V_1 = initial volume
V_2 = final volume

And, for the relationship between pressure and temperature:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Where: Volume is constant

P_1 = initial pressure (absolute)
P_2 = final pressure (absolute)
T_1 = initial temperature (absolute)
T_2 = final temperature (absolute)

Sample Problem 1. An open diving bell of 24 cubic feet capacity is lowered into the ocean to a depth of 99 fsw. The surface temperature is 80°F, and the temperature at depth is 45°F. From the sample problem illustrating Boyle's law, we know that the volume of the gas was compressed to 6 cubic feet when the bell was lowered to 99 fsw. Apply Charles'/Gay-Lussac's law to determine the volume when it is effected by temperature.

1. Convert Fahrenheit temperatures to absolute temperatures (Rankine):

$$°R = °F + 460$$

$$T_1 = 80°F + 460$$

$$= 540°R$$

$$T_2 = 45°F + 460$$

$$= 505°R$$

2. Transpose the formula for Charles'/Gay-Lussac's law to solve for the final volume (V_2):

$$V_2 = \frac{V_1 T_2}{T_1}$$

3. Substitute known values to solve for the final volume (V_2):

$$V_2 = \frac{6\ \text{ft.}^3 \times 505}{540}$$

$$= 5.61\ \text{ft.}^3$$

The volume of the gas at 99 fsw is 5.61 ft^3.

Sample Problem 2. A 6-cubic foot flask is charged to 3000 psig and the temperature in the flask room is 72 °F. A fire in an adjoining space causes the temperature in the flask room to reach 170 °F. What will happen to the pressure in the flask?

1. Convert gauge pressure unit to atmospheric pressure unit:

$$P_1 = 3000 \text{ psig} + 14.7 \text{ psi}$$

$$= 3014.7 \text{ psia}$$

2. Convert Fahrenheit temperatures to absolute temperatures (Rankine):

$$°R = °F + 460$$

$$T_1 = 72°F + 460$$

$$= 532°R$$

$$T_2 = 170°F + 460$$

$$= 630°R$$

3. Transpose the formula for Gay-Lussac's law to solve for the final pressure (P_2):

$$P_2 = \frac{P_1 T_2}{T_1}$$

4. Substitute known values and solve for the final pressure (P_2):

$$P_2 = \frac{3014.7 \times 630}{532}$$

$$= \frac{1,899,261}{532}$$

$$= 3570.03 \text{ psia} - 14.7$$

$$= 3555.33 \text{ psig}$$

The pressure in the flask increased from 3000 psig to 3555.33 psig. Note that the pressure increased even though the flask's volume and the volume of the gas remained the same.

This example also shows what would happen to a scuba cylinder that was filled to capacity and left unattended in the trunk of an automobile or lying in direct sunlight on a hot day.

2-11.3 **The General Gas Law.** Boyle, Charles, and Gay-Lussac demonstrated that temperature, volume, and pressure affect a gas in such a way that a change in one factor must be balanced by corresponding change in one or both of the others. Boyle's law describes the relationship between pressure and volume, Charles'/ Gay-Lussac's law describes the relationship between temperature and volume and the relationship between temperature and pressure. The general gas law combines the laws to predict the behavior of a given quantity of gas when any of the factors change.

The formula for expressing the general gas law is: $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$

Where:

P_1 = initial pressure (absolute)
V_1 = initial volume
T_1 = initial temperature (absolute)
P_2 = final pressure (absolute)
V_2 = final volume
T_2 = final temperature (absolute)

Two simple rules must be kept in mind when working with the general gas law:

- There can be only one unknown value.

- The equation can be simplified if it is known that a value remains unchanged (such as the volume of an air cylinder) or that the change in one of the variables is of little consequence. In either case, cancel the value out of both sides of the equation to simplify the computations.

Sample Problem 1. Your ship has been assigned to salvage a sunken LCM landing craft located in 130 fsw. An exploratory dive, using scuba, is planned to survey the wreckage. The scuba cylinders are charged to 2,250 psig, which raises the temperature in the tanks to 140 °F. From experience in these waters, you know that the temperature at the operating depth will be about 40°F. Apply the general gas law to find what the gauge reading will be when you first reach the bottom. (Assume no loss of air due to breathing.)

1. Simplify the equation by eliminating the variables that will not change. The volume of the tank will not change, so V_1 and V_2 can be eliminated from the formula in this problem:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

2. Calculate the initial pressure by converting the gauge pressure unit to the atmospheric pressure unit:

$$\begin{aligned} P_1 &= 2{,}250 \text{ psig} + 14.7 \\ &= 2{,}264.7 \text{ psia} \end{aligned}$$

3. Convert Fahrenheit temperatures to Rankine (absolute) temperatures:

Conversion formula: °R = °F + 460

$$\begin{aligned} T_1 &= 140\ °F + 460 \\ &= 600\ °R \\ T_2 &= 40\ °F + 460 \\ &= 500°R \end{aligned}$$

4. Rearrange the formula to solve for the final pressure (P_2):

$$P_2 = \frac{P_1 T_2}{T_1}$$

5. Fill in known values:

$$\begin{aligned} P_2 &= \frac{2,264.7 \text{ psia} \times 500°R}{600°R} \\ &= 1887.25 \text{ psia} \end{aligned}$$

6. Convert final pressure (P_2) to gauge pressure:

$$\begin{aligned} P_2 &= 1{,}887.25 \text{ psia} - 14.7 \\ &= 1{,}872.55 \text{ psig} \end{aligned}$$

The gauge reading when you reach bottom will be 1,872.55 psig.

Sample Problem 2. During the survey dive for the operation outlined in Sample Problem 1, the divers determined that the damage will require a simple patch. The

Diving Supervisor elects to use surface-supplied MK 21 equipment. The compressor discharge capacity is 60 cubic feet per minute, and the air temperature on the deck of the ship is 80°F.

Apply the general gas law to determine whether the compressor can deliver the proper volume of air to both the working diver and the standby diver at the operating depth and temperature.

1. Calculate the absolute pressure at depth (P_2):

$$P_2 = \frac{130\ \text{fsw} + 33\ \text{fsw}}{33\ \text{fsw}}$$

$$= 4.93\ \text{ata}$$

2. Convert Fahrenheit temperatures to Rankine (absolute) temperatures:

Conversion formula:

$$°R = °F + 460$$

$$T_1 = 80°F + 460$$

$$= 540°R$$

$$T_2 = 40°F + 460$$

$$= 500°R$$

3. Rearrange the general gas law formula to solve for the volume of air at depth (V_2):

$$V_2 = \frac{P_1 V_1 T_2}{P_2 T_1}$$

4. Substitute known values and solve:

$$V_2 = \frac{1\ \text{ata} \times 60\ \text{cfm} \times 500°R}{4.93\ \text{ata} \times 540°R}$$

$$= 11.26\ \text{acfm at bottom conditions}$$

Based upon an actual volume (displacement) flow requirement of 1.4 acfm for a deep-sea diver, the compressor capacity is sufficient to support the working and standby divers at 130 fsw.

Sample Problem 3. Find the actual cubic feet of air contained in a 700-cubic inch internal volume cylinder pressurized to 3,000 psi.

1. Simplify the equation by eliminating the variables that will not change. The temperature of the tank will not change so T_1 and T_2 can be eliminated from the formula in this problem:

   $P_1V_1 = P_2V_2$

2. Rearrange the formula to solve for the initial volume:

   $$V_1 = \frac{P_2V_2}{P_1}$$

   Where:

   P_1 = 14.7 psi

   P_2 = 3,000 psi + 14.7 psi

   V_2 = 700 in^3

3. Fill in the known values and solve for V_1:

   $$V_1 = \frac{3014.7 \text{ psia} \times 700 \text{ in}^3}{14.7 \text{ psi}}$$
   $$= 143,557.14 \text{ in}^3$$

4. Convert V_1 to cubic feet:

   $$V_1 = \frac{143,557.14 \text{in}^3}{1728^3} \quad (1728 \text{ in}^3 = 1 \text{ ft}^3)$$
   $$= 83.07 \text{ scf}$$

2-12 GAS MIXTURES

If a diver used only one gas for all underwater work, at all depths, then the general gas law would suffice for most of his necessary calculations. However, to accommodate use of a single gas, oxygen would have to be chosen because it is the only one that provides life support. But 100 percent oxygen can be dangerous to a diver as depth and breathing time increase. Divers usually breathe gases in a mixture, either air (21 percent oxygen, 78 percent nitrogen, 1 percent other gases) or oxygen with one of the inert gases serving as a diluent for the oxygen. The human body has a wide range of reactions to various gases under different conditions of pressure and for this reason another gas law is required to help compute the differences between breathing at the surface and breathing under pressure.

2-12.1 **Dalton's Law.** Dalton's law states: "The total pressure exerted by a mixture of gases is equal to the sum of the pressures of each of the different gases making up the mixture, with each gas acting as if it alone was present and occupied the total volume."

In a gas mixture, the portion of the total pressure contributed by a single gas is called the partial pressure (pp) of that gas. An easily understood example is that of a container at atmospheric pressure (14.7 psi). If the container were filled with oxygen alone, the partial pressure of the oxygen would be one atmosphere. If the same container at 1 atm were filled with dry air, the partial pressures of all the constituent gases would contribute to the total partial pressure, as shown in Table 2-3.

If the same container was filled with air to 2,000 psi (137 ata), the partial pressures of the various components would reflect the increased pressure in the same proportion as their percentage of the gas, as illustrated in Table 2-4.

Table 2-3. *Partial Pressure at 1 ata.*

Gas	Percent of Component	Atmospheres Partial Pressure
N_2	78.08	0.7808
O_2	20.95	0.2095
CO_2	.03	0.0003
Other	.94	0.0094
Total	100.00	1.0000

Table 2-4. *Partial Pressure at 137 ata.*

Gas	Percent of Component	Atmospheres Partial Pressure
N_2	78.08	106.97
O_2	20.95	28.70
CO_2	.03	0.04
Other	.94	1.29
Total	100.00	137.00

The formula for expressing Dalton's law is:

$$P_{Total} = pp_A + pp_B + pp_C + \dots$$

Where: A, B, and C are gases and

$$pp_A = \frac{P_{Total} \times \%Vol_A}{1.00}$$

Another method of arriving at the same conclusion is to use the T formula. When using the T formula, there can be only one unknown value. Then it is merely a case of multiplying across, or dividing up to solve for the unknown value.The T formula is illustrated as:

$$\frac{\text{partial pressure}}{\text{atmosphere(s) absolute} \mid \text{\% volume (in decimal form)}}$$

Sample Problem 1. Use the T formula to calculate oxygen partial pressure given 10 ata and 16 percent oxygen.

1. Fill in the known values:

$$\frac{pp}{10 \mid .16}$$

2. Multiply the pressure by the volume to solve for the oxygen partial pressure (pp):

$$\frac{1.6 \ ppO_2}{10 \mid .16}$$

The oxygen partial pressure is 1.6.

Sample Problem 2. What happens to the breathing mixture at the operating depth of 130 fsw (4.93 ata)? The air compressor on the ship is taking in air at the surface, at normal pressure and normal mixture, and sending it to the diver at pressure sufficient to provide the necessary balance. The composition of air is not changed, but the quantity being delivered to the diver is five times what he was breathing on the surface. More molecules of oxygen, nitrogen, and carbon dioxide are all compressed into the same volume at the higher pressure. Use Dalton's law to determine the partial pressures at depth.

1. Calculate the oxygen partial pressure at depth.

$$\begin{aligned} ppO_2 &= .21 \text{ (surface)} \times 4.93 \text{ ata} \\ &= 1.03 \text{ ata} \end{aligned}$$

2. Calculate the nitrogen partial pressure at depth.

$$\begin{aligned} ppN_2 &= .79 \text{ (surface)} \times 4.93 \text{ ata} \\ &= 3.89 \text{ ata} \end{aligned}$$

3. Calculate the carbon dioxide partial pressure at depth.

$$\begin{aligned} ppCO_2 &= .0003 \text{ (surface)} \times 4.93 \text{ ata} \\ &= .0014 \text{ ata} \end{aligned}$$

2-12.1.1 **Expressing Small Quantities of Pressure.** Expressing partial pressures of gases in atmospheres absolute (ata) is the most common method employed in large quantities of pressure. Partial pressures of less than 0.1 atmosphere are usually expressed in millimeters of mercury (mmHg). At the surface, atmospheric pressure is equal to 1 ata or 14.7 psia or 760 mmHg. The formula used to calculate the $ppCO_2$ at 130 fsw in millimeters of mercury is:

$$\begin{aligned} ppCO_2 &= \frac{0.03}{100} \times 4.93 \text{ ata} \times \frac{760\text{mmHg}}{1\text{ata}} \\ &= 1.12\text{mmHg} \end{aligned}$$

2-12.1.2 **Calculating Surface Equivalent Value.** From the previous calculations, it is apparent that the diver is breathing more molecules of oxygen breathing air at 130 fsw than he would be if using 100 percent oxygen at the surface. He is also inspiring five times as many carbon dioxide molecules as he would breathing normal air on the surface. If the surface air were contaminated with 2 percent (0.02 ata) carbon dioxide, a level that could be readily accommodated by a normal person at one ata, the partial pressure at depth would be dangerously high—0.0986 ata (0.02 x 4.93 ata). This partial pressure is commonly referred to as a surface equivalent value (sev) of 10 percent carbon dioxide. The formula for calculating the surface equivalent value is:

$$\begin{aligned} \text{sev} &= \frac{\text{pp at depth (in ata)} \times 100\%}{1 \text{ ata}} \\ &= \frac{0.0986 \text{ ata}}{1 \text{ ata}} \times 100\% \\ &= 9.86\%\ CO_2 \end{aligned}$$

2-12.2 **Gas Diffusion.** Another physical effect of partial pressures and kinetic activity is that of gas diffusion. Gas diffusion is the process of intermingling or mixing of gas molecules. If two gases are placed together in a container, they will eventually mix completely even though one gas may be heavier. The mixing occurs as a result of constant molecular motion.

An individual gas will move through a permeable membrane (a solid that permits molecular transmission) depending upon the partial pressure of the gas on each side of the membrane. If the partial pressure is higher on one side, the gas molecules will diffuse through the membrane from the higher to the lower partial pressure side until the partial pressure on sides of the membrane are equal. Molecules are actually passing through the membrane at all times in both directions due to kinetic activity, but more will move from the side of higher concentration to the side of lower concentration.

Body tissues are permeable membranes. The rate of gas diffusion, which is related to the difference in partial pressures, is an important consideration in determining the uptake and elimination of gases in calculating decompression tables.

2-12.3 **Humidity.** Humidity is the amount of water vapor in gaseous atmospheres. Like other gases, water vapor behaves in accordance with the gas laws. However, unlike other gases encountered in diving, water vapor condenses to its liquid state at temperatures normally encountered by man.

Humidity is related to the vapor pressure of water, and the maximum partial pressure of water vapor in the gas is governed entirely by the temperature of the gas. As the gas temperature increases, more molecules of water can be maintained in the gas until a new equilibrium condition and higher maximum partial pressure are established. As a gas cools, water vapor in the gas condenses until a lower partial pressure condition exists regardless of the total pressure of the gas. The temperature at which a gas is saturated with water vapor is called the *dewpoint*.

In proper concentrations, water vapor in a diver's breathing gas can be beneficial to the diver. Water vapor moistens body tissues, thus keeping the diver comfortable. As a condensing liquid, however, water vapor can freeze and block air passageways in hoses and equipment, fog a diver's faceplate, and corrode his equipment.

2-12.4 **Gases in Liquids.** When a gas comes in contact with a liquid, a portion of the gas molecules enters into solution with the liquid. The gas is said to be *dissolved* in the liquid. Solubility is vitally important because significant amounts of gases are dissolved in body tissues at the pressures encountered in diving.

2-12.5 **Solubility.** Some gases are more soluble (capable of being dissolved) than others, and some liquids and substances are better solvents (capable of dissolving another substance) than others. For example, nitrogen is five times more soluble in fat than it is in water.

Apart from the individual characteristics of the various gases and liquids, temperature and pressure greatly affect the quantity of gas that will be absorbed. Because a diver is always operating under unusual conditions of pressure, understanding this factor is particularly important.

2-12.6 **Henry's Law.** Henry's law states: "The amount of any given gas that will dissolve in a liquid at a given temperature is directly proportional to the partial pressure of that gas." Because a large percentage of the human body is water, the law simply states that as one dives deeper and deeper, more gas will dissolve in the body tissues and that upon ascent, the dissolved gas must be released.

2-12.6.1 **Gas Tension.** When a gas-free liquid is first exposed to a gas, quantities of gas molecules rush to enter the solution, pushed along by the partial pressure of the gas. As the molecules enter the liquid, they add to a state of gas tension. Gas tension is a way of identifying the partial pressure of that gas in the liquid.

The difference between the gas tension and the partial pressure of the gas outside the liquid is called the *pressure gradient*. The pressure gradient indicates the rate at which the gas enters or leaves the solution.

2-12.6.2 **Gas Absorption.** At sea level, the body tissues are equilibrated with dissolved nitrogen at a partial pressure equal to the partial pressure of nitrogen in the lungs. Upon exposure to altitude or increased pressure in diving, the partial pressure of nitrogen in the lungs changes and tissues either lose or gain nitrogen to reach a new equilibrium with the nitrogen pressure in the lungs. Taking up nitrogen in tissues is called *absorption* or *uptake*. Giving up nitrogen from tissues is termed *elimination* or *offgassing*. In air diving, nitrogen absorption occurs when a diver is exposed to an increased nitrogen partial pressure. As pressure decreases, the nitrogen is eliminated. This is true for any inert gas breathed.

Absorption consists of several phases, including transfer of inert gas from the lungs to the blood and then from the blood to the various tissues as it flows through the body. The gradient for gas transfer is the partial pressure difference of the gas between the lungs and blood and between the blood and the tissues.

The volume of blood flowing through tissues is small compared to the mass of the tissue, but over a period of time the gas delivered to the tissue causes it to become equilibrated with the gas carried in the blood. As the number of gas molecules in the liquid increases, the tension increases until it reaches a value equal to the partial pressure. When the tension equals the partial pressure, the liquid is saturated with the gas and the pressure gradient is zero. Unless the temperature or pressure changes, the only molecules of gas to enter or leave the liquid are those which may, in random fashion, change places without altering the balance.

The rate of equilibration with the blood gas depends upon the volume of blood flow and the respective capacities of blood and tissues to absorb dissolved gas. For example, fatty tissues hold significantly more gas than watery tissues and will thus take longer to absorb or eliminate excess inert gas.

2-12.6.3 **Gas Solubility.** The solubility of gases is affected by temperature—the lower the temperature, the higher the solubility. As the temperature of a solution increases, some of the dissolved gas leaves the solution. The bubbles rising in a pan of water being heated (long before it boils) are bubbles of dissolved gas coming out of solution.

The gases in a diver's breathing mixture are dissolved into his body in proportion to the partial pressure of each gas in the mixture. Because of the varied solubility of different gases, the quantity of a particular gas that becomes dissolved is also governed by the length of time the diver is breathing the gas at the increased pressure. If the diver breathes the gas long enough, his body will become saturated.

The dissolved gas in a diver's body, regardless of quantity, depth, or pressure, remains in solution as long as the pressure is maintained. However, as the diver ascends, more and more of the dissolved gas comes out of solution. If his ascent rate is controlled (i.e., through the use of the decompression tables), the dissolved gas is carried to the lungs and exhaled before it accumulates to form significant bubbles in the tissues. If, on the other hand, he ascends suddenly and the pressure is reduced at a rate higher than the body can accommodate, bubbles may form, disrupt body tissues and systems, and produce decompression sickness.

Table 2-5. *Symbols and Values.*

Symbol	Value
°F	Degrees Fahrenheit
°C	Degrees Celsius
°R	Degrees Rankine
A	Area
C	Circumference
D	Depth of Water
H	Height
L	Length
P	Pressure
r	Radius
T	Temperature
t	Time
V	Volume
W	Width
Dia	Diameter
Dia^2	Diameter Squared
Dia^3	Diameter Cubed
Π	3.1416
ata	Atmospheres Absolute
pp	Partial Pressure
psi	Pounds per Square Inch
psig	Pounds per Square Inch Gauge
psia	Pounds per Square Inch Absolute
fsw	Feet of Sea Water
fpm	Feet per Minute
scf	Standard Cubic Feet
BTU	British Thermal Unit
cm^3	Cubic Centimeter
kw hr	Kilowatt Hour
mb	Millibars

Table 2-6. *Buoyancy (In Pounds).*

Fresh Water	(*V cu ft* x 62.4) - *Weight of Unit*
Salt Water	(*V cu ft* x 64) - *Weight of Unit*

Table 2-7. *Formulas for Area.*

Square or Rectangle	A = L x W
Circle	$A = 0.7854 \times Dia^2$ *or* $A = \pi r^2$

Table 2-8. *Formulas for Volumes.*

Compartment	$V = L \times W \times H$
Sphere	$= \pi \times 4/3 \times r^3$ $= 0.5236 \times Dia^3$
Cylinder	$V = \pi \times r^2 \times L$ $= \pi \times 1/4 \times Dia^2 \times L$ $= 0.7854 \times Dia^2 \times L$

Table 2-9. *Formulas for Partial Pressure/Equivalent Air Depth.*

Partial Pressure Measured in psi	$pp = (D + 33\text{ fsw}) \times 0.445\text{ psi} \times \left(\frac{\%V}{100\%}\right)$
Partial Pressure Measured in ata	$pp = \frac{D + 33\text{ fsw}}{33\text{ fsw}} \times \frac{\%V}{100\ \%}$
Partial Pressure Measured in fsw	$pp = (D + 33\text{fsw}) \times \frac{\%V}{100\%}$
T formula for Measuring Partial Pressure	$\frac{pp}{ata \mid \%}$
Equivalent Air Depth for N_2O_2 Diving Measured in fsw	$EAD = \left[\frac{(1.0 - O_2\%)(D + 33)}{.79}\right] - 33$
Equivalent Air Depth for N_2O_2 Diving Measured in meters	$EAD = \left[\frac{(1.0 - O_2\%)(M + 10)}{.79}\right] - 10$

Table 2-10. Pressure Equivalents.

				Columns of Mercury at 0°C		Columns of Water* at 15° C			
Atmos-pheres	**Bars**	**10 Newton Per Square Centimeter**	**Pounds Per Square Inch**	**Meters**	**Inches**	**Meters**	**Inches**	**Feet (FW)**	**Feet (FSW)**
1	1.01325	1.03323	14.696	0.76	29.9212	10.337	406.966	33.9139	33.066
0.986923	1	1.01972	14.5038	0.750062	29.5299	10.2018	401.645	33.4704	32.6336
0.967841	0.980665	1	14.2234	0.735559	28.959	10.0045	393.879	32.8232	32.0026
0.068046	0.068947	0.070307	1	0.0517147	2.03601	0.703386	27.6923	2.30769	2.25
1.31579	1.33322	1.35951	19.33369	1	39.37	13.6013	535.482	44.6235	43.5079
0.0334211	0.0338639	0.0345316	0.491157	0.0254	1	0.345473	13.6013	1.13344	1.1051
0.09674	0.09798	0.099955	1.42169	0.073523	2.89458	1	39.37	3.28083	3.19881
0.002456	0.002489	0.002538	0.03609	0.001867	0.073523	0.02540	1	0.08333	0.08125
0.029487	0.029877	0.030466	0.43333	0.02241	0.882271	0.304801	12	1	0.975
0.030242	0.030643	0.031247	0.44444	0.022984	0.904884	0.312616	12.3077	1.02564	1

1. Fresh Water (FW) = 62.4 lbs/ft^3; Salt Water (fsw) = 64.0 lbs/ft^3.
2. The SI unit for pressure is Kilopascal (KPA)—1KG/CM^2 = 98.0665 KPA and by definition 1 BAR = 100.00 KPA @ 4ºC.
3. In the metric system, 1 MSW is defined as 1 BAR. Note that pressure conversion from MSW to FSW is different than length conversion; i.e., 10 MSW = 32.6336 FSW and 10 M = 32.8083 feet.

Table 2-11. Volume and Capacity Equivalents.

Cubic Centi-meters	Cubic Inches	Cubic Feet	Cubic Yards	Milliliters	Liters	Pint	Quart	Gallon
1	.061023	3.531×10^{-5}	1.3097×10^{-6}	.999972	9.9997×10^{-4}	2.113×10^{-3}	1.0567×10^{-3}	2.6417×10^{-4}
16.3872	1	5.787×10^{-4}	2.1434×10^{-5}	16.3867	0.0163867	0.034632	0.017316	4.329×10^{-3}
28317	1728	1	0.037037	28316.2	28.3162	59.8442	29.9221	7.48052
764559	46656	27	1	764538	764.538	1615.79	807.896	201.974
1.00003	0.0610251	3.5315×10^{-5}	1.308×10^{-6}	1	0.001	2.1134×10^{-3}	1.0567×10^{-3}	2.6418×10^{-4}
1000.03	61.0251	0.0353154	1.308×10^{-3}	1000	1	2.11342	1.05671	0.264178
473.179	28.875	0.0167101	6.1889×10^{-4}	473.166	0.473166	1	0.5	0.125
946.359	57.75	0.0334201	1.2378×10^{-3}	946.332	0.946332	2	1	0.25
3785.43	231	0.133681	49511×10^{-3}	3785.33	3.78533	8	4	1

Table 2-12. *Length Equivalents.*

Centi-meters	Inches	Feet	Yards	Meters	Fathom	Kilo-meters	Miles	Int. Nau-tical Miles
1	0.3937	0.032808	0.010936	0.01	5.468×10^{-3}	0.00001	6.2137×10^{-5}	5.3659×10^{-6}
2.54001	1	0.08333	0.027778	0.025400	0.013889	2.540×10^{-5}	1.5783×10^{-5}	1.3706×10^{-5}
30.4801	12	1	0.33333	0.304801	0.166665	3.0480×10^{-4}	1.8939×10^{-4}	1.6447×10^{-4}
91.4403	36	3	1	0.914403	0.5	9.144×10^{-4}	5.6818×10^{-4}	4.9341×10^{-4}
100	39.37	3.28083	1.09361	1	0.5468	0.001	6.2137×10^{-4}	5.3959×10^{-4}
182.882	72	6	2	1.82882	1	$1.8288 \times 10\text{-}^{3}$	1.1364×10^{-3}	9.8682×10^{-4}
100000	39370	3280.83	1093.61	1000	546.8	1	0.62137	0.539593
160935	63360	5280	1760	1609.35	80	1.60935	1	0.868393
185325	72962.4	6080.4	2026.73	1853.25	1013.36	1.85325	1.15155	1

Table 2-13. *Area Equivalents.*

Square Miles	Square Centimeters	Square Inches	Square Feet	Square Yards	Acres	Square Miles
1	10000	1550	10.7639	1.19599	2.471×10^{-4}	3.861×10^{-7}
0.0001	1	0.155	1.0764×10^{-3}	1.196×10^{-4}	2.471×10^{-8}	3.861×10^{-11}
6.4516×10^{-4}	6.45163	1	6.944×10^{-3}	7.716×10^{-4}	1.594×10^{-7}	2.491×10^{-10}
0.092903	929.034	144	1	0.11111	2.2957×10^{-5}	3.578×10^{-8}
0.836131	8361.31	1296	9	1	2.0661×10^{-4}	3.2283×10^{-7}
4046.87	4.0469×10^{7}	6.2726×10^{6}	43560	4840	1	1.5625×10^{-3}
2.59×10^{6}	2.59×10^{10}	4.0145×10^{9}	2.7878×10^{7}	3.0976×10^{6}	640	1

Table 2-14. *Velocity Equivalents.*

Centimeters Per Second	Meters Per Second	Meters Per Minute	Kilometers Per Hour	Feet Per Second	Feet Per Minute	Miles Per Hour	Knots
1	0.01	0.6	0.036	0.0328083	1.9685	0.0223639	0.0194673
100	1	60	3.6	3.28083	196.85	2.23693	1.9473
1.66667	0.016667	1	0.06	0.0546806	3.28083	0.0372822	0.0324455
27.778	0.27778	16.667	1	0.911343	54.6806	0.62137	0.540758
30.4801	0.304801	18.288	1.09728	1	60	0.681818	0.593365
0.5080	5.080×10^{-3}	0.304801	0.018288	0.016667	1	0.0113636	9.8894×10^{-3}
44.7041	0.447041	26.8225	1.60935	1.4667	88	1	0.870268
51.3682	0.513682	30.8209	1.84926	1.6853	101.118	1.14907	1

Table 2-15. *Mass Equivalents.*

Kilograms	Grams	Grains	Ounces	Pounds	Tons (short)	Tons (long)	Tons (metric)
1	1000	15432.4	35.274	2.20462	1.1023×10^{-3}	9.842×10^{-4}	0.001
0.001	1	15432.4	0.035274	2.2046×10^{-3}	1.1023×10^{-6}	9.842×10^{-7}	0.000001
6.4799×10^{-5}	0.6047989	1	2.2857×10^{-3}	1.4286×10^{-4}	7.1429×10^{-8}	6.3776×10^{-8}	6.4799×10^{-8}
0.0283495	28.3495	437.5	1	0.0625	3.125×10^{-5}	2.790×10^{-5}	2.835×10^{-5}
0.453592	453.592	7000	16	1	0.0005	4.4543×10^{-4}	4.5359×10^{-4}
907.185	907185	1.4×10^{7}	32000	2000	1	0.892857	0.907185
1016.05	1.016×10^{6}	1.568×10^{7}	35840	2240	1.12	1	1.01605
1000	10^{6}	1.5432×10^{7}	35274	2204.62	1.10231	984206	1

Table 2-16. *Energy or Work Equivalents.*

International Joules	Ergs	Foot - Pounds	International Kilowatt Hours	Horse Power Hours	Kilo - Calories	BTUs
1	10^{7}	0.737682	2.778×10^{-7}	$3.7257\ 10^{-7}$	2.3889×10^{-4}	9.4799×10^{-4}
10^{-7}	1	7.3768×10^{-8}	2.778×10^{-14}	3.726×10^{-14}	2.389×10^{-11}	9.4799×10^{-11}
1.3566	1.3556×10^{7}	1	3.766×10^{-7}	5.0505×10^{-7}	3.238×10^{-4}	1.285×10^{-3}
3.6×10^{6}	3.6×10^{13}	2.6557×10^{6}	1	1.34124	860	3412.76
2.684×10^{6}	2.684×10^{13}	1.98×10^{6}	0.745578	1	641.197	2544.48
4186.04	4.186×10^{10}	3087.97	1.163×10^{-3}	1.596×10^{-3}	1	3.96832
1054.87	1.0549×10^{10}	778.155	2.930×10^{-4}	3.93×10^{-4}	0.251996	1

Table 2-17. *Power Equivalents.*

Horse Power	International Kilowatts	International Joules/ Second	Kg-M Second	Foot lbs. Per Second	IT Calories Per Second	BTUs Per Second
1	0.745578	745.578	76.0404	550	178.11	0.7068
1.34124	1	1000	101.989	737.683	238.889	0.947989
1.3412×10^{-3}	0.001	1	0.101988	0.737682	0.238889	9.4799×10^{-4}
0.0131509	9.805×10^{-3}	9.80503	1	7.233	2.34231	9.2951×10^{-3}
1.8182×10^{-3}	1.3556×10^{-3}	1.3556	0.138255	1	0.323837	1.2851×10^{-3}
5.6145×10^{-3}	4.1861×10^{-3}	4.18605	0.426929	3.08797	1	3.9683×10^{-3}
1.41483	1.05486	1054.86	107.584	778.155	251.995	1

Table 2-18. *Temperature Equivalents.*

Conversion Formulas: $°C = (°F - 32) \times \frac{5}{9}$ $°F = \left(\frac{9}{5} \times °C\right) + 32$

°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
-100	-148.0	-60	-76.0	-20	-4.0	20	68.0	60	140.0	100	212.0	140	284.0
-98	-144.4	-58	-72.4	-18	-0.4	22	71.6	62	143.6	102	215.6	142	287.6
-96	-140.8	-56	-68.8	-16	3.2	24	75.2	64	147.2	104	219.2	144	291.2
-94	-137.2	-54	-65.2	-14	6.8	26	78.8	66	150.8	106	222.8	146	294.8
-92	-133.6	-52	-61.6	-12	10.4	28	82.4	68	154.4	108	226.4	148	298.4
-90	-130.0	-50	-58.0	-10	14.0	30	86.0	70	158.0	110	230.0	150	302.0
-88	-126.4	-48	-54.4	-8	17.6	32	89.6	72	161.6	112	233.6	152	305.6
-86	-122.8	-46	-50.8	-6	21.2	34	93.2	74	165.2	114	237.2	154	309.2
-84	-119.2	-44	-47.2	-4	24.8	36	96.8	76	168.8	116	240.8	156	312.8
-82	-115.6	-42	-43.6	-2	28.4	38	100.4	78	172.4	118	244.4	158	316.4
-80	-112.0	-40	-40.0	0	32	40	104.0	80	176.0	120	248.0	160	320.0
-78	-108.4	-38	-36.4	2	35.6	42	107.6	82	179.6	122	251.6	162	323.6
-76	-104.8	-36	-32.8	4	39.2	44	111.2	84	183.2	124	255.2	164	327.2
-74	-101.2	-34	-29.2	6	42.8	46	114.8	86	186.8	126	258.8	166	330.8
-72	-97.6	-32	-25.6	8	46.4	48	118.4	88	190.4	128	262.4	168	334.4
-70	-94.0	-30	-22.0	10	50.0	50	122.0	90	194.0	130	266.0	170	338.0
-68	-90.4	-28	-18.4	12	53.6	52	125.6	92	197.6	132	269.6	172	341.6
-66	-86.8	-26	-14.8	14	57.2	54	129.2	94	201.2	134	273.2	174	345.2
-64	-83.2	-24	-11.2	16	60.8	56	132.8	96	204.8	136	276.8	176	348.8
-62	-79.6	-22	-7.6	18	64.4	58	136.4	98	208.4	138	280.4	178	352.4

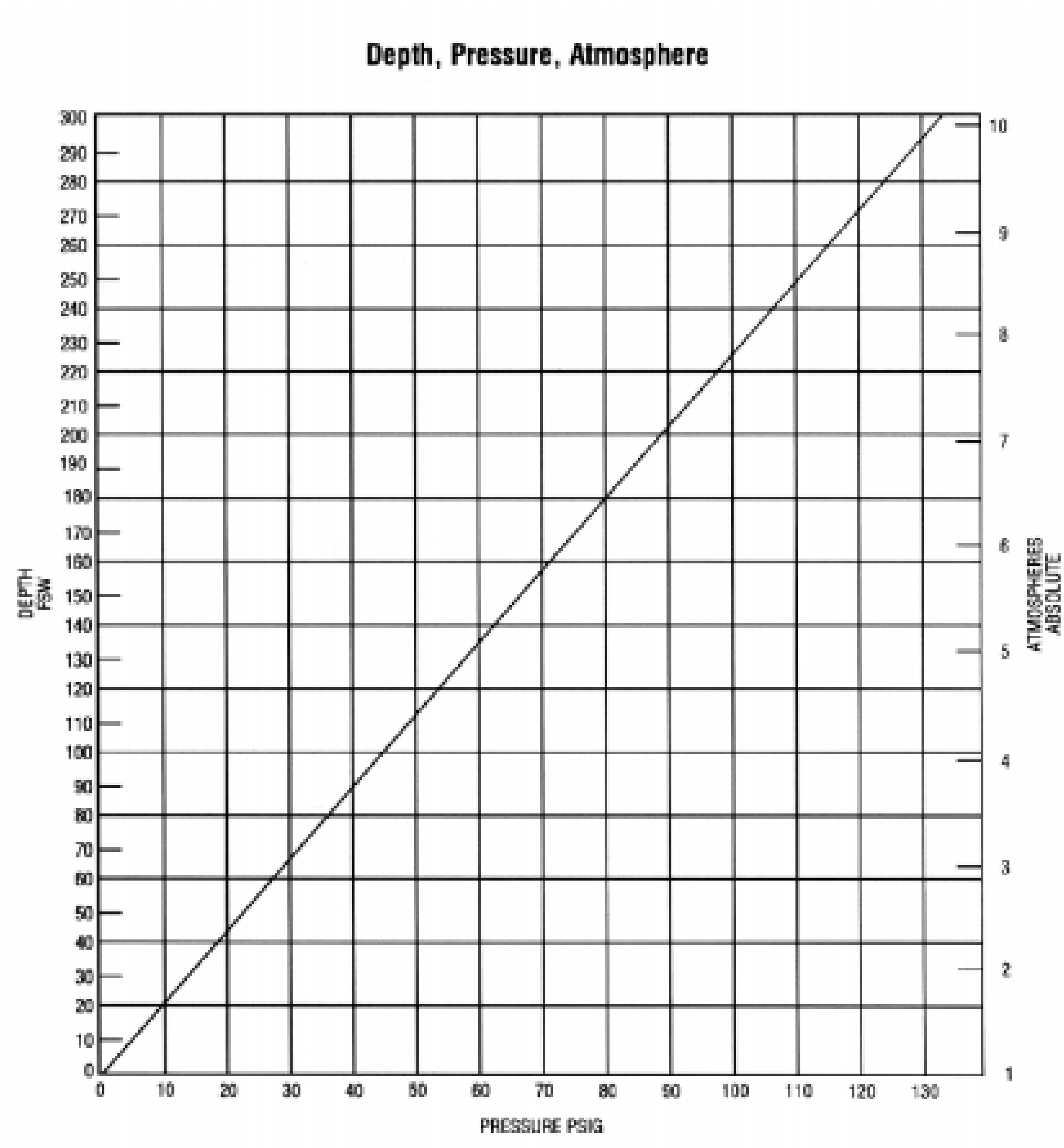

Figure 2-7. Depth, Pressure, Atmosphere Graph.