CHAPTER 7

PHYSICS

GENERAL

Physics is the term applied to that area of knowledge regarding the basic and fundamental nature of matter and energy. It does not attempt to determine why matter and energy behave as they do in their relation to physical phenomena, but rather how they behave.

The persons who maintain and repair aircraft should have a knowledge of basic physics, which is sometimes called the science of matter and energy.

MATTER

Although matter is the most basic of all things related to the field of physics and the material world, it is the hardest to define. Since it cannot be rigidly defined, this chapter will point out those characteristics which are easily recognizable.

Matter itself cannot be destroyed, but it can be changed from one state into another state by chemical or physical means. It is usually considered in terms of the energy it contains, absorbs, or gives off. Under certain controlled conditions, it can be made to aid man in his everyday life.

Matter is any substance that occupies space and has weight. There are three states of matter: (1) Solids, (2) liquids, and (3) gases. Solids have a definite volume and a definite shape; liquids have a definite volume, but they take the shape of the containing vessel; gases have neither a definite volume nor a definite shape. Gases not only take the shape of the containing vessel, but they expand and fill the vessel, no matter what its volume.

Water is a good example of matter changing from one state to another. At high temperature it is in the gaseous state known as steam. At moderate temperatures it is a liquid, and at low temperatures it becomes ice, a solid state. In this example, the temperature is the dominant factor in determining the state that the substance assumes. Pressure is another important factor that will effect changes in the state of matter. At pressures lower than atmospheric, water will boil and thus change into steam at temperatures lower than 212° F. Pressure is a critical factor in changing some gases to liquids or solids. Normally, when pressure and chilling are both applied to a gas, it assumes a liquid state. Liquid air, which is a mixture of oxygen and nitrogen, is produced in this manner.

Characteristics of Matter

All matter has certain characteristics or general properties. These properties are defined elementally and broadly at this point, and more specifically in applications throughout the text. Among these properties and relationships are:

a. Volume—meaning to occupy space; having some measurements such as length, width, and height. It may be measured in cubic inches, cubic centimeters, or the like.

b. Mass—the measurement of quantity or the measure of the quantity of matter in a body. Mass does not vary even though the state changes.

c. Attraction—a force acting mutually between particles of matter, tending to draw them together. Sir Issac Newton called this the "Law of Universal Gravitation." He showed how each particle of matter attracts every other particle, how people are bound to the earth, and how the planets are attracted in the solar system.

d. Weight—the measure of universal gravitation. The pull of gravity on a body is called the weight of the body and indicates how heavy the body is.

e. Density—the mass (weight) of a substance per unit volume. Density can be used to distinguish various types of matter. If a substance is very dense, a large quantity of this matter would occupy a small volume.

f. Inertia—the opposition which a body offers to any change of motion. The property of inertia is common to all matter. It is best expressed in Newton's first law: "A body at rest remains at rest, and a body in motion continues to move at constant speed along a straight line, unless the body is acted upon in either case by an external force."

g. Porosity—having pores or spaces where smaller particles may fit when a mixture takes place. This is sometimes referred to as granular; consisting or appearing to consist of small grains or granules.

h. Impenetrability—simply stated means that no two objects can occupy the same place at the same time. Thus, two portions of matter cannot at the same time occupy the same space.

Matter may be classified as either an element or a compound, depending upon the complexity of its structure. An element is matter that cannot be reduced chemically into a simpler substance. A compound is matter formed by some combination of elements.

Two basic particles, the atom and the molecule, make up all matter. The molecule is the smallest particle of a substance which still has all the properties of the original substance. In *physics* the molecule is the unit of matter. The atom is the smallest particle of an element that can combine with other atoms to form molecules. In *chemistry*, the atom is the unit of matter.

While the subject of matter may seem complex, it is difficult to think of anything simpler than matter. It can be referred to as "anything that occupies space."

Systems of Measurement

The two most commonly used systems of measurement are the English system, which is still in general use in the United States, and the metric system, used in most European countries and now adopted by the Armed Forces of the United States. The metric system is normally used in all scientific applications.

The three basic quantities which require units of measurement are mass (weight), length (distance), and time.

The metric system is sometimes called the CGS system because it uses as basic measuring units, the centimeter (C) to measure length, the gram (G) to measure mass, and the second (S) to measure time.

The English system uses different units for the measurement of mass and length. The pound is the unit of weight; the foot is used to measure length. The second is used to measure time as in the metric system.

The units of one system can be converted to units in the other system by using a conversion factor or by referring to a chart similar to that shown in figure 7-1. In this figure the English and the metric systems are compared; in addition, a column of equivalents is included which can be used to convert units from one system to the other.

FLUIDS

General

Because both liquids and gases flow freely, they are called fluids, from the Latin word "fluidus," meaning to flow. A fluid is defined as a substance which changes its shape easily and takes the shape of its container. This applies to both liquids and gases. The characteristics of liquids and gases may be grouped under similarities and differences.

Similar characteristics are as follows:

1. Each has no definite shape but conforms to the shape of the container.
2. Both readily transmit pressures.

Differential characteristics are as follows:

1. Gases fill their containers completely, but liquids may not.
2. Gases are lighter than equal volumes of liquids.
3. Gases are highly compressible, but liquids are only slightly so.

These differences are described in the appropriate areas of the following discussion concerning the properties and characteristics of fluids at rest. Also included are some of the factors which affect fluids in different situations.

Density and Specific Gravity

The density of a substance is its weight per unit volume. The unit volume selected for use in the English system of measurement is 1 cubic foot. In the metric system it is 1 cubic centimeter. Therefore, density is expressed in lbs./cu. ft. (pounds per cubic foot) or in g./cu. cm. (grams per cubic centimeter).

To find the density of a substance, its weight and volume must be known. Its weight is then divided by its volume to find the weight per unit volume.

	Metric System	English System	Equivalents
Length	CENTIMETER	FOOT	
(distance)	1 centimeter = 10 millimeters	1 foot = 12 inches	1 in. = 2.54 cm.
	1 decimeter = 10 centimeters	1 yard = 3 feet	1 ft. = 30.5 cm.
	1 meter = 100 centimeters	1 mile = 5,280 feet	1 meter = 39.37 in.
	1 kilometer = 1000 meters		1 km.= 0.62 mile
Weight	GRAM	POUND	
(mass)	1 gram = 1000 milligrams	1 pound = 16 ounces	1 lb. = 453.6 gr.
	1 kilogram = 1000 grams	1 ton = 2,000 pounds	1 kg. = 2.2 lb.
Time	SECOND	SECOND	
	Same as for English system	1 second = $\frac{1}{86{,}400}$ of average solar day.	Time same for both systems

FIGURE 7–1. Comparison of metric and English systems of measurement.

For example, the liquid which fills a certain container weighs 1,497.6 pounds. The container is 4 feet long, 3 feet wide, and 2 feet deep. Its volume is 24 cubic feet (4 ft. × 3 ft. × 2 ft.). If 24 cubic feet of liquid weights 1,497.6 pounds, then 1 cubic foot weighs 1,497.6/24, or 62.4 pounds. Therefore, the density of the liquid is 62.4 lbs./cu. ft.

This is the density of water at 4° C. (centigrade) and is usually used as the standard for comparing densities of other substances. (In the metric system the density of water is 1 g./cu. cm.). The standard temperature of 4° C. is used when measuring the density of liquids and solids. Changes in temperature will not change the weight of a substance, but will change the volume of the substance by expansion or contraction, thus changing its weight per unit volume.

The procedure for finding density applies to all substances; however, it is necessary to consider the pressure when finding the density of gases. Temperature is more critical when measuring the density of gases than it is for other substances. The density of a gas increases in direct proportion to the pressure exerted on it. Standard conditions for the measurement of the densities of gases have been established at 0° C. for temperature and a pressure of 76 cm. of mercury. (This is the average pressure of the atmosphere at sea level.) Density is computed based on these conditions for all gases.

It is often necessary to compare the density of one substance with that of another. For this purpose, a standard is needed. Water is the standard that physicists have chosen to use when comparing the densities of all liquids and solids. For gases, air is most commonly used. However, hydrogen is sometimes used as a standard for gases. In physics, the word specific implies a ratio. Thus, specific gravity is calculated by comparing the weight of a definite volume of the given substance with the weight of an equal volume of water. The terms "specific weight" or "specific density" are sometimes used to express this ratio.

The following formulas are used to find the sp. gr. (specific gravity) of liquids and solids:

$$\text{sp. gr.} = \frac{\text{Weight of the substance}}{\text{Weight of an equal volume of water}}$$

or,

$$\text{sp. gr.} = \frac{\text{Density of the substance}}{\text{Density of water}}$$

The same formulas are used to find the density of gases by substituting air or hydrogen for water.

Specific gravity is not expressed in units, but as pure numbers. For example, if a certain hydraulic liquid has a sp. gr. of 0.8, 1 cu. ft. of the liquid weighs 0.8 times as much as 1 cu. ft. of water: 62.4 times 0.8 or 49.92 pounds. In the metric system, 1 cu. cm. of a substance with a

Solids	Sp. gr.	Liquids (Room temperatures)	Sp. gr.	Gases (Air standard at 0°C, and 76.0 centimeters of mercury)	Sp. gr.
Aluminum	2.7	Alcohol, ethyl	0.789	Air	1.000
Bronze	8.8	Gasoline	0.68 0.72	Hydrogen	0.0695
Copper	8.9	Oil (paraffin)	0.8	Nitrogen	0.967
Ice	0.917	Water	1.00	Oxygen	1.105

FIGURE 7–2. Typical values of specific gravity.

specific gravity of 0.8 weighs 1 times 0.8 or 0.8 gr. (Note that in the metric system the specific gravity of a liquid or solid has the same numerical value as its density. Since air weighs 1.293 gr./l. (grams per liter), the specific gravity of gases does not equal the metric densities.)

Specific gravity and density are independent of the size of the sample under consideration and depend only upon the substance of which it is made. See figure 7–2 for typical values of sp. gr. for various substances.

A device called a hydrometer is used for measuring specific gravity of liquids. This device consists of a tubular-shaped glass float contained in a larger glass tube. (See figure 7–3.) The larger glass tube provides the container for the liquid. A rubber suction bulb draws the liquid up into the container. There must be enough liquid to raise the float and prevent it from touching the bottom. The float is weighted and has a vertically graduated scale. To determine specific gravity, the scale is read at the surface of the liquid in which the float is immersed. An indication of 1000 is read when the float is immersed in pure water. When immersed in a liquid of greater density, the float rises, indicating a greater specific gravity. For liquids of lesser density the float sinks, indicating a lower specific gravity.

An example of the use of the hydrometer is its use in determining the specific gravity of the electrolyte (battery liquid) in an aircraft battery. When a battery is discharged, the calibrated float immersed in the electrolyte will indicate approximately 1150. The indication of a charged battery is between 1275 and 1310.

Buoyancy

A solid body submerged in a liquid or a gas weighs less than when weighed in free space. This is because of the upward force, called buoyant force, which any fluid exerts on a body submerged in it. An object will float if this upward force of the fluid is greater than the weight of the object. Objects denser than the fluid, even though they sink readily, appear to lose a part of their weight when submerged. A person can lift a larger weight under water than he can possibly lift in the air.

The following experiment is illustrated in figure 7–4. The overflow can is filled up to the spout with water. The heavy metal cylinder is first weighed in still air and then is weighed while completely submerged in the water. The difference between the two weights is the buoyant force of the water. As the cylinder is lowered into the overflow can, the water is caught in the catch bucket. The volume of water which overflows equals the volume of the cylinder. (The volume of irregular-shaped objects can be measured by this method.) If this experiment is performed carefully, the weight of the water displaced by the metal cylinder exactly equals the buoyant force of the water.

Similar experiments were performed by Archimedes (287–212 B.C.). As a result of his experiments, he discovered that the buoyant force which a fluid exerts upon a submerged body is equal to the weight of the fluid the body displaces. This statement is referred to as Archimedes' principle. This principle applies to all fluids, gases as well as liquids. Just as water exerts a buoyant

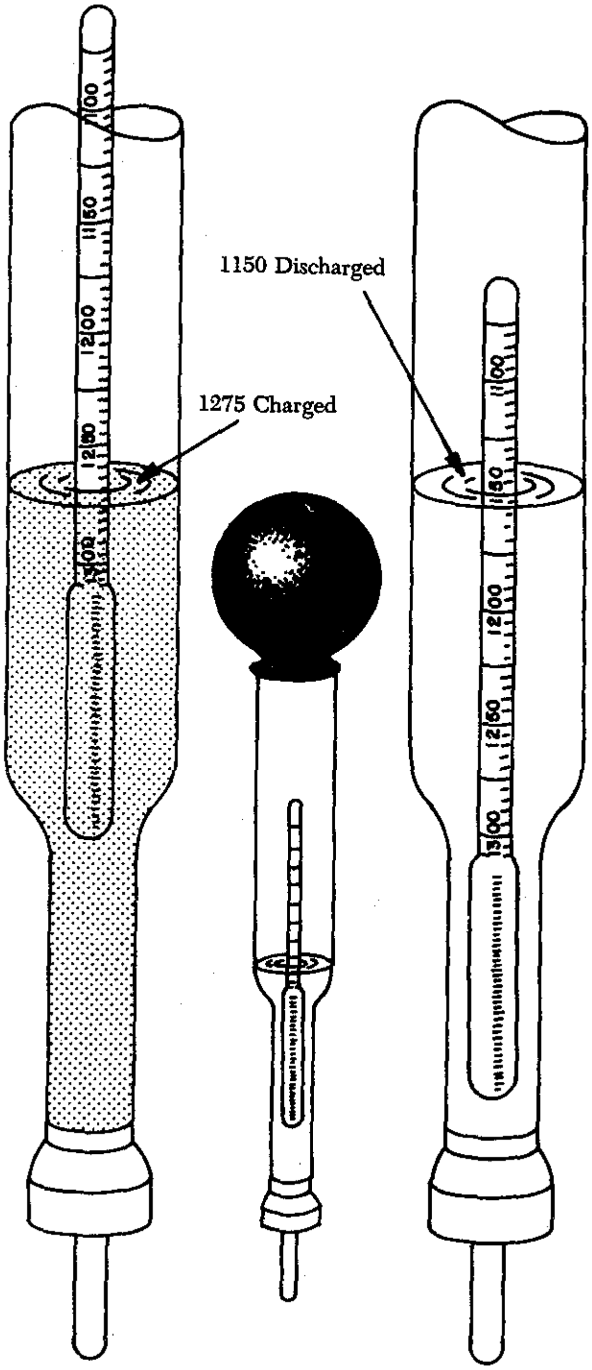


FIGURE 7–3. A hydrometer.

force on submerged objects, air exerts a buoyant force on objects submerged in it.

TEMPERATURE

Temperature is a dominant factor affecting the physical properties of fluids. It is of particular concern when calculating changes in the state of gases.

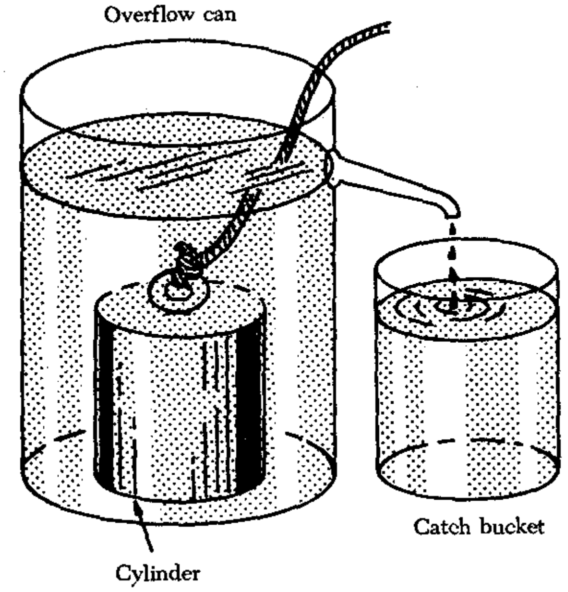
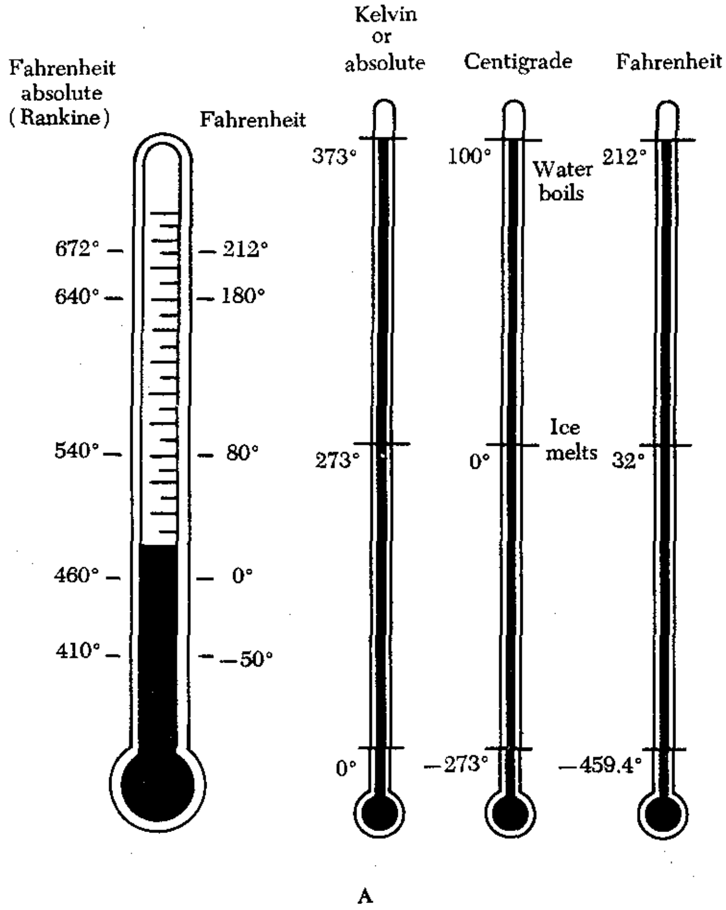


FIGURE 7–4. Measurement of buoyant force.

The three temperature scales used extensively are the centigrade, the Fahrenheit, and the absolute or Kelvin scales. The centigrade scale is constructed by using the freezing and boiling points of water, under standard conditions, as fixed points of zero and 100, respectively, with 100 equal divisions between. The Fahrenheit scale uses 32° as the freezing point of water and 212° as the boiling point, and has 180 equal divisions between. The absolute or Kelvin scale is constructed with its zero point established as −273° C., or −459.4° F. below the freezing point of water. The relationships of the other fixed points of the scales are shown in B of figure 7–5.

Absolute zero, one of the fundamental constants of physics, is commonly used in the study of gases. It is usually expressed in terms of the centigrade scale. If the heat energy of a given gas sample could be progressively reduced, some temperature would be reached at which the motion of the molecules would cease entirely. If accurately determined, this temperature could then be taken as a natural reference, or as a true "absolute zero" value.

Experiments with hydrogen indicated that if a gas were cooled to −273.16° C. (used as −273° for most calculations), all molecular motion would cease, and no additional heat could be extracted from the substance.



TEMPERATURE CONVERSION

Kelvin to centigrade and fahrenheit

$$°K = C + 273$$
$$= \frac{5}{9}(F - 32) + 273$$
$$= \frac{5}{9}F + 255.23$$

Centigrade to kelvin and fahrenheit

$$°C = K - 273$$
$$= \frac{5}{9}(F - 32)$$

Fahrenheit to kelvin and centigrade

$$°F = \frac{9}{5}(K - 273) + 32$$
$$= \frac{9}{5}K - 459.4$$
$$= \frac{9}{5}C + 32$$

B

FIGURE 7–5. (A) Rankine scale used to convert Farenheit to absolute. (B) Comparison of Fahrenheit, centigrade, and Kelvin temperature.

When temperatures are measured with respect to the absolute zero reference, they are expressed as zero in the absolute or Kelvin scale. Thus, absolute zero may be expressed as 0° K., as −273° C., or as −459.4° F. (used as −460° for most calculations).

When working with temperatures, always make sure which system of measurement is being used and know how to convert from one to another. The conversion formulas are shown in B of figure 7–5. For purposes of calculations, the Rankine scale illustrated in A of figure 7–5 is commonly used to convert Fahrenheit to absolute. For Fahrenheit readings above zero, 460° is added. Thus, 72° F. equals 460° plus 72°, or 532° absolute. If the Fahrenheit reading is below zero, it is subtracted from 460°. Thus −40° F. equals 460° minus 40°, or 420° absolute. It should be stressed that the Rankine scale does not indicate absolute temperature readings in accordance with the Kelvin scale, but these conversions may be used for the calculations of changes in the state of gases.

The Kelvin and centigrade scales are used more extensively in scientific work; therefore, some technical manuals may use these scales in giving directions and operating instructions. The Fahrenheit scale is commonly used in the United States, and most people are familar with it. Therefore, the Fahrenheit scale is used in most areas of this text.

PRESSURE

The term "pressure" as used throughout this chapter is defined as a force per unit area. Pressure is usually measured in p.s.i. (pounds per square inch). Sometimes pressure is measured in inches of mercury or, for very low pressure, inches of water.

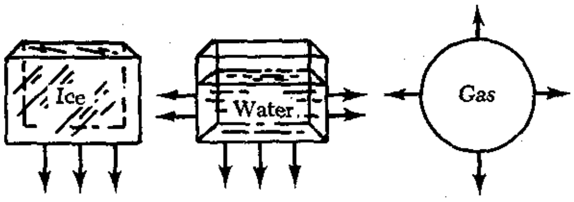


FIGURE 7–6. Exertion of pressure.

Pressure may be in one direction, several directions, or in all directions. (See figure 7–6.) Ice (a solid) exerts pressure downward only. Water (a fluid) exerts pressure on all surfaces with which it comes in contact. Gas (a fluid) exerts pressure in all directions because it completely fills the *container.*

Atmospheric Pressure

The atmosphere is the whole mass of air surrounding the earth. Although it extends upward for about 500 miles, the section which is of primary interest is that portion of the air which rests on the earth's surface and extends upward for about 7½ miles. This layer is called the troposphere, and the higher above the earth, the lower its pressure.

This is because air has weight. If a column of *air 1-inch square extending all the way to the top* of the atmosphere could be weighed, it would weigh approximately 14.7 pounds at sea level. Thus, atmospheric pressure at sea level is approximately 14.7 p.s.i. As altitude increases, the atmospheric pressure decreases approximately 1.0 p.s.i. for every 2,343 feet. However, below sea level, atmospheric pressure increases. Pressures under water differ from those under air only because the weight of the water must be added to the weight of the air.

Atmospheric pressure, its temperature effects, and the means used to measure it are discussed in greater detail in another section of this chapter.

Absolute Pressure

As stated previously, absolute temperature is used in the calculation of changes in the state of gas. It is also necessary to use absolute pressure for these calculations.

Absolute pressure is measured from absolute zero pressure rather than from normal or atmospheric pressure (approximately 14.7 p.s.i.). Gage pressure is used on all ordinary gages, and indicates pressure in excess of atmospheric. Therefore, absolute pressure is equal to atmospheric pressure plus gage pressure. For example, 100 p.s.i.g. (pounds per square inch gage) equals 100 p.s.i. plus 14.7 p.s.i. or 114.7 p.s.i.a. (pounds per square inch absolute).

Incompressibility and Expansion of Liquids

Liquids can be compressed only slightly; that is, the reduction of the volume which they occupy, even under extreme pressure, is very small. If a pressure of 100 p.s.i. is applied to a body of water, the volume will decrease only 3/10,000 of its original volume. It would take a force of 64,000 p.s.i. to reduce its volume 10 percent. Since other liquids behave in about the same manner, liquids are usually considered incompressible.

In some applications of hydraulics where extremely close tolerances are required, the compressibility of liquids must be considered in the design of the system. In this study, however, liquids are considered to be incompressible.

Liquids usually expand when heated. This action is normally referred to as thermal expansion. All liquids do not expand the same amount for a certain increase in temperature. If two flasks are placed in a heated vessel, and if one of these flasks is filled with water and the other with alcohol, it will be found that the alcohol expands much more than the water for the same rise in temperature. Most oils expand more than water. Aircraft hydraulic systems contain provisions for compensating for this increase of volume in order to prevent breakage of equipment.

Compressibility and Expansion of Gases

The two major differences between gases and liquids are their compressibility and expansion characteristics. Although liquids are practically incompressible, gases are highly compressible. Gases completely fill any closed vessel in which they are contained, but liquids fill a container only to the extent of their normal volume.

KINETIC THEORY OF GASES

The simple structure of gases makes them readily adaptable to mathematical analysis from which has evolved a detailed theory of the behavior of gases. This is called the kinetic theory of gases. The theory assumes that a body of gas is composed of identical molecules which behave like minute elastic spheres, spaced relatively far apart and continuously in motion.

The degree of molecular motion is dependent upon the temperature of the gas. Since the molecules are continuously striking against each other and against the walls of the container, an increase in temperature with the resulting increase in molecular motion causes a corresponding increase in the number of collisions between the molecules. The increased number of collisions results in an increase in pressure because a greater number of molecules strike against the walls of the container in a given unit of time.

If the container were an open vessel, the gas would expand and overflow from the container. However, if the container is sealed and possesses elasticity (such as a rubber balloon), the increased pressure causes the container to expand.

For instance, when making a long drive on a hot day, the pressure in the tires of an automobile increases, and a tire which appeared to be somewhat "soft" in cool morning temperature may appear normal at a higher midday temperature.

Such phenomena as these have been explained and set forth in the form of laws pertaining to gases and tend to support the kinetic theory.

At any given instant, some molecules of a gas are moving in one direction, some in another direction; some are traveling fast while some are traveling slowly; some may even be in a state of rest. The combined effect of these varying velocities corresponds to the temperature of the gas. In any considerable amount of gas, there are so many molecules present that in accordance with the "laws of probability" some average velocity can be found. If this average velocity were possessed by every molecule in the gas, it would produce the same effect at a given temperature as the total of the many varying velocities.

Boyle's Law

As previously stated, compressibility is an outstanding characteristic of gases. The English scientist Robert Boyle was among the first to study this characteristic which he called the "springiness of air." By direct measurement he discovered that when the temperature of a combined sample of gas was kept constant and the pressure doubled, the volume was reduced to half the former value; as the applied pressure was decreased, the resulting volume increased. From these observations, he concluded that for a constant temperature the product of the volume and pressure of an enclosed gas remains constant. Boyle's law is normally stated: "The volume of an enclosed dry gas varies inversely with its pressure, provided the temperature remains constant."

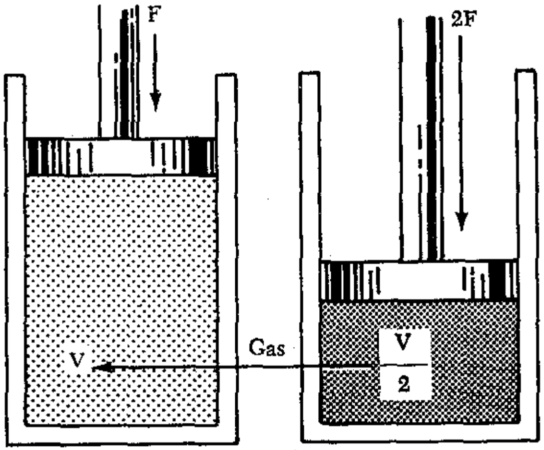


FIGURE 7–7. Gas compressed to half its original volume by a double force.

This law can be demonstrated by confining a quantity of gas in a cylinder which has a tightly fitted piston. A force is then applied to the piston so as to compress the gas in the cylinder to some specific volume. When the force applied to the piston is doubled, the gas is compressed to one-half its original volume, as indicated in figure 7–7.

In equation form, this relationship may be expressed either

$$V_1P_1 = V_2P_2$$

or

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

where V_1 and P_1 are the original volume and pressure, and V_2 and P_2 are the revised volume and pressure.

Example of Boyle's law: 4 cu. ft. of nitrogen are under a pressure of 100 p.s.i.g. The nitrogen is allowed to expand to a volume of 6 cu. ft. What is the new gage pressure?

Formula or equation:

$$V_1P_1 = V_2P_2$$

Substituting:

$$4 \times (100) = 6 \times P_2$$

$$P_2 = \frac{4 \times 100}{6}$$

$$P_2 = 66.6 \text{ p.s.i.g.}$$

A gas which conforms to Boyle's law is termed an ideal gas. When pressure is increased upon such a gas, its volume decreases proportionally and its density is increased. Thus, the density of a gas varies directly with the pressure, if the temperature remains constant as in the case of an ideal gas. Density also varies with temperature, since gases expand when heated and contract when cooled.

The useful applications of Boyle's law are many and varied. Some applications more common to aviation are: (1) The carbon dioxide (CO_2) bottle used to inflate life rafts and life vests; (2) the compressed oxygen and the acetylene tanks used in welding; (3) the compressed air brakes and shock absorbers; and (4) the use of oxygen tanks for high-altitude flying and emergency use.

Charles' Law

The French scientist Jacques Charles provided much of the foundation for the modern kinetic theory of gases. He found that all gases expand and contract in direct proportion to the change in the absolute temperature, provided the pressure is held constant. In equation form, this part of the law may be expressed.

$$V_1T_2 = V_2T_1$$

or

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

This equation means that with a constant volume, the absolute pressure of a gas varies directly with the absolute temperature,

Examples of Charles' law: A cylinder of gas under a pressure of 1,800 p.s.i.g. at 70° F. is left out in the sun in the tropics and heats up to a temperature of 130° F. What is the new pressure within the cylinder? The pressure and temperature must be converted to absolute pressure and temperature.

Formula or equation:

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

Using the Rankine system:

70° F. = 530° absolute

130° F. = 590° absolute

Substituting:

$$\frac{1{,}800 + 14.7}{P_2} = \frac{530}{590}$$

Then:

$$P_2 = \frac{(590)(1{,}814.7)}{530}$$

$$P_2 = 2{,}020 \text{ p.s.i.a.}$$

Converting absolute pressure to gage pressure:

$$\begin{array}{r} 2{,}020.0 \\ -14.7 \\ \hline 2{,}005.3 \text{ p.s.i.g.} \end{array}$$

Free balloon flights into the stratosphere, the expanding gases of jet-propelled aircraft, and the effects of clouds and weather on instrument recordings may be explained by the use of Charles' law. Here are practical applications of a law of physics that aid the pilot, air controller, and aerographer in their work. Flying is made safer when humans are able to apply this law in handling weather data so vital to aviation.

General Gas Law

The facts concerning gases discussed in the preceding sections are summed up and illustrated in figure 7–8. Boyle's law is expressed in (A) of the figure, and the effects of temperature changes on pressure and volume (Charles' law) are illustrated in (B) and (C), respectively.

By combining Boyle's and Charles' laws, a single expression can be derived which states all the information contained in both. This expression is called the general gas law, a very useful form of which is given in the following equation. (NOTE: The capital P and T signify absolute pressure and temperature, respectively.)

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

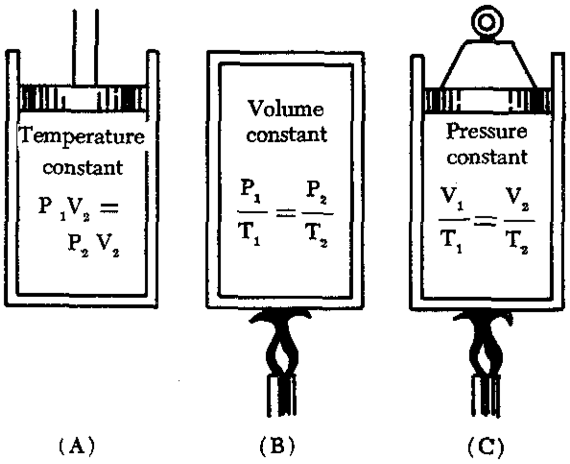


FIGURE 7–8. The general gas law.

An examination of figure 7–8 reveals that the three equations are special cases of the general equation. Thus, if the temperature remains constant, T_1 equals T_2, and both can be eliminated from the general formula, which then reduces to the form shown in (A). When the volume remains constant, V_1 equals V_2, reducing the general equation to the form given in (B). Similarly P_1 is equated to P_2 for constant pressure, and the equation then takes the form given in (C).

The general gas law applies with exactness only to "ideal" gases in which the molecules are assumed to be perfectly elastic. However, it describes the behavior of actual gases with sufficient accuracy for most practical purposes.

Two examples of the general equation follow:

1. Two cu. ft. of a gas at 75 p.s.i.g. and 80° F. are compressed to a volume of 1 cu. ft. and then heated to a temperature of 300° F. What is the new gage pressure?

Formula or equation:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Using the Rankine system:

80° F. = 540° absolute

300° F. = 760° absolute

Substituting:

$$\frac{(75 + 14.7)(2)}{540} = \frac{P_2(1)}{760}$$

Then:

$$\frac{179.4}{540} = \frac{P_2}{760}$$

$$P_2 = \frac{(179.4)(760)}{540}$$

$$P_2 = 252.5 \text{ p.s.i.a.}$$

Converting absolute pressure to gage pressure:

$$\begin{array}{r} 252.5 \\ -14.7 \\ \hline 237.8 \end{array} \text{ p.s.i.g.}$$

2. Four cubic feet of a gas at 75 p.s.i.g. and 80° F. are compressed to 237.8 p.s.i.g. and heated to a temperature of 300° F. What is the volume of the gas resulting from these changes?

Formula or equation:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Using the Rankine system:

80° F. = 540° absolute

300° F. = 760° absolute

Substituting:

$$\frac{(75 + 14.7)(4)}{540} = \frac{(237.8 + 14.7)V_2}{760}$$

Then:

$$\frac{(89.7)(4)}{540} = \frac{(252.5)V_2}{760}$$

$$V_2 = \frac{358.8 \times 760}{540 \times 252.5}$$

$$V_2 = 2 \text{ cu. ft.}$$

Avogadro's Law

An Italian physicist, Avogadro, conceived the theory that "at the same temperature and pressure, equal volumes of different gases contain equal numbers of molecules." This theory was proven by experiment and found to agree with the kinetic theory, so it has come to be known as Avogadro's law.

Dalton's Law

If a mixture of two or more gases which do not combine chemically is placed in a container, each

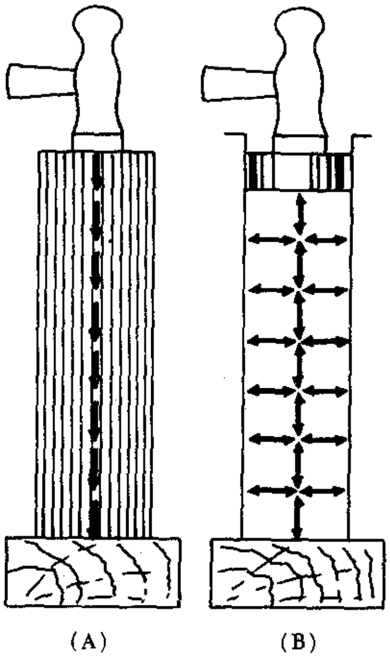


FIGURE 7–9. Transmission of force: (A) solid; (B) fluid.

gas expands throughout the total space and the absolute pressure of each gas is reduced to a lower value, called its partial pressure. This reduction is in accordance with Boyle's law. The pressure of the mixed gases is equal to the sum of the partial pressures. This fact was discovered by Dalton, an English physicist, and is set forth in Dalton's law: "A mixture of several gases which do not react chemically exerts a pressure equal to the sum of the pressures which the several gases would exert separately if each were allowed to occupy the entire space alone at the given temperature."

Transmission of Forces Through Fluids

When the end of a bar is struck, the main force of the blow is carried straight through the bar to the other end (see A of figure 7–9). This happens because the bar is rigid. The direction of the blow almost entirely determines the direction of the transmitted force. The more rigid the bar, the less force is lost inside the bar or transmitted outward at right angles to the direction of the blow.

When a force is applied to the end of a column of confined liquid (B of figure 7–9), it is transmitted straight through to the other end and also equally and undiminished in every direction throughout the column—forward, backward, and sideways—so that the containing vessel is literally filled with pressure.

If a gas is used instead of a liquid, the force is transmitted in the same manner. The one difference is that gas, being compressible, provides a much less rigid force than the liquid, which is incompressible. (This is the main difference in the action of liquids and gases in fluid power systems.)

Pascal's Law

The foundations of modern hydraulics and pneumatics were established in 1653 when Pascal discovered that pressure set up in a fluid acts equally in all directions. This pressure acts at right angles to containing surfaces. Thus, in figure 7–10, if the liquid standing on a square inch (A) at the bottom of the tank weighs 8 pounds, a pressure of 8 p.s.i. is exerted in every direction at (A). The liquid resting on (A) pushes equally downward and outward. The liquid on every square inch of the bottom surface is pushing downward and outward in the same way, so that the pressures on different areas are in balance. At the edge of the tank bottom, the pressures act against the wall of the tank, which must be strong enough to resist them with a force exactly equal to the push. Every square inch of the bottom of the tank must also be strong enough to resist the downward pressure of the liquid resting on it. The same balance of pressures exists at every other level in the tank, though of lesser pressures as one approaches the surface. There-

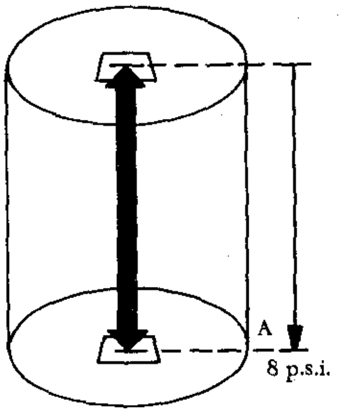


FIGURE 7–10. Pressure acting on a container.

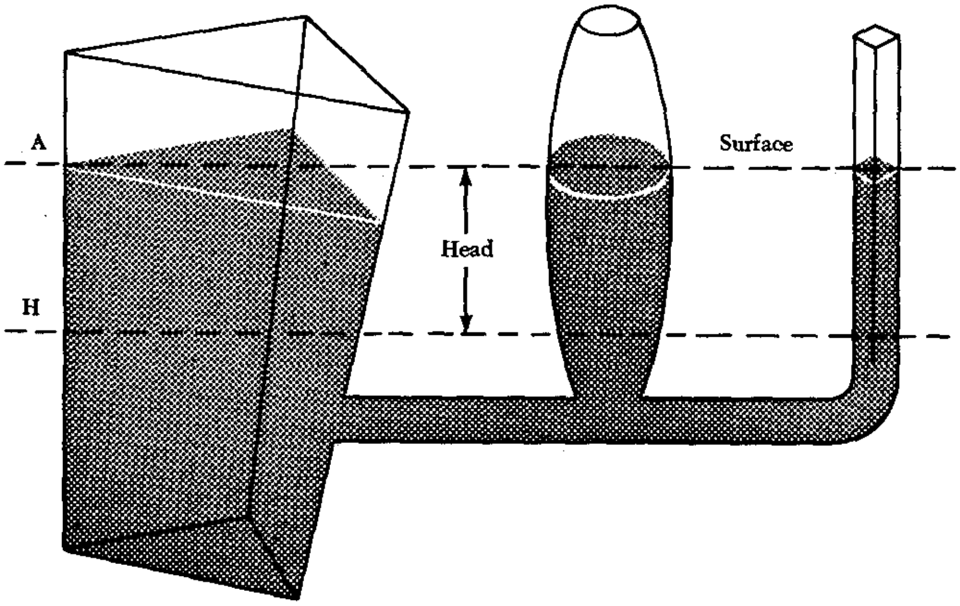


FIGURE 7–11. Pressure relationship with shape.

fore, the liquid remains at rest; it does not leak out and the tank does not collapse.

One of the consequences of Pascal's law is that the shape of the container in no way alters pressure relations. Thus, in figure 7–11, if the pressure due to the weight of the liquid at one point on the horizontal line (H) is 8 p.s.i., the pressure is 8 p.s.i. everywhere at level (H) in the system.

Pressure due to the weight of a fluid depends, at any level, on the height of the fluid from the level to the surface of the fluid. The vertical distance between two horizontal levels in a fluid is known as the head of the fluid. In figure 7–11, the liquid head of all points on level (H) with respect to the surface is indicated.

Pressure due to fluid head also depends on the density of the fluid. Water, for example, weighs 62.4 lbs./cu. ft. or 0.036 lb./cu. in., but a certain oil might weigh 55 lbs./cu. ft., or 0.032 lb./cu. in. To produce a pressure of 8 p.s.i., it would take 222 inches of head using water, and 252 inches of head using the oil (see figure 7–12).

Force and Pressure

In order to understand how Pascal's law is applied to fluid power, a distinction must be made between the terms "force" and "pressure." Force may be defined as a push or pull. It is the push or pull exerted against the total area of a particular surface and is expressed in pounds. As previously stated, pressure is the amount of force on a unit area of the surface acted upon. In hydraulics and pneumatics, pressure is expressed in pounds per square inch. Thus, pressure is the amount of force acting upon 1 square inch of area.

Computing Force, Pressure, and Area

A formula, similar to those used with the gas laws, is used in computing force, pressure, and area in fluid power systems. Although there appears to be three formulas, it is only one formula written in three variations, where *P* refers to pressure, *F* indicates force, and *A* represents area.

Force equals pressure times area. Thus, the

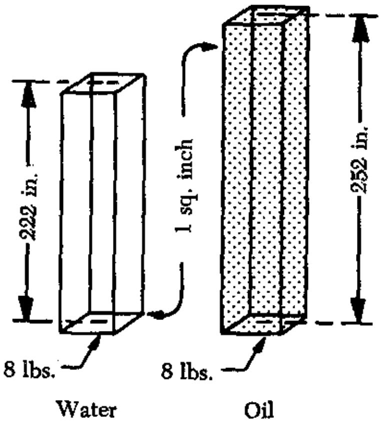


FIGURE 7–12. Pressure and density relationship.

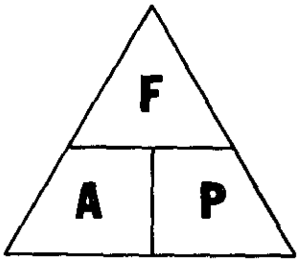


FIGURE 7–13. Device for determining the arrangement of the force, pressure, and area formulas.

formula is written:

$$F = P \times A.$$

Pressure equals force divided by the area. By rearranging the formula, this statement is condensed into:

$$P = \frac{F}{A}.$$

Since area equals force divided by pressure, the formula is written:

$$A = \frac{F}{P}.$$

Figure 7–13 illustrates a device for recalling these formulas. Any letter in the triangle may be expressed as the product or quotient of the other two, depending upon its position within the triangle.

For example, to find area, consider the letter "A" as being set off by itself, followed by an equal sign. Now look at the other two letters. The letter "F" is above the letter "P"; therefore, $A = F/P$.

In order to find pressure, consider the letter "P" as being set off by itself, and look at the other two letters. The letter "F" is above the letter "A"; therefore, $P = F/A$.

In a similar manner, to find force, consider the letter "F" as being set off by itself. The letters "P" and "A" are side by side; therefore, $F = P \times A$.

Sometimes the area may not be expressed in square inches. If it is a rectangular surface, the area may be found by multiplying the length (in inches) by the width (in inches). The majority of areas to be considered in these calculations are circular. Either the diameter or the radius (one half the diameter) may be given. The radius in inches must be known to find the area. Then, the formula for finding the area of a circle is used. This is written $A = \pi r^2$, where A is the area, π is 3.1416 (3.14 or $3\frac{1}{7}$ for most calculations), and r^2 indicates radius squared.

Pressure and Force in Fluid Power Systems

In accordance with Pascal's law, any force applied to a confined fluid is transmitted equally in all directions throughout the fluid regardless of the shape of the container. Consider the effect of this in the system shown in figure 7–14, which is a modification of B in figure 7–9. The column of fluid is curved upward to its original level, with a second piston at this point. It is clear that when the input piston (1) is pushed downward, a pressure is created through the fluid, which acts equally at right angles to surfaces in all parts of the container.

Referring to figure 7–14, if the force (1) is 100 lbs. and the area of the piston is 10 sq. in., then the pressure in the fluid is 10 p.s.i. ($^{100}/_{10}$). This pressure acts on piston (2), so that for each square inch of its area it is pushed upward with a force of 10 pounds. In this case, a fluid column of uniform cross section is considered so that the area of the output piston (2) is the same as the input piston (1), or 10 square inches. Therefore, the upward force on the output piston (2) is 100 pounds, the same as applied to the input piston (1). All that has been accomplished in this system was to transmit the 100-pound force around a

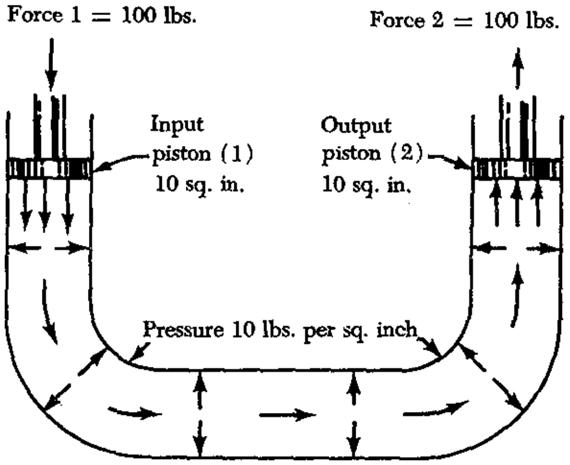


FIGURE 7–14. Force transmitted through fluid.

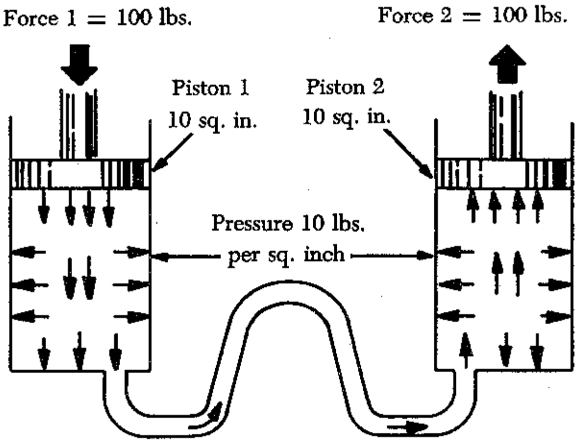


FIGURE 7–15. Transmitting force through small tube.

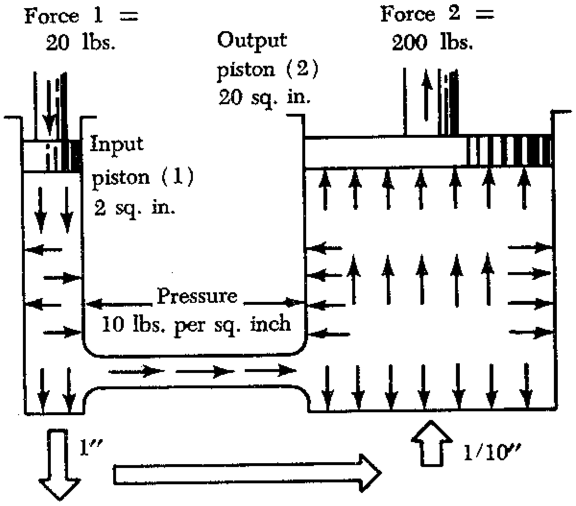


FIGURE 7–16. Multiplication of forces.

bend. However, this principle underlies practically all mechanical applications of fluid power.

At this point it should be noted that since Pascal's law is independent of the shape of the container, it is not necessary that the tube connecting the two pistons be the full area of the pistons. A connection of any size, shape, or length will do if an unobstructed passage is provided. Therefore, the system shown in figure 7–15, in which a relatively small, bent tube connects two cylinders, will act exactly the same as that shown in figure 7–14.

Multiplication of Forces

In figures 7–14 and 7–15 the systems contain pistons of equal area in which the output force is equal to the input force. Consider the situation in figure 7–16, where the input piston is much smaller than the output piston. Assume that the area of the input piston (1) is 2 sq. in. Pushing down on the input piston (1) with a force of 20 pounds creates 10 p.s.i. ($^{20}\!/_{2}$) in the fluid. Although this force is much smaller than the applied force in figures 7–14 and 7–15, the pressure is the same. This is because the force is concentrated on a relatively small area.

This pressure of 10 p.s.i. acts on all parts of the fluid container, including the bottom of the output piston (2). The upward force on the output piston (2) is therefore 10 pounds for each of its 20 square inches of area, or 200 pounds (10 × 20). In this case, the original force has been multiplied tenfold while using the same pressure in the fluid as before. Obviously, the system would work just the same for any other forces and pressures, so that the ratio of output force to input force is always the same.

The system works the same in reverse. Consider piston (2) in figure 7–16 as the input and piston (1) as the output. Then the output force will always be one-tenth the input force. Sometimes such results are desired.

Therefore, if two pistons are used in a fluid power system, the force acting on each is directly proportional to its area, and the magnitude of each force is the product of the pressure and its area.

Differential Areas

Consider the special situation shown in figure 7–17. Here, a single piston in a cylinder has a piston rod attached to one side of the piston which extends out of the cylinder at one end. Fluid under pressure is admitted to both ends of the cylinder equally through tubes. The opposed faces of the piston behave like two pistons acting against each other. The area of one face is the full area of the cylinder, for example, 6 sq. in. The area of the other face is the area of the cylinder minus the area of the piston rod, which is 2 sq. in., leaving an effective area of 4 sq. in. on the right face of the piston. The pressure on both faces is the same, in this case, 20 p.s.i. Applying the rule just stated, the force pushing the piston to the right is its area times the pressure, or 120 pounds (20 × 6). Similarly, the force pushing it to the left is its area times the pressure, or 80 pounds. Therefore, there is a net

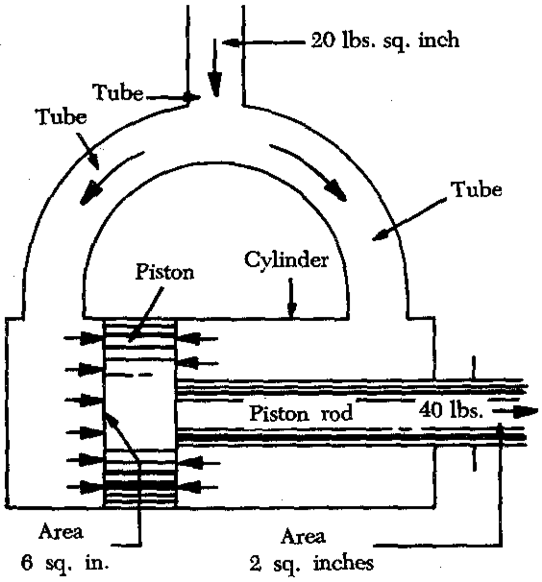


FIGURE 7-17. Differential areas on a piston.

unbalanced force of 40 pounds acting to the right, and the piston will move in that direction. The net effect is the same as if the piston and cylinder were just the size of the piston rod, since all other forces are in balance.

Volume and Distance Factors

In the systems illustrated in figures 7-14 and 7-15, the pistons have areas of 10 sq. in. each. Therefore, if one of these pistons is pushed down 1 inch, 10 cu. in. of fluid is displaced. Since liquid is practically incompressible, this volume must go somewhere. In the case of a gas, it will compress momentarily, but will eventually expand to its original volume. Thus, this volume moves the other piston. Since the area of this piston is also 10 sq. in., it will move 1 inch in order to accommodate the 10 cu. in. of fluid. The pistons are of equal areas, and will therefore move equal distances, though in opposite directions.

Applying this reasoning to the system in figure 7-16, it is obvious that if the input piston (1) is pushed down 1 inch, only 2 cu. in. of fluid is displaced. In order to accommodate these 2 cu. in. of fluid, the output piston (2) will have to move only one-tenth of an inch, because its area is 10 times that of the input piston (1). This leads to the second basic rule for two pistons in the same fluid power system, which is, that the distances moved are inversely proportional to their areas.

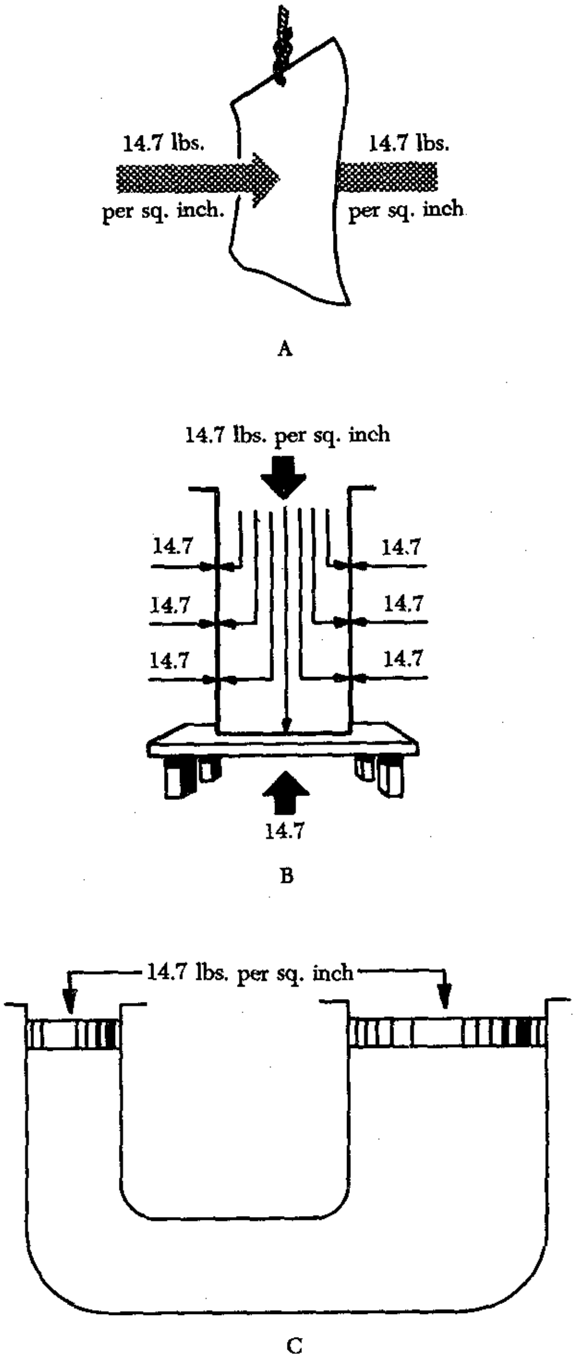


FIGURE 7-18. Effects of atmospheric pressure.

Effects of Atmospheric Pressure

Atmospheric pressure, described previously, obeys Pascal's law the same as pressure set up in fluids. As illustrated in figure 7-14, pressures due to a liquid head are distributed equally in all directions. This is also true of atmospheric pres-

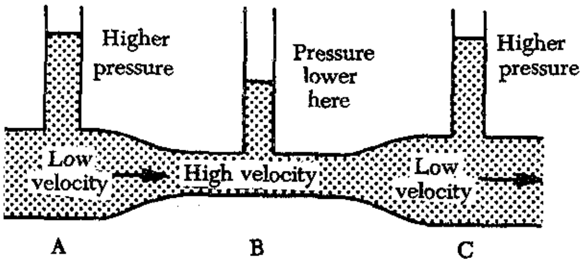


FIGURE 7–19. Pressures and velocities in a venturi tube.

sures. The situation is the same if these pressures act on opposite sides of any surface, or through fluids. In A of figure 7–18 the suspended sheet of paper is not torn by atmospheric pressure, as it would be by an unbalanced force, because atmospheric pressure acts equally on both sides of the paper. In B of figure 7–18, atmospheric pressure acting on the surface of the liquid is transmitted equally throughout the liquid to the walls of the container, but is balanced by the same pressure acting directly on the outer walls of the container. In C of figure 7–18, atmospheric pressure acting on the surface of one piston is balanced by the same pressure acting on the surface of the other. The different areas of the two surfaces make no difference, since for a unit of area, the pressures are in balance.

Bernoulli's Principle

Bernoulli's principle was originally stated to explain the action of a liquid flowing through the varying cross-sectional areas of tubes.

In figure 7–19 a tube is shown in which the cross-sectional area gradually decreases to a minimum diameter in its center section. A tube constructed in this manner is called a "venturi," or "venturi tube."

As a liquid (fluid) flows through the venturi tube, the three vertical tubes act as pressure gages, filling with liquid until the pressure of the liquid in each tube equals the pressure of the moving liquid in the venturi.

The venturi in figure 7–19 can be used to illustrate Bernoulli's principle, which states that: The pressure of a fluid (liquid or gas) decreases at points where the velocity of the fluid increases.

In the wide section of the venturi (points A and C of figure 7–19), the liquid moves at low velocity, producing a high pressure, as indicated by the height of the liquid in the vertical tubes at these two points. As the tube narrows in the center, it must contain the same volume of fluid as the two end areas. In this narrow section, the liquid moves at a higher velocity, producing a lower pressure than that at points A and C, as indicated by the height of the column of liquid in the vertical tube above point B of figure 7–19.

The venturi principle, in any of a number of shapes and sizes, is used in aircraft systems. They may be referred to as restrictions or orifices. For example, an orifice is generally installed in a hydraulic line to limit the rate of fluid flow. A hydraulically operated aircraft landing gear, when being extended, will tend to drop with great speed because of the weight of the mechanism. If a restrictor is installed in the hydraulic return line the extension of the gear will be slowed, thus preventing possible structural damage.

ATMOSPHERE

General

Aviation is so dependent upon that category of fluids called gases and the effect of forces and pressures acting upon gases, that a discussion of the subject of the atmosphere is important to the persons maintaining and repairing aircraft.

Data available about the atmosphere may determine whether a flight will succeed, or whether it will even become airborne. The various components of the air around the earth, the changes in temperatures and pressures at different levels above the earth, the properties of weather encountered by aircraft in flight, and many other detailed data are considered in the preparation of flight plans.

Pascan and Torricelli have been credited with developing the barometer, and instrument for measuring atmospheric pressure. The results of their experiments are still used today with very little improvement in design or knowledge. They determined that air has weight which changes as altitude is changed with respect to sea level. Today scientists are also interested in how the atmosphere affects the performance of the aircraft and its equipment.

Composition of the Atmosphere

The atmosphere is a complex and ever changing mixture. Its ingredients vary from place to place and from day to day. In addition to a number of gases, it contains quantities of foreign matter such as pollen, dust, bacteria, soot, volcanic ash, spores, and dust from outer space.

The composition of the air remains almost constant from sea level up to its highest level, but its density diminishes rapidly with altitude. Six miles up, for example, it is too thin to support respiration, and 12 miles up there is not enough oxygen to support combustion. At a point several hundred miles above the earth, some gas particles spray out into space; some dragged by gravity fall back into the ocean of air below; others never return, but travel like satellites around the earth; and still others like hydrogen and helium escape forever from the earth's gravitational field. Physicists disagree as to the boundaries of the outer fringes of the atmosphere. Some think it begins 240 miles above the earth and extends to 400 miles; others place its lower edge at 600 miles and its upper boundary at 6,000 miles.

There are also certain nonconformities at various levels. Between 12 and 30 miles, high solar ultraviolet radiation reacts with oxygen molecules to produce a thin curtain of ozone, a very poisonous gas without which life on earth could not exist. This ozone filters out a portion of the sun's lethal ultraviolet rays, allowing only enough to come through to give man sunburn, kill bacteria, and prevent rickets. At 50 or 65 miles up, most of the oxygen molecules begin to break down under solar radiation into free atoms, and to form the incomplete molecule, hydroxyl (OH) from water vapor. Also in this region all the atoms become ionized.

Studies of the atmosphere have revealed that the temperature does not decrease uniformly with increasing altitude; instead it gets steadily colder up to a height of about 7 miles, where the rate of temperature change slows down abruptly and remains almost constant at −55° C. (218° K.) up to about 20 miles. Then the temperature begins to rise to a peak value of 77° C. (350° K.) at the 55-mile level. Thereafter it climbs steadily, reaching 2,270° C. (2,543° K.) at a height of 250 to 400 miles. From the 50-mile level upward, a man or any other living creature, without the protective cover of the atmosphere, would be broiled on the sunny side and frozen on the other.

The atmosphere is divided into concentric layers or levels. Transition through these layers is gradual and without sharply defined boundaries. However, one boundary, the tropopause, exists between the first and second layer. The tropopause is defined as the point in the atmosphere at which the decrease in temperature (with increasing altitude) abruptly ceases, between the troposphere and the stratosphere. The four atmosphere layers are the troposphere, stratosphere, ionosphere, and the exosphere. The upper portion of the stratosphere is often called the chemosphere or ozonosphere, and the exosphere is also known as the mesophere.

The troposphere extends from the earth's surface to about 35,000 feet at middle latitudes; but varies from 28,000 feet at the poles to about 54,000 feet at the equator. The troposphere is characterized by large changes in temperature and humidity and by generally turbulent conditions. Nearly all cloud formations are within the troposphere. Approximately three-fourths of the total weight of the atmosphere is within the troposphere. The temperature and absolute pressure in the troposphere steadily decrease with increasing altitude to a point where the temperature is approximately −55° C. (or 218° K.), and the pressure is about 6.9 Hg on a standard day.

The stratosphere extends from the upper limits of the troposphere (and the tropopause) to an average altitude of 60 miles. In the stratosphere the temperature decline virtually stops; however, at 18 or 20 miles up, it often descends to −63° C. (210° K.).

The ionosphere ranges from the 50-mile level to a level of 300 to 600 miles. Little is known about the characteristics of the ionosphere, but it is thought that many electrical phenomena occur there. Basically, this layer is characterized by the presence of ions and free electrons, and the ionization seems to increase with altitude and in successive layers. The temperature increases from about 200° K. at the lower limit to about 2,500° K. at the upper limit. These extremely high temperatures in the upper altitudes do not have the same significance as would corresponding temperatures at sea level. A thermometer reading in this region would be determined more by solar radiation than by the temperature, because of the energy of the particles.

The exosphere (or mesosphere) is the outer layer of the atmosphere. It begins at an altitude of 600 miles and extends to the limits of the atmosphere. In this layer the temperature is fairly constant at 2,500° K., and propagation of sound is thought to be impossible due to lack of molecular substance.

Atmospheric Pressure

The human body is under pressure, since it exists at the bottom of a sea of air. This pressure is due to the weight of the atmosphere. The pressure which the atmosphere applies to a square inch of area is equal to the weight of a column of air one square inch in cross section which extends from that area to the "top" of the atmosphere.

Since atmospheric pressure at any altitude is due to the weight of air above it, pressure decreases with increased altitude, Obviously, the total weight of air above an area at 15,000 feet would be less than the total weight of the air above an area at 10,000 feet.

Atmospheric pressure is often measured by a mercury barometer. A glass tube somewhat over 30 inches in length is sealed at one end and filled with mercury (Hg). It is then inverted and the open end placed in a dish of mercury. Immediately, the mercury level in the inverted tube will drop a short distance, leaving a small volume of mercury vapor at nearly zero absolute pressure in the tube just above the top of the liquid mercury column. The pressure acting upward at the lower end of the tube above the level of mercury in the dish is atmospheric pressure. The pressure acting downward at the same point is the weight of the column of mercury. Thus, the height of the column of mercury indicates the pressure exerted by the atmosphere.

This means of measuring atmospheric pressure gives rise to the practice of expressing atmospheric pressure in inches of mercury (in. Hg) rather than in pounds per square inch (p.s.i.). It may be seen, however, that a simple relationship exists between pressure measurements in p.s.i. and in inches Hg. One cu. in. of mercury weighs 0.491 pound. Therefore, a pressure of 30 inches of mercury would be the equivalent of:

$$0.491 \times 30 = 14.73 \text{ p.s.i.}$$

A second means of measuring atmospheric pressure is with an aneroid barometer. This mechanical instrument lends itself to use on airplanes much more adequately than does the mercury barometer. Aneroid barometers (altimeters) are used to indicate altitude in flight. The calibrations are made in thousands of feet rather than in p.s.i. For example, the standard pressure at sea level is 29.92 in. Hg, or 14.69 p.s.i. At 10,000 feet above sea level, standard pressure is 20.58 in. Hg, or 10.10 p.s.i. Altimeters are calibrated so that if the pressure exerted by the atmosphere were 20.58 in. Hg, the altimeter would point to 10,000 feet. In other words, the altimeter is calibrated so that it indicates the altitude at which the prevailing atmospheric pressure would be considered standard pressure. Thus, the altitude read from the altimeter, being dependent upon atmospheric pressure, is called pressure altitude (H_p). Actually, an altimeter will read pressure altitude only when the altimeter adjustment is set at 29.92 inches Hg.

A third expression is occasionally used to indicate atmospheric pressure. Atmospheric pressure may be expressed in atmospheres. For example, a test may be conducted in a pressurized chamber under a pressure of six atmospheres. This merely means that the pressure is six times as great as standard sea level pressure.

Atmospheric Density

Since both temperature and pressure decrease with altitude, it might appear that the density of the atmosphere would remain fairly constant with increased altitude. This is not true, however, for pressure drops more rapidly with increased altitude than does the temperature. The result is that density decreases with increased altitude.

By use of the general gas law, studied earlier, it can be shown that for a particular gas, pressure and temperature determine the density. Since standard pressures and temperatures have been associated with each altitude, the density of the air at these standard temperatures and pressures must also be considered standard. Thus, a particular atmospheric density is associated with each altitude. This gives rise to the expression "density altitude," symbolized H_d. A density altitude of 15,000 feet is the altitude at which the density is the same as that considered standard for 15,000 feet. Remember, however, that density altitude is not necessarily true altitude. For example, on a day when the atmospheric pressure is higher than standard and the temperature is lower than standard, the density which is standard at 10,000 feet might occur at 12,000 feet. In this case, at an actual altitude of 12,000 feet, we have air which has the same density as standard air at 10,000 feet. Density altitude is a calculated altitude obtained by correcting pressure altitude for temperature.

The water content of the air has a slight effect on the density of the air. It should be remembered that humid air at a given temperature and pressure is lighter than dry air at the same temperature and pressure.

Water Content of the Atmosphere

In the troposphere the air is seldom completely dry. It contains water vapor in either of two forms: (1) Fog or (2) water vapor. Fog consists of minute droplets of water held in suspension by the air. Clouds are composed of fog. The height to which some clouds extend is a good indication of the presence of water in the atmosphere almost up to the stratosphere.

As a result of evaporation, the atmosphere always contains some moisture in the form of water vapor. The moisture in the air is called the humidity of the air. Moisture does not consist of tiny particles of liquid held in suspension in the air as in the case of fog, but is an invisible vapor truly as gaseous as the air with which it mixes.

Fog and humidity both affect the performance of an aircraft. In flight, at cruising power, the effects are small and receive no consideration. During takeoff, however, humidity has important effects. Two things are done to compensate for the effects of humidity on takeoff performance. Since humid air is less dense than dry air, the allowable takeoff gross weight of an aircraft is generally reduced for operation in areas that are consistently humid. Secondly, because the power output of reciprocating engines is decreased by humidity, the manifold pressure may have to be increased above that recommended for takeoff in dry air in order to obtain the same power output.

Engine power output is calculated on dry air. Since water vapor is incombustible, its pressure in the atmosphere is a total loss as far as contributing to power output. The mixture of water vapor and air is drawn through the carburetor and fuel is metered into it as though it were all air. This mixture of water vapor, air, and fuel enters the combustion chamber where it is ignited. Since the water vapor will not burn, the effective fuel/air ratio is enriched and the engine operates as though it were on an excessively rich mixture. The resulting horsepower loss under humid conditions can therefore be attributed to the loss in volumetric efficiency due to displaced air, and the incomplete combustion due to excessively rich fuel/air mixture.

The reduction in power that can be expected from humidity is usually given in charts in the flight manual. There are several types of charts in use. Some merely show the expected reduction in power due to humidity; others show the boost in manifold pressure necessary to restore full takeoff power.

The effect of fog on the performance of an engine is very noticeable, particularly on engines with high compression ratios. Normally, some detonation will occur during acceleration, due to the high BMEP (Brake Mean Effective Pressures) developed. However, on a foggy day it is difficult to cause detonation to occur. The explanation of this lies in the fact that fog consists of unvaporized particles of water. When these particles enter the cylinders, they absorb a tremendous amount of heat energy in the process of vaporizing. The temperature is thus lowered, and the decrease is sufficient to prevent detonation.

Fog will generally cause a decrease in horsepower output. However with a supercharged engine, it will be possible to use higher manifold pressures without danger of detonation.

Absolute Humidity

Absolute humidity is the actual amount of the water vapor in a mixture of air and water. It is sometimes expressed in g./cu.m. (grams per cubic meter), sometimes in lbs./cu. ft. The amount of water vapor that can be present in the air is dependent upon the temperature and pressure. The higher the temperatures, the more water vapor the air is capable of holding, assuming constant pressure. When air has all the water vapor it can hold at the prevailing temperature and pressure, it is said to be saturated.

Relative Humidity

Relative humidity is the ratio of the amount of water vapor actually present in the atmosphere to the amount that would be present if the air were saturated at the prevailing temperature and pressure. This ratio is usually multiplied by 100 and expressed as a percentage. Suppose, for example, that a weather report includes the information that the temperature is 75° F. and the relative humidity is 56 percent. This indicates that the air holds 56 percent of the water vapor required to saturate it at 75° F. If the temperature drops and the absolute humidity remains constant, the relative humidity will increase. This is because less water vapor is required to saturate the air at the lower temperature.

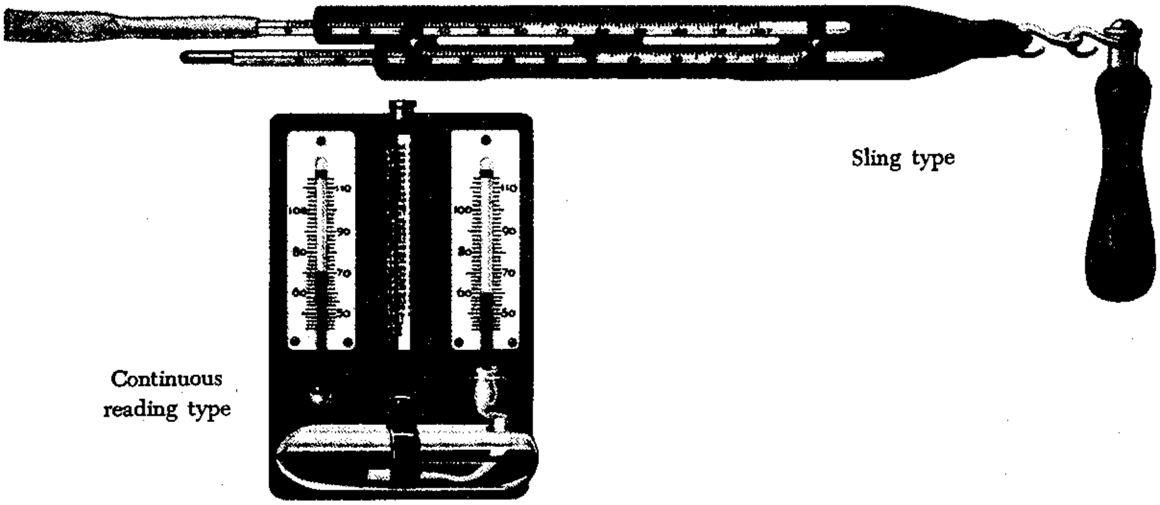


FIGURE 7–20. Wet-bulb hygrometers.

Dew Point

The dew point is the temperature to which humid air must be cooled at constant pressure to become saturated. If the temperature drops below the dew point, condensation occurs. People who wear glasses have had the experience of going from cold outside air into a warm room and having moisture collect quickly on their glasses. This happened because the glasses were below the dew point temperature of the air in the room. The air immediately in contact with the glasses was cooled below its dew point temperature, and some of the water vapor was condensed out. This principle is applied in determining the dew point. A vessel is cooled until water vapor begins to condense on its surface. The temperature at which this occurs is the dew point.

Vapor Pressure

Vapor pressure is the portion of atmospheric pressure that is exerted by the moisture in the air (expressed in tenths of an inch Hg). The dew point for a given condition depends on the amount of water pressure present; thus a direct relationship exists between the vapor pressure and the dew point.

Wet- and Dry-Bulb Temperatures

Vapor pressure and humidity may be determined from charts based on the wet- and dry-bulb temperatures (figure 7–20). The dry-bulb temperature is obtained from an ordinary thermometer. The wet-bulb temperature is obtained from a thermometer which has its bulb covered with a thin piece of wet cloth.

Because of moisture evaporation from the wet cloth, the wet bulb will read lower than the dry bulb. The more rapid the evaporation, the greater will be the difference in readings. The rate of evaporation is dependent upon the degree of saturation of the air. In using the wet-bulb thermometer, it must be moved through the air at a rate of about 1,200 f.p.m. to give a worthwhile reading. This is accomplished by mounting both the wet- and dry-bulb thermometers on a frame which can be hand rotated around a pivot and the desirable rate of 1,200 f.p.m. attained.

If the air is saturated, no evaporation will take place and the wet- and dry-bulb temperatures will be the same. Thus, these two temperatures coincide at the dew point.

Physical Laws Related to the Atmosphere

Although air is composed of various gases and must be treated as a mixture for certain purposes, it is treated as a uniform gas in aerodynamic calculations. Air is a fluid since it has the fluid property to flow, and it is also a gas, since its density is readily varied.

As is usual in engineering work, certain simplifying assumptions are made. One standard assumption is that in dry air there is no water vapor present. Ordinary flight-takeoff charts may be corrected for vapor pressure, but subsonic flight does not consider vapor pressure as an appreciable factor. Another standard assumption is that friction or "viscosity effect" may be neglected when dealing with airflow. The air is then considered to be a perfect fluid. However, some exceptions must be made, particularly in the case of thin boundary layers of slow moving air directly adjacent to a moving body.

The Kinetic Theory of Gases Applied to Air

The kinetic theory states that a gas is composed of small, distinct particles called molecules. The size of the molecules is small compared to the average distance between them. Further, the molecules are moving about at a high rate of speed in random directions so that they are constantly colliding with one another and with the walls of any container that may surround them. The pressure produced by a gas is the result of these continuous impacts against a surface, and since the impacts are essentially infinite in number, a steady pressure is effected.

Just as pressure is produced by molecular impact against a surface, it is also transmitted by molecular impact. Assuming that molecules are perfectly elastic (that no friction exists between them), a pressure wave once started will continue indefinitely. For most purposes this assumption is adequate; however, it is not completely correct. For instance, sound represents a series of weak pressure waves to which the ear is sensitive. If the energy that the sound represents were not lost, the sound would continue indefinitely. It follows then that this imperfect elasticity must in some way be associated with fluid friction or viscosity, since the presence of viscosity is also a source of energy loss.

On the basis of the kinetic theory, pressure may be increased in two ways: First, by increasing the number of molecules in a given space, which is the same as increasing the density; and secondly, by increasing the speed of the molecules, which can be done by increasing the temperature, since the temperature increase produces an increase in the molecular speed.

Analysis of the kinetic theory leads to one definite relationship between the temperature, pressure, and density of a gas when the gas is subjected to a given set of conditions. This relationship is known as the equation of state.

Equation of State

Provided that the temperature and pressure of a gas are not excessively different from those normally experienced on the earth's surface, the following equation holds true:

$$PV = RT$$

where: P = pressure in lbs./sq. ft.
V = specific volume.
R = a constant for a given gas (for air $R = 53.345$).
T = absolute temperature (Rankine = °F. + 459.4).

If the temperature and pressure are such that the gas becomes a liquid, or if the pressure falls to such a value that uniform pressure no longer exists, the equation will be invalid. In practical aeronautical work, these extremes are only encountered in a supersonic wind tunnel or in the outer portions of the atmosphere. This formula must be further clarified for practical engineering, by the introduction of air density.

Standard Atmosphere

If the performance of an aircraft is computed, either through flight tests or wind tunnel tests, some standard reference condition must be determined first in order to compare results with those of similar tests. The conditions in the atmosphere vary continuously, and it is generally not possible to obtain exactly the same set of conditions on two different days or even on two successive flights. Accordingly, there must be set up a group of standard conditions that may be used arbitrarily for reference. The set of standard conditions presently used in the United States is known as the U. S. Standard Atmosphere.

The standard atmosphere approximates the average conditions existing at 40° latitude, and is determined on the basis of the following assumptions. The standard sea level conditions are:

Pressure at 0 altitude (P_0) = 29.92 inches of mercury.
Temperature at 0 altitude (T_0) = 15° C. = 59° F.
Gravity at 0 altitude (g_0) = 32.174 ft./sec.^{2}

The U.S. Standard Atmosphere is in agreement with the International Civil Aviation Organization (ICAO) Standard Atmosphere over their common altitude range. The ICAO Standard Atmosphere has been adopted as standard by most of the principal nations of the world.

Variations from Standard Days

As may be expected, the temperature, pressure, density, and water vapor content of the air varies considerably in the troposphere. The temperature at 40° latitude may range from 50° C. at low altitudes during the summer to −70° C. at high altitudes during the winter. As previously stated, temperature usually decreases with an increase in altitude. Exceptions to this rule occur when cooler air is trapped near the earth by a warmer layer. This is called a temperature inversion, commonly associated with frontal movement of air masses.

Pressure likewise varies at any given point in the atmosphere. On a standard day, at sea level, pressure will be 29.92 in Hg. On nonstandard days, pressure at sea level will vary considerably above or below this figure.

Density of the air is determined by the pressure and temperature acting upon it. Since the atmosphere can never be assumed to be "standard," a convenient method of calculating density has been devised. Since air pressure is measured in inconvenient terms, it is expedient to utilize the aneroid altimeter as a pressure gage and refer to the term "pressure altitude" instead of atmospheric pressure.

Pressure Altitude

Pressure altitude is the altitude in the standard atmosphere corresponding to a particular value of air pressure. The aircraft altimeter is essentially a sensitive barometer calibrated to indicate altitude in the standard atmosphere.

With the altimeter of an aircraft set at 29.92 in. Hg, the dial will indicate the number of feet above or below a level where 29.92 in. Hg exists, not necessarily above or below sea level, unless standard day conditions exist. In general, the altimeter will indicate the altitude at which the existing pressure would be considered standard pressure. The symbol H_p is used to indicate pressure altitude.

BERNOULLI'S PRINCIPLE

General

In the earlier discussion of fluids, Bernoulli's principle was introduced to explain the relationship between velocity and pressure of a liquid flowing through a venturi. Since Bernoulli's principle applies to fluids, which by definition include both gases and liquids, its application to gases (air) is included at this point to explain the relationship between air velocity and pressure on the surfaces of an airfoil.

How an Aircraft Wing Reacts with the Atmosphere

An airfoil is any surface designed to obtain a reaction from the air through which it moves. Wings, ailerons, elevators, stabilizers, propeller blades, and helicopter rotors are all airfoils.

The reaction for which wings are designed is called lift. A wing produces lift because of a pressure difference; and the greater this difference, the more lift developed. If the air pressure above a wing is the same as that below it, there is no lift. But if the pressure above a wing is reduced and the pressure below increased, then lift is produced. The strong air pressure below the wing moves the wing upward against the weaker pressure above the wing. But what causes these unequal pressures?

An examination of the shape of an aircraft wing discloses that it has been designed to create a pressure difference. If a wing is cut from leading edge to trailing edge, the end view of the cut is a profile section similar to the one shown in figure 7–21. The forward part of the airfoil profile is rounded and is called the leading edge. The aft part is narrow and tapered and is called the trailing edge. A reference line often used in discussing airfoils is the chord, an imaginary straight line joining the extremities of the leading and trailing edges. The curved upper surface of the airfoil is called the camber. The lower surface is normally straight, or only slightly curved.

An airfoil is very similar in shape to half a venturi section. In A of figure 7–22, the throat, or restricted portion of a venturi is illustrated. The airflow through the venturi is indicated by flow lines. In B of figure 7–22, one-half of a

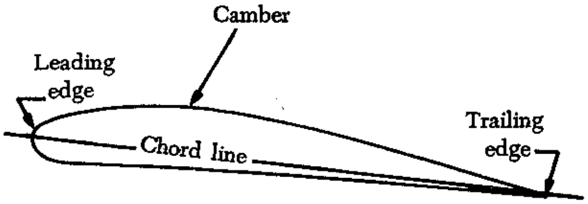


FIGURE 7–21. Cross-sectional view of an airfoil.

FIGURE 7–22. Airflow in venturi sections.

venturi restriction is shown, together with the airflow over its curved surface. Note that this portion of a venturi has the same profile as that of an airfoil.

To understand how lift is produced by an aircraft's wings, Bernoulli's principle is applied to an airfoil. This principle reveals that the pressure of fluid (liquid or gas) decreases at points where the speed of the fluid increases. In other words, high speed is associated with low pressure, and low speed with high pressure. The wing, or airfoil, of an aircraft is designed to increase the velocity of the airflow above its surface, thereby decreasing pressure above the airfoil. Simultaneously, the impact of the air on the lower surface of the airfoil increases the pressure below. This combination of pressure decrease above the airfoil and increase below the airfoil produces lift.

MACHINES

General

Ordinarily, a machine is thought of as a complex device, such as an internal-combustion engine or a typewriter. These are machines, but so is a hammer, a screwdriver, or a wheel. A machine is any device with which work may be accomplished. Machines are used to transform energy, as in the case of a generator transforming mechanical energy into electrical energy. Machines are used to transfer energy from one place to another, as in the examples of the connecting rods, crankshaft, and reduction gears transferring energy from an aircraft's engine to its propeller.

Another use of machines is to multiply force; for example, a system of pulleys may be used to lift a heavy load. The pulley system enables the load to be raised by exerting a force which is smaller than the weight of the load.

Machines are also used to multiply speed. A good example is the bicycle, by which speed can be gained by exerting a greater force.

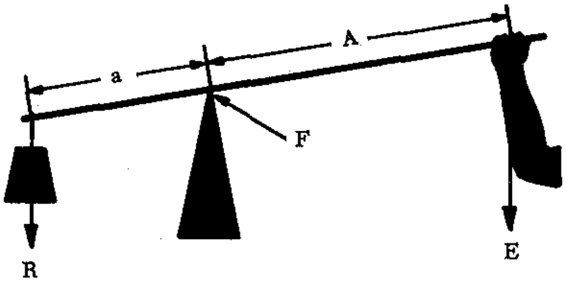


FIGURE 7–23. A simple lever.

Finally, machines can be used to change the direction of a force. An example of this use is the flag hoist. A downward force on one side of the rope exerts an upward force on the other side, raising the flag toward the top of the pole.

There are only six simple machines. They are the lever, the pulley, the wheel and axle, the inclined plane, the screw, and the gear. However, physicists recognize only two basic principles in machines; namely, the lever and the inclined plane. The wheel and axle, the block and tackle, and gears may be considered levers. The wedge and the screw use the principle of the inclined plane.

An understanding of the principles of simple machines provides a necessary foundation for the study of compound machines, which are combinations of two or more simple machines.

The Lever

The simplest machine, and perhaps the most familiar one, is the lever. A seasaw is a familiar example of a lever in which one weight balances the other.

There are three basic parts in all levers; namely, the fulcrum "*F*," a force or effort "*E*," and a resistance "*R*." Shown in figure 7–23 are the pivotal point "*F*" (fulcrum); the effort "*E*," which is applied at a distance "*A*" from the fulcrum; and a resistance "*R*," which acts at a distance "*a*" from the fulcrum. Distances "*A*" and "*a*" are the lever arms.

Classes of Levers

The three classes of levers are illustrated in figure 7–24. The location of the fulcrum (the fixed or pivot point) with relation to the resistance (or weight) and the effort determines the lever class.

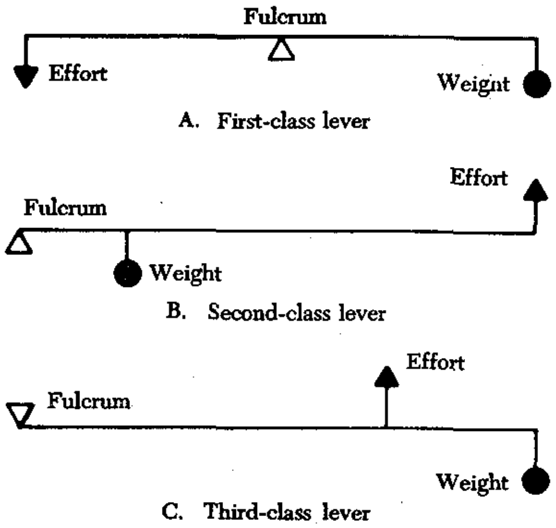


FIGURE 7–24. Three classes of levers.

First-Class Levers

In the first-class lever (A of figure 7–24), the fulcrum is located between the effort and the resistance. As mentioned earlier, the seesaw is a good example of the first-class lever. The amount of weight and the distance from the fulcrum can be varied to suit the need. Another good example this case, as in A of figure 7–24, the force is applied on one side of the fulcrum, and the resistance to be overcome is applied to the opposite side; hence, this is a first-class lever. Crowbars, shears, and pliers are common examples of this class of lever.

Second-Class Levers

The second-class lever (B of figure 7–24) has the fulcrum at one end; the effort is applied at the other end. The resistance is somewhere between these points. The wheelbarrow in figure 7–26 is a good example of a second-class lever.

Both first- and second-class levers are commonly used to help in overcoming big resistances with a relatively small effort.

Third-Class Levers

There are occasions when it is desirable to speed up the movement of the resistance even though a large amount of effort must be used. Levers that help accomplish this are third-class levers. As shown in C of figure 7–24, the fulcrum is at one end of the lever and the weight or resistance to be overcome is at the other end, with the effort applied at some point between.

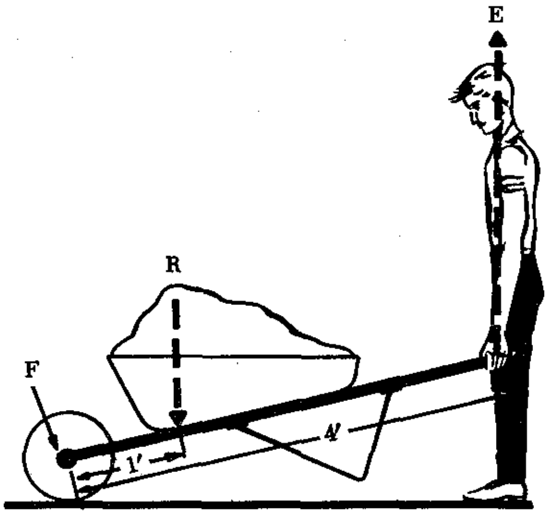


FIGURE 7–26. A second-class lever.

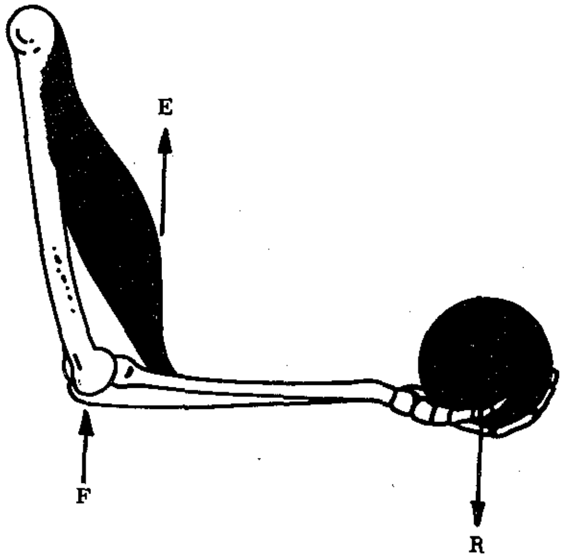


FIGURE 7–28. The arm is a third-class lever.

distance "*e*," the resistance "*R*" moves a greater distance "*r*." The speed of "*R*" must be greater than that of "*E*," since "*R*" covers a greater distance in the same length of time.

The human arm (figure 7–28) is a third-class lever. It is this lever action that makes possible the quick flexing of the arms. Note that the elbow is the fulcrum. The biceps muscle, which is tied onto the forearm below the elbow, applies the effort; and the hand, is the resistance. Third-class levers should be used to gain speed, rather than to move heavy loads.

The forces required to operate machines, as well as the forces they will exert, can be easily determined. Consider the iron bar used as a first-class lever in figure 7–29. The bar is 9 feet long and is used to raise a 300-pound weight. Assume that a maximum of 100 pounds is available to lift the weight. If a fulcrum "*F*" is placed 2 feet from the center of the weight, a 6-foot length of the bar becomes the effort arm. This 6-foot length is three times as long as the distance from the fulcrum to the center of the weight. With a 100-pound effort at "*E*", the 300-pound weight can be lifted, since the length of the effort arm has multiplied the effort three times. This is an example of the direct relationship between lengths of lever arms and the forces acting on the arms.

This relationship can be stated in general terms: The length of the effort arm is the same number of times greater than the length of the resistance arm as the resistance to be overcome is greater than the effort that must be applied.

The mathematical equation for this relation-

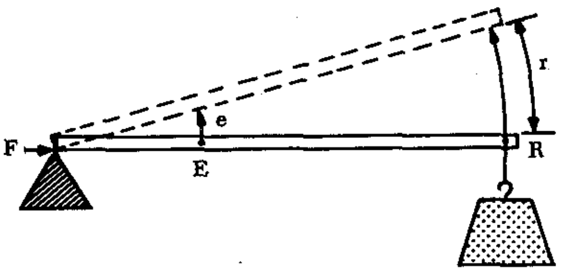


FIGURE 7–27. A third-class lever.

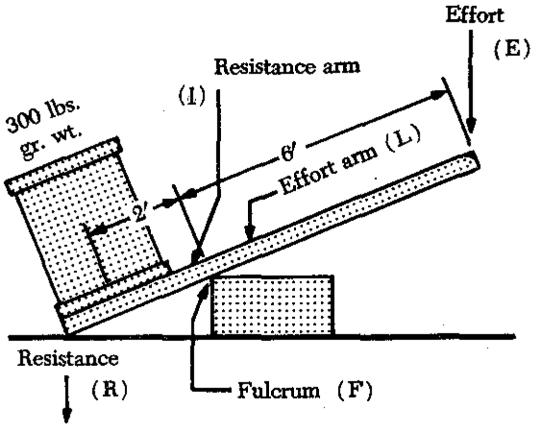


FIGURE 7–29. Computing the forces in a first-class lever.

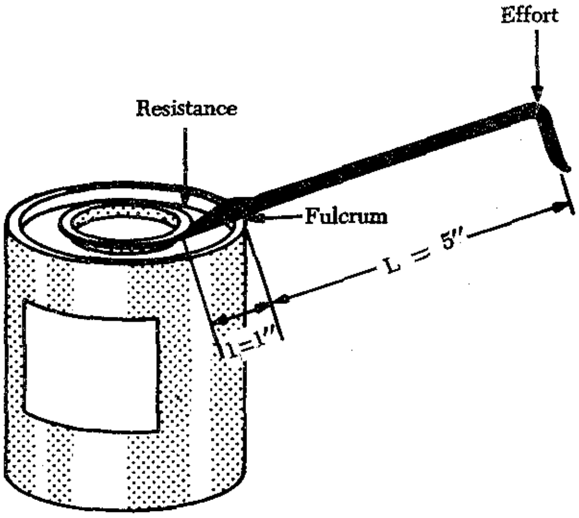


FIGURE 7–30. A first-class lever problem.

ship is:

$$\frac{L}{1} = \frac{R}{E}$$

where:
L = length of effort arm.
1 = length of resistance arm.
R = resistance weight or force.
E = effort force.

Remember that all distances must be in the same units, and all forces must also be in the same units.

In figure 7–30 another first-class lever problem is illustrated: To pry up the lid of the paint can with a 6-inch bar when the average force holding the lid is assumed to be 50 pounds. If the distance from the edge of the can to the edge of the cover is 1 inch, what force must be applied to the end of the bar?

According to the formula:

$$\frac{L}{1} = \frac{R}{E}$$

Here, $L = 5$ inches; $1 = 1$ inch; $R = 50$ pounds, and E is unknown. Substitute the numbers in their proper places; then

$$\frac{5}{1} = \frac{50}{E}$$

and $$E = \frac{50 \times 1}{5} = 10 \text{ pounds.}$$

A force of 10 pounds is required.

The same general formula applies for second-class levers; but it is important to measure the proper lengths of the effort arm and the resistance arm. Referring to figure 7–26, the length of the wheelbarrow handles from the axle of the wheel (which is the fulcrum) to the grip is 4 feet. This is an effort arm 4 feet in length. The center of the load of sand is 1 foot from the axle; thus, the length of the resistance arm is 1 foot.

By substituting in the formula,

$$\frac{L}{1} = \frac{R}{E}$$

$$\frac{4}{1} = \frac{200}{E}$$

$$E = 50 \text{ lb.}$$

A third-class lever problem is illustrated in figure 7–28. With one hand, a weight of 10 pounds is to be lifted. If the biceps muscle is attached to the forearm 1 inch below the elbow, and the distance from the elbow to the palm of the hand is 18 inches, what pull must the muscle exert in order to hold the weight and flex the arm at the elbow? By substituting in the formula,

$$\frac{L}{1} = \frac{R}{E} \text{ it becomes } \frac{1}{18} = \frac{10}{E}$$

and $$E = 18 \times 10 = 180 \text{ lb.}$$

The muscle must exert a 180-pound pull to hold up the 10-pound weight. This illustrates that the biceps muscle is poorly arranged for lifting or pulling. It also illustrates that third-class levers should be used primarily to speed up motion of a resistance.

Mechanical Advantage of Levers

Levers may provide mechanical advantages, since they can be applied in such manner that they can magnify an applied force. This is true of first- and second-class levers. The third-class lever provides what is called a fractional disadvantage, i.e., one in which a greater force is required than the force of the load lifted.

In the problem involving the wheelbarrow (figure 7-26), a 50-pound pull overcomes the 200-pound weight of the sand. In this case, the effort was magnified four times. Thus the mechanical advantage gained by using the wheelbarrow is 4.

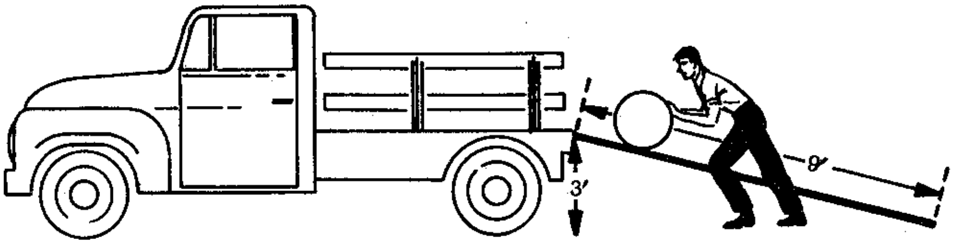


FIGURE 7–31. An inclined plane.

Expressing the same idea in mathematical terms,

$$\text{Mechanical Advantage} = \frac{\text{Resistance}}{\text{Effort}}$$

or

$$MA = \frac{R}{E}$$

Thus, in the case of the wheelbarrow,

$$MA = \frac{200}{50} = 4.$$

This rule applies to all machines.

Mechanical advantage of levers may also be found by dividing the length of the effort arm "*A*" by the length of the resistance arm "*a*." Stated as a formula, this reads:

$$\text{Mechanical Advantage} = \frac{\text{Effort Arm}}{\text{Resistance Arm}}$$

or $$MA = \frac{A}{a}$$

How does this apply to third-class levers? If a muscle pulls with a force of 1,800 pounds in order to lift a 100-pound projectile, a mechanical advantage of $^{100}/_{1,800}$ or $^{1}/_{18}$ is obtained. This is a fractional disadvantage, since it is less than 1.

The Inclined Plane

The inclined plane is a simple machine that facilitates the raising or lowering of heavy objects by application of a small force over a relatively long distance. Some familiar examples of the inclined plane are mountain highways and cattle loading ramps.

The inclined plane permits a large resistance to be overcome by application of a small force through a longer distance than the load is to be raised. In figure 7–31, a 300-pound barrel is being rolled up a ramp to the bed of a truck, 3 feet above the sidewalk. The ramp is 9 feet long.

Without the ramp, a force of 300 pounds, applied straight up through the 3-foot distance, would be required to load the barrel. With the ramp, a force can be applied over the entire 9 feet of the ramp as the barrel is rolled slowly up to a height of 3 feet. It can be determined by observation that a force of only three-ninths of 300, or 100 pounds, will be required to raise the barrel by using an inclined plane. This can also be determined mathematically, using the formula,

$$\frac{L}{1} = \frac{R}{E}$$

where:

L = length of the ramp, measured along the slope.
1 = height of the ramp.
R = weight of object to be raised, or lowered.
E = force required to raise or lower object.

In this case, $L = 9$ ft.; $1 = 3$ ft.; and $R = 300$ lb. Substituting these values in the formula,

$$\frac{9}{3} = \frac{300}{E}$$

$$9E = 900$$

$$E = 100 \text{ pounds.}$$

Since the ramp is three times as long as its height, the mechanical advantage is three. The theoretical mechanical advantage is found by dividing the total distance through which the effort is exerted by the vertical distance through which the load is raised or lowered.

The Wedge

The wedge is a special application of the inclined plane. The blades of knives, axes, hatchets, and

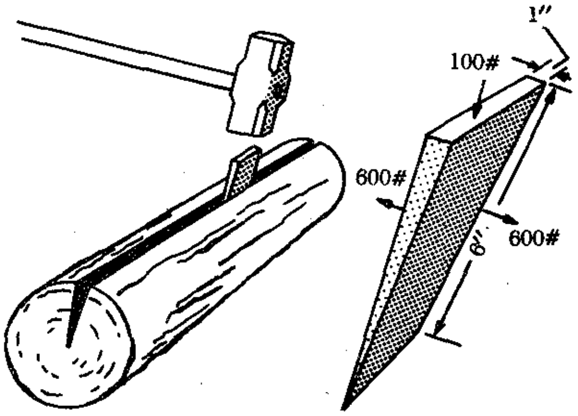


FIGURE 7–32. A wedge.

chisels act as wedges when they are forced into a piece of wood. The wedge is two inclined planes, set base-to-base. By driving the wedge full-length into the material to be cut or split, the material is forced apart a distance equal to the width of the broad end of the wedge (see figure 7–32).

Long, slim wedges have high mechanical advantages. For example, the wedge in figure 7–32 has a mechanical advantage of 6. The greatest value of wedges is found in situations where other simple machines cannot be used. For example, imagine trying to pull a log apart with a system of pulleys.

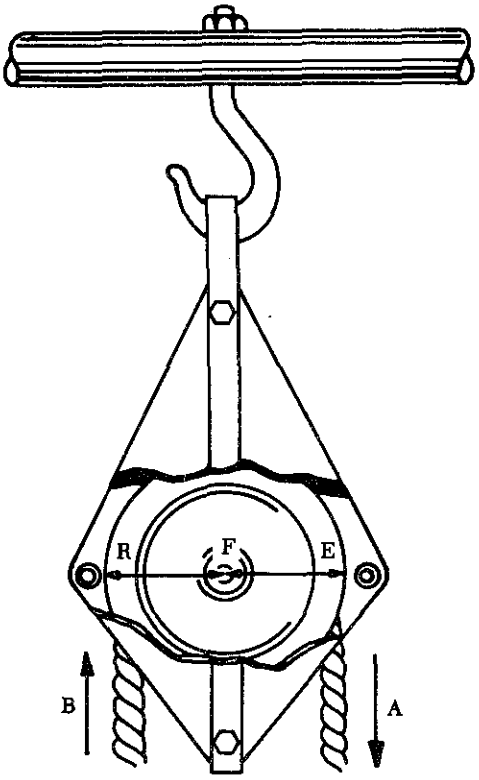


FIGURE 7–33. A single fixed pulley.

The Pulley

Pulleys are simple machines in the form of a wheel mounted on a fixed axis and supported by a frame. The wheel, or disk, is normally grooved to accommodate a rope. The wheel is sometimes referred to as a "sheave" (sometimes "sheaf"). The frame that supports the wheel is called a block. A block and tackle consists of a pair of blocks. Each block contains one or more pulleys and a rope connecting the pulley(s) of each block.

Single Fixed Pulley

A single fixed pulley is really a first-class lever with equal arms. The arms "*EF*" and "*FR*" in figure 7–33 are equal; hence the mechanical advantage is one. Thus, the force of the pull on the rope must be equal to the weight of the object being lifted. The only advantage of a single fixed pulley is to change the direction of the force, or pull on the rope.

A single pulley can be used to magnify the force exerted. In figure 7–34 the pulley is not

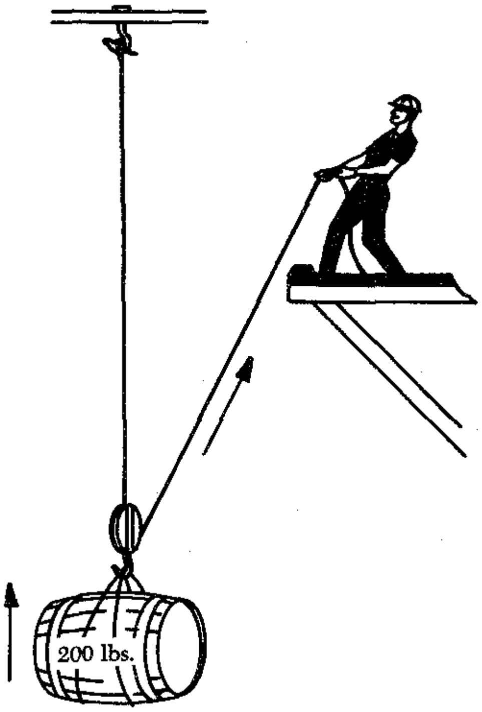


FIGURE 7–34. A single movable pulley.

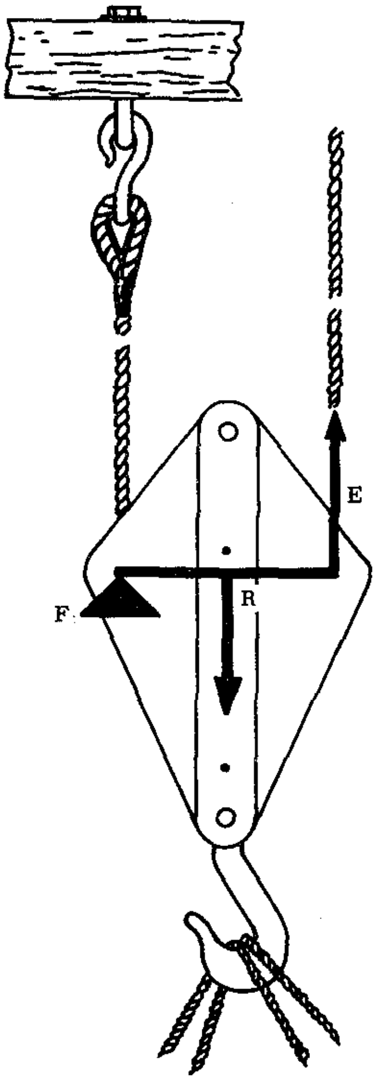


FIGURE 7–35. A single movable pulley as a second-class lever.

fixed, and the rope is doubled because it supports a 200-pound weight. Used in this manner, a single block and tackle can lift the 200-pound weight with a 100-pound pull, since each half of the rope (tackle) carries one-half the total load. The mechanical advantage is 2, which can be verified by using the formula:

$$MA = \frac{R}{E} = \frac{200}{100} = 2.$$

The single movable pulley used in the manner shown in figure 7-34 is a second-class lever. To see this refer to figure 7–35. The effort "*E*" acts upward on the arm "*EF*," which is the diameter of the pulley. The resistance "*R*" acts downward on the arm "*FR*," which is the radius of the pulley. Since the diameter is twice the radius, the mechanical advantage is 2.

However, when the effort at "*E*" moves up 2 feet, the load at "*R*" is raised only 1 foot. This is true of all systems of block and tackle, for if a mechanical advantage is obtained, the length of rope passed through the hands is greater than the distance that the load is raised.

The mechanical advantage of a pulley system is found by measuring the resistance and the effort and dividing the amount of resistance by the effort. A shorthand method often used is simply to count the number of rope strands that move or support the movable block.

WORK, POWER, AND ENERGY

Work

The study of machines, both simple and complex, is in one sense a study of the energy of mechanical work. This is true because all machines transfer input energy, or the work done on the machine to output energy, or the work done by the machine.

Work, in the mechanical sense of the term, is done when a resistance is overcome by a force acting through a measurable distance. Two factors are involved: (1) Force and (2) movement through a distance. As an example, suppose a small aircraft is stuck in the snow. Two men push against it for a period of time, but the aircraft does not move. According to the technical definition, no work was done in pushing against the aircraft. By definition, work is accomplished only when an object is displaced some distance against a resistive force.

In equation form, this relationship is,

Work = Force (F) x distance (d).

The physicist defines work as "work is force times displacement. Work done by a force acting as a body is equal to the magnitude of the force multiplied by the distance through which the force acts."

In the metric system, the unit of work is the *joule*, where one joule is the amount of work done by a force of one newton when it acts through a distance of one meter. That is,

1 joule = 1 newton-m

Hence we can write the definition in the form

W (joules) $= F$ (newtons) x d (meters)

If we push a box for 8 m across a floor with a force of 100 newtons, the work we perform is

$W = Fd = 100$ newtons x 8 m $= 800$ joules

How much work is done in raising a 500-kg (kilogram) elevator cab from the ground floor of a building to its tenth floor, 30 m (meters) higher? We note that the force needed is equal to the weight of the cab, which is *mg*.

In the metric system, mass rather than weight is normally specified. To find the weight in newtons (the metric unit of force) of something whose mass in kilograms is known, we simply turn to $F = mg$ and set $G = 9.8 \text{ m/SEC}^2$

F (newtons) = M (kilograms) x G (9.8 m/sec^2)

W (joules) = M (kilograms) x G (9.8 m/sec^2) x D (meters)

$W = Fd = mgd = 500 \text{ kg} \times 9.8 \text{ m/Sec}^2 \times 30\text{m}$

$= 147{,}000$ joules

$= 1.47 \times 10^5$ joules

Force Parallel To Displacement

If force is expressed in pounds and distances in feet, work will be expressed in ft. lbs. (foot-pounds). Example: How much work is accomplished in lifting a 40-pound weight to a vertical height of 25 feet?

$W = Fd$

$= 40 \times 25$

$= 1{,}000$ ft.-lb.

Example: How much work is accomplished in pushing a small aircraft into a hangar a distance of 115 feet if a force of 75 pounds is required to keep it moving?

$W = Fd$

$= 75 \times 115$

$= 8{,}625$ ft.-lb.

Force Not Parallel To Displacement

In this equation, F is assumed to be in the same direction as *d*. If it is not, for example the case of a body pulling a wagon with a rope not parallel to the ground, we must use *F* for the component of the applied force that acts in the direction of the motion, figure 7–37(A).

The component of a force in the direction of a displacement *d* is:

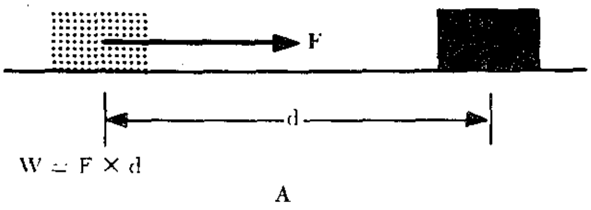
$F \cos \theta$

where θ is the angle between *F* and *d*. Hence the most general equation for work is

$W = Fd \cos \theta$

When *F* and *d* are parallel, $\theta = 0$ and $\cos \theta = 1$, so that $Fd \cos \theta$ reduces to just *Fd*. When *F* and *d* are perpendicular, $\theta = 90°$ and $\cos \theta = 0$, so that no work is done. A force that is perpendicular to the motion of an object can do no work upon it. Thus gravity, which results in a downward force on everything near the earth, does no work on objects moving horizontally along the earth's surface. However, if we drop an object, as it falls to the ground work is definitely done upon it.

When a force and the distance through which it acts are parallel, the work done is equal to the product of F and d.



When they are not in the same direction, the work done is equal to the product of d and the component of F in the direction of d, namely (F cos θ) × d.

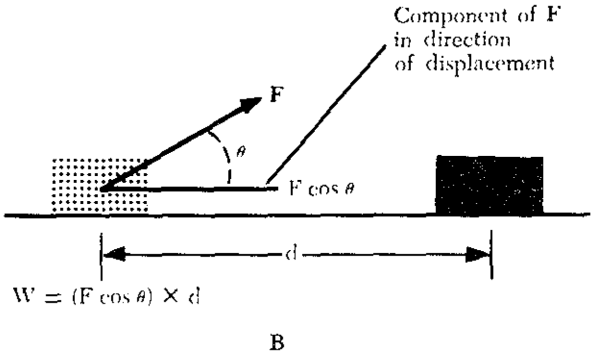


FIGURE 7–36. Direction of work.

Friction

In calculating work done, the actual resistance overcome is measured. This is not necessarily the weight of the object being moved. This point can be illustrated by referring to figure 7–37. A 900-pound load is being pulled a distance of 200 feet. This does not mean that the work done (force x distance) is 180,000 foot-pounds (900 pounds x 200 feet). This is because the man pulling the load is not working against the total weight of the load, but rather against the rolling friction of the cart, which may be no more than 90 pounds.

Friction is one of the most important aspects of life. Without friction it would be impossible to walk. One would have to shove oneself from place to place, and would have to bump against some obstacle to stop at a destination. Yet friction is a liability as well as an asset, and requires consideration when dealing with any moving mechanism.

In experiments relating to friction, measurement of the applied forces reveals that there are three kinds of friction. One force is required to start a body moving, while another is required to keep the body moving at constant speed. Also, after a body is once in motion, a definitely larger force is required to keep it sliding than to keep it rolling.

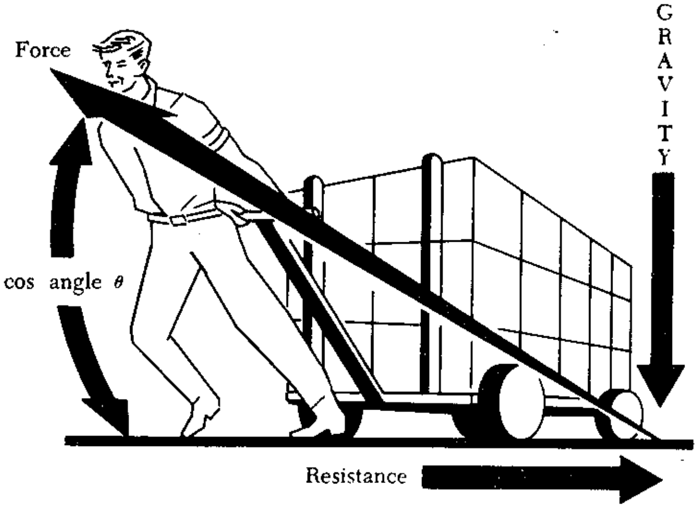


FIGURE 7–37. Working against friction.

Thus, the three kinds of friction may be classified as: (1) Starting (static) friction, (2) sliding friction, and (3) rolling friction.

Static Friction

When an attempt is made to slide a heavy object along a surface, the object must first be broken loose or started. Once in motion, it slides more easily. The "breaking loose" force is, of course, proportional to the weight of the body. The force necessary to start the body moving slowly is designated "F," and "F'" is the normal force pressing the body against the surface (usually its weight). Since the nature of the surfaces rubbing against each other is important, they must be considered. The nature of the surfaces is indicated by the coefficient of starting friction which is designated by the letter "k." This coefficient can be established for various materials and is often published in tabular form. Thus, when the load (weight of the object) is known, starting friction can be calculated by using the equation,

$$F = kF'.$$

For example, if the coefficient of sliding friction of a smooth iron block on a smooth, horizontal surface is 0.3, the force required to start a 10-pound block would be 3 pounds; a 40-pound block, 12 pounds.

Starting friction for objects equipped with wheels and roller bearings is much smaller than that for sliding objects. Nevertheless, a locomotive would have difficulty getting a long train of cars in motion all at one time. Therefore, the couples between the cars are purposely made to have a few inches of play. When the engineer is about to start the train, he backs the engine until all the cars are pushed together. Then, with a quick start forward the first car is set in motion. This technique is employed to overcome the static friction of each wheel (as well as the inertia of each car). It would be impossible for the engine to start all of the cars at the same instant, for static friction, which is the resistance of being set in motion, would be greater than the force exerted by the engine. Once the cars are in motion, however, static friction is greatly reduced and a smaller force is required to keep the train in motion than was required to start it.

Sliding Friction

Sliding friction is the resistance to motion offered by an object sliding over a surface. It pertains to friction produced after the object has once been set into motion, and is always less than starting friction. The amount of sliding resistance is dependent on the nature of the surface of the object, the surface over which it slides, and the normal force between the object and the surface. This resistive force may be computed by the formula,

$$F = \mu N$$

where: "F" is the resistive force due to friction expressed in pounds; "N" is the force exerted on or by the object perpendicular (normal) to the surface over which it slides; and "μ" (mu) is the coefficient of sliding friction. (On a horizontal surface, N is equal to the weight of the object in pounds.) The area of the sliding object exposed to the sliding surface has no effect on the results. A block of wood, for example, will not slide any easier on one of the broad sides than it will on a narrow side, (assuming all sides have the same smoothness). Therefore, area does not enter into the equation above.

Rolling Friction

Resistance to motion is greatly reduced if an object is mounted on wheels or rollers. The force of friction for objects mounted on wheels or rollers is called rolling friction. This force may be computed by the same equation used in computing sliding friction, but the values of μ will be much smaller. For example, μ for rubber tires on concrete or macadam is about .02. The value of μ for roller bearings is very small, usually ranging from .001 to .003 and is often disregarded.

Example:

An aircraft with a gross weight of 79,600 lb. is towed over a concrete ramp. What force must be exerted by the towing vehicle to keep the airplane rolling after once set in motion?

$$F = \mu N$$

$$= .02 \times 79{,}600 = 1{,}592 \text{ lb.}$$

Power

Power is a badly abused term. In speaking of power-driven equipment, people often confuse the term "power" with the ability to move heavy loads. This is not the meaning of power. A sewing machine motor is powerful enough to rotate an aircraft engine propeller providing it is connected to the crankshaft through a suitable mechanism. It could not rotate the propeller at 2,000 r.p.m., however, for it is not powerful enough to move a large load at a high speed. Power, thus, means rate of doing work. It is measured in terms of work accomplished per unit of time. In equation form, it reads:

$$\text{Power} = \frac{\text{Force x Distance}}{\text{time}}$$

$$\text{or, } P = \frac{FD}{t}$$

If force is expressed in pounds, distance in feet, and time in seconds, then power is given in ft.-lbs./sec. (foot-pounds per second). Time may also be given in minutes. If time in minutes is used in this equation, then power will be expressed in ft.-lbs./min.

$$\text{Power} = \frac{\text{pounds x feet}}{\text{seconds}} = \text{ft.-lbs./sec.}$$

or,

$$\text{Power} = \frac{\text{pounds x feet}}{\text{minutes}} = \text{ft.-lbs./min.}$$

Example:

An aircraft engine weighing 3,500 pounds was hoisted a vertical height of 7 feet in order to install it on an aircraft. The hoist was hand-powered and required 3 minutes of cranking to raise the engine. How much power was developed by the man cranking the hoist? (Neglect friction in the hoist.)

$$\text{Power} = \frac{Fd}{t}$$

$$= \frac{3{,}500 \text{ pounds x } 7 \text{ feet}}{3 \text{ minutes}}$$

$$= 8{,}167 \text{ ft.-lbs./min.}$$

Power is often expressed in units of horsepower. One horsepower is equal to 550 ft.-lbs./sec. or 33,000 ft.-lbs./min.

Example:

In the hoist example above, calculate the horsepower developed by the man.

$$\text{Horsepower} = \frac{\text{Power in ft.-lbs./min.}}{33{,}000}$$

$$\text{hp.} = \frac{\frac{Fd}{t}}{33{,}000}$$

$$= \frac{8167}{33{,}000} = 0.247, \text{ or about } \tfrac{1}{4} \text{ hp}$$

Power is rate of doing work:

$$P = \frac{W}{t}$$

In the metric system the unit of power is the *watt*, where

1 watt = 1 joule/sec.

The watt is the metric unit of power, thus a motor with a power output of 5,000 watts is capable of doing 5,000 joules of work per second.

A *kilowatt* (kw) is equal to 1,000 watts. Hence the above motor has a power output of 5 kw.

How much time does the elevator cab of the previous example need to ascend 30 meters if it is being lifted by a 5-kw motor? We rewrite $P=W/t$ in the form

$$t=\frac{W}{P}$$

and then substitute $w=1.47 \times 10^5$ joules and $p=5.10^3$ watts to find that

$$t=\frac{W}{P}=\frac{1.47 \times 10^5 \text{ joules}}{5 \times 10^3 \text{ watts}}=29.4 \text{ sec.}$$

Energy

In many cases when work is done on an object, something is given to the object which it retains and which later enables it to do work. When a weight is lifted to a certain height such as in the case of a trip-hammer, or when a clock spring is wound, the object acquires, through having work done on it, the ability to do work itself. In storage batteries and gasoline, energy is stored which can be used later to do work. Energy stored in coal or food can be used to do work. This storage gives such objects the ability to do work; thus, energy is defined as the ability to do work

In general, a change in energy is equal to the work done; the loss in energy of a body may be measured by the work it does, or the gain in energy of a body may be measured by the amount of work done on it. For convenience, energy which bodies possess is classified into two categories: (1) Potential and (2) kinetic.

Potential energy may be classified into three groups: (1) That due to position, (2) that due to distortion of an elastic body, and (3) that which produces work through chemical action. Water in an elevated reservoir, and the lifted weight of a pile-driver are examples of the first group; a stretched rubber band or compressed spring are examples of the second group; and energy in coal, food, and storage batteries are examples of the third group.

Bodies in motion required work to put them in motion. Thus, they possess energy of motion. Energy due to motion is known as kinetic energy. A moving vehicle, a rotating flywheel, and a hammer in motion are examples of kinetic energy.

Energy is expressed in the same units as those used to express work. The quantity of potential energy possessed by an elevated weight may be computed by the equation,

$$\text{Potential Energy} = \text{Weight} \times \text{Height.}$$

If weight is given in pounds and height in feet, the final unit of energy will be ft.-lbs. (foot-pounds).

Example: An aircraft with a gross weight of 110,000 pounds is flying at an altitude of 15,000 feet above the surface of the earth. How much potential energy does the airplane possess with respect to the earth?

$$\begin{aligned}\text{Potential Energy} &= \text{Weight} \times \text{Height}\\ PE &= 110{,}000 \times 15{,}000\\ &= 1{,}650{,}000{,}000 \text{ ft.-lbs.}\end{aligned}$$

Forms of Energy

The most common forms of energy are heat, mechanical, electrical, and chemical. The various forms of energy can be changed, or transformed, into another form in many different ways. For example, in the case of mechanical energy, the energy of work done against friction is always converted into heat energy, and the mechanical energy that turns an electric generator develops electrical energy at the output of the generator.

MOTION OF BODIES

General

The study of the relationship between the motion of bodies or objects and the forces acting on them is often called the study of "force and motion." In a more specific sense, the relationship between velocity, acceleration, and distance is known as kinematics.

Uniform Motion

Motion may be defined as a continuing change of position or place, or as the process in which a body undergoes displacement. When an object is at different points in space at different times, that object is said to be in motion, and if the distance the object moves remains the same for a given period of time, the motion may be described as uniform. Thus, an object in uniform motion always has a constant speed.

Speed and Velocity

In everyday usage, speed and velocity often mean the same thing. In physics they have definite and distinct meanings. Speed refers to how fast an object is moving, or how far the object will travel in a specific time. The speed of an object tells nothing about the direction an object is moving. For example, if the information is supplied that an airplane leaves New York City and travels 8 hours at a speed of 150 m.p.h., this information tells nothing about the direction in which the airplane is moving. At the end of 8 hours, it might be in Kansas City, or if it traveled in a circular route, it could be back in New York City.

Velocity is that quantity in physics which denotes both the speed of an object and the direction in which the object moves. Velocity can be defined as the rate of motion in a particular direction.

The average velocity of an object can be calculated using the formula,

$$V_a = \frac{s}{t}$$

where:

V_a = the average velocity.
s = the rate of motion or average speed.
t = the elapsed time.

Acceleration

Acceleration is defined by the physicist as the rate of change of velocity. If the velocity of an object is increased from 20 m.p.h. to 30 m.p.h., the object has been accelerated. If the increase in velocity is 10 m.p.h. in 5 seconds, the rate of change in velocity is 10 m.p.h. in 5 seconds, or $\frac{2 \text{ m.p.h.}}{\text{sec.}}$. Expressed as an equation,

$$A = \frac{V_f - V_i}{t}$$

where:

A = acceleration.
V_f = the final velocity (30 m.p.h.).
V_i = the initial velocity (20 m.p.h.).
t = the elapsed time.

The example used can be expressed as follows:

$$A = \frac{30 \text{ m.p.h.} - 20 \text{ m.p.h.}}{5 \text{ sec.}}$$

$$A = \frac{2 \text{ m.p.h.}}{\text{sec.}}$$

If the object accelerated to 22 m.p.h. in the first second, 24 m.p.h. in the next second, and 26 m.p.h. in the third second, the change in velocity each second is 2 m.p.h. The acceleration is said to be constant, and the motion is described as uniformly accelerated motion.

If a body has a velocity of 3 m.p.h. at the end of the first second of its motion, 5 m.p.h. at the end of the next second, and 8 m.p.h. at the end of the third second, its motion is described as acceleration, but it is variable accelerated motion.

Newton's Law of Motion

When a magician snatches a tablecloth from a table and leaves a full setting of dishes undisturbed, he is not displaying a mystic art; he is demonstrating the principle of inertia.

Inertia is responsible for the discomfort felt when an airplane is brought to a sudden halt in the parking area and the passengers are thrown forward in their seats. Inertia is a property of matter. This property of matter is described by Newton's first law of motion, which states:

> Objects at rest tend to remain at rest; objects in motion tend to remain in motion at the same speed and in the same direction.

Bodies in motion have the property called momentum. A body that has great momentum has a strong tendency to remain in motion and is therefore hard to stop. For example, a train moving at even low velocity is difficult to stop because of its large mass. Newton's second law applies to this property. It states:

> When a force acts upon a body, the momentum of that body is changed. The rate of change of momentum is proportional to the applied force.

The momentum of a body is defined as the product of its mass and its velocity. Thus,

Momentum = mass x velocity or,
$M = mV$

Now if a force is applied, the momentum changes at a rate equal to the force or:

$$F = \text{rate of change of momentum}$$

$$= \frac{M_f - M_i}{t}$$

Substituting mV for M:

$$F = \frac{m_f V_f - m_i V_i}{t}$$

Since the mass does not usually change, $mf = mi = m$. Then

$$F = \frac{mV_f - mV_i}{t}$$

$$= m \frac{(V_f - V_i)}{t}$$

From the previous section the second term is recognized as acceleration. Then the second law becomes:

$F = ma$

On earth, gravity exerts a force on each body causing an acceleration of 32 ft./sec.^{2} which is usually designated as "g". The force is commonly called weight, W. Using the formula above:

$W = mg$

and;

$$m = \frac{W}{g}$$

Then on earth the second law becomes:

$$F = ma$$

$$= \frac{W}{g} \ (a)$$

The following examples illustrate the use of this formula.

Example:

A train weighs 32,000 lbs. and is traveling at 10 ft./sec. What force is required to bring it to rest in 10 seconds?

$$F = \frac{W}{g} \ (a)$$

$$= \frac{W}{g} \ \frac{(V_f - V_i)}{t}$$

$$= \frac{32{,}000}{32} \ \frac{(0-10)}{10}$$

$$= \frac{32{,}000 \times (-10)}{32 \times 10}$$

$$= -1{,}000 \text{ lbs.}$$

The negative sign means that the force must be applied against the train's motion.

Example:

An aircraft weighs 6,400 pounds. How much force is needed to give it an acceleration of 6 ft./sec.^{2}?

$$F = \frac{W}{g} \ (a)$$

$$= \frac{6400 \times 6}{32} = 1{,}200 \text{ lb.}$$

Newton's third law of motion is often called the law of action and reaction. It states that for every action there is an equal and opposite reaction. This means that if a force is applied to an object, the object will supply a resistive force exactly equally to and in the opposite direction of the force applied. It is easy to see how this might apply to objects at rest. For example, as a man stands on the floor, the floor exerts a force against his feet exactly equal to his weight. But this law is also applicable when a force is applied to an object in motion.

When a force applied to an object is more than sufficient to produce and sustain uniform motion, inertia of the object will cause such a resistive force that the force opposing the motion of the object equals the force producing the motion. This resistance to change in velocity due to inertia is usually referred to as internal force. When several forces act upon an object to produce accelerated motion, the sums of the external forces are in a state of unbalance; however, the sums of the external and the internal forces are always in a state of balance, whether motion is being either sustained or produced.

Forces always occur in pairs. The term "acting force" means the force one body exerts on a second body, and reacting force means the force the second body exerts on the first.

When an aircraft propeller pushes a stream of air backward with a force of 500 pounds, the air pushes the blades forward with a force of 500 pounds. This forward force causes the aircraft to move forward. In like manner, the discharge of exhaust gases from the tailpipe of a turbine engine is the action which causes the aircraft to move forward.

The three laws of motion which have been discussed here are closely related. In many cases, all three laws may be operating on a body at the same time.

Circular Motion

Circular motion is the motion of an object along a curved path that has a constant radius. For example, if one end of a string is tied to an object and the other end is held in the hand, the object can be swung in a circle. The object is constantly deflected from a straight (linear) path by the pull exerted on the string, as shown in figure 7–38.

As an object in figure 7–38 travels along the circumference from X to Y, the pull or force on the string deflects it from Y toward Z. This pull is called centripetal force, which deflects an object from a straight path and forces it to travel in a curved path. Thus, the string exerts a centripetal

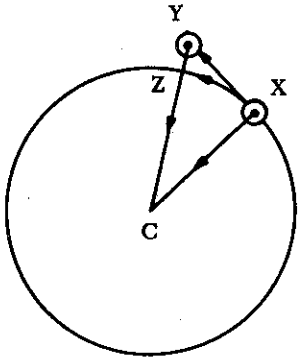


FIGURE 7–38. Circular motion.

force on the object, and the object exerts an equal but opposite force on the string, obeying Newton's third law of motion.

The force that is equal to centripetal force, but acting in an opposite direction, is called centrifugal force. In the example of figure 7–38, it is the force exerted by the object on the string. Without a centripetal force, there is no centrifugal force.

Centripetal force is always directly proportional to the mass of the object in circular motion. Thus, if the mass of the object in figure 7–38 is doubled, the pull on the string must be doubled to keep the object in its circular path, provided the speed of the object remains constant.

Centripetal force is inversely proportional to the radius of the circle in which an object travels. If the string in figure 7–38 is shortened and the speed remains constant, the pull on the string must be increased since the radius is decreased, and the string must pull the object from its linear path more rapidly.

Using the same reasoning, the pull on the string must be increased if the object is swung more rapidly in its orbit. Centripetal force is thus directly proportional to the square of the velocity of the object. The formula for centripetal force is:

$$\text{C.P.} = \frac{MV^2}{R}$$

where:

M=the mass of the object.
V=velocity.
R=radius of the object's path.

Rotary Motion

The motion of a body turning about an axis is called rotary motion. This is the familiar motion that occurs as the crankshaft of an engine turns. The difference between rotary and circular motion is that, in the case of rotary motion, the body or object spins, while in circular motion the whole object moves along a curved path.

When an object spins at a constant speed about a fixed axis, it has uniform rotary motion. When its direction or rate of spin changes, it has variable rotary motion.

Momentum

Momentum is defined as the product of an object's mass and its velocity. The force required to accelerate an object is proportional to an object's mass and the acceleration given it. Acceleration has been defined as the rate of change of an object's velocity. This is expressed as a formula:

$$A = \frac{V_f - V_i}{t}$$

where:

A = acceleration.
V_f = final velocity.
V_i = initial velocity.
t = elapsed time.

Newton's second law of motion, $F = MA$, involves acceleration. If the original expression for acceleration is substituted in Newton's second law, it becomes:

$$F = \frac{MV_f - MV_i}{t}.$$

This formula can be further resolved to illustrate momentum by multiplying both sides by t:

$$Ft = MV_f - MV_i.$$

This formula illustrates that an object's momentum is a product of its mass and its velocity.

HEAT

Heat is a form of energy. It is produced only by the conversion of one of the other forms of energy. Heat may also be defined as the total kinetic energy of the molecules of any substance.

Some forms of energy which can be converted into heat energy are as follows:

(1) ***Mechanical Energy.*** **This includes all methods of producing increased motion of molecules such as friction, impact of bodies, or compression of gases.**

(2) *Electrical Energy.* Electrical energy is converted to heat energy when an electric current flows through any form of resistance. This might be an electric iron, electric light, or an electric blanket.

(3) *Chemical Energy.* Most forms of chemical reaction convert stored potential energy into heat. Some examples are the explosive effects of gunpowder, the burning of oil or wood, and the combining of oxygen and grease.

(4) *Radiant Energy.* Electromagnetic waves of certain frequencies produce heat when they are absorbed by the bodies they strike. Included are X-rays, light rays, and infrared rays.

(5) *Nuclear Energy.* Energy stored in the nucleus of atoms is released during the process of nuclear fission in a nuclear reactor or atomic explosion.

(6) *The Sun.* All heat energy can be directly or indirectly traced to the nuclear reactions occurring in the sun.

Mechanical Equivalent of Heat

When a gas is compressed, work is done and the gas becomes warm or hot. Conversely, when a gas under high pressure is allowed to expand, the expanding gas becomes cool. In the first case, work was converted into energy in the form of heat; in the second case heat energy was expended. Since heat is given off or absorbed, there must be a relationship between heat energy and work. Also, when two surfaces are rubbed together, the friction develops heat. However, work was required to cause the heat, and by experimentation, it has been shown that the work required and the amount of heat produced by friction are proportional. Thus, heat can be regarded as a form of energy.

According to this theory of heat as a form of energy, the molecules, atoms, and electrons in all bodies are in a continual state of motion. In a hot body, these small particles possess relatively large amounts of kinetic energy, but in cooler bodies they have less. Because the small particles are given motion, and hence kinetic energy, work must be done to slide one body over the other. Mechanical energy apparently is transformed, and what we know as heat is really kinetic energy of the small molecular subdivisions of matter.

Two different units are used to express quantities of heat energy. They are the calorie and the British thermal unit. One calorie is equal to the amount of heat required to change the temperature of 1 gram of water 1 degree centigrade. This term "calorie" (spelled with a small c) is $\frac{1}{1,000}$ of the Calorie (spelled with a capital C) used in the measurement of heat-producing or energy-producing value in foods. One B.t.u. (British thermal unit) is defined as the amount of heat required to change the temperature of 1 pound of water 1 degree Fahrenheit. The calorie and the gram are seldom used in discussing aviation maintenance. The B.t.u., however, is commonly referred to in discussions of engine thermal efficiencies and the heat content of aviation fuel.

A device known as the calorimeter is used to measure quantities of heat energy. For example, it may be used to determine the quantity of heat energy available in 1 pound of aviation gasoline. A given weight of the fuel is burned in the calorimeter, and the heat energy is absorbed by a large quantity of water. From the weight of the water and the increase in its temperature, it is possible to compute the heat yield of the fuel.

A definite relationship exists between heat and mechanical energy. This relationship has been established and verified by many experiments which show that:

One B.t.u. = 778 ft.-lbs.

Thus, if the 1-pound sample of the fuel mentioned above were found to yield 20,000 B.t.u., it would be the equivalent of 20,000 B.t.u. × 778 ft.-lbs./B.t.u. or 15,560,000 ft.-lbs. of mechanical energy.

Unfortunately no heat engine is capable of transforming all of the available heat energy in the fuel it burns into mechanical energy. A large portion of this energy is wasted through heat losses and operational friction.

Methods of Heat Transfer

There are three methods by which heat is transferred from one location to another or from one substance to another. These three methods are conduction, convection, and radiation.

Conduction

Everyone knows from experience that the metal handle of a heated pan can burn the hand. A

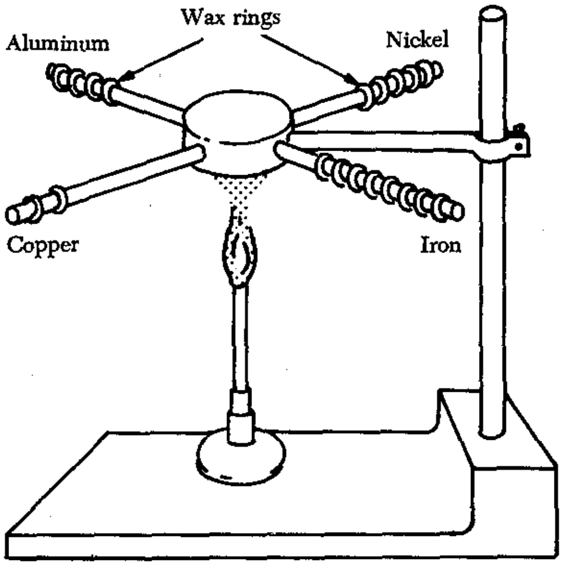


FIGURE 7–39. Various metals conduct heat at different rates.

plastic or wood handle, however, remains relatively cool even though it is in direct contact with the pan. The metal transmits the heat more easily than the wood because it is a better conductor of heat. Different materials conduct heat at different rates. Some metals are much better conductors of heat than others. Aluminum and copper are used in pots and pans because they conduct heat very rapidly. Woods and plastics are used for handles because they conduct heat very slowly.

Figure 7–39 illustrates the different rates of conduction of various metals. Four rods of different metals have several wax rings handing on them. One flame is used to heat one end of each rod simultaneously. The rings melt and drop off the copper rod first, then from the aluminum rod, then from the nickel rod, and last from the iron rod. This example shows that among the four metals used, copper is the best conductor of heat and iron is the poorest.

Liquids are poorer conductors of heat than metals. Notice that the ice in the test tube shown in figure 7–40 is not melting rapidly even though the water at the top is boiling. The water conducts heat so poorly that not enough heat reaches the ice to melt it.

Gases are even poorer conductors of heat than liquids. It is possible to stand quite close to a stove without being burned because air is such a poor conductor. Since conduction is a process whereby the increase in molecular energy is passed along by actual contact, gases are poor conductors.

At the point of application of the heat source the molecules become violently agitated. These molecules strike adjacent molecules causing them to become agitated. This process continues until the heat energy is distributed evenly throughout the substance. Because molecules are farther apart in gases than in solids, the gases are much poorer conductors of heat.

Materials that are poor conductors are used to prevent the transfer of heat and are called heat insulators. A wooden handle on a pot or a soldering iron serves as a heat insulator. Certain materials such as finely spun glass or asbestos are particularly poor heat conductors. These materials are therefore used for many types of insulation.

Convection

Convection is the process by which heat is transferred by movement of a heated fluid (gas or liquid). For example, an electronic tube will, when heated, become increasingly hotter until the air surrounding it begins to move. The motion of the air is upward. This upward motion of the heated air carries the heat away from the hot tube by convection. Transfer of heat by convection may be hastened by using a ventilating fan to move the air surrounding a hot object. The rate of cooling of a hot vacuum tube can be increased if it is provided with copper fins that conduct heat

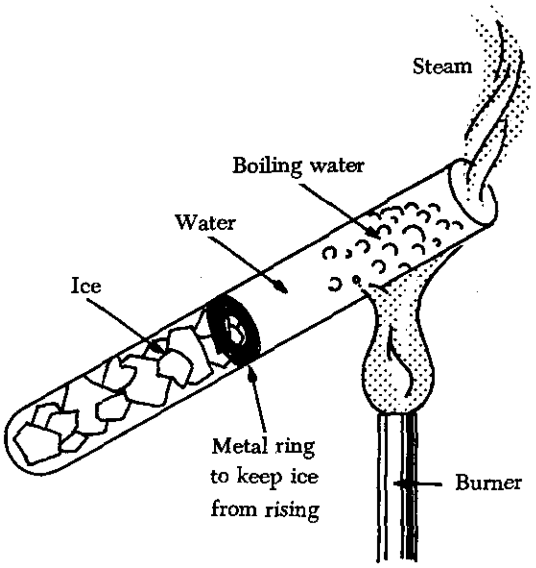


FIGURE 7–40. Water is a poor conductor of heat.

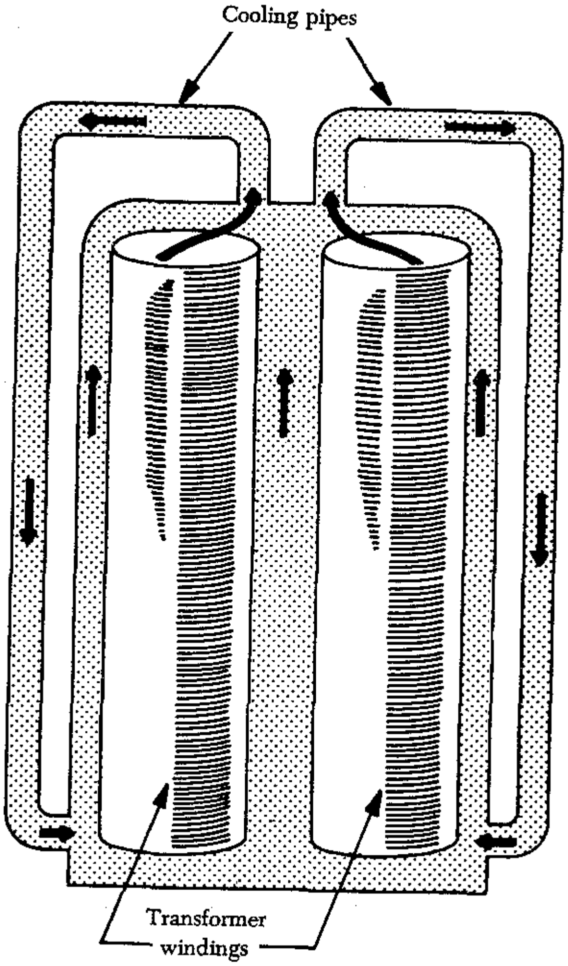


FIGURE 7–41. Oil convection currents cool a transformer.

away from the hot tube. The fins provide large surfaces against which cool air can be blown.

A convection process may take place in a liquid as well as in a gas. Figure 7–41 shows a transformer in an oil bath. The hot oil is less dense (has less weight per unit volume) and rises, while the cool oil falls, is heated, and rises in turn.

When the circulation of gas or liquid is not rapid enough to remove sufficient heat, fans or pumps are used to accelerate the motion of the cooling material. In some installations, pumps are used to circulate water or oil to help cool large equipment. In airborne installations electric fans and blowers are used to aid convection.

Radiation

Conduction and convection cannot wholly account for some of the phenomena associated with heat transfer. For example, the heat one feels when sitting in front of an open fire cannot be transferred by convection because the air currents are moving toward the fire. It cannot be transferred through conduction because the conductivity of the air is very small, and the cooler currents of air moving toward the fire would more than overcome the transfer of heat outward. Therefore, there must be some way for heat to travel across space other than by conduction and convection.

The existence of another process of heat transfer is still more evident when the heat from the sun is considered. Since conduction and convection take place only through some medium, such as a gas or a liquid, heat from the sun must reach the earth by another method, since space is an almost perfect vacuum. Radiation is the name given to this third method of heat transference.

The term "radiation" refers to the continual emission of energy from the surface of all bodies. This energy is known as radiant energy. It is in the form of electromagnetic waves, radio waves, or X-rays, which are all alike except for a difference in wave lengths. These waves travel at the velocity of light and are transmitted through a vacuum more easily than through air because air absorbs some of them. Most forms of energy can be traced back to the energy of sunlight. Sunlight is a form of radiant heat energy which travels through space to reach the earth. These electromagnetic heat waves are absorbed when they come in contact with nontransparent bodies. The result is that the motion of the molecules in the body is increased as indicated by an increase in the temperature of the body.

The differences between conduction, convection, and radiation may now be considered. First, although conduction and convection are extremely slow, radiation takes place with the speed of light. This fact is evident at the time of an eclipse of the sun when the shutting off of the heat from the sun takes place at the same time as the shutting off of the light. Second, radiant heat may pass through a medium without heating it. For example, the air inside a greenhouse may be much warmer than the glass through which the sun's rays pass. Third, although conducted or convected heat may travel in roundabout routes, radiant heat always travels in a straight line. For example, radiation can be cut off with a screen placed between the source of heat and the body to be protected.

Material	Specific heat
Mercury	0.033
Copper	0.095
Iron and steel	0.113
Glass	0.200
Alcohol	0.500
Water	1.000

FIGURE 7–42. Specific heat values for some common materials.

The sun, a fire, and an electric light bulb all radiate energy, but a body need not glow to give off heat. A kettle of hot water or a hot soldering iron radiates heat. If the surface is polished or light in color, less heat is radiated. Bodies which do not reflect are good radiators and good absorbers, and bodies that reflect are poor radiators and poor absorbers. For this reason white clothing is worn in the summer season.

A practical example of the control of loss of heat is the thermos bottle. The flask itself is made of two walls of glass separated by a vacuum. The vacuum prevents the loss of heat by conduction and convection, and a silver coating on the walls prevents the loss of heat by radiation.

Specific Heat

One important way in which substances differ is in the requirement of different quantities of heat to produce the same temperature change in a given mass of the substance. Each substance requires a quantity of heat, called its specific heat capacity, to increase the temperature of a unit of its mass 1° C. The specific heat of a substance is the ratio of its specific heat capacity to the specific heat capacity of water. Specific heat is expressed as a number which, because it is a ratio, has no units and applies to both the English and the metric systems.

It is fortunate that water has a high specific heat capacity. The larger bodies of water on the earth keep the air and solid matter on or near the surface of the earth at a fairly constant temperature. A great quantity of heat is required to change the temperature of a large lake or river. Therefore, when the temperature falls below that of such bodies of water, they give off large quantities of heat. This process keeps the atmospheric temperature at the surface of the earth from changing rapidly.

The specific heat values of some common materials are listed in figure 7–42.

Thermal Expansion

Thermal expansion takes place in solids, liquids, and gases when they are heated. With few exceptions, solids will expand when heated and contract when cooled. Because the molecules of solids are much closer together and are more strongly attracted to each other, the expansion of solids when heated is very slight in comparison to the expansion in liquids and gases. The expansion of fluids has been discussed in the study of Boyle's law. Thermal expansion in solids must be explained in some detail because of its close relationship to aircraft metals and materials.

Expansion in Solids

Solid materials expand in length, width, and thickness when they are heated. An example of the expansion and contraction of substances is the ball and ring, illustrated in figure 7–43. The ball and ring are made of iron. When both are at the same temperature, the ball will barely slip through the ring. When the ball is heated or the ring is cooled, however, the ball cannot slip through the ring.

Experiments show that for a given change in temperature, the change in length or volume is different for each substance. For example, a given change in temperature causes a piece of copper

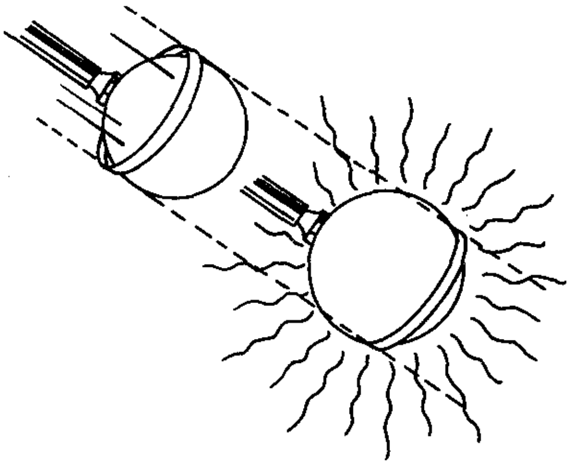


FIGURE 7–43. Ball and ring.

to expand nearly twice as much as a piece of glass of the same size and shape. For this reason, the lead wires into an electronic tube cannot be made of copper but must be made of a metal that expands at the same rate as glass. If the metal does not expand at the same rate as the glass, the vacuum in the tube is broken by air leaking past the wires in the glass stem.

Because some substances expand more than others, it is necessary to measure experimentally the exact rate of expansion of each one. The amount that a unit length of any substance expands for a one-degree rise in temperature is known as the coefficient of linear expansion for that substance.

Coefficients of Expansion

To estimate the expansion of any object, such as a steel rail, it is necessary to know three things about it; namely, its length, the rise in temperature to which it is subjected, and its coefficient of expansion. This relationship is expressed by the equation:

$$\text{Expansion} = (\text{coefficient}) \times (\text{length}) \times (\text{rise in temperature})$$

$$e = kL(t_2 - t_1).$$

In this equation, the letter "k" represents the coefficient of expansion for the particular substance. In some instances, the Greek letter "α" (alpha) is used to indicate the coefficient of linear expansion.

If a steel rod measures exactly 9 feet at 21° C., what is its length at 55° C.? The value of "k" for steel is 10×10^{-6}. If the equation $e = kL(t_2 - t_1)$ is used,

then:
$$e = (10 \times 10^{-6}) \times 9 \times (55 - 21)$$
$$e = 0.000010 \times 9 \times 34$$
$$e = 0.00306.$$

This amount, when added to the original length of the rod, makes the rod 9.00306 feet long.

The increase in the length of the rod is relatively small; but if the rod were placed where it could not expand freely, there would be a tremendous force exerted due to thermal expansion. Thus, thermal expansion must be taken into consideration when designing airframes, powerplants, or related equipment.

Figure 7–44 contains a list of the coefficients of linear expansion for some common substances.

Substance	Coefficient of linear expansion (per degree C.)
Aluminum	24×10^{-6}
Brass	19×10^{-6}
Copper	17×10^{-6}
Glass	$4 \text{ to } 9 \times 10^{-6}$
Quartz	0.4×10^{-6}
Steel	11×10^{-6}
Zinc	26×10^{-6}

FIGURE 7–44. Expansion coefficients of some common materials.

A practical application which uses the difference in the coefficients of linear expansion of metals is the thermostat. This instrument consists of an arrangement of two bars of dissimilar metal fastened together. When the temperature changes, a bending takes place because of the unequal expansion of the metals. Figure 7–45 shows such an instrument, made with a wooden handle for laboratory demonstrations. Thermostats are used in overload relays in motors, in temperature-sensitive switches, and in heating systems.

SOUND

Sound has been defined as a series of disturbances in matter that the human ear can detect. This definition can also be applied to disturbances which are beyond the range of human hearing.

There are three elements which are necessary for the transmission and reception of sound. These are the source, a medium for carrying the sound,

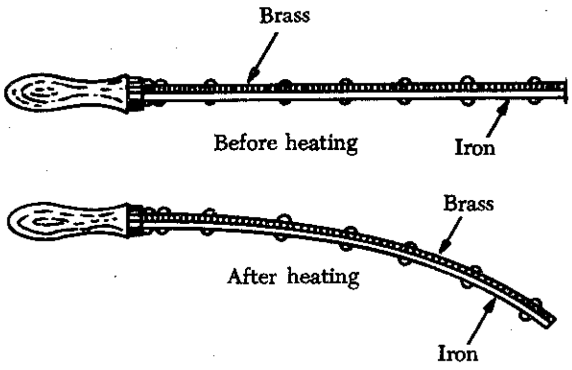


FIGURE 7–45. Compound bar.

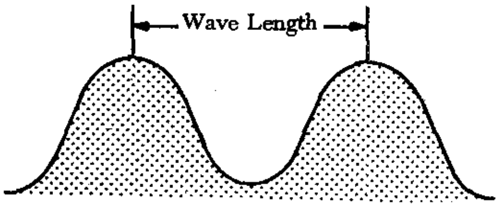


FIGURE 7–46. A transverse wave.

and the detector. Anything which moves back and forth (vibrates) and disturbs the medium around it may be considered a sound source.

An example of the production and transmission of sound is the ring of a bell. When the bell is struck and begins to vibrate, the particles of the medium (the surrounding air) in contact with the bell also vibrate. The vibrational disturbance is transmitted from one particle of the medium to the next, and the vibrations travel in a "wave" through the medium until they reach the ear. The eardrum, acting as detector, is set in motion by the vibrating particles of air, and the brain interprets the eardrum's vibrations as the characteristic sound associated with a bell.

Wave Motion

Since sound is a wave motion in matter, it can best be understood by first considering water waves. When a stone is thrown into a pool, a series of circular waves travel away from the disturbance. In figure 7–46 such waves are diagramed as though seen in cross section, from the side. Notice that water waves are a succession of crests and troughs. The wavelength is the distance from the crest of one wave to the crest of the next. Water waves are known as transverse waves because the motion of the water molecules is up and down, or at right angles to the direction in which the waves are traveling. This can be seen by observing a cork on the water, bobbing up and down as the waves pass by; the corks moves very little from side to side.

Sound traveles through matter in the form of longitudinal wave motions. These waves are called longitudinal waves because the particles of the medium vibrate back and forth longitudinally in the direction of propagation, as shown in figure 7–47.

When the tine of a tuning fork (figure 7–47) moves in an outward direction, the air immediately in front of the tine is compressed so that its momentary pressure is raised above that at other points in the sorrounding medium. Because air is elastic, this disturbance is transmitted progressively in an outward direction from the tine in the form of a compression wave.

When the tine returns and moves in an inward direction, the air in front of the tine is rarefied so that its momentary pressure is reduced below that at other points in the surrounding medium. This disturbance is transmitted in the form of a rarefaction (expansion) wave and follows the compression wave through the medium.

The progress of any wave involves two distinct motions: (1) The wave itself moves forward with constant speed, and (2) simultaneously, the particles of the medium that convey the wave vibrate harmonically. (Examples of harmonic motion are the motion of a clock pendulum, the balance wheel in a watch, and the piston in a reciprocating engine.)

The period of a vibrating particle is the time "t" (in seconds) required for the particle to complete one vibration.

The frequency "f" is the number of vibrations completed per second and may be expressed in c.p.s. When expressed in this unit, the word "cycles" means vibrations. The period is the reciprocal of the frequency:

$$t = 1/f.$$

The velocity of a wave is equal to the wavelength λ (lambda) divided by the period. Since the period is the reciprocal of the frequency, the velocity is,

$$v = f\lambda$$

where:

v = velocity in ft./sec.
f = frequency in c.p.s.
λ = wavelength in ft.

The amplitude of vibration is the maximum displacement of the particle from its equilibrium position.

Two particles are in phase when they are vibrating with the same frequency, and continually pass through corresponding points of their paths at the same time. For any other condition the particles are out of phase. The two particles are in phase opposition when they reach their maximum displacement in opposite directions at the same time.

The wavelength is the distance measured along the direction of propagation between two corre-

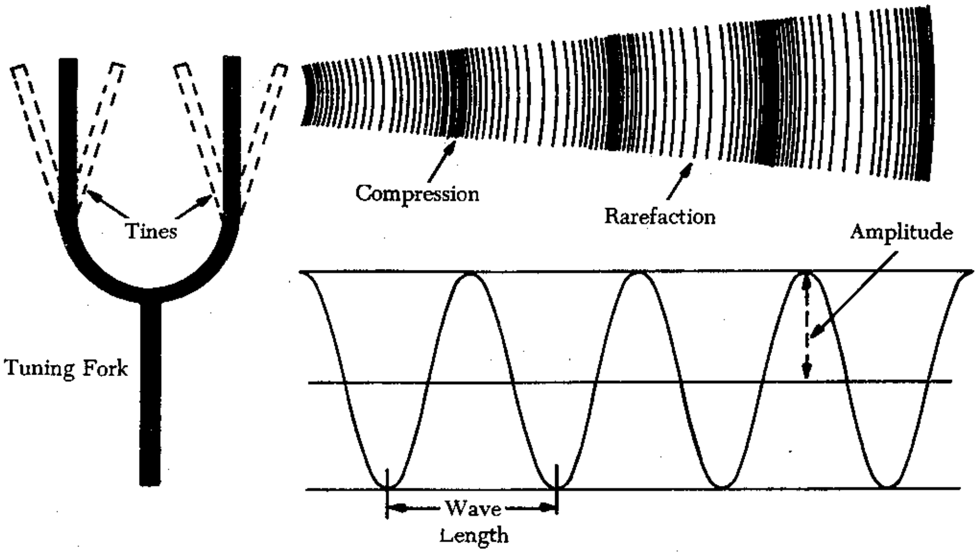


FIGURE 7–47. Sound propagation by a tuning fork.

sponding points of equal intensity that are in phase on adjacent waves. This length can be represented by the distance between the adjacent maximum rarefaction points in the traveling sound wave (figure 7–47). When referring to figure 7–47, keep in mind that the transverse wave drawn below the compressional wave is merely a device for simplifying the concept and relating it to the type of wave illustration commonly used in discussions of electromagnetic waves.

When an advancing wave encounters a medium of different character, some of its energy is reflected back into the initial medium, and some is transmitted into the second medium.

Reflection of Sound Waves

To understand wave reflection, it is helpful to think of the wave as a ray. A ray is a line which indicates the direction the wave is traveling. In a uniform medium, a ray will travel in a straight line. Only at the boundary of two media or in an area where the medium is changing do the rays change their direction.

If a line, called a "normal," is drawn perpendicular to a boundary, the angle between an incoming ray and this normal is called the angle of incidence, "*i*" as shown in figure 7–48. The angle which the reflected ray makes with the normal is called the angle of reflection "*r*." Any wave being reflected is reflected in such a way that the angle of incidence equals the angle of reflection.

Light is often thought of first when reflection is discussed; however, reflection is equally common in other types of waves. As an example, echoes are caused by reflection of sound waves.

When a hard surface is situated so that a sound reflection from it is outstanding, it appears as a distinct echo, and is heard an appreciable interval later than the direct sound. If the surface is concave, it may have a focusing effect and concentrate the reflected sound energy at one locality. Such a reflection may be several levels higher in intensity than the direct sound, and its arrival at a later time may have particular significance in such applications as sonar.

Speed of Sound

In any uniform medium, under given physical conditions, sound travels at a definite speed. In

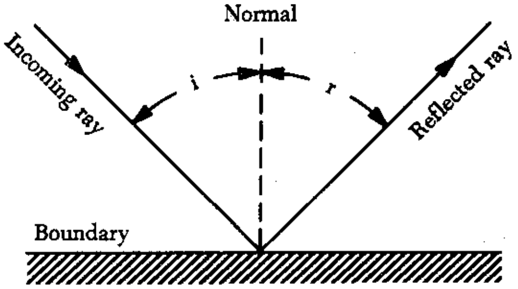


FIGURE 7–48. Reflection of a ray.

some substances, the velocity of sound is higher than in others. Even in the same medium under different conditions of temperature, pressure, etc., the velocity of sound varies. Density and elasticity of a medium are the two basic physical properties which govern the velocity of sound.

In general, a difference in density between two substances is sufficient to indicate which one will be the faster transmission medium for sound. For example, sound travels faster through water than it does through air at the same temperature. However, there are some surprising exceptions to this rule-of-thumb. An outstanding example among these exceptions involves comparison of the speed of sound in lead and aluminum at the same temperature. Sound travels at 16,700 f.p.s. in aluminum at 20° C., and only 4,030 f.p.s. in lead at 20° C., despite the fact that lead is much more dense than aluminum. The reason for such exceptions is found in the fact, mentioned above, that sound velocity depends on elasticity as well as density.

Using density as a rough indication of the speed of sound in a given substance, it can be stated as a general rule that sound travels fastest in solid materials, slower in liquids, and slowest in gases.

For a fixed temperature, the velocity of sound is constant for any medium and is independent of the period, frequency, or amplitude of the disturbance. Thus, the velocity of sound in air at 0° C. (32° F.) is 1,087 f.p.s. and increases by 2 f.p.s. for each centrigrade degree of temperature rise (1.1 f.p.s. for each degree Fahrenheit). For practical purposes, the speed of sound in air may be considered 1,100 f.p.s.

Mach Number

In the study of aircraft that fly at supersonic speeds, it is customary to discuss aircraft speed in relation to the velocity of sound (approximately 750 miles per hour). The term "Mach number" has been given to the ratio of the speed of an aircraft to the speed of sound, in honor of Ernst Mach, an Austrian scientist.

Thus, if the speed of sound at sea level is 750 miles per hour, an aircraft flying at a Mach number of 2.2 would be traveling at a speed of 750 m.p.h. × 2.2 = 1,650 miles per hour.

Frequency of Sound

The term "pitch" is used to describe the frequency of a sound. The outstanding recognizable difference between the tones produced by two different keys on a piano is a difference in pitch. The pitch of a tone is proportional to the number of compressions and rarefactions received per second, which in turn, is determined by the vibration frequency of the sounding source.

Frequency, or pitch, is usually measured by comparison with a standard. The standard tone may be produced by a tuning fork of known frequency or by a siren whose frequency is computed for a particular speed of rotation. By regulating the speed, the pitch of the siren is made equal to that of the tone being measured.

Loudness

When a bell rings, the sound waves spread out in all directions and the sound is heard in all directions. When a bell is struck lightly, the vibrations are of small amplitude and the sound is weak. A stronger blow produces vibrations of greater amplitude in the bell, and the sound is louder. It is evident that the amplitude of the air vibrations is greater when the amplitude of the vibrations of the source is increased. Hence, the loudness of the sound depends on the amplitude of the vibrations of the sound waves. As the distance from the source increases, the energy in each wave spreads out, and the sound becomes weaker.

The intensity of sound is the energy per unit area per second. In a sound wave of simple harmonic motion, the energy is half kinetic and half potential; half is due to the speed of the particles, and half is due to the compression and rarefaction of the medium. These two energies are 90 degrees out of phase at any instant. That is, when the speed of particle motion is at a maximum, the pressure is normal, and when the pressure is at a maximum or a minimum, the speed of the particles is zero.

The loudness of sound depends upon both intensity and frequency. The intensity of a sound wave in a given medium is proportional to the following quantities;

(1) Square of the frequency of vibration.
(2) Square of the amplitude.
(3) Density of the medium.
(4) Velocity of propagation.

At any distance from a source of sound (point), the intensity of the wave varies inversely as the square of the distance from the source.

As the sound wave advances, variations in pressure occur at all points in the transmitting medium. The greater the pressure variations, the more intense the sound wave will be. It can be shown that the intensity is proportional to the square of the pressure variation regardless of the frequency. Thus, by measuring pressure changes, the intensities of sounds having different frequencies can be compared directly.

Measurement of Sound Intensity

The loudness (intensity) of sound is not measured by the same type of scale used to measure length. The human ear has a nonlinear response pattern, and units of sound measurement are used that vary logarithmically with the amplitude of the sound variations. These units are the "bel" and "decibel," which refer to the difference between sounds of unequal intensity or sound levels. The decibel, which is one-tenth of a bel, is the minimum change of sound level perceptible to the human ear. Hence, the decibel merely describes the ratio of two sound levels. For example, 5 decibels may represent almost any volume of sound, depending on the intensity of the reference level or the sound level on which the ratio is based.