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ELEMENTARY PHYSICS FOR AIR CREW TRAINEES

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SECTION I

SCIENCE, PHYSICS, AND METEOROLOGY

1. Definitions.—*a.* Science, in the generally accepted meaning of the term, is knowledge systematized and formulated with reference to the discovery of general truths or the operation of natural laws.

b. Physics is the science which treats of the laws and properties of matter and the forces acting upon it. It is the science of energy and rests upon the fundamental modern doctrine of the conservation of energy. Physics is an experimental science. However, most of the relationships or physical laws discovered through experimentation can be expressed by mathematical formulas or equations. Hence physics uses the language of mathematics to a large extent. At one time the great divisions of science were kept well apart. Now we find such lines of inquiry as physical chemistry, astrophysics,

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biochemistry, physical optics, etc., filling the gaps between them so effectively that they run together and fade into one another like the colors of the spectrum.

c. Meteorology is sometimes considered as a branch of physics ("Physics of the Air") and in its broader sense includes a study of the laws of physics as applied to the atmosphere. Meteorology is a branch of natural science that treats of changing conditions in the atmosphere. It is the science of the atmosphere and its phenomena (events), those phenomena which collectively are called "the weather."

2. Importance of weather.—*a.* Because of their great variety and their close relation to all our activities, the phenomena of the weather are subjects of never ending interest. They are not only of interest but of great importance, since weather is one of the chief elements in man's life.

b. The importance of weather and weather forecasting to aviation is obvious. Aviators, who are especially at the mercy of the weather since flying schedules are maintained in all seasons, are asking meteorologists to forecast the weather conditions not only for points on the ground but for elevations far above the ground.

c. Weather has played an important part in wars throughout history. In modern warfare, weather assumes even greater importance because of the use of airplanes and because of the swift moves made over great distances by mobile units. Early campaigns by the German army apparently were timed to take advantage of weather conditions which had been accurately forecast. Knowledge of Atlantic weather conditions and the forecasting of weather over northwest Europe would have been facilitated had Germany succeeded in establishing weather stations in Greenland.

3. Purpose of weather course.—*a.* Weather courses for airmen are not given for the purpose of training them to be accurate forecasters.

b. The aim of a weather course for aviators is to acquaint them with the terminology and fundamental principles of meteorology. This is necessary if airmen are to be able to make adequate use of the weather information available. Airmen should be taught to interpret weather maps, weather reports, and weather forecasts; and should know how to make use of this information in flight. When weather information is either inadequate or in error, aviators should have sufficient understanding of weather principles to make correct decisions if trouble arises.

c. On any flight, it is necessary for air crews to have a reasonable idea of probable weather to be encountered, and it is also necessary for them to have enough knowledge of weather to recognize unforeseen, hazardous conditions encountered en route, and make decisions which will bring about successful termination of the flight and not endanger themselves, their passengers, or their cargo.

d. The importance of weather to an airman cannot be overemphasized. A large percentage of all aircraft accidents are attributable to ignorance concerning weather.

4. Reason for weather course.—*a.* Experience has shown that the fundamentals of meteorology cannot be grasped without first preparing the student for the subject. Weather for airmen cannot be set down as a simple set of rules that anybody can memorize. It is absolutely essential that some of the fundamental theory of weather be known and understood.

b. Rules are good things to have along with a knowledge of the fundamental theory. By themselves, however, they are not sufficient. Rules are easily forgotten, and an aviator who depends on them may find death just around the corner. If he forgets his rules when tough going is encountered in flights, he will not be able to figure out what to do. If, on the other hand, an aviator knows the fundamental theory of meteorology, he will be able to determine which way to turn and what to do when flying through bad weather. That is, the situation may be correctly analyzed by the airman and he should not have to depend on memory, which is forever a human failing.

c. Since the theory of meteorology needs to be understood and since 75 percent of all would-be pilots lack the proper background for an understanding of this theory, a course to supply this background is necessary. Hence the principal aim of this course is a preparation for studies in meteorology. Since the importance of meteorology cannot be overemphasized, it follows that this course in physics will be fundamental to skillful and safe piloting.

QUESTIONS

1. Define science; physics; meteorology.
2. Why is this course in "Physics of Weather" essential to a student pilot?
3. Give essential differences between flying in wartime and peacetime.

SECTION II

UNITS OF MEASURE

5. General.—It has already been stated that the facts and laws of physics may frequently be expressed in mathematical language. Physics is not merely descriptive. One cannot pursue it far without recognizing the existence of numerous quantitative relationships that require expression. Not only does one wish to know *what happens* under given conditions, but to what degree effects are produced by causes of given amount.

6. Magnitudes (fundamental and derived).—*a.* A magnitude is anything that may be considered as being greater or less in amount, degree, or extent. Thus, the height of a tower and the brightness of a lamp are magnitudes. Many kinds of magnitude are involved in the different branches of physics. Some of those most familiar are length, time, speed, weight, power, temperature, strength of an electric current, etc. One's ideas of some of these are so deep-seated and elemental that it is unnecessary or impossible to define them. This is true, for example, of length (meaning simply distance) and of time.

b. So far as the layman's understanding of them is concerned, these magnitudes are independent of each other and of everything else. Of many other familiar magnitudes, this is not true. To illustrate: speed cannot be thought of without connecting it with both length and time. It is distance per unit of time; that is, length and time must be combined in a definite way in order to express the idea of speed.

c. Just as chemistry recognizes certain primary substances, called elements, out of which other substances are formed, so also in physics there are a small number of fundamental or elementary magnitudes, in terms of which most of the other magnitudes (consequently called secondary or derived magnitudes) can be expressed. Physicists are accustomed to regard the three magnitudes, length, time, and mass, as fundamental. All the other magnitudes, such as speed, are derived.

7. Idea of units and need for standards of weights and measures.—*a.* Before the fundamental and derived units are discussed, the idea of units and the need for standards should be made clear. Perhaps they can be best explained by taking the fundamental unit of length and tracing some of its history.

b. Undoubtedly, the measurement of length must have come about through necessity. It is quite probable that pieces of string may have been used to produce desired lengths. For example, somebody may have used pieces of string to represent the length and width of a proposed hut. The timber was then cut to size by using these pieces of string to measure off the desired lengths.

c. However, each piece of string would measure only one thing. One string could measure the length of the hut but did not take into account its width. It is easily understood how extraordinarily difficult and troublesome this process might have been when many such measurements were to be made and recorded; still more so when others had to be informed about them. In addition, one can imagine how difficult it would have been to estimate long distances by such a process.

d. An enormous advance in the science of measurement was made when it was recognized that a long length could be defined by means of a unit and a number, which indicated how many times the unit must be placed end to end in a straight line in order to attain the desired longer length. It is possible that someone in building a hut discovered that the length or width of the hut could be determined by the number of strides it would take to walk from one corner to another. The length of one stride was, therefore, chosen as the unit of length. Later this rather indefinite length of a stride was replaced by that of the foot, a more clearly defined unit, and still later, a stick was chosen as the standard foot which was to be the basis of all measurements of length.

e. It is not surprising that the first units were connected in some way with human beings; the stride, foot, the fathom equaling the distance which can be encompassed when the arms are outstretched, and the acre equaling the area of land which could be ploughed in a day. Each individual industry chose these primary units without concerning itself with another. Thus, until 1875, there were in existence the Prussian, Rhineland, English, and French foot. Even in the same country, different units were used for different purposes. The mariner used knots and fathoms, the surveyor, rods, the weaver, ells, while the carpenter worked with feet and inches.

f. This variety of independent units was bound to cause inconveniences, especially when the introduction of the railway, steamship, telegraph, and telephone caused people of different countries to exchange their material as well as their intellectual goods with one another. The need for having an absolutely permanent basis for weights and measures, and the desirability of harmonizing the chaos which existed in this matter throughout the world resulted in the establishment of the metric system by the French Government in 1793. It has since been adopted by nearly every civilized country, although in Great Britain and the United States the familiar English system is still in use, except in scientific work, where the metric system prevails.

g. The English system and its variation, the British engineering system, are used more from habit than because of any real advantage they may possess. The metric system, arranged decimally like our system of money, is admirably adapted to every practical and scientific purpose. Thus millimeters, centimeters, kilometers, etc., are expressible in terms of the meter by simply moving the decimal point. Units of mass have a similar arrangement and notation.

h. In this manual, the metric system and the British engineering system (B. E. S.) only are used. The ignoring of the English system should not confuse the student as the units used in the English and the British engineering system are the same except for mass and weight.

i. With all this in mind, a discussion of both the fundamental and derived units in both the British and metric systems is in order.

8. Fundamental units.—The fundamental units are length, mass, and time. An absolute unit is one from which all like units may be derived. For example, the centimeter is considered the absolute unit of length in the metric system and from it one can obtain other units of length such as the millimeter and kilometer. Thus it is evident why the metric system is often called the centimeter-gram-second (C. G. S.) system of absolute units, since the centimeter, gram, and second are taken as the units of length, mass, and time, respectively. The British engineering system (frequently called merely the British system) of units uses length, time, and force as the fundamental units. Hence weight is used in place of mass and the system is referred to as a gravitational system instead of an absolute system. The units used are the foot, pound, and second.

a. Unit of length (*L*).—(1) The unit of length in the metric system is the centimeter, or one-hundredth part of a meter. The meter conforms to the distance between ends of a bar of platinum which is kept in Paris, the bar being measured when it is the temperature of melting ice. This bar as a standard of length was established by the French Government in 1799 with a view to its becoming universal. It was intended to be exactly 1 ten-millionth of the distance from the equator to the pole measured along a meridian of the earth.

(2) The British standard of length, from which the foot and inch are determined, is the standard yard. This is the "distance between the centers of the transverse lines in the two gold plugs in the bronze bar deposited in the office of the Exchequer," measured at a temperature of 62° F.

(3) That there is rhyme and reason to the metric system may be seen from the following table of conversions:

$$1 \text{ millimeter (mm)} = \frac{1}{1{,}000} \text{ meter (m)}$$
$$1 \text{ centimeter (cm)} = \frac{1}{100} \text{ meter}$$
$$1 \text{ decimeter (dm)} = \frac{1}{10} \text{ meter}$$
$$1 \text{ kilometer (km)} = 1{,}000 \text{ meters}$$

or:

$$1{,}000 \text{ mm} = 100 \text{ cm} = 10 \text{ dm} = 1 \text{ m} = 0.001 \text{ km}$$

(4) That there is no rhyme nor reason to the British system other than force of habit is apparent from the following table:

36 inches (in.) = 1 yard (yd.)
3 feet (ft.) = 1 yard
1 mile (mi.) = 1,760 yards

Other equivalents in the British system are—

1 foot = 12 inches
1 mile = 5,280 feet

(5) A comparison between the two systems gives—

1 yard = 91.44 centimeters
1 foot = 30.48 centimeters
1 inch = 2.54 centimeters
1 mile = 1.61 kilometers
1 centimeter = 0.39 inch
1 meter = 39.37 inches
1 kilometer = 0.62 mile (approximately $5/8$ mile)

(6) Before the other fundamental units are discussed, it might be best to explain area and volume, since both are measured in terms of length.

(7) An area is defined as having length and breadth but no thickness. Thus the floor of a house whose dimensions are 20 by 20 feet has an area of 400 square feet (sq. ft. or $ft.^2$) and the unit of area is 1 square foot in the British system. In the metric system the unit of surface is 1 square centimeter (cm^2).

(8) Volume is defined as the amount of space included by the surfaces of a solid. Thus the volume of a room having width, breadth, and height of 20 feet is 20 by 20 by 20 feet or 8,000 cubic feet (cu. ft. or $ft.^3$), the unit of volume in the British system being 1 cubic foot. One cubic centimeter (cc or cm^3) is the unit of volume in the metric system.

(9) Volume is also defined as capacity or the ability to hold. Thus, there are measurements such as liter, quart, etc.

1 liter (1) =1,000 cc
1 liter (1) =1.057 quarts
1 quart=57¾ cubic inches

b. Unit of mass (*M*).—(1) The unit of mass in the metric system is the gram, one-thousandth part of the standard kilogram. The standard kilogram, which is a mass of platinum kept in Paris, was intended to represent the exact mass of a cubic decimeter of distilled water at its greatest density or at the temperature of 4° C.

(2) Since two masses may be compared with a far higher degree of accuracy than that with which the weight of a cubic decimeter of water can be determined, the mass of platinum kept in Paris is the real standard on which all metric weights are based. The following table illustrates the metric units of mass:

1 gram (gm or g) =1,000 milligrams (mg)
1 gram=100 centigrams
1 gram=10 decigrams
1 gram=1/1000 kilogram

(3) The British system of units has no commonly used, well-known unit of mass. The reason the British system does not have a well-known unit of mass is because this system uses weight as a fundamental unit instead of mass. In the British system, the unit of weight is the pound, which is familiar to everyone. When a pound mass is mentioned, what is really meant is the quantity of matter or mass that will weigh 1 pound. But the pound unit cannot be used interchangeably for both mass and weight because these quantities, although proportional, are not the same thing. A discussion of the relation

between mass and weight is given in section V. The mass of a 1-pound weight is approximately 453.59 grams.

c. Unit of time (t).—(1) Because of the earth's exact periodic movement, it is easy to see why the standard of time chosen is that which the earth requires for a single rotation around on its axis. More exactly, it is the mean time elapsing between successive transits of the sun across the meridian at any one place. This period (mean solar day) is divided into 24 hours, every hour into 60 minutes, and every minute into 60 seconds.

(2) The unit of time in both the metric and British systems is the mean solar second or one 86,400th part of a mean solar day.

9. Derived units.—Derived units, as explained, are those like speed which are dependent upon one or more of the fundamental units.

a. Density (d).—(1) Density is the mass of weight or quantity of matter of a substance per unit of its volume. In the metric system it is expressed in grams per cubic centimeter, while pounds per cubic foot is the measure used in the English system. The density of water at 4° C. is 1 gram per cubic centimeter in the metric system and 62.4 pounds per cubic foot in the English system. The density of air at 0° C. and a pressure of 76 cm of mercury is 0.00129 gm per cm^3 and in the English system is 0.0765 lb. per $ft.^3$

(2) The value of the density of the air, 0.00129 gm per cm^3, implies that if all elements (nitrogen, oxygen, argon, etc.) within the space of 1 cubic centimeter could be picked out and weighed, their total weight would come to 0.00129 grams.

(3) (a) In the metric system, $d=\frac{m}{V}$, where d is density, m is mass and v is volume. Therefore $m=vd$ and if the volume and density of a body are known it is possible to calculate its mass. Likewise, knowing the mass and density, the volume can be calculated, since $v=\frac{m}{d}$.

$$v=\frac{m}{d}=\frac{\text{grams}}{\frac{\text{grams}}{\text{cm}^3}}=\frac{\text{grams}}{\text{grams}}\cdot cm^3=cm^3$$

which is the unit of volume.

(b) In the British system, the density is expressed as weight per unit volume and if weight is substituted for mass in the preceding formulas a similar set will be obtained for use with English units.

Thus—

$$d=\frac{w}{v}$$
$$w=vd$$
$$v=\frac{w}{d}$$

b. Velocity (V).—(1) Velocity is defined as the distance traveled per unit of time. If, then, s is the distance traveled per unit of time t,

$$V=\frac{s}{t} \text{ or } \frac{\text{cm}}{\text{sec.}} \text{ or } \frac{ft.}{\text{sec.}} \text{ or } \frac{\text{miles}}{\text{hour}}.$$

(2) By means of this equation the value of any one of the quantities in it can be found if the other two are known. For example, if an airplane traveling at 100 miles per hour took 5 hours to go in a direct line from Randolph Field to New Orleans, the distance between these two places would be—

$$s=Vt=(100 \text{ mph})\ (5 \text{ hr.})=500 \text{ miles}$$

(3) Here the unit of time is 1 hour and the velocity is 100 miles per hour. Assuming that the airplane's velocity was constant, it flew 100 miles for each unit of time of which there were 5, making a total of 500 miles flown.

c. Acceleration (a).—(1) Acceleration is the rate of increase or decrease (sometimes called deceleration) of velocity. It is defined by the equation:

$$a=\frac{V}{t}=(V \text{ is the change in velocity during a time } t)$$

(2) The units of acceleration in both the English and metric systems are easy to understand.

(*a*) *British system.*

$$a=\frac{V}{t}=\frac{\left(\frac{1 \text{ ft.}}{\text{sec.}}\right)}{\text{sec.}}=1 \text{ foot per second per second}$$

or: $$a=\left(\frac{1 \text{ ft.}}{\text{sec.}}\right)\left(\frac{1}{\text{sec.}}\right)=\frac{1 \text{ ft.}}{(\text{sec.})^2}=1 \text{ foot per second squared}$$

(*b*) *Metric system.*

$$a=\frac{\left(\frac{1 \text{ cm}}{\text{sec.}}\right)}{\text{sec.}}=1 \text{ cm per second per second}$$

or: $$a=\left(\frac{1 \text{ cm}}{\text{sec.}}\right)\left(\frac{1}{\text{sec.}}\right)=\frac{1 \text{ cm}}{(\text{sec.})^2}=1 \text{ cm per second squared}$$

(3) Thus, if a body starts from rest and at the end of the first second has a velocity of 10 feet per second and at the end of the second second has a velocity of 20 feet per second, and at the end of the third second has a velocity of 30 feet per second, its acceleration is 10 feet per second per second.

$$a=\frac{V}{t}=\frac{\frac{10\text{ ft.}}{\text{sec.}}}{\text{sec.}}$$

QUESTIONS AND PROBLEMS

1. What are the three fundamental units and why are they so called?
2. What are derived units?
3. Why is the metric system more logical and better adapted to every practical and scientific purpose?
4. What are the fundamental units in the metric and British systems?
5. One meter is equal to how many decimeters? centimeters? millimeters?
6. Ten miles equal how many kilometers?
7. Change 755 milligrams to grams.
8. Change 1,540 grams to kilograms.
9. A certain airplane weighs 5,000 kilograms. Express its weight in pounds.
10. How many liters does a tank hold which is 6 meters long, 1.5 meters wide, and 1 meter deep? How many cubic centimeters does it hold?
11. Define velocity; acceleration.
12. In his transatlantic flight from New York to Paris in 1927, Lindbergh traveled 3,630 miles in 33.5 hours. What was his average speed?
13. A ball rolling down an incline has a velocity of 60 cm per second at a certain instant and 11 seconds later it has attained a velocity of 181 cm per second. Find its acceleration.
14. A body has an acceleration of 10 ft./sec.^{2} What will be its velocity at the end of 20 seconds, assuming that it started from rest?
15. An airplane lands at a velocity of 40 miles per hour and is brought to rest in 1 minute. Find the negative acceleration (deceleration) in feet per second per second.

SECTION III

ATMOSPHERE

10. General.—The atmosphere is the laboratory in which the meteorologist carries on his experiments. This vast laboratory is unique among scientific laboratories in that the experimenter has practically no control over the reactions that take place within it. While the chemist, the physicist, the biologist, and even the geologist may more or less control the conditions of the problem that he is investigating, the meteorologist can do little more than observe and ponder. His experimental problems are very difficult because the elements with which he has to deal are constantly changing. It is the purpose of this section to point out some of the more interesting features of this ocean of air in the lowermost depths of which man walks and flies.

11. Definition.—The word atmosphere is derived from the Greek words "atmos," which means vapor, and "sphaira," which means sphere. It is, therefore, the spherical gaseous layer which envelops the earth, the fluid sea at the bottom of which we live.

12. Composition.—*a.* The air, or the material of which the atmosphere is composed, is a mechanical mixture of a number of different gases.

b. That air is a mixture and not a compound is evident from the following facts:

(1) The relative weights of the components are not in proportion to their atomic weights.

(2) The relative portions of the components vary somewhat (they are not constant).

(3) The components can be separated by physical methods. For example, if pure dry air is cooled, oxygen condenses (liquefies) before nitrogen, since it has a higher boiling point; whereas if air were a compound, there would not be a separation of the constituents of the air by separate liquefaction. Likewise, when liquid air evaporates, the nitrogen evaporates first because it has a lower boiling point,

leaving almost pure oxygen. If air were a compound, there would be no separate evaporation, since there would be just one substance to evaporate.

c. A sample of dry and pure air contains about 78 percent (by volume) nitrogen (N_2), 21 percent oxygen (O_2), almost 1 percent argon (A), and about 0.03 percent carbon dioxide (CO_2). Together these four gases constitute about 99.99 percent of dry and pure air. The remaining 0.01 percent represents traces of hydrogen and several rare gases such as neon, krypton, helium, and xenon.

d. The air also contains a variable amount of water vapor and dust particles. In many respects, the water vapor is the most important constituent of the atmosphere in spite of the fact that the weight of the water vapor never exceeds 4 percent of the total weight of the atmosphere. Its importance to agriculture is obvious, yet it is also responsible for adverse flying conditions. The three most dangerous flying hazards are fog, thunderstorms, and icing.

e. The maximum amount of water vapor that the air can absorb depends entirely upon the temperature of the air; the higher the temperature of the air, the more water vapor it can hold. The air is said to be saturated with moisture when this maximum amount is reached at a particular temperature.

f. Dust and other minute particles also exist in the atmosphere in variable amounts. When there is a high concentration of these particles (impurities) in the atmosphere, one observes what is known as *haze*. This phenomenon is a definite flying hazard because it results in lowering of visibility.

g. The main sources of these impurities are arid regions, seas, industrial regions, forest fires, and volcanoes.

h. Arid regions such as deserts, and very dry country as in Kansas and Oklahoma, are prominent sources of dust particles. Minute grains of dust are picked up and whirled by the winds which readily distribute them throughout the lower atmosphere, sometimes far from the source. Strong winds may give rise to sand and dust storms of such intensity as to make flying extremely hazardous.

i. Observations show that the air normally contains a considerable amount of salts. Spray is whirled up from the ocean through the action of the winds, and when it evaporates, the salt remains in the air in the form of minute particles.

j. Combustion contributes a considerable quantity of impurities to the atmosphere. The smoke from cities, forest fires, and volcanoes contains many very fine particles. The smoke from a fire may seem to clear up and disappear at a small distance from its source, but this simply means that the myriads of particles have lost their shape as a group and are scattered. Being extremely fine, they stay in the air for a long time.

k. Such dust and salt particles as have been discussed are inorganic. A small part of the vast amount of dust in the atmosphere is of organic origin.

l. Pollen from flowering plants and plant spores is a good example of organic dust in the air. Being so small, it is picked up by the air and often blown hundreds of miles. Hay fever has been attributed to the pollen of ragweeds and other plants.

m. Other examples of organic dust in the air are the various kinds of minute living creatures such as bacteria and yeast cells. The germs causing many of man's most dreaded diseases are sometimes carried by the air.

n. The presence of dust in the atmosphere is important for other reasons besides its influence on visibility. If the air were perfectly pure, there could be no appreciable condensation of water vapor. When the air is cooled to its saturation temperature, condensation takes place on certain active (hygroscopic) nuclei. Salt particles from the ocean and various products of combustion are most active as condensation nuclei, observations showing that such particles are present in the atmosphere in abundant amounts.

o. Dust particles scatter light and help to give the sky its characteristic blue appearance. They also help to color sunsets by acting as a light filter, removing the blue and leaving the red transmitted light. Scattered light also promotes twilight after the sun has set.

p. Dust absorbs some of the sun's heat, and any great increase in the dust content of the air is likely to be accompanied by a decrease in insolation (solar radiation received by the earth's surface).

13. Density.—*a.* Man lives at the bottom of a deep sea composed of a mixture of many gases that make up a very highly compressible fluid, the air. This fluid has a mass similar to any other substance and is therefore subject to the forces of gravity. The gravitational force, owing to the mass of the earth, pulls the air toward it and thus holds the earth's atmosphere.

b. Since this fluid, the atmosphere, is compressible, those layers or parts at the bottom are compressed considerably more than the upper layers that are not supporting so great a weight of air above them.

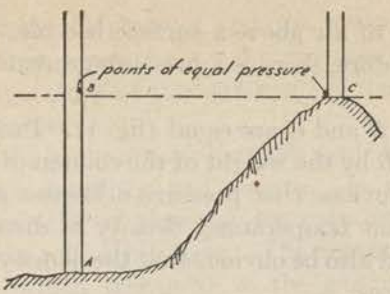

FIGURE 1.—Decrease of pressure with altitude.

Thus the density of the air close to the surface will be greater than the density of air at a higher elevation.

c. Density is defined as mass per unit volume $\left(\frac{\text{mass}}{\text{volume}}\right)$. Thus the density of the atmosphere may be measured and expressed either in terms of grams per cubic centimeter or in pounds per cubic foot.

d. At ordinary pressure and temperature, the weight of a sample of air near the earth's surface is about $1/800$ of the weight of an equal volume of water. Thus it has been found that 1 cubic foot of air weighs about 0.0765 pound and that 1 cubic centimeter of air weighs about 13×10^{-4} grams (0.0013 gram) near the earth's surface. Thus, the density of air near the earth's surface is about 0.0765 pound per cubic foot and 13×10^{-4} grams per cubic centimeter.

e. It might be of interest to note and compare the molecular weights of air and water. That of air is 28.735, whereas water has a molecular weight of 18.00, hence, moist air is somewhat lighter than dry air.

f. In consequence of this weight, the atmosphere exerts a certain pressure upon the earth's surface. The physicist defines pressure as the force distributed over a unit area in terms of pounds per square inch, grams per square centimeter, and so on. In any fluid, the pressure on the bottom is equal to the weight of the fluid above the surface divided by the area of the surface.

g. At the earth's surface, the atmosphere exerts a pressure amounting to about 14.7 pounds per square inch. This means that, under normal conditions, a column of air 1 inch square reaching from the earth's surface to the upper limits of the atmosphere will weigh 14.7 pounds. This is equivalent in weight to a column of water 34 feet high, or to a column of mercury 29.92 inches (76 centimeters) high. Since water barometers would be too big to measure atmospheric pressure, mercurial barometers are used.

h. The column of air above a surface becomes shorter as we go up in the air. Therefore, there is a pressure decrease with an increase in altitude.

i. Pressures at *B* and *C* are equal (fig. 1). Pressure at *A* is greater than pressure at *B* by the weight of the column of air *AB*.

j. It is quite obvious that pressure decreases as altitude increases. Since, for constant temperature, density is directly proportional to pressure, it should also be obvious that the density of air also decreases as altitude increases.

14. Height.—*a.* It is hard to visualize the upper atmosphere. Since the density of the air decreases with increase in altitude, one naturally thinks of the air as becoming thinner and thinner with increased elevation until it merges with whatever traces of gases there may be in interplanetary space. It is quite certain that the atmosphere could not extend upward for more than about 20,000 miles and still turn with the earth as it rotates on its axis. At this distance the centrifugal force due to the earth's rotation approaches the magnitude of gravity, and the earth could not retain the air.

b. Even though the atmosphere extends to great altitudes, it is only the lower part which is of importance to weather phenomena. The highest clouds (cirrus) are seldom more than 35,000 feet above the earth's surface, while 50 percent of the total weight and 90 percent of the total moisture content of the atmosphere are within 18,000 feet of the surface.

c. Although it is conceivable that the atmosphere may extend upward about 20,000 miles, little is known of that part above 150 miles (about 800,000 feet). Below 150 miles, however, scientists have been able to find out enough about the atmosphere to divide it into various well-defined layers.

15. Stratification.—*a.* It will be seen from figure 2 that the air temperature normally decreases with elevation up to about 36,000 feet and then remains more or less constant. The rate of decrease in temperature along the vertical is called the *lapse rate.* The lower part of the atmosphere, which normally is characterized by a relatively large lapse rate (rate of temperature decrease with altitude being greater in this part), is called the *troposphere.* The upper part of the atmosphere, which is characterized by an almost constant temperature along the vertical, is called the *stratosphere.* The transitional layer separating the stratosphere from the troposphere is called the *tropopause.* The height of the tropopause above the earth's surface varies considerably with latitude and season. Figure 3 shows the normal height of the tropopause and the mean distribution of temperature in the lower atmosphere. It is interesting to note that on the whole the temperature of the stratosphere decreases from the North Pole to the Equator.

b. Observations in the lower atmosphere are made by an instrument called a radio meteorograph or radio-sonde. It is a very light, small instrument consisting of pressure, temperature, and humidity measuring instruments rolled into one. The instrument includes a minute radio sender which transmits to the ground radio signals indicating the values of pressure, temperature, and humidity. These instruments are carried by balloons which normally attain altitudes of 40,000 feet before they burst. Occasionally such balloons have reached altitudes exceeding 100,000 feet. From these observations and from recent studies of radiation, meteors, aurora borealis, the propagation of sound and radio waves, etc., it is possible to draw conclusions as to the structure of the upper atmosphere. Present knowledge of the stratification of the atmosphere may be summarized briefly as follows:

(1) In the troposphere the temperature normally decreases with altitude at a rate of approximately 2.0° C. per thousand feet. The

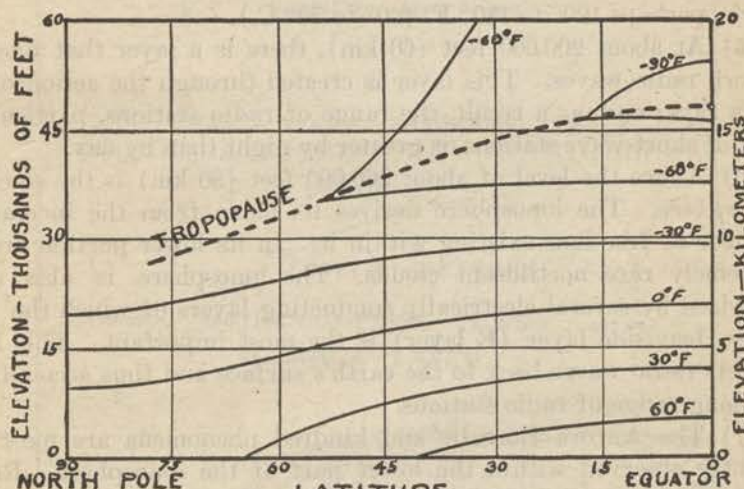

FIGURE 2.—Mean annual temperature in troposphere and lower stratosphere. (Note that stratosphere is warmer at Pole than at Equator.)

troposphere is relatively unstable; vertical currents occur frequently, leading to condensation, the formation of clouds, and precipitation.

All ordinary weather phenomena develop within the troposphere, particularly in its lower half.

(2) At the tropopause the temperature stops decreasing with altitude. From this level, the temperature remains constant or increases along the vertical as far as meteorograph instruments have reached.

(3) Above the tropopause lies a layer particularly rich in ozone (see fig. 3). Ozone is an allotropic form of oxygen having 3 atoms in its molecule (O_3) instead of the usual 2 (O_2). The ozone absorbs from 5 to 7 percent of the total incoming solar energy but radiates only a small amount, which in part at least may account for the higher temperature encountered in the upper atmosphere. Although the stratosphere is usually cloudless, a special type of cloud (mother-of-pearl) is occasionally observed within the ozone layer. The space between the tropopause and ozone layer (see fig. 3) is always cloudless and in addition there are no vertical currents (rough air) here; therefore the lower stratosphere offers the nearest approach to ideal flying conditions.

(4) Statistical investigations show that meteors disappear most frequently either at about 260,000 feet (80 km), or at about 130,000 feet (40 km) above the earth's surface. This fact as well as the results of the propagation of sound waves seems to indicate that there is a layer of air between 130,000 and 260,000 feet which is extremely warm, perhaps 120° to 130° F. (60° to 70° C.).

(5) At about 200,000 feet (60 km), there is a layer that tends to absorb radio waves. This layer is created through the action of the sun's rays; and, as a result, the range of radio stations, particularly that of short-wave stations, is greater by night than by day.

(6) Above the level of about 260,000 feet (80 km) is the so-called *ionosphere*. The ionosphere derives its name from the increase in number of free ions existing within it. In its lower portion are the extremely rare noctilucent clouds. The ionosphere is also characterized by several electrically conducting layers of which the Kennelly-Heaviside layer (E layer) is the most important. This layer reflects radio waves back to the earth's surface and thus accounts for the long range of radio stations.

(7) The Aurora Borealis and kindred phenomena are most frequently observed within the lower part of the ionosphere. Recent measurements by Stormer have shown that auroras may occur even as high as 4,000,000 feet (about 758 miles or 1,220 kilometers) above the earth's surface. This shows that atmospheric matter is present in measurable amounts at great altitudes.

16. Function.—*a.* Perhaps the most important function of the atmosphere lies in the dependence of animal and plant life upon air. Without oxygen there could be no animal life and without carbon dioxide plants could not exist.

b. The atmosphere, however, serves many purposes other than sustaining animal and plant life.

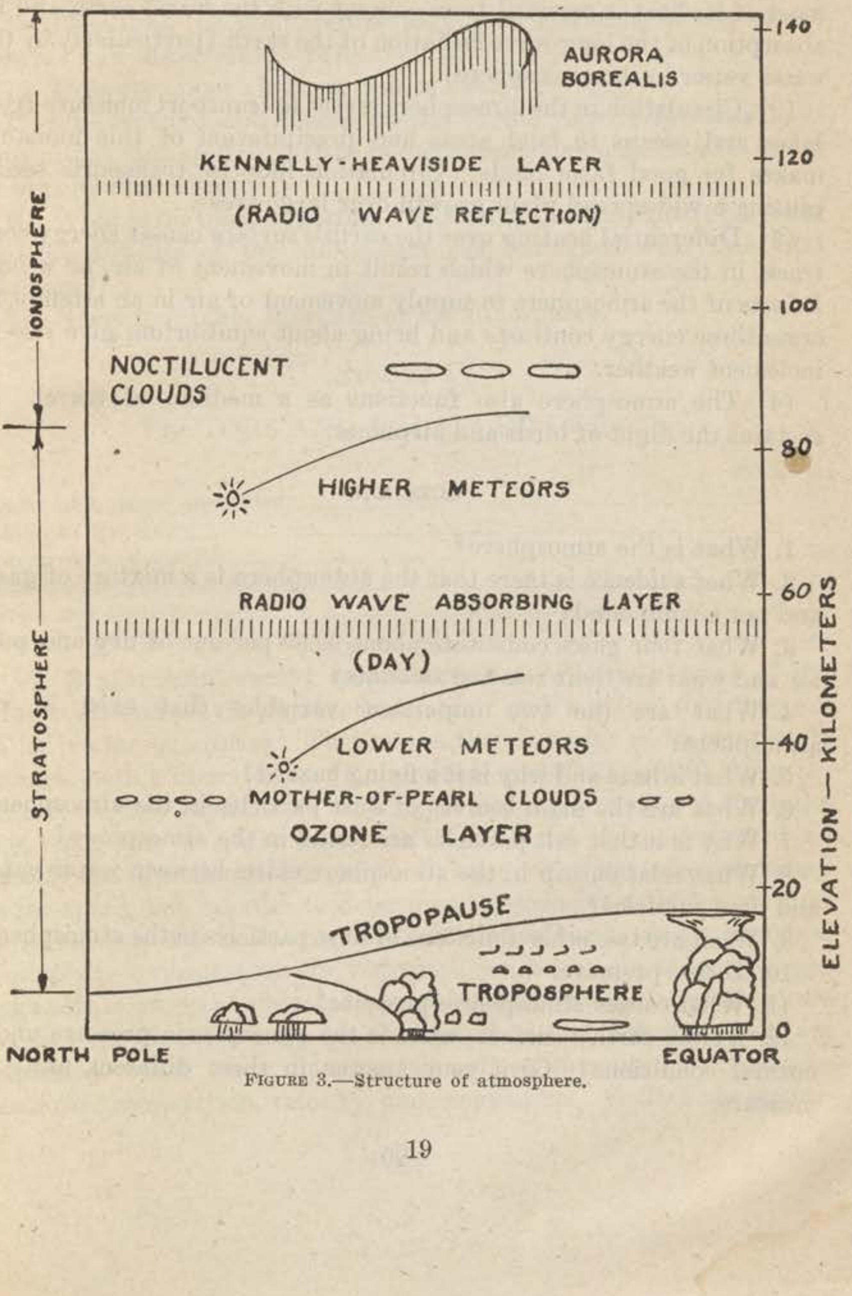

FIGURE 3.—Structure of atmosphere.

(1) It serves as a blanket; that is, it keeps some of the ultraviolet radiation out, and yet keeps heat in. Air is a very poor conductor of heat, conducting it only about one-third as well as asbestos. It thus makes a good heat-insulating material, especially if it is not allowed to circulate. It is very transparent to the sun's radiation, and consequently is warmed but little by sunlight passing through it. Rather, most of its heat is received from contact with the warm earth and by absorption of the long-wave radiation of the earth (particularly by the water vapor in the atmosphere).

(2) Circulation in the atmosphere serves to transport moisture from lakes and oceans to land areas and precipitation of this moisture makes for good farm lands. Circulation likewise transports seeds, causing a widespread plant growth over large areas.

(3) Differential heating over the earth's surface causes energy contrasts in the atmosphere which result in movement of air, or winds. Efforts of the atmosphere to supply movement of air in an attempt to erase these energy contrasts and bring about equilibrium give rise to inclement weather.

(4) The atmosphere also functions as a medium of travel. It sustains the flight of birds and airplanes.

QUESTIONS

1. What is the atmosphere?
2. What evidence is there that the atmosphere is a mixture of gases and not a compound?
3. What four gases constitute about 99.99 percent of dry and pure air and what are their relative amounts?
4. What are the two important variables that exist in the atmosphere?
5. What is haze and why is it a flying hazard?
6. What are the main sources of dust particles in the atmosphere?
7. Why is it that salt particles are found in the atmosphere?
8. What relationship in the atmosphere exists between water vapor and dust particles?
9. What are two other functions of dust particles in the atmosphere?
10. Define pressure.
11. What causes atmospheric pressure?
12. At the earth's surface, what is the atmospheric pressure under normal conditions? Give your answer in three different units of measure.

13. Define density, and give values for the density of air near the earth's surface.

14. How do density and pressure vary with an increase in elevation?

15. What is the theoretical upper limit of the atmosphere? Explain.

16. Up to about what altitude is the weather important as far as flying is concerned?

17. How does the temperature vary with elevation in the troposphere? In the stratosphere?

18. How are upper air observations made?

19. Observations and measurements of the Aurora Borealis have shown that atmospheric matter in measurable amounts may be found as high as what altitude?

20. What is the most important function of the atmosphere? What two constituents of the atmosphere are concerned with this vital function?

21. Name four other functions of the atmosphere.

Section IV

VECTORS AND BALANCED FORCES

17. Scalar and vector quantities.—*a*. A large number of the quantities with which physics deals are of such a nature that they are called vector quantities. This means that in order to be completely defined, both a direction and a magnitude must be specified. For instance, we may say that an airplane is moving at a rate of 300 miles per hour, but we really do not know all about its motion until we specify the direction in which it is flying. The "300 miles per hour" is the speed, but in order to determine the velocity we must say that it is moving 300 miles per hour north-northeast, as an example. Velocity is a vector quantity, but speed is a scalar quantity. Scalars are another group of physical quantities distinguishable from vectors because no direction may be ascribed to them. Vectors, then, are quantities which have direction as well as magnitude. Examples are force, acceleration, velocity, and momentum. Scalars are quantities which can be specified by magnitude only. Examples are temperature, energy, volume, mass, time, and power.

b. For convenience in graphical calculations with vector quantities, a system is used whereby an arrow known as a vector is drawn on a graph. The magnitude of the quantity is indicated by the length of the arrow and it is drawn pointing in the direction of the quantity. The point in space where the quantity applies may also be indicated by beginning the arrow at the point of application.

Example: An airplane is passing over Chicago at 300 miles per hour going north-northeast. Show its velocity vectorially using a scale of ¼ inch equals 50 miles per hour. (See fig. 4.)

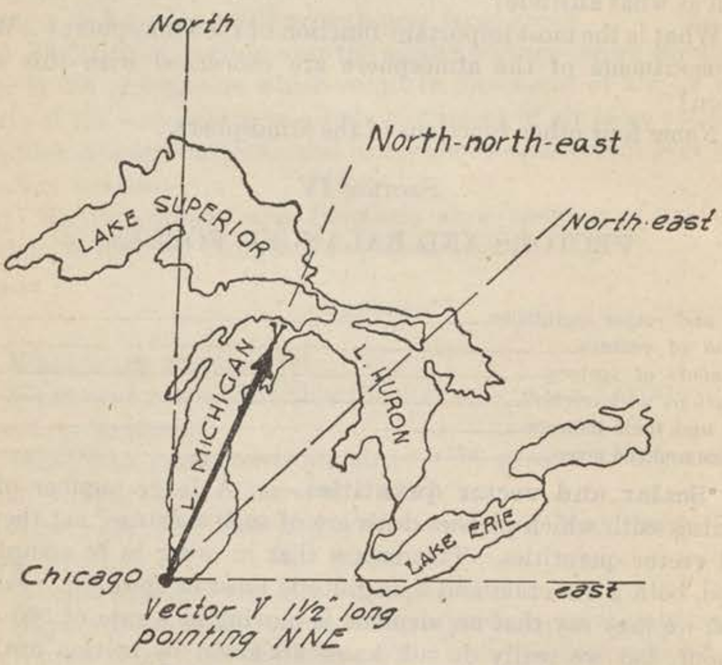

FIGURE 4.—Velocity of airplane as vector.

18. Addition of vectors.—A special set of rules is required for the addition of vectors.

a. Parallelogram law.—The parallelogram law is the fundamental principle on which the addition of vectors is based. The law states that the resultant of two vectors is represented in direction and in magnitude by the diagonal of a parallelogram whose sides represent the magnitudes and directions of the two vectors.

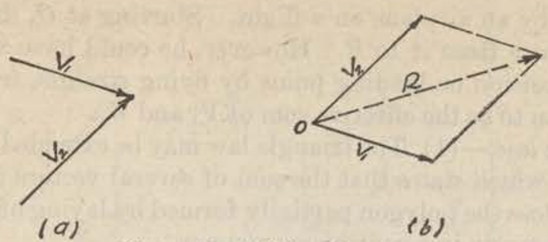

FIGURE 5.—Addition of vectors.

In figure 5, let V_1 and V_2 represent two vectors. The resultant of V_1 and V_2 is the vector sum of the two vectors. If V_1 and V_2 are drawn from a common point O and the parallelogram completed, then R (the diagonal drawn from point O) is the vector sum of V_1 and V_2.

b. Triangle law.—(1) The same resultant could have been found by drawing a triangle with V_1 and V_2 as two sides, in which case R would be the missing or closing side. In drawing the triangle, lay off V_1 from any point O; and from the end of V_1, draw V_2. The arrows of V_1 and V_2 must point in a continuous general direction, that is, starting at the initial point O of V_1 the arrows lead to the end of V_2. Note that V_2 could have been drawn from point O and V_1 from the end of V_2 with the same result. The order in which the vectors are laid off does not affect the result.

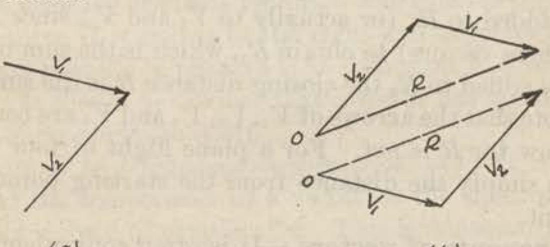

FIGURE 6.—Triangle addition of vectors.

In figure 6(a) are shown two vectors; their sum, R, is found graphically in figure 6(b). Note that the arrows V_1 and V_2 both lead away from O, and that R starts at O and ends at B, the same point where V_2 ends. Thus it is seen that R is simply the third or closing side of a triangle whose other sides are V_1 and V_2.

(2) The correctness of this law can be easily understood by the following line of reasoning: suppose V_1 and V_2 represent the two

tracks flown by an airplane on a flight. Starting at O, the pilot flew to A and thence from A to B. However, he could have achieved the same final position or landing point by flying straight from O to B. Thus R is seen to be the effective sum of V_1 and V_2.

c. Polygon law.—(1) The triangle law may be extended to form the polygon law which states that the sum of several vectors is the vector required to close the polygon partially formed by laying off the several vectors successively in a continuous manner.

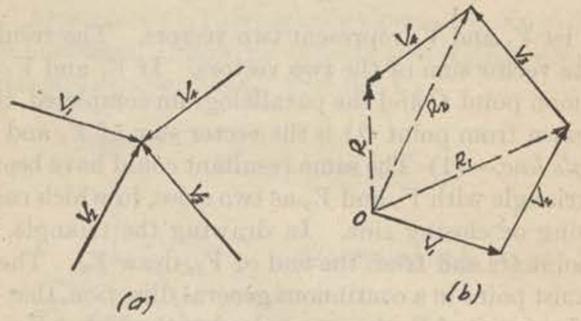

FIGURE 7.—Addition of vectors by polygon method.

(2) Figure 7(a) shows four vectors; V_1, V_2, V_3, and V_4. In figure 7(b), V_1 and V_2 are added to find R_1, which may replace V_1 and V_2. Then V_3 is added to R_1 (or actually to V_1 and V_2, since R_1 is simply the sum of these vectors) to obtain R_2, which is the sum of V_1, V_2 and V_3. If V_4 is added to R_2 the closing distance R is the sum of all four vectors. Note that the arrows of V_1, V_2, V_3 and V_4 are continuous, but that the arrow for R is not. For a plane flight of four legs, V_1, V_2, V_3, V_4, R is simply the distance from the starting point to the final landing point.

19. Components of vectors.—It is often convenient to replace a vector by two or more other vectors. This is just the reverse of adding two vectors. Graphically, the only rule required is that the vector sum of the several substitute vectors must be the original vector. Though vectors in any direction may be used, the only case of much importance is where the original vector is replaced by two vectors at right angles to each other. These new vectors are called the rectangular components of the original vector. These components are generally taken in the x and y directions. Figure 8(a) shows a vector V_1 to be broken up into its x and y components which are V_x and V_y.

a. Graphical method.—The breaking up of a vector into its components is accomplished by drawing the x and y axes through the

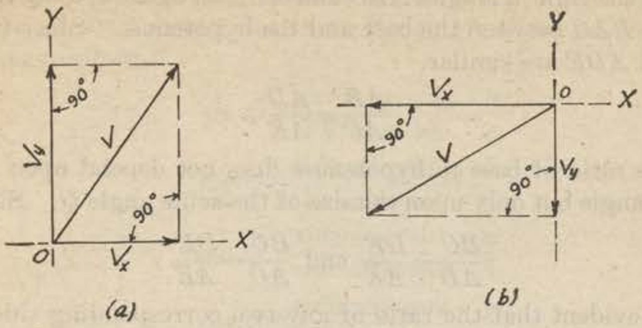

FIGURE 8.—Resolution (breaking up) of vector into components.

beginning O of the vector and dropping perpendiculars from the end of the vector to both the x and y axes. The lengths cut off by these perpendiculars are the magnitudes of V_x and V_y. The direction of these vectors is known; they must point away from O, the same as did the vector V. It should be noted that if V_x and V_y are added by the parallelogram law the resultant is V. This shows that breaking a vector into components is simply the reverse of adding two perpendicular vectors. In figure 8 (b) the vector is broken into V_x and V_y in the same manner, but since V_x points to the left and V_y points downward, they are negative or minus vectors. The rule for signs is simply that V_x is positive if it points to the right and negative if it points to the left; and that V_y is positive if it points up and negative if it points down. It should be obvious that a vector has no component in a direction at right angles to itself.

b. Mathematical or trigonometrical method.—(1) It is often convenient to find the components of a vector or the sides of a triangle mathematically instead of graphically. This is done easily by the use of trigonometry. A simple explanation of the most elementary concepts will be given in order to explain the solution of right triangles by trigonometrical methods.

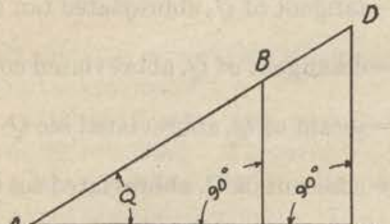

FIGURE 9.—Similar or proportionate triangles.

(2) In the right triangles ABC and ADE in figure 9, let Q represent the angle BAC between the base and the hypotenuse. Since triangles ABC and ADE are similar,

$$\frac{AB}{AC}=\frac{AD}{AE}$$

Thus, the ratio of base to hypotenuse does not depend upon the size of the triangle but only upon the size of the acute angle Q. Similarly,

$$\frac{BC}{AB}=\frac{DE}{AE} \text{ and } \frac{BC}{AC}=\frac{DE}{AE}$$

and it is evident that the ratio of any two corresponding sides is the same in both triangles even though the triangles themselves are of different sizes.

(3) Since the ratio of the sides of the right triangle depend only upon the size of the base angle, Q, it is possible to name the ratios and tabulate them for convenient use. The names of ratios are given in *c.* below.

c. Names of triangle ratios.—(1) For a triangle lettered as in figure 10 the ratios (often called functions) of the sides are given names as follows:

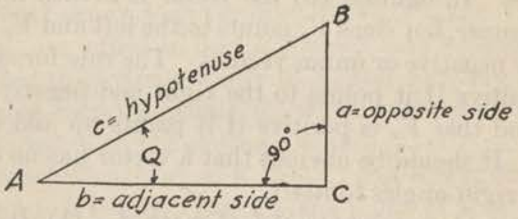

FIGURE 10.—Ratios of the sides of a triangle.

$\frac{a}{c}$=sine of Q, abbreviated sin Q

$\frac{b}{c}$=cosine of Q, abbreviated cos Q

$\frac{a}{b}$=tangent of Q, abbreviated tan Q

$\frac{b}{a}$=cotangent of Q, abbreviated cot Q

$\frac{c}{b}$=secant of Q, abbreviated sec Q

$\frac{c}{a}$=cosecant of Q, abbreviated scs Q

(2) In solving problems with these ratios as defined in figure 10, Q should be chosen and written on the figure, the side opposite Q should

be called a, the other leg b, and the hypotenuse c. In other words, in the case of the triangle shown in figure 10, these ratios should be written as follows:

$$\sin Q = \frac{\text{side opposite}}{\text{hypotenuse}} = \frac{a}{c}$$

$$\cos Q = \frac{\text{side adjacent}}{\text{hypotenuse}} = \frac{b}{c}$$

$$\tan Q = \frac{\text{side opposite}}{\text{side adjacent}} = \frac{a}{b}$$

$$\cot Q = \frac{\text{side adjacent}}{\text{side opposite}} = \frac{b}{a}$$

$$\sec Q = \frac{\text{hypotenuse}}{\text{side adjacent}} = \frac{c}{b}$$

$$\csc Q = \frac{\text{hypotenuse}}{\text{side opposite}} = \frac{c}{a}$$

With the definitions thus stated, any letters may be used and the triangle may be in any position.

d. Solution of right triangles using ratios.—The solution of a right triangle using these ratios is quite simple. Tables are available which give the values of all the ratios—sin, cos, tan, cot, sec, and csc—though in some tables sec and csc are not given. However, secant is simply the reciprocal of cosine and cosecant the reciprocal of sine. Consequently, multiplying by secant is the same as dividing by cosine; hence, the cosine table can be used in place of a table of secants. In a similar way the sine table can be used in the case of cosecants.

(1) *Example 1.*—If the hypotenuse of a right triangle and the angle Q are known, sides a and b are easily found since—

$$\sin Q = \frac{a}{c} \text{ or } a = c \cdot \sin Q$$

and

$$\cos Q = \frac{b}{c} \text{ or } b = c \cdot \cos Q.$$

Problem: The hypotenuse of a right triangle, c, is 200 feet and the angle Q is 30°. Find sides a and b.

Solution: From a table of sines and cosines it is found that $\sin 30° = 0.50000$ and $\cos 30° = 0.86603$. Therefore—

$$a = c \cdot \sin Q = 200(0.50000) = 100.00 \text{ feet}$$
$$b = c \cdot \cos Q = 200(0.86603) = 173.21 \text{ feet.}$$

(2) *Example 2.*—If the angle Q and the side a are known, sides b and c are easily found since—

$$\cot Q=\frac{b}{a} \text{ or } b=a\cdot\cot Q$$

and

$$\csc Q=\frac{c}{a} \text{ or } c=a\cdot\csc Q$$

If a table of cosecants is not available, then—

$$\sin Q=\frac{a}{c} \text{ or } c=\frac{a}{\sin Q}$$

Problem: Assume a to be 100.00 feet and Q to be 30°. Find b and c.

Solution: From the table, cot 30°=1.73205 and sin 30°=0.50000 as before.

Then

$$b=a\cdot\cot Q=100\ (1.73.205)=173.21 \text{ feet}$$

and

$$c=\frac{a}{\sin Q}=\frac{100}{.50000}=200.00 \text{ feet.}$$

(3) *Example 3.*—If Q and the side b are known, sides a and c are easily found, since—

$$\tan Q=\frac{a}{b} \text{ or } a=b\cdot\tan Q$$

and

$$\sec Q=\frac{c}{b} \text{ or } c=b\cdot\sec Q$$

If no table of secants is available—

$$\cos Q=\frac{b}{c} \text{ or } c=\frac{b}{\cos Q}$$

Problem: Assuming b to be the known side, find a and c.

Solution: From the table, tan 30°=.57735 and cos 30°=.86603. Hence—

$$a=b\cdot\tan 30°=173.21\ (.57735)=100.00 \text{ feet}$$

and

$$c=\frac{30°}{\cos b}=\frac{173.21}{.86603}=200.00 \text{ feet.}$$

(4) *Example 5.*—If any two sides are known, the angle Q can easily be found since—

$$\sin Q=\frac{a}{c} \qquad \cos Q=\frac{b}{c} \quad \text{and}$$

$$\tan Q=\frac{a}{b} \qquad \cot Q=\frac{b}{a}$$

Problem: Assume $c=200$, $a=100$. Find Q.

$$\sin Q=\frac{a}{c}=\frac{100}{200}=0.5000$$

Solution: From a table of sines it is found that 30° is the angle which has a sine equal to 0.5000.

(5) *Example 5.*—If the direction of one component of a vector is known, its value and that of the other component can easily be found by the use of trigonometry.

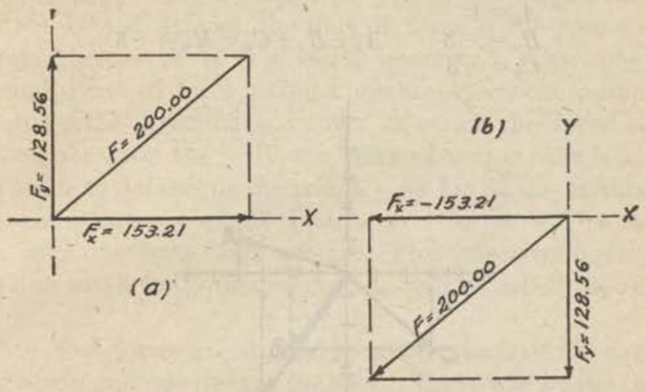

FIGURE 11.—Components of a vector.

Problem 1: In figure 11(a) the vector has a magnitude of 200 pounds and makes an angle of 40° with the x axis. Find the values of the components.

Solution:

$$F_x=F\cdot \cos 40^\circ=200\ (.76604)=153.21 \text{ pounds}$$

and

$$F_y=F\cdot \sin 40^\circ=200\ (.64279)=128.56 \text{ pounds.}$$

Problem 2 and solution: In figure 11(b) the vector has the same magnitude but a different direction. The only difference in the components of the vectors in figures 11(a) and 11(b) are the signs, those in figure 11(b) being negative or minus.

20. Calculations with vectors.—A special set of rules is required when calculating with vectors, and some of these operations are described below.

a. Addition.—The addition of two or more vectors can be accomplished by first breaking each down into its x and y components. The sum of the vectors will be a new vector, called the resultant, whose x component will be the algebraic sum of the x components of the original vectors and whose y component will be the algebraic sum of their individual y components. The resultant of several vectors is defined as a single vector which has the same effect as all of the others working together and is the vector sum of all these vectors.

b. Example: Add the vectors A, B, and C shown on the graph in figure 12 into a resultant vector M.

$$A_x=4$$
$$B_x=2 \qquad A_x+B_x+C_x=M_x=3$$
$$C_x=-3$$
$$A_y=1$$
$$B_x=-3 \qquad A_y+B_y+C_y=M_y=-5$$
$$C_y=-3$$

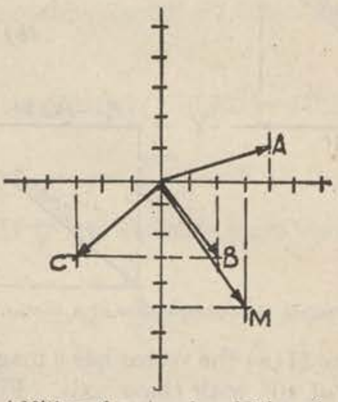

FIGURE 12.—Addition of vectors by addition of components.

(1) The resultant of the three vectors is obtained by the Pythagorean theorem* and is—

$$M=\sqrt{M_x^2+M_y^2}=\sqrt{3^2+5^2}=\sqrt{9+25}=\sqrt{34}=5.831$$

(2) The angle between the resultant x and the x-axis is the angle whose tangent is $\frac{M_y}{M_x}=\frac{-5}{3}=-1.66667$ and is found from the table to be 59° 02′.

(3) The vector must be drawn so that it is to the right of the y-axis and below the x-axis, since the y component, M_y, was negative.

21. Forces and their balance.—*a.* Everyone is familiar with forces and has some idea as to their effects. If a man's muscles are required to exert forces for a long period of time, he will become fatigued. If a compressional force is exerted on a spiral spring, it

*The name applied to the theorem that, in a right triangle the square of the hypotenuse is equal to the sum of the squares of the other two sides.

will shorten; and the greater the force, the greater the compression. Force could probably be well described as the intensity of "push" or "pull" exerted between one body and another.

b. Physically, force is defined by its effect upon the motion of bodies. A complete discussion of force is given in the section on accelerated motion. For balanced forces (forces in equilibrium) the simple concept of force as "push" or "pull" suffices. The most common example of force is weight. The unit of force in the metric system is the dyne. The dyne may be taken as $1/980$ of the weight of a gram mass. In the British system, the unit of force is the pound weight.

c. As stated before, force is a vector quantity. When one speaks of a thousand dynes of force acting upon an object, one cannot know its effect unless the direction is known in which the force acts. If several forces act upon the body, the rules of vector calculation must be used in order to determine the result. As far as the motion of the body is concerned, the result of these several forces will be the same as though only one force were acting. This effective force will be the vector sum of all the forces acting and will be called the resultant force.

Example.—Two forces are applied to a body, each of 100 dynes, one toward the north and one toward the east. What will be the resultant force on the body? See figure 13 for the graphical solution.

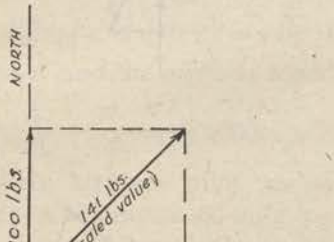

FIGURE 13.—Graphical addition of forces.

d. If the vector sum of all the concurrent forces (that is, forces acting at the same time) acting on a body is zero, the body is said to be in equilibrium, for there will be no tendency for acceleration in any direction. This equilibrium condition is merely a balance between all of the forces so that there is a general cancelation by oppositely directed forces. Suppose that several forces act on a body and that it is desired to place the body in equilibrium. This may always be done by applying an additional force of the correct direction and magnitude to cause general cancelation, so that the final vector sum will be zero. This additional force necessary for equilibrium is called the equilibrant. It will always be equal in magnitude to, but opposite in direction from, the resultant of all the other forces acting.

e. Mathematically, the criterion for equilibrium of several forces is that the algebraic sum of their x components must equal zero and the algebraic sum of their y components must equal zero. Likewise, the x and y components of the equilibrant of several unbalanced forces must be the negative of the x and y components respectively of their resultant.

(1) *Example 1.*—Show in two ways that the forces in figure 14(a) are in equilibrium.

(*a*) *Graphical solution* (fig. 14).—The three vectors form a triangle and are therefore balanced.

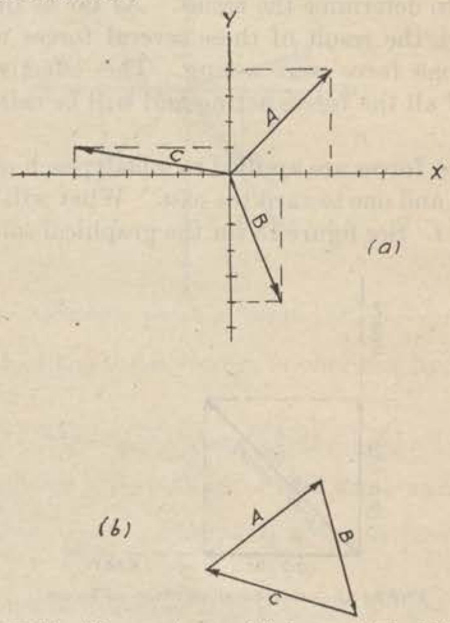

FIGURE 14.—Three vectors and their graphical addition.

(*b*) *Mathematical solution.*

$$A_x=4 \qquad A_y=4$$
$$B_x=2 \qquad B_y=-5$$
$$C_x=-6 \qquad C_y=1$$
$$A_x+B_x+C_x=4+2-6=0$$
$$A_y+B_y+C_y=4-5+1=0$$

Since the sum of both x and y components are zero, the forces are in equilibrium.

(2) *Example 2.*—Find in two ways the equilibrant of the forces shown in figure 15(a), whose components are:

$$A_x=2 \qquad B_x=3 \qquad C_x=1$$
$$A_y=2 \qquad B_y=-1 \qquad C_y=-4$$

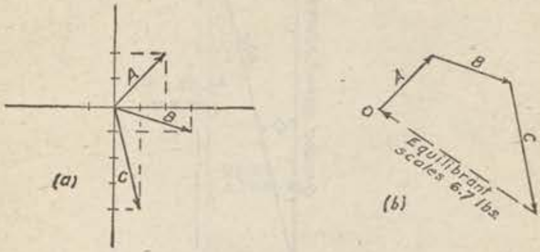

FIGURE 15.—Forces and their equilibrant.

(*a*) *Graphical solution.*—In figure 15(b) the vectors A, B, C, are laid off in succession to scale according to the polygon law. The equivalent vector X must extend from the end of C to the starting point O as shown.

(*b*) *Mathematical solution.*

$$E_x+A_x+B_x+C_x=0, \text{ or } E_x+2+3+1=0. \quad E_x=-6.$$
$$E_y+A_y+B_y+C_y=0, \text{ or } E_y+2-1-4=0. \quad E_y=+3.$$
$$E=E_x^2+E_y^2=\sqrt{36+9}=\sqrt{45}=6.71 \text{ lbs.}$$

The angle Q between X and the x axis is found as follows:

$$\text{Tan } Q=\frac{E_y}{E_x}=\frac{3}{-6}=-0.5000 \qquad Q=26°34'$$

(3) *Example 3.*—An airplane pilot wishes to fly straight north. A wind is blowing from the east at 50 miles per hour and the cruising speed of the plane is 200 miles per hour. What course must he fly in order that his track be straight north, and what is his northward ground speed?

NOTE.—The track (direction) and ground speed form a velocity vector which is the vector sum of the air speed and the wind velocity. The airplane moves in the air, but the air moves over the ground so that the airplane's actual velocity relative to the ground is the vector sum of the air speed and wind velocity.

(*a*) *Graphical solution.*

1. Graphically the problem is solved if the resultant of air speed and wind speed has a north component but no east or west component.

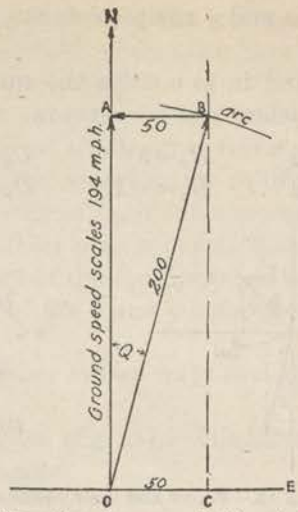

FIGURE 16.—Correction for crosswind in airplane flight.

2. This is done in figure 16 by intersecting a line B located 50 miles per hour to scale on the east side of the north axis OA with an arc drawn with a radius of 200 miles per hour to scale from point O, the origin of the air speed. This makes the air-speed vector OB equal 200 miles per hour and the wind vector AB equal 50 miles per hour. The resultant OA, which scales 194 miles per hour, is obviously straight north.

(*b*) *Mathematical solution.*—The x axis is taken as east and the y axis as north. The x component of the true ground velocity must be zero, so the angle Q between the air speed OB and north OA must be such that:

$$\sin Q = \frac{50}{200} = 0.2500. \quad Q = 14°29'$$

Then

$$OA = 200 \cos \quad Q = 200 \quad (0.96822) = 193.6 \text{ miles per hour}$$

(4) *Example 4.*—On a certain airplane weighing 2,500 pounds, the total air reaction in level flight at a certain uniform speed makes an angle of 10° to the vertical. Find the lift (vertical lifting force), the thrust of the propeller, and the total air reaction.

(*a*) *Graphical solution.*—Since the airplane is in level flight at uniform speed there is no acceleration in any direction. Therefore the vector sum of all forces acting on the airplane must be zero. Draw line AC_1 (fig. 17) to scale to represent the force of gravity, that is,

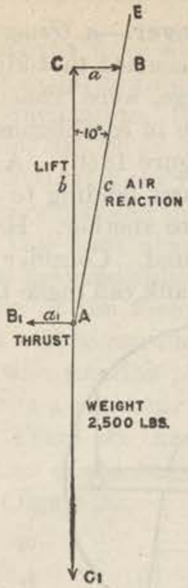

FIGURE 17.—Forces acting on airplane in flight.

the weight of the airplane. Next draw line AC vertically upward and of the same length as AC_1. AC is the lift since the force of gravity must be balanced by an equal force in the opposite direction. Now draw line AE, 10° to the right of vector AC. AE shows the direction of the air reaction. Resolve AE into its components. One component AC is already drawn to scale. Therefore from point C draw a horizontal line CB perpendicular to line AC. This line intersects AE at B. Vector AB is the total air reaction on the airplane and vector CB is the rearward component of the air reaction. This tendency of the air reaction to push the plane backwards must be balanced by an equal force, AB_1 in the opposite direction. Therefore AB_1 is the thrust exerted by the propeller.

(*b*) *Mathematical solution.*—Referring to figure 17—

$$\text{Lift } b = \text{weight } AC$$
$$= 2{,}500 \text{ lbs}$$
$$\text{Air reaction } c = b \sec 10°$$
$$= 2{,}500 \text{ lbs} \times \frac{1}{0.985}$$
$$= 2{,}548 \text{ lbs}$$
$$\text{Thrust } a_1 = a = b \tan 10°$$
$$= 2{,}500 \text{ lbs} \times 0.176$$
$$= 540 \text{ lbs}$$

22. Moments and the lever.—*a. General.*—In the previous discussion of equilibrium it was assumed that all the forces met at a point, or, in mathematical language, were "concurrent." If forces are not concurrent, they may not be in equilibrium even though their vector sum is zero, as shown in figure 18(b). A vector sum of zero means that there is no resultant force tending to translate the body, that is, to move it from one point to another. However, a body may rotate even though it is not translated. Consider a grindstone, figure 18(a). A force P applied to the crank can make the grindstone rotate but it

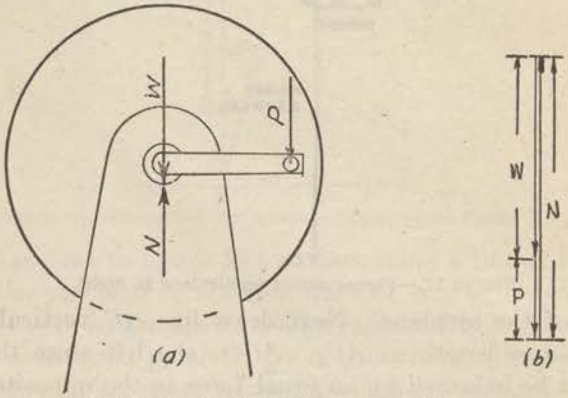

FIGURE 18.—Forces acting on a grindstone.

will not move in space, since the vector sum of the forces acting is zero. But the grindstone is not in equilibrium because it rotates. This brings us to a new concept of force action called moment. The moment of a force is its tendency to cause rotation. It is the product of two things: the magnitude of the force and the perpendicular distance between the line of action of the force and the axis of rotation. It is thus a product of two units; force and length, and in the English system is expressed in foot-pounds if the force is in pounds

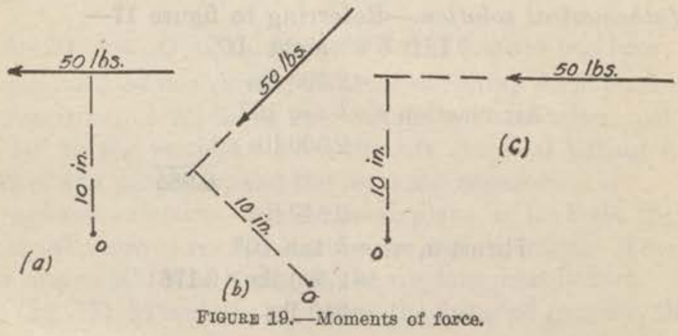

FIGURE 19.—Moments of force.

and the distance in feet. If the force was in dynes and the distance in centimeters, the moment would be in dyne-centimeters. Figure 19 shows three 50-pound forces. In figure 19(a), the moment about point O is obviously 50×10 or 500 inch-pounds. In figure 19(b) and (c), the line of action of the forces had to be extended to get the perpendicular distance between the line of action of the force and the moment center. This must always be done as the distance (moment arm) must be the perpendicular distance from the moment center to the line of action of the force. Moments which tend to produce clockwise rotation will be considered positive and those that tend to cause counterclockwise rotation negative.

b. The lever.—The lever is a rigid bar arranged to rotate about a point called the fulcrum. There are three classes of levers, depending upon the relative location of the resistance, the fulcrum, and the effort. These are shown in figure 20.

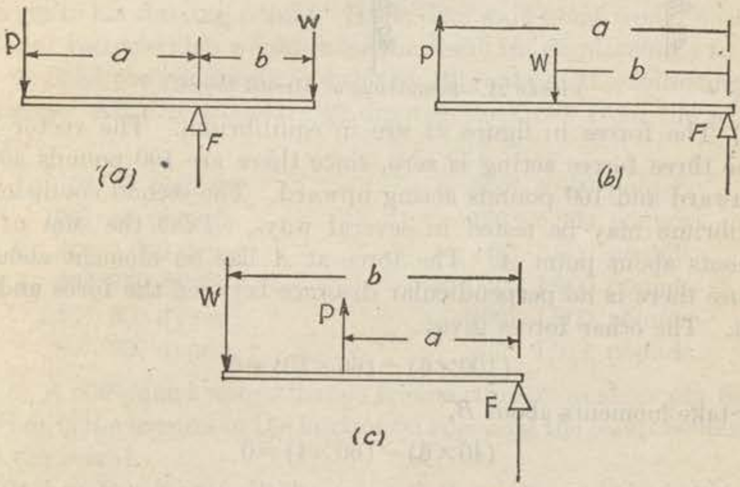

FIGURE 20.—Three classes of levers.

In figure 20, p represents the applied force or effort, w the resisting force, and F the pivot or fulcrum. The law of the lever for equilibrium may be stated as a formula:

$$P\cdot a=W\cdot b\cdot$$

This formula simply states that the moment of the effort about the moment center or fulcrum must be equal to that of the resistance about the same point for equilibrium to exist.

c. Equilibrium of parallel forces.—(1) Parallel forces which are concurrent will be in equilibrium if their vector sum is zero. Since the forces are all parallel, simple algebraic addition (paying attention to direction) will give the vector sum. If parallel forces do not all act at a common point, or are noncurrent, two conditions must be satisfied for equilibrium to exist.

(*a*) The vector or algebraic sum of the forces must be zero to prevent translation.

(*b*) The sum of the moments of all the forces about any point must be zero to prevent rotation about that point.

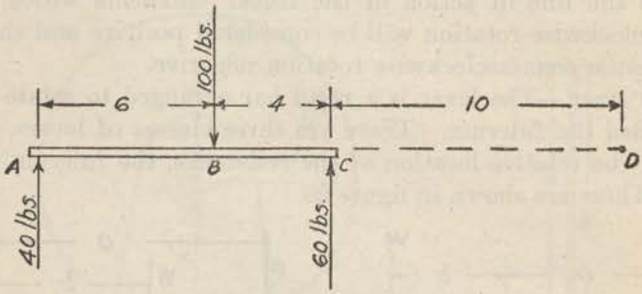

FIGURE 21.—Equilibrium of parallel forces.

(2) The forces in figure 21 are in equilibrium. The vector sum of the three forces acting is zero, since there are 100 pounds acting downward and 100 pounds acting upward. The second condition of equilibrium may be tested in several ways. Take the sum of the moments about point *A*. The force at *A* has no moment about *A* because there is no perpendicular distance between the force and the point. The other forces give:

$$(100\times6)-(60\times10)=0$$

Now take moments about *B*.

$$(40\times6)-(60\times4)=0$$

Now take moments about *D*, a point off the actual rod and 10 feet from *C*.

$$(40\times20)-(100\times14)+(60\times10)=0$$

It is thus seen that if the sum of the moments of the three forces about one point is zero it will be zero about any other point. Therefore any point can be selected as the moment center in checking to see if the sum of the moments about any point is zero.

PROBLEMS

1. The wind resistance of a human body falling through the air may be approximately expressed as $R=.01V^2$. This resistance is in

pounds of force resisting the motion downward and V is in miles per hour. After falling for a short time, the body attains a constant velocity. What will be this velocity for a man weighing 144 pounds?

2. Four different forces act on a body: one of 3 pounds from the north, one of 2 pounds from the east, one of 10 pounds from the west, and one of 1 pound from the south. Find graphically the resultant of these forces by addition, using two different sequences of the individual additions. Show that these results are the same and that they coincide with the result of mathematical calculation.

3. Displacement is a vector quantity, as are force and velocity. A hiker found that he was lost. He could remember that he had made his hike in three parts but could not remember the order in which they were made. One part was a walk northwest for 3 minutes, one due north for 20 minutes, and one southeast for an hour. If he always walked at the same speed, which way and for how long should he walk to get to his starting point? Hint: The walk home would be an additional vector which would cause the resultant displacement to be zero.

4. Find the resultants and the equilibrants of the following sets of forces. All directions are in degrees clockwise from the y (north) axis:

a.	0°	10 pounds	*c.*	350°	5,000 pounds
	100°	40 pounds		120°	5,000 pounds
b.	10°	1,000 dynes		240°	5,000 pounds
	50°	750 dynes	*d.*	10°	1,000 pounds
	270°	900 dynes		100°	1,000 pounds
	180°	500 dynes		235°	1,414 pounds

5. A 500-pound weight hangs from a support as shown in figure 22. What is the tension in the horizontal rope and the compressional force in the beam?

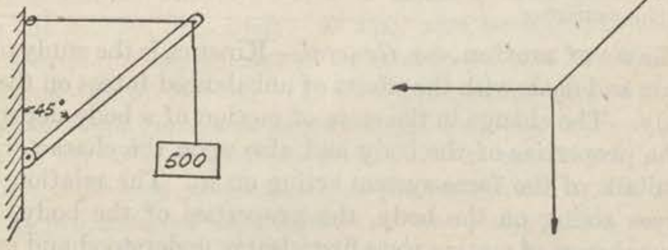

FIGURE 22.—Suspension of weight from equilibrium of forces.

6. A 500-pound weight hangs from a support as shown in figure 23. What is the tension in the upper rope and the compressional force in the beam?

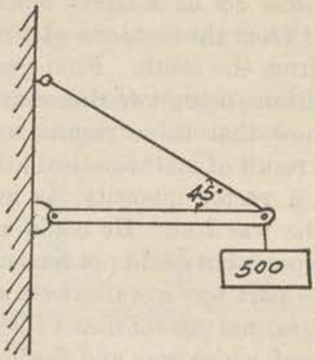

FIGURE 23.—Suspension of weight by horizontal beam.

7. When a certain 2,500-pound airplane is grounded, its tail skid is 25 feet (horizontally) behind the front wheels and the center of gravity of the plane is 2 feet behind the wheels. How much load is supported by the wheels *A* and by the skid *B* in figure 24? Hint: As an axis, take the line which joins the two points at which the wheels touch the ground.

SECTION V

KINETICS

23. Laws of motion.—*a. General.*—Kinetics is the study of bodies in motion and deals with the effects of unbalanced forces on the motion of a body. The change in the state of motion of a body depends both upon the properties of the body and also upon the characteristics of the resultant of the force system acting on it. The relation between the forces acting on the body, the properties of the body, and the resulting change of motion were first clearly understood and expressed by Sir Isaac Newton. He formulated three general statements which are now accepted as the three laws of motion.

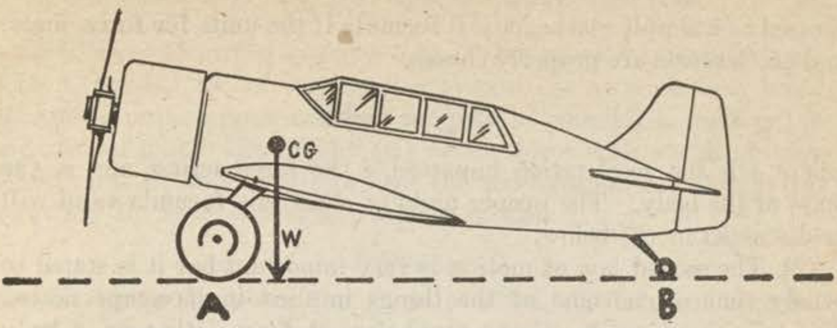

FIGURE 24.—Equilibrium of moments of a grounded airplane.

b. Newton's first law of motion.—(1) Newton's first law of motion is: *If no force acts on a body it remains at rest or continues to move with uniform velocity in a straight line.* That a body at rest remained at rest unless some force acted upon it had been known and accepted as fact long before Newton's time. But that a body in motion would continue to move with a uniform velocity in a straight line unless acted upon by some force was not understood or believed. Prior to Newton's time it had been assumed that a body free from the action of external forces would eventually come to rest. This belief was apparently confirmed by the fact that actual moving bodies always did come to rest if some force did not continue to act upon them. However, bodies which apparently were moving with no forces acting upon them were in actuality being acted upon by some force, generally friction, which caused them to eventually come to rest. As a matter of fact the body came to rest simply because some force did act upon it. The first law of motion simply states that force is required to change the existing state of motion of a body. An airplane flying straight and level and at a constant speed is in equilibrium because all forces acting on it are in balance.

(2) This law implies a new definition of force. This definition may be stated as follows: *Force is whatever changes or tends to change the motion of a body.* It may also be stated: *Force is the cause of acceleration, or change in velocity.*

c. Second law of motion.—(1) Newton's second law of motion is: *If an unbalanced force acts upon a body, the body is given an acceleration in the direction of the force and the magnitude of the acceleration is directly proportional to the magnitude of the force and inversely proportional to the mass of the body.* This may be expressed as a simple mathematical formula if the units for force, mass, and acceleration are properly chosen.

$$a=\frac{f}{m} \text{ or } f=ma$$

where a is the acceleration imparted, f the force acting, and m the mass of the body. The proper units to make this formula valid will be discussed in (2) below.

(2) The second law of motion is very important but it is stated so briefly that often some of the things implied in it escape notice. The law simply states that an unbalanced force acting on a body causes an acceleration in the direction of the force, without any reference to whether the body was at rest or already in motion when the force was applied. Hence the effect of a force acting on a body is the same whether the body is at rest or already in motion. The force simply produces a change in the state of motion of the body. If the body is at rest, the unbalanced force starts it in motion. If it is already in motion and the force acts in the same direction as the motion, the velocity of the body is increased. If the resultant force acts opposite to the existing motion, the body is slowed down. If the force continues to act, it will eventually reverse the direction of motion. Thus a ball thrown vertically upward is immediately subjected to the force of gravity which slows it down until finally it comes to rest and then starts downward.

(3) The law states how a force will effect the motion of a body but makes no reference to whether other forces may be acting on the body or not. Hence it is concluded that each force produces its own effect independently of the simultaneous action of other forces. This means that the actual acceleration of a body is the vector sum of the accelerations produced by each of the forces.

d. Metric units.—When the metric system of units is used, the mass is in grams, the acceleration in centimeters per second per second, and the force in dynes. The dyne is the force required to give a mass of one gram an acceleration of one centimeter per second per second. If both m and a are taken as unity in the formula $f=ma$, then $f=1\times1=1$ and $f=1$ dyne. If a gram mass is dropped in a vacuum the force of gravity produces an acceleration of about 980 centimeters per second per second (abbreviated cm/sec.^{2}). Therefore, $f=ma$ gives $f=1\times980=980$ dynes. Consequently the weight (downward force) exerted by 1 gram of mass is about 980 dynes.

e. British engineering system.—(1) It was previously stated (par. 8*b* (3)) that the British engineering system has no commonly used, well-known unit of mass and that weight (in pounds) is used as the fundamental unit. Let weight (w) be the force with which gravity acts on mass m, and let g represent the acceleration due to gravity. According to Newton's second law of motion

$$f = ma$$

Substituting w in pounds for f and g for a, the formula becomes

$$w \text{ in pounds} = mg$$

If a body is dropped in a vacuum the acceleration produced by gravity in British units is 32.2 ft/sec.^{2}.

Therefore

$$w \text{ in pounds} = m \cdot 32.2 \text{ ft/sec.}^2.$$

or

$$m = \frac{w \text{ in pounds}}{g}$$

or

$$m = \frac{w \text{ in pounds}}{32.2 \text{ ft/sec.}^2}.$$

The m in this expression is the unit of mass in the British engineering system. As previously stated, the unit has no name.*

(2) The last equation is not exact because the acceleration of a falling body is not a true constant but varies with altitude. However, g is generally taken at 32.2 feet per second per second, and this value is sufficiently correct for most practical problems. The formula for mass and weight in British units enables the formula

$$f = ma$$

for Newton's second law of motion to be rewritten

$$f = \frac{w}{g} \cdot a$$

where f is force in pounds, w is weight in pounds, g is acceleration

*The "slug" is sometimes used as a unit of mass. One slug is equal to 1 pound weight multiplied by the acceleration due to gravity, that is, a weight of 32.2 pounds has a mass of 1 slug. The slug is not used as a unit in this manual.

The "poundal" is used in what is known as the "English" system as a unit of force and the pound as a unit of mass. Where these units are used 1 pound mass weighs 32.2 poundals. This system is confusing and conflicts with the British engineering system which uses the pound as a unit of force and of weight, not of mass. It is, therefore, best that the student avoid the use of any supplementary texts that use the poundal as a unit of force and the pound as a unit of mass. The distinction between mass and weight is not important in the ground covered by this manual except in the formulas for motion.

due to gravity (32.2 ft./sec.^{2}), and a is acceleration in feet per second per second.

(3) In this manual, force will be expressed in pounds and mass as weight divided by g or w/g. It is thus seen that if w equals 32.2 pounds, m equals 1. The British engineering system (B. E. S.) is also called the foot-pound-second system or simply F. P. S. system.

f. Newton's third law of motion: *Action and reaction are equal and opposite.* This simply means that when one body exerts a force on a second body, the second exerts an equal but opposite force on the first. Thus forces always go in pairs, but only one of the pair acts on one body. If a person presses his hand against a wall, the wall presses back on the hand with an equal but opposite force.

24. Uniformly accelerated rectilinear motion.—*a.* Occasionally the force acting on a body has a constant direction and a constant magnitude, and produces a constant acceleration. The most common example of this is the action of the force of gravity on a freely falling body. A train gathering speed with a constant drawbar pull is another example. The relations between distance, time, velocity, and acceleration, for uniformly accelerated motion, may be deduced as follows: let V_0 be the velocity of a body at the beginning of an interval of time of duration t, and let V be the velocity of the body at the end of the time t, and let a be the constant acceleration. Then

$$a=\frac{V-V_0}{t}$$

since by definition, acceleration is rate of change of velocity, or the change in velocity divided by the time of change. Hence,

$$V=V_0+at \qquad (1)$$

Example: A taxying airplane is accelerating at the rate of 10 feet per second per second. Seven seconds ago its velocity was 18 feet per second. What is it now?

Solution 1: By definition of acceleration the velocity will increase 10 feet per second for each second the acceleration is operating. Hence in 7 seconds the increase in velocity is 7×10 or 70 feet per second and after adding the initial velocity of 18 feet per second the final velocity is found to be 70+18 or 88 feet per second.

Solution 2: The same result can be obtained by substitution in the foregoing formula for V. Here V_0 equals 18 feet per second and a equals 10 feet per second per second. Hence V equals 18+7×10 or 88 feet per second.

b. (1) It is also easy to deduce a formula for finding the distance traveled by a body subjected to a uniform acceleration. Since the acceleration is constant the velocity increases uniformly and the true average velocity is simply

$$\text{average } V=\frac{V_o+V}{2}$$

and the distance traveled is the average velocity multiplied by the time, t. Let d represent the distance traveled. Then

$$d=\frac{(V_o+V)t}{2}$$

or

$$d=\frac{(V_o+V_o+at)t}{2}$$

or

$$d=V_o t+\frac{1}{2}at^2 \qquad (2)$$

Example: How far did the airplane taxi in the 7 seconds of the previous example?

Solution:

$$d=18(7)+\frac{1}{2}(10)(7^2)$$

$$d=126+245=371 \text{ feet}$$

This could also be solved by reasoning that the average velocity was $\frac{18+88}{2}$ or 53 feet per second, so in 7 seconds the distance traveled was $7\times 53=371$ feet.

(2) If a body starts from rest, V_o is equal to 0. Then

$$d=\frac{1}{2}at^2 \qquad (2a)$$

A special case of this is for a body freely falling in a vacuum. Here the only force acting is gravity and the acceleration is g, directed vertically downward. For this case:

$$d=\frac{1}{2}gt^2 \qquad (2b)$$

This formula has many practical applications.

Example: A bomb is dropped from an airplane which is traveling horizontally at 3,000 feet altitude. How long will it take for the bomb to hit the ground, assuming no air resistance?

Solution: Since the airplane is traveling horizontally the bomb has no vertical velocity when released. Its rate of fall will be the same as if it had been dropped from a stationary balloon at 3,000 feet, since the bomb in both cases is subjected to exactly the same vertical acceleration.

$$3000=\tfrac{1}{2}\cdot(32.2)t^2$$

$$t^2=\frac{3000\times 2}{32.2}=186$$

$$t=\sqrt{186}=13.6 \text{ seconds}$$

(3) From the two previously given equations,

$$V=V_o+at \qquad (1)$$

$$d=V_ot+\tfrac{1}{2}at^2 \qquad (2)$$

by algebraic elimination another useful formula is obtained as follows: From (1)

$$t=\frac{V-V_o}{a}$$

Substitute this value of t in equation (2)—

$$d=V_o\frac{(V-V_o)}{a}+\frac{a}{2}\frac{(V-V_o)^2}{a^2}$$

$$d=\frac{V_oV}{a}-\frac{V^2_o}{a}+\frac{V^2}{2a}-\frac{2VV_o}{2a}+\frac{V^2_o}{2a}$$

$$d=\frac{V^2}{2a}-\frac{V^2_o}{2a}$$

or

$$V^2=V^2_o+2ad \qquad (3)$$

If $V_o=0$, that is the body starts from rest, and

$$V^2=2ad \qquad (3a)$$

This formula is useful when the time is not known or desired.

Example 1: An automobile starts from rest at constant acceleration. After traveling 1,000 feet it reaches a velocity of 90 feet per second. What was the acceleration? Here $V_o=0$.

Solution:

$$V^2=2ad \qquad (3b)$$

$$90^2=2.a\ (1{,}000)$$

$$a=\frac{8100}{2000}=4.05 \text{ feet per second per second}$$

Example 2: Suppose the car in the foregoing problem had been traveling at 30 feet per second when the acceleration was applied. What would the acceleration have been?

Solution: Here $V_o=30$ but $V=90$ as before.

$$V^2=V^2_o+2ad \quad (3)$$

$$90^2=30^2+2a\ (1{,}000)$$

$$a=\frac{8100-900}{2000}=\frac{7200}{2000}=3.6 \text{ feet per second per second}$$

25. Momentum.—*a.* Certain properties of moving bodies depend both on the mass of the body and its velocity. Thus, the time required for the brakes to stop an automobile depends jointly on the mass of the car and on its velocity. Hence, it is convenient to define a property which depends both on mass and velocity. This property is called momentum. The momentum of a body, at any instant, is defined as the product of the mass of the body and its velocity at that instant. The direction of the momentum is the same as that of the velocity and is a vector quantity, since velocity is a vector quantity. Expressed as a formula:

$$\text{Momentum}=\text{mass}\times\text{velocity}=mV=\frac{wV}{g}$$

b. When the velocity of a body changes, its momentum changes. Since the mass of a body is constant, any change in the momentum of a body is due to a change in its velocity. The change in momentum is equal to the product of the mass and the change in velocity.

Example: A 2,000-pound car is accelerated from 10 feet per second to 80 feet per second. What is the change in momentum?

Solution: Change of momentum = mass × change in velocity.

$$\text{Change of momentum}=m(V-V_o)$$

$$m=\frac{w}{g}=\frac{2{,}000 \text{ lbs.}}{32.2 \text{ ft./sec.}^2}$$

$$V-V_o=(80-10) \text{ ft./sec.}$$

Hence

$$\text{Change of momentum}=\frac{2{,}000 \text{ lbs.}}{32.2 \text{ ft./sec.}^2}\times(80-10) \text{ ft./sec.}$$

$$=4{,}348 \text{ pound-seconds.}$$

The units in these calculations were deliberately carried through each step in order to show that momentum is essentially the product of force (pounds) and time (seconds). This is of interest because of the relationship between momentum and impulse (par. 26).

26. Impulse.—*a. General.*—When a force acts on a body, its effect depends both upon the magnitude of the force and the time of its action. A force acting on a body for 2 seconds causes a greater change in the motion of the body than the same force acting for 1 second. The product of the magnitude of the force and the time of its action is called impulse. Expressed as a formula:

$$\text{Impulse} = \text{force} \times \text{time} = F \cdot t$$

It is evident from the formula that 100 pounds acting for 2 seconds produces the same impulse as 200 pounds acting for 1 second.

(1) The units of impulse are pound-seconds in the British engineering system and dyne-seconds in the absolute C. G. S. system.

(2) Impulse is a vector quantity and has the same direction as the force which produces it.

b. Relation of impulse and momentum.—In order to change the momentum of a body an impulse must be applied. This can be shown in the following manner:

$$F = ma$$

For uniform accelleration—

$$a = \frac{V - V_o}{t}$$

where V_o is the velocity at the beginning and V the velocity at the end of the time interval t.

Hence,

$$F = m\frac{(V - V_o)}{t} \text{ or } F \cdot t = m\ (V - V_o)$$

However, $m\ (V - V_o)$ is the change in the momentum of the body which occurs during the time the impulse is applied. It is thus evident that the impulse applied to a body equals the change in momentum of the body.

Example: A plane weighing 10,000 pounds is to be shot from a catapult 100 feet long. The plane is to leave the catapult at 100 feet per second. What impulse is required? If both the force and acceleration are constant, what force is required?

Solution: $F \cdot t = m\ (V - V_o)$ and $m = \frac{w}{g}$ and $V_o = 0$ for this case then $F \cdot t = \frac{10{,}000}{32.2}(100\text{–}0) = 31{,}060$ pound-seconds which is the impulse required. Since the final velocity was 100 feet per second and the acceleration was assumed to be uniform, the average velocity was 50 feet per second. Therefore, $t = \frac{100}{50} = 2$ seconds. Hence, since impulse $= F \cdot t = 31{,}060$, $F = \frac{31{,}060}{2} = 15{,}530$ pounds.

27. Conservation of momentum.—*a.* Newton's third law of motion states that when two bodies act upon each other that action and reaction are equal. This means that they exert equal but opposite forces upon each other. Hence, equal but opposite impulses act on the two bodies, and the two bodies gain equal but opposite changes in momentum. Consequently, the action of the two bodies on each other can cause no change in the total momentum of the two bodies, though the momentum of each may change. Hence,

$$m_1V_1+m_2V_2=m_1V^1_1+m_2V^1_2$$

In this formula m_1 and m_2 are the masses of the two bodies, and V_1 and V_2 their respective velocities before the action and V^1_1 and V^1_2 their velocities after the action. It is seen from the formula that the total momentum of the two bodies remains constant. In using this formula weight may be used instead of mass, since the g terms cancel.

Example 1: A gun fires a 1-ounce bullet at 3,000 feet per second. If the gun weighs 7 pounds, what is its recoil velocity?

Solution: The gun must gain the same momentum backwards as the bullet gains forward. Hence,

$$m_1\cdot V_1=m_2\cdot V_2$$

or

$$w_1\cdot V_1=w_2\cdot V_2$$

$$\frac{1}{16}(3{,}000)=7V_2$$

$$V_2=\frac{3{,}000}{(7)\cdot(16)}=26.8 \text{ feet per second.}$$

Example 2: If the bullet in example 1 imbeds itself in a block of wood weighing 5 ounces, suspended by a cord, how fast will the block and bullet together move after impact?

Solution: The momentum of the block and bullet together after impact must be equal to the momentum of the bullet alone before the impact.

$$m_1V_1=(m_1+m_2)V_2$$

$$V_2=\frac{m_1V_1}{m_1+m_2}=\frac{(1)(3{,}000)}{1+5}=500 \text{ feet per second}$$

b. In case the forces and velocities are in various directions, the rules of vector calculation will be used; the sum of the x components and the sum of the y components of the total momentum will remain constant throughout the action, provided there are no outside forces acting.

Example: Two putty balls collide as shown in figure 25. What will be the speed after impact if the balls stick together?

V_1=2 cm per second
m_1= 3 gm
V_2=4 cm per second
m_2=2 gm

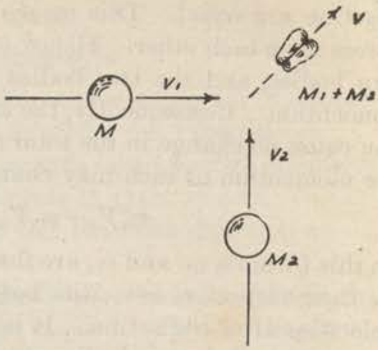

FIGURE 25.—Inelastic impact of two putty balls.

Solution: Before impact—

Momentum in x-direction$=4\times2=8$ gm cm per second.

Momentum in y-direction$=3\times2=6$ gm cm per second.

After impact, the momentum of the two combined masses must be the vector sum of the momentum of the two masses before impact. The magnitude and direction of the final momentum may be found from the vector triangle as shown in figure 26.

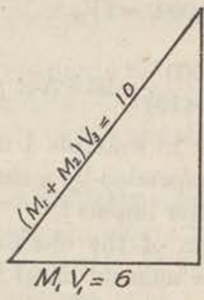

FIGURE 26.—Vector triangle for momentums.

Since $(m_1+m_2)V_3=10$ from the vector triangle, and

$m_1+m_2=3+2=5$ grams, then

$V_3=\frac{10}{m_1+m_2}=\frac{10}{5}=2$ centimeters per second in the same direction as the final momentum.

28. Centripetal force.—*a.* According to Newton's first law, a body in motion will continue to move with a uniform velocity in a straight line unless acted upon by an unbalanced force. Therefore a body moving in a curved path must be acted upon by some force. If it is moving in a circular path with uniform speed this force is called centripetal force and it is directed towards the center of the circle. This force is required to produce the acceleration necessary to continually change the direction of the velocity from a straight to a curved path. The acceleration is equal to $\frac{V^2}{r}$, where V is the speed and r the radius of curvature. The force required according to Newton's second law is $f=ma$ or $f=m\frac{V^2}{r}$. If m is in grams, V in centimeters per second and r in centimeters, then f is in dynes. If V is feet per second, r in feet, and m replaced by $\frac{w}{g}$, where w is in pounds and g is 32.2 feet per second per second, then f is in pounds.

Example: A 1-pound ball attached to a string is whirled in a horizontal circle of 10 feet radius with a speed of 100 feet per second. What is the centripetal force?

Solution: $F=\frac{w}{g}\frac{V^2}{r}=\frac{1}{32.2}\frac{(100)^2}{10}=31.06$ pounds.

b. In the foregoing example, the string exerted a force on the ball which acted back toward the center of the circle and that force was called centripetal force. The ball in turn exerted an equal but opposite force on the string. This force, acting outward from the circle, is called centrifugal force. Centripetal and centrifugal force are simply action and reaction.

29. Illustrative examples.—*a. Example 1:* A bomber flies 300 miles per hour at 30,000 feet. Ignoring wind resistance, how far from the target must the bombs be released?

Solution: The vertical and horizontal motions are quite independent. That is, the motion downward will follow the normal rules of acceleration under gravity and the horizontal velocity during the fall will remain constant at 300 miles per hour. The problem is then to find how far an object will move at 300 miles per hour during the time necessary for a normal fall of 30,000 feet.

$$d=\frac{1}{2}at^2$$

$$d=30{,}000=\frac{32.2}{2}t^2$$

$$t=\sqrt{\frac{60{,}000}{32.2}}=\sqrt{1862}=43.1 \text{ seconds time for fall}$$

$$43.1 \text{ seconds}=\frac{43.1}{60\times60} \text{ or } .0120 \text{ hour}$$

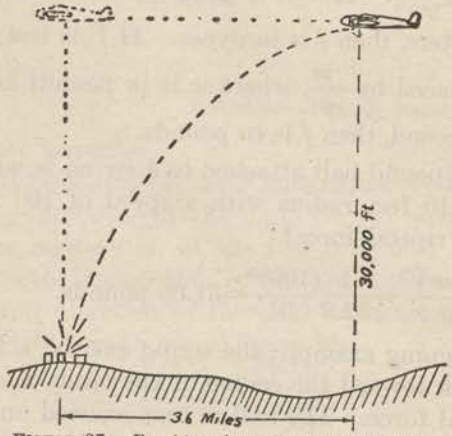

FIGURE 27.—Bombing from horizontal flight.

Horizontal distance traveled will then be $.012\times300$ or 3.60 miles.

b. Example 2: Three weights are strung as shown in figure 28. Ignoring friction, how far will they move in 3 seconds after release?

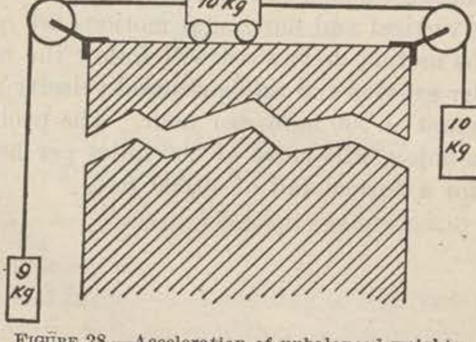

FIGURE 28.—Acceleration of unbalanced weights.

Solution: There is 1 kilogram of unbalanced force on the system and 29 kilograms of mass to be accelerated.

$$a=\frac{F}{m}$$

$$F=1{,}000\ (980)=980{,}000 \text{ dynes}$$

$$m=29{,}000 \text{ gr}$$

$$a=\frac{980{,}000}{29{,}000}=33.8 \text{ cm. per second per second}$$

$$d=\frac{1}{2}\,at^2=\frac{33.8(9)}{2}=152 \text{ cm}$$

c. Example 3: A one pound weight hangs from a string 20 inches long and is whirled as shown in figure 29. If the weight revolves in a circle of 10-inch radius, how fast is it moving?

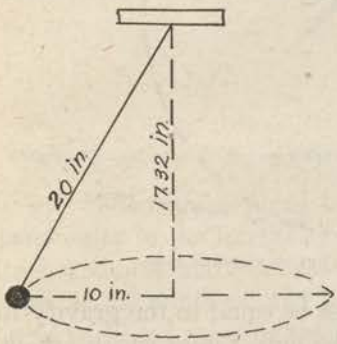

FIGURE 29.—Pendulum with circular motion.

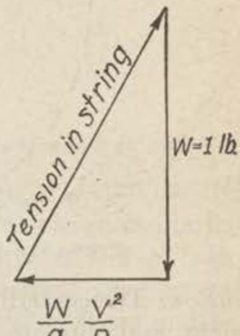

FIGURE 30.—Vector diagram for figure 29.

Solution: The tension in the string and the weight are the two external forces acting on the body. Their resultant is the centripetal force and their equilibrant is the centrifugal force acting on the body. Therefore the tension, weight, and centrifugal force must form a closed vector triangle. By similar triangles,

$$\frac{\frac{w}{g}\frac{V^2}{r}}{w}=\frac{10}{17.32}=$$

$$V^2=\frac{10}{17.32}\cdot(32.2)\frac{(10)}{12}=15.5$$

$$V=\sqrt{15.5}=3.94 \text{ feet per second}$$

Note that r (the radius) was in feet, not inches, when substituted in the formula. This was necessary since g was used as 32.2 feet per second per second, and the units used must be consistent.

d. Example 4: An airplane makes a loop of 400-feet radius. How fast must the airplane be traveling in order that the pilot, who forgot to fasten his safety belt, will not fall out at the top of the loop?

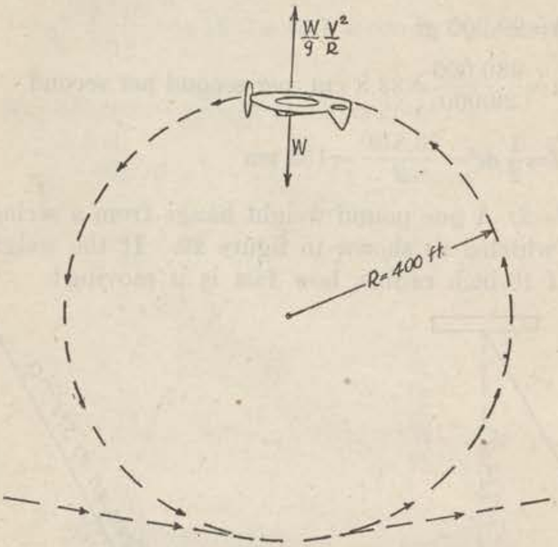

FIGURE 31.—Forces acting on pilot in airplane loop.

Solution: The centrifugal force must be equal to the gravity force, or weight, and opposite. These are the only forces which act on the pilot and must exactly balance each other.

$$\frac{w}{g}\frac{V^2}{r}=w$$

$$V^2=rg=400\ (32.2)=12{,}880$$

$$V=\sqrt{12{,}880}=113.5 \text{ ft. per second}$$

e. Example 5: Suppose a pursuit ship with multiple machine guns can fire 1,200 4-ounce bullets per minute at 3,000 feet per second muzzle velocity. How much additional thrust must the propeller exert if the speed is to remain constant while the guns are firing?

Solution: During 1 minute the total weight of projectile fired will be $1{,}200\times4=4{,}800$ ounces$=300$ pounds. During 1 second the weight fired is 5 pounds. The change in momentum will be $\frac{w}{g}\ (V-V_o)$ or

$\frac{5}{32.2} \times 3{,}000 = 465.9$ pound-seconds. The impulse required equals the change in momentum, or $F \cdot t = 465.9$ and since $t = 1$ second, $F = 465.9$ pounds. This impulse must be provided by the propeller thrust.

f. Example 6: What is the radius of the path of a 3,000-pound airplane which makes a 45° bank when turning at a speed of 150 miles per hour?

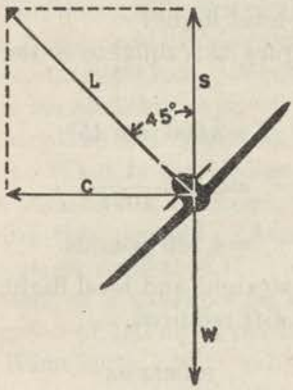

FIGURE 32.—Forces acting on airplane when making a turn with 45° bank

Solution: When an airplane banks at an angle of 45° the lift L is perpendicular to the lateral axis of the airplane as shown in figure 32. Its horizontal and vertical components are C and S both of which are at an angle of 45° to L, and therefore equal in value. S is the force which sustains the plane in horizontal flight and hence is equal to the weight of the airplane (3,000 pounds). Therefore the value of C is likewise 3,000 pounds.

$$F = \frac{w}{g} \cdot \frac{V^2}{r}$$

or

$$r = \frac{w V^2}{F g}$$

But both the weight w and the centripetal force are 3,000 pounds. Therefore the terms w and F in the equation cancel for an angle of bank of 45° and—

$$r = \frac{V^2}{g}$$

150 miles per hour is equal to 220 feet per second.

Therefore $$r=\frac{(200\text{ ft./sec.})^2}{32.2\text{ ft./sec.}^2}$$

$$=\frac{48{,}400}{32.2}\text{ feet}$$

$$=1{,}503\text{ feet}$$

g. Example 7: In example 6, what lift is needed in addition to that needed for straight and level flight?

Solution: Lift L in figure 32 is equal to $S\cdot\sec 45°$ and $S=W=3{,}000$ pounds.

Therefore $$L=3{,}000\cdot\sec 45°.$$

$$=3{,}000\frac{1}{.7071}.$$

$$=4{,}243\text{ pounds.}$$

As the lift required for straight and level flight is 3,000 pounds, 1,243 pounds is the additional lift required.

PROBLEMS

1. If an airplane drops a bomb and it strikes the ground in 30 seconds, how high was the airplane? (Ignore air resistance.)

2. If an airplane is flying at a height of 20,000 feet with a horizontal velocity of 220 miles per hour, how long will it take for a bomb to strike the ground after release? How far from the target should the bomb be released? (Ignore air resistance.)

3. A freight train can accelerate at 1 foot per second per second and can stop by braking with an acceleration of 5 feet per second per second. If 30 miles per hour is the maximum permissible top speed, how long will the train take to travel between two stations 3 miles apart if it must stop at both of them?

4. An airplane in a perfect turn must be banked so that the resultant force on the airplane is perpendicular to the wings. If the airplane is banked at a 45° angle and is traveling at 90 meters per second, what is the radius of its circle of turn?

5. A baseball is thrown upward with a speed of 80 feet per second. How high will it go and how long will it take to return to the ground?

6. If an imaginary rocket ship burns 5 grams of fuel per second, ejecting it as gas with a velocity of 500,000 centimeters per second, what will be the force acting to accelerate the ship in free space?

7. An anchor chain 200 feet long lies on the deck of a boat. The weight of the chain is constant along its length and we may assume that the friction when it slides along the deck is negligible. If one end starts over the edge and it is allowed to fall, what will be its acceleration when (a) 1 foot, (b) 20 feet, (c) 150 feet have gone over?

8. A certain pilot can stand six "g's" of acceleration. If the acceleration of gravity is ignored, what is the minimum radius in which he can turn in an airplane doing 350 miles per hour?

9. A pilot weighing 150 pounds bails out at an altitude of 5,000 feet and his parachute opens at 4,300 feet. What is the flyer's downward momentum at the time his parachute opens? (Ignore air resistance.)

10. A 5,000-pound airplane is accelerated from 150 miles per hour to 175 miles per hour. What is the change in momentum? If this increase in speed was obtained in 1 minute, what was the additional propeller thrust during this period? (Assume airplane is flying a straight course. Ignore air resistance.)

11. The angle of bank of a 3,000-pound airplane when making a horizontal turn at a speed of 150 miles per hour is 30°. What is the radius of the turn? What is the additional lift required?

Section VI

WORK AND ENERGY

30. Definition of work and energy.—*a. Work.*—(1) When a cadet stands in ranks with a rifle on his shoulder, he does not become very fatigued. However, let him begin to do rifle calisthentics, and perspiration and aching muscles will give ample testimony of the labor required to perform the rifle drill.

(2) This illustrates the difference between doing work and merely exerting force. Work involves not only the exertion of force but action that makes something move. Pushing or pulling on a hangar is not doing work on the hangar. A force that keeps itself up without any motion in the direction of the force does not involve the doing of work. For example, a chair may support a sitting man and exert a force thereby, but no work is being done by the chair.

(3) What is commonly called work may be considered as a physical quantity proportional to each of two factors: the amount of force acting and the amount of movement or displacement in the direction in which the force acts.

(4) A body may be moving, and may be acted upon at the same time by a force, yet without any work being done; for example, a stone whirled around at the end of a string. The stone is acted upon by a force pulling through the string, toward the center of the circle. Since there is no displacement toward the center, there is no displacement in the direction of the force, so there is no work being done by simply holding the string. The amount of work done, when a force is exerted and there is at the same time a displacement in the direction of the force, is the product of that force by the displacement. This is expressed by $W=Fd$, in which W is work done, F is the force, and d is the displacement, or distance over which the force operates. If the force is not constant during the displacement, use the average force.

(5) Work units are simple and natural. Just combine the unit of force with the units of displacement or distance. A foot-pound is the work done when the exertion of 1 pound of force is accompanied by a displacement of 1 foot in the direction of that force. If a Springfield rifle weighs 9 pounds and is lifted 4 feet off the ground, the work done is 9×4 or 36 foot-pounds.

(6) Any combination of a force unit with a length unit might be selected as a unit of work. Only a few are generally used. The most common unit in the British system is the foot-pound. In the metric system there is the dyne-centimeter. This is the absolute unit of work used in almost all theoretical discussions. The expression "dyne centimeter" is so awkward that the unit has been given a name of its own, the erg. The amount of work represented by an erg is very small; when you turn your hand over, thousands of ergs of work are done. A more convenient multitple of this unit, the joule, is often used. A joule is defined as 10 million (10^7) ergs.

(7) A joule is equal to 0.74 foot-pounds; a foot-pound equals 1.35 joules.

b. Energy.—The fact that a cadet can lift a rifle off the ground indicates that he has ability to do work. This ability to do work is called energy. Its amount is the same as the amount of work it will do, and is expressed in the same units as work, that is, foot-pounds, ergs, etc. The term work is applied to energy only during the process of transfer of energy.

31. Power.—*a.* When a cadet drills in double time, he is drilling at a rate greater than usual. He is doing the same amount of work in half the time. The rate of doing work is called power. Power is the rate at which work is done or the amount of work done per unit of time.

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

The unit by which power is measured must be a unit of work per unit of time. The absolute unit of power in the metric system is the erg per second; but, since this unit is too small for convenient practical use, it is customary to employ the watt, which is defined as one joule per second. The kilowatt, or 1,000 watts, is more convenient than the watt when measuring large amounts of power. The kilowatt-hour is a unit of energy (not of electricity). It is the amount of energy transferred in 1 hour to any agency (as a motor) that is consuming 1 kilowatt of power. In paying the electric bill at so much per kilowatt-hour, you do not pay for a quantity of electricity, but for work done, that is, for energy supplied.

b. The common unit of power in the English system of measurement is the horsepower (hp), based originally on measurements made by James Watt on the work rate of horses. It is now standardized at the arbitrary value of 550 foot-pounds of work per second.

c. One horsepower is equivalent to about 746 watts, or roughly ¾ kilowatt, so that a 750-kilowatt dynamo would require a 1,000-horsepower engine to drive it. One kilowatt-hour equals 2.66×10^6 foot-pounds of work.

Example 1: A force of 9,800 dynes acts for 10 seconds and pushes a body 1 meter. How much work is done?

$$\begin{aligned} W=F\times d &= 9{,}800\times100 \text{ dyne centimeters or ergs} \\ &= 980{,}000 \text{ ergs} \\ &= 1{,}000 \text{ gram centimeters} \\ &= 1 \text{ kilogram centimeter} \\ &= .098 \text{ joule} \\ &= .098 \text{ watt-second.} \end{aligned}$$

At what power is the above amount of work done?

$$P=\frac{W}{t}=\frac{.098}{10}=.0098 \text{ watt}$$

as one horsepower is 746 watts—

$$\text{hp}=\frac{.0098}{746}=.0000132 \text{ horsepower}$$

If this work is done by an electric motor at 100 percent efficiency, what will be the cost at 10 cents per kilowatt-hour?

$$.098 \text{ watt-second is } \frac{.098}{1000} \text{ kilowatt-second, or } \frac{.000098}{60\times 60} \text{ kilowatt-}$$

hour costing 0.000000272 cent.

Example 2: A force of 100 pounds acts on a body for 3 minutes and moves it a distance of 1,800 feet in the direction of the force.

How much work is done?

$$W=F.d=100(1{,}800)=180{,}000 \text{ foot-pounds.}$$

At what power was the work done?

$$P=\frac{W}{t}=\frac{180{,}000}{180}=1{,}000 \text{ foot-pounds per second.}$$

As 550 foot-pounds per second is one horsepower:

$$\text{hp}=\frac{1{,}000}{550}=1.82 \text{ horsepower.}$$

32. Kinetic energy.—*a.* Energy has been defined as the ability to do work. The energy contained by a body in motion is called kinetic energy. Before a moving body can be brought to rest, a force must be applied and this force will move for some finite distance, doing a definite amount of work in the process. If a body of mass m grams has a velocity of V centimeters per second, it contains a definite amount of kinetic energy. If a force F applied for a distance d will bring the body to rest, the ability of the body to do work may be expressed as $F\times d$. From the formulas (par. 24) for accelerated motion,

$$V^2=2ad \text{ (}a\text{ is acceleration in centimeters per second).}$$

If both sides are multiplied by $\frac{m}{2}$:

$$\frac{mV^2}{2}=mad$$

but force F is equal to the mass times the acceleration, or

$$\frac{mV^2}{2}=Fd=KE=\frac{mV^2}{2}$$

which is the amount of work obtainable in bringing the body to rest. In this derivation, forces were expressed in dynes and distances in centimeters; so the expression $mV^2/2$ will be the kinetic energy in ergs of a body of mass m grams and moving with velocity of V centimeters per second. Since in the British engineering system mass is taken as being:

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

the formula for kinetic energy (KE) will be

$$KE=\tfrac{1}{2}\frac{w}{g}V^2$$

where w is in pounds of weight, $g=32.2$ feet per second per second, V is velocity in feet per second, and KE is in foot-pounds.

b. A body in motion is able to do an amount of work equal to its kinetic energy, and conversely, if a certain amount of work is done accelerating a body, it will obtain a kinetic energy of this amount. So, if the only resistance is that due to inertia, the kinetic energy of translation imparted to a body by the action of a force is equal to the work done upon it. Thus the kinetic energy of a body at any instant can be calculated without any knowledge of the forces which produced the motion or of the previous history of the body, provided its mass and speed at the instant in question are known.

c. Since the kinetic energy of a body depends on the square of the magnitude of the velocity and not on direction, it is a scalar quantity. It is a quantity equivalent to work and is measured in the same units as work.

33. Potential energy.—*a.* Besides kinetic energy, which manifests itself by movement, bodies also have energy because of their position with reference to other bodies or because of the relative positions of their parts. For example, a coiled spring has potential energy. Another example is potential energy of height. In a waterfall, the potential energy of the water at the top may be converted into mechanical energy as it loses elevation and passes through a turbine. Other examples, the nature of which is less obvious, are the energy apparently stored in coal or other fuel, which is made available by combustion, and the energy in a battery or in a stick of dynamite. In none of these cases is any motion apparent after the energy is once stored. Energy existing in an apparently inactive or latent form is usually called potential energy.

b. It is evident that energy can pass from the potential to the kinetic form and back again. When a pendulum swings, for example, the pendulum bob rises to a certain level and stops, its energy being all potential; it then begins to descend, and as it loses potential energy, it gains speed and kinetic energy until at the lowest point of the swing it has its greatest kinetic and its least potential energy. The process is now reversed until the motion again stops and the energy is again all potential. A vibrating piano string and the waves of the ocean also illustrate this transformation. Potential energy is measured the same way work is measured. That is, the ability of a body to perform work is initially measured by the amount of work it does. Work is equal to force times distance. If a monkey wrench weighing 1 pound were dropped from an airplane at 5,000 feet, gravity would exert a force of 1 pound for 5,000 feet of distance doing $5{,}000 \times 1$ foot-pounds of work. The wrench will, just before it strikes the ground, have converted 5,000 foot-pounds of potential energy into 5,000 foot-pounds of kinetic energy. When it collides with the ground, this energy will be dissipated as heat.

c. When a man gets a flat tire on his car and starts pumping up the tire, he does work on the pump. The pump compresses the air, and the air is forced into the tire until it can support the weight of the car.

34. Conservation of energy.—*a.* Next to the concept of energy itself and the reality of its existence, the most important principle connected with this subject is stated thus: *The total amount of energy in the universe remains constant.*

b. It cannot be asserted that this is absolutely known, but the more information there is gained about physical and chemical processes, and the better their nature is understood, the stronger the evidence becomes that the principle is universally true. This principle of the conservation of energy is regarded as a cornerstone of physics.

c. If a man does 1,000 foot-pounds of work, turning the crank of a derrick, exactly that amount of energy will appear in the way of raising the weight, hauling up the blocks and chains, heating the bearings and pulleys, and filling the air with squeaks. Every erg of energy can be accounted for. Some of the energy supplied to the crank appears as potential energy of height as the weight is lifted, but a considerable percentage will be lost in the form of heat from friction. The heat generated in this way will be another form of energy but quite useless as far as man is concerned.

d. Example 1: A 1-ounce bullet is fired vertically upwards from a rifle with an initial muzzle velocity of 2,000 feet per second.

(1) What is its initial *KE?*

(2) How high will it go if air resistance is neglected?

(3) What is its potential energy of height just before it starts down?

(4) What is its *KE* when it returns to the earth?

Solution:

$$(1)\ KE=\frac{1}{2}\frac{wV^2}{g}=\frac{1}{2}\cdot\frac{1}{16}\cdot\frac{(2000)^2}{32.2}=3{,}882 \text{ foot-pounds}$$

(2) Since air resistance is neglected there is no loss of energy by the bullet and at the top of its flight, where $V=0$ and $KE=0$ also, the potential energy of height must equal the initial KE, or 3,882 foot-pounds.

(3) Since the potential energy of height equals the initial kinetic energy, this may be expressed as a formula:

$$KE=w\,h$$

where h is the height in feet and w is the weight in pounds.
Or

$$KE=\frac{1}{16}\times h=3{,}882 \text{ foot-pounds}$$

Therefore $h=62{,}112$ feet

(4) As the bullet starts back down it begins to lose potential energy of height but it gains velocity and therefore kinetic energy. At any point in its flight the sum of its potential energy and kinetic energy is equal to its original kinetic energy of 3,882 foot-pounds. Or

$$wh+KE=3{,}882 \text{ foot-pounds}$$

When the bullet returns to the earth $h=0$, so just before striking the ground the formula gives

$$\frac{1}{16}(0)+KE=3{,}882 \text{ foot-pounds}$$

$$KE=3{,}882 \text{ foot-pounds}$$

which is the same as at the beginning. It must be remembered that in this problem air resistance was taken as zero. Actually it is a force of considerable magnitude and slows the bullet rapidly. The energy used up in overcoming air resistance is dissipated in the air as heat and cannot be recovered by the bullet on the return to earth. Consequently its true final KE is much less than the KE at the muzzle.

e. Example 2.—An airplane dives from an altitude of 8,000 feet to an altitude of 7,000 feet. During this dive the propeller thrust is just enough to compensate for all energy losses due to air resistance. If the velocity of the plane was 100 miles per hour at the higher altitude, what will be its velocity at the lower altitude?

$$\text{Loss of potential energy} = w\,h$$
$$= w\ 1{,}000 \text{ feet}$$
$$\text{Gain in kinetic energy} = \frac{w\,V^2}{2g}$$
$$= \frac{w\,V^2}{64.4}$$

where V is the change in velocity.

Loss of potential energy = gain in kinetic energy

$$w\ 1{,}000 = \frac{w\,V^2}{64.4}$$
$$1{,}000 = \frac{V^2}{64.4}$$
$$V = \sqrt{1{,}000 \times 64.4}$$
$$= 253 \text{ feet per second}$$
$$= 172.6 \text{ miles per hour}$$
$$\text{Final velocity} = \text{initial } V + \text{final } V$$
$$= 100 + 172.6 = 272 \text{ miles per hour}$$

35. *Friction.*—Friction is the resistance to the relative motion of one body sliding over another. This resistance naturally requires that work be done to overcome it, and this work is dissipated in the form of heat. There are three kinds of friction: starting, sliding, and rolling.

a. Starting friction.—(1) If one body is resting upon another, it will require a certain amount of force to start sliding the one body over the other. This force is directly proportioned to the force acting between the two bodies (in this case, the weight of the upper body) and varies with the materials of which the bodies are made. The area of contact has very little to do with the resistance. Suppose that a block of wood weighing 10 pounds is resting on a plate of glass. In order to start the wood moving over the glass it is found that a force of 2.5 pounds must be exerted. In this case one fourth of the force between the bodies (10 pounds) must be exerted to overcome friction. This ratio is called the coefficient of starting (or static) friction. If the force holding the two bodies together is designated as F, the coefficient of starting friction C, and the starting resistive force as R, then

$$R = CF \text{ or } C = \frac{R}{F}$$

(2) As an example, the coefficient of starting friction of iron on iron is 0.3. If a locomotive at rest exerts a drawbar pull of 30 percent or more of its weight on the drive wheels, the wheels will slip on the rails.

If on the other hand, it exerts a drawbar pull of only 20 percent of its weight, the wheels will grab the rails and the train will move.

b. Sliding friction.—(1) After the 10-pound block of wood mentioned in *a* above is started sliding over the glass, it will be found that it can be kept sliding over the glass by a lesser force, say 2 pounds, than was required to start it sliding. The ratio of this force (2 pounds) to the force between the two bodies (10 pounds) is 0.2. This ratio is called the coefficient of sliding friction. The formula for coefficient of starting friction given in *a* above holds true for sliding friction if C represents the coefficient of sliding friction and R the sliding resistive force. Sliding friction, sometimes called kinetic friction, is always slightly less than starting (or static) friction and decreases to some extent with time and relative velocity, but is increased by reversal of motion.

(2) The coefficient of sliding friction of iron on iron is 0.25. Therefore if the locomotive in *a* (2) above exerts a drawbar pull of 25 percent or more of its weight on the rails after it is in motion, the wheels will slip on the rails.

c. Rolling friction.—If a hard ball is placed upon a hard, smooth surface, the contact is only a point. Similarly if a hard cylinder is placed upon a hard smooth surface, the contact is only a line. It would, hence, seem as if both the ball and the cylinder would roll without any opposing friction. However, this is not true, for regardless of how hard the materials are, they are slightly depressed or flattened at the point of contact in the case of a ball and at the line of contact in the case of a roller. As a result there is some resistance to rolling but this resistance is much smaller than resistance to sliding. The small value of rolling friction as compared with sliding friction is put to practical use in ball and roller bearings wherein loads are supported on hardened steel balls or rollers which rotate between hardened steel runways called races.

d. Lubrication.—If oil or grease is applied to a metallic surface over which another metallic body slides, both starting friction and sliding friction are greatly reduced. What actually happens in such a case is that the two metallic bodies are separated by a thin film of oil or grease and are not in actual contact with each other. The only resistance offered to sliding is the friction that exists between layers or particles of the oil or grease. This friction or resistance is considerably less than would exist if the two metallic surfaces were in actual contact. It is because of the greatly reduced friction between metallic surfaces when separated by a film of oil, that bearings and sliding metallic parts are lubricated at frequent intervals with oil or grease. If lubrication of bearings or other sliding parts is neglected, the resulting metal-to-metal contact results in excessive wear, friction, and heating.

Example: The coefficient of sliding friction between wood and concrete is about .4. How much work is done by a man in pushing a box weighing 175 pounds for a distance of 20 feet along a sidewalk?

Solution:

Resistive force $(R) = .4 \times 175 = 70$ pounds

$$\text{Work} = F \times D = Rd = 70 \times 20 = 1{,}400 \text{ foot-pounds}$$

e. Air resistance.—(1) When a body moves through air there is a certain resistance to the movement which may be considered a type of friction. This resistance increases as the speed and size of the body increase, and decreases as the density of the air decreases. An example of this is the pilot ballon used by weather stations to measure winds aloft. The accuracy of this measurement depends on a constant rate of ascent of the balloon. As the balloon rises it expands under the reduced pressure at higher elevations. This would slow the balloon in its ascent except that the density of the air decreases and the balloon continues to rise at an approximately constant rate of speed.

(2) Another example of the effect of air viscosity may be mentioned. When raindrops form and grow in size, they fall with an increasing velocity which is greater for large drops than for small drops.

QUESTIONS AND PROBLEMS

1. When a ball player catches a baseball, does the man or the ball do work as the ball is stopped?
2. If a ball weighing 50 grams and traveling 30 meters per second is stopped, how much work is done? Explain the amount of work in ergs, joules, and kilowatt hours.
3. If a 50-pound bomb is dropped from an airplane at 20,000 feet, how much potential and how much kinetic energy does the bomb have at 20,000 feet, at 15,000 feet, and at the ground just before striking? (Ignore the chemical energy of the explosive. Ignore air friction.)
4. How much power is required to accelerate a 2,000-kilogram (about 4,400 pounds) car from 14 meters per second (about 30 mph) to 28 meters per second (about 60 mph) in 20 seconds? (Ignore friction and wind resistance.)

5. How much horsepower is used for lifting if an airplane weighing 2,000 kilograms climbs 1,000 meters (about 3,000 feet) in 60 seconds? Assume no change in speed and neglect air resistance.

6. If an automobile loses half of its velocity in ¼ mile of coasting, what fraction of its kinetic energy has been transformed into heat?

7. A pendulum bob in swinging lifts ½ inch at the outer limits of its stroke. If the bob weighs 1 kilogram, what is the potential energy at the end of the stroke? At the center? What is the kinetic energy at these points?

SECTION VII

FLUIDS AT REST

36. Properties of fluids.—*a.* The subject of hydrostatics includes the study of pressure and allied problems in stationary as opposed to moving fluids. Everyone has had so many daily experiences with fluids that their distinguishing property should be readily perceived. Fluids tend to conform to the shape of the vessel in which they are contained. Solids, the other class of matter, retain their original shape, no matter where they are moved or how they are enclosed. Thus, if a hammer is taken out of a box, it will have the same shape as before; but if water is poured out of a bucket, the form alters markedly. A gas will distribute itself evenly throughout an entire container, but a liquid can do so only if enough is admitted to fill the container.

b. Another difference between liquids and gases is their compressibility. It is common knowledge that the air admitted to the cylinder of an aircraft engine readily contracts in volume as the piston moves toward the head. A gas, then, is readily compressible and, in general, can be compressed to a small fraction of its original volume. If compressed and cooled sufficiently they become liquids. But liquids, on the other hand, are practically incompressible.

37. Pressure in fluids.—*Definition of pressure.*—When a fluid is in contact with a solid such as the wall of a container, it exerts a force against this solid. The amount of this force per unit area is the pressure of the fluid. If the fluid exerts 1 dyne of force on 1 square centimeter of area, the pressure is 1 dyne per square centimeter. This same pressure would exert a force of 100 dynes on a wall with 100 square centimeters of area. Other units more commonly used to measure pressure are pounds per square inch, grams or kilograms per square centimeter, atmospheres, inches of mercury, and millibars. An "atmosphere" is the pressure exerted by the standard atmosphere (approximately 14.7 pounds per square inch); for instance, a pressure of 10 atmospheres would be 10 times the pressure normally exerted by the atmosphere or about 14.7 pounds per square inch. Inches of mercury and millibars are units commonly used to express the pressure in the atmosphere. A millibar is 1,000 dynes per square centimeter; an inch of mercury as a pressure unit will be explained later in connection with mercurial barometers.

38. Distribution of pressure with depth.—*a.* All fluids have weight, and as a result the pressure in any fluid increases with depth. A fluid will exert a force on the bottom of a rectangular container which is equal to the weight of the fluid above. Imagine a horizontal boundary within the fluid at some height above the bottom. The fluid above the boundary is exerting on the fluid below a force equal to the weight of the fluid above. Suppose that a pipe with one unit of cross section area is standing vertically and is filled with water. At any depth in the pipe, the weight of the fluid above is equal to the density of the fluid times the depth at that point; and as this weight acts on a unit area, the pressure must be equal to the density times the depth.

b. Action of pressure.—Though pressure is usually measured by determining the force exerted on a solid wall, pressure may exist within a fluid whether or not a wall is nearby for the fluid to push against. In other words, there is pressure at the center of a pipe as well as at the sides where the force is actually exerted. This pressure within a fluid acts in all directions. Pressure within a fluid may be visualized if one imagines that a thin wall is suddenly built up within the fluid extending in any direction. This wall would have no tendency to move, since the fluid exerts the same force on each side. If the fluid on one side were removed, however, the wall would be forced toward that side by the pressure.

This may be expressed as a formula in the British system as follows:

$$p=dh$$

where p is the pressure per unit area, h the depth of the point considered, and d is the weight density of the fluid. Thus for water, which weighs 62.4 pounds per cubic foot,

$$p=62.4 \cdot h$$

where the depth h is in feet and p is in pounds per square foot. There are 144 square inches in a square foot. Therefore, pressure in pounds per square inch may be obtained by dividing the answer just found by 144. Or

$$p=\frac{dh}{144}=\frac{62.4h}{144}=.433h$$

where h is still in feet but p is now in pounds per square inch.

c. In the mertic system, density is generally taken as mass per unit volume instead of weight per unit volume and the formula for pressure needs modification. Since pressure is a force unit, and since $f=m.a$, the change from mass density to weight density is made by multiplying by g. Therefore

$$p=gdh$$

where p is in dynes per square centimeter, d is in grams per cubic centimeter, h is in centimeters, and g is 980, the acceleration due to gravity in the metric system. Or, since 1 cubic centimeter of water weighs one gram, $d=1$ for water and the formula becomes—

$$p=980\ h$$

where p is again in dynes per square centimeter and h is in centimeters. The pressure, p, may be given in millibars by dividing the equation just given by 1,000.

d. Example 1: Ignoring atmospheric pressure, what is the pressure at a depth of 100 feet below the surface of a lake? Express the answer in pounds per square foot and pounds per square inch.

Solution:

$$p=dh$$
$$p=62.4\times100=6{,}240 \text{ pounds per sq. ft.}$$
$$p=.433\times100=43.3 \text{ pounds per sq. ft.}$$

e. Example 2: Ignoring atmospheric pressure, what is the pressure at a depth of 30 centimeters below the surface of a pond?

Solution:

$$p=ghd=980\times1\times30=29{,}400 \text{ dynes per square cm.}$$

$$p=\frac{29{,}400}{1{,}000}=29.4 \text{ millibars}$$

39. Buoyancy.—Imagine the fluid within the dotted lines in figure 33 to be inclosed by a thin-walled, practically weightless box. Gravity exerts a force downward on this box of fluid equal to the weight of the fluid inclosed, yet the box remains in equilibrium with no tendency to sink to the bottom. In order that such equilibrium be possible, the fluid outside the box must exert a force upward on the box equal to the weight of the fluid within. If any other substance were placed in the space that the box occupies, it will experience the same upward force because conditions in the fluid outside the space have not changed. This effect was first accurately expressed by Archimedes as follows: "The buoyant or upward force experienced by a body immersed in a fluid is equal to the weight of the fluid displaced by the body." If a body weighs less than the fluid it displaces (has a smaller density), there will be a net force upward, and the body will rise to the top and float. A body which has a greater density than the fluid will sink to the bottom. The cause of the buoyant force is the difference in hydrostatic pressure between the top and the bottom of the body immersed. Again in reference to figure 33, this difference in pressure is equal to the height of the body times the density of the fluid in which it is immersed. The net force exerted upward is equal to the horizontal cross-sectional area multiplied by the difference in pressure between the top and the bottom of the box. This may be expressed as follows:

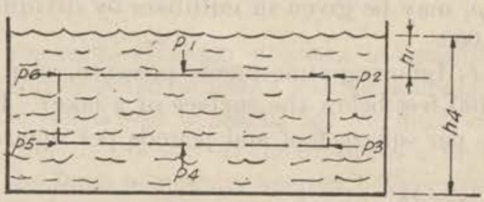

FIGURE 33.—Buoyancy in fluids.

Buoyant force = (area) × (height) × (density)
= (volume) × (density)
= weight of fluid displaced.

The buoyant force depends only upon the volume displayed and is in no way influenced by the shape of the body. If two fluids which do not mix readily are placed in the same container, the one with the greater density will sink to the bottom and the lighter fluid will rise. This principle plays an important part in weather, as often in the atmosphere one body of air is forced to rise over another colder and denser mass of air, forming clouds and precipitation.

40. Pressure in fluids under compression.—*a.* If an additional pressure is applied to a confined fluid, this pressure is transmitted equally throughout, provided the fluid is at rest. Such pressure applied will be in addition to pressures caused by the weight of the fluid above any specified point. The applications of this principle are innumerable. There are the barber's chair, the hydraulic repair rack at the service station, and also the brakes upon airplanes.

b. In all such cases the operator exerts a force upon the smaller piston which produces an equal increase in pressure throughout the entire fluid. However, since pressure is equal to force divided by area.

$$\frac{F_1}{A_1}=\frac{F_2}{A_2}$$

or

$$\frac{F_1}{F_2}=\frac{A_1}{A_2}$$

or

$$\frac{F_1}{F_2}=\frac{r_1^2}{r_2^2}=\frac{d_1^2}{d_2^2}$$

and it is seen that the ratio of the forces exerted on the two pistons is equal to the ratio of the area of the pistons and, hence, the ratio of the

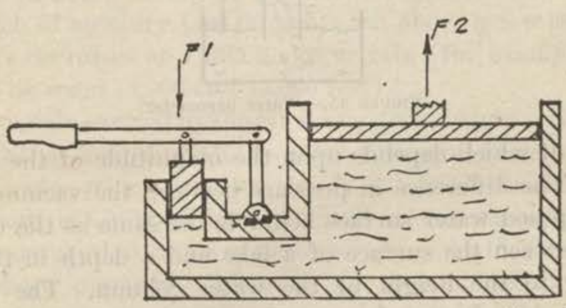

FIGURE 34.—Principle of hydraulic jack. (With the same pressure throughout, the small force F_1 balances the large force F_2.)

squares of the piston radii or diameters. Therefore the force exerted by the operator is magnified by the ratio of the areas of the two pistons or by the ratio of the squares of their diameters.

41. Pressure in atmosphere.—*a.* The atmospheric pressure is of interest for many reasons, particularly for the following, as far as the pilot is concerned.

(1) Pressure differences across the land produce the winds.

(2) Pressure measurements give the pilot his altitude.

(3) The low pressure of a high altitude may mean insufficient oxygen to sustain life.

(4) A study of the pressure configurations over the whole world is one of the best aids in forecasting future weather phenomena.

b. That the atmosphere exerts a pressure upon the earth's surface has long been known. If a long tube is filled with water and inverted, and the excess water allowed to collect in a pool, a column of water 34 feet high would still be left within the tube. This was the first crude barometer. Assuming that a vacuum is left within the tube at the top above the water, the pressure difference between the outside water surface and this vacuum is the atmospheric pressure. This pressure difference will support a column of water within the tube

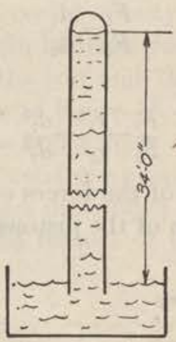

FIGURE 35.—Water barometer.

the height of which depends upon the magnitude of the atmospheric pressure. The difference in pressure between the vacuum at the top and the exposed water surface below is the same as the difference in pressure between the surface of a lake and a depth in the lake corresponding to the height of the water column. The present-day barometer is based upon the same principle, using mercury, however, instead of water. Because of its greater density, a column of mercury about 30 inches high is sufficient to balance the pressure in the atmosphere.

42. Standard atmosphere.—More precise measurements of the height of the mercury column have shown that the atmospheric pressure varies at any given locality; therefore some average value has had to be arbitrarily set for figuring altitudes and other quantities, the accurate estimation of which depends upon atmospheric pressure. The International Meteorological Committee in conjunction with the Bureau Internationale de Poids et Mesures has adopted 29.92 inches, or 76 cm of mercury, for standard atmospheric pressure at mean sea level. Scientists have adopted the millibar which is 1,000 dynes/cm^2. In these units the standard pressure (29.92 inches of mercury) is 1,013.2 mb or $1{,}013 \times 10^6$ dynes/cm^2. The reason this pressure is not felt is that a counterpressure is created in the human body to balance it. It is interesting to note that a sudden and marked lowering of the external pressure, as pursuit pilots can testify, has several undesirable and dangerous physiological effects.

43. Variation of pressure with height.—*a.* The atmosphere, though a gas, is not inclosed in a chamber as is gasoline in a cylinder. Rather it extends into space and is kept from escaping or diffusing by the attraction of each molecule to the earth. The effect of gravity is to cause all molecules to try to fall back to earth, creating a pressure proportional to the number of molecules above any one point. The pressure thus increases as one descends in the atmosphere, just as in liquids; or viewed from the surface, pressure decreases as one goes aloft, so that for every increase of 18,000 feet, the pressure is about one-half its former value. Because air, unlike water, is compressible, a rapid decrease in pressure occurs at low altitudes, about 34 mb per 1,000 feet or 1 inch of mercury (see table I); but above a few thousand feet the pressure decreases at a much slower rate (for example, 0.69 inch of mercury between 14,000 and 15,000 feet).

b. The pressure exerted by the air at any given height is the sum of the pressures at that height of all the gases, nitrogen, oxygen, argon, carbon dioxide, etc., which compose it. At sea level, the normal atmospheric pressure is 1,013 millibars of which approximately 200 millibars is the pressure exerted by its oxygen content. At 18,520 feet altitude the atmospheric pressure is 500 millibars (see table III) or less than half as great as at sea level. The pressure exerted by the oxygen in the air at that height is proportionately less, or less than 100 millibars. When oxygen equipment is being used at high altitudes, it is regulated to supply oxygen at the normal sea-level oxygen pressure of 200 millibars.

c. Just as the pressure on the surface varies from point to point, so does the pressure aloft vary from point to point at the same level, and, also, since the standard atmospheric pressure was defined, we must define an average pressure condition aloft. Starting with the standard sea level pressure at a temperature of 59° F., the average condition assumes a mean lapse or decrease in temperature of 3.57° F. per 1,000 feet, and the following tables may then be computed:

TABLE I.—*Standard pressures at 1,000-foot levels and pressure differences between 1,000-foot levels*

Altitude in feet	Pressure in inches of mercury	Pressure difference, inches of mercury
18, 000	14. 94	. 62
17, 000	15. 56	. 65
16, 000	16. 21	. 67
15, 000	16. 88	. 69
14, 000	17. 57	. 72
13, 000	18. 29	. 74
12, 000	19. 03	. 76
11, 000	19. 79	. 79
10, 000	20. 58	. 80
9, 000	21. 38	. 84
8, 000	22. 22	. 87
7, 000	23. 09	. 89
6, 000	23. 98	. 91
5, 000	24. 89	. 95
4, 000	25. 84	. 97
3, 000	26. 81	1. 01
2, 000	27. 82	1. 04
1, 000	28. 86	1. 06
Sea level	29. 92	

TABLE II.—*Vertical distance corresponding to 1-inch mercury change at various altitudes*

Inches of mercury	Altitude in feet	Distance in feet for 1-inch of mercury
13. 92	19, 696	1, 670
14. 92	18, 026	1, 581
15. 92	16, 445	1, 503
16. 92	14, 942	1, 433
17. 92	13, 509	1, 369
18. 92	12, 140	1, 313
19. 92	10, 827	1, 259
20. 92	9, 568	1, 212
21. 92	8, 356	1, 168
22. 92	7, 188	1, 127
23. 92	6, 061	1, 083
24. 92	4, 978	1, 062
25. 92	3, 916	1, 023
26. 92	2, 893	992
27. 92	1, 901	964
28. 92	937	937
29. 92	Sea level	

TABLE III.—*Vertical relation of 100-millibar levels*

Millibars	Feet	Meters	Millibars	Feet	Meters
400	24, 370	7, 425	800	6, 200	1, 889
500	18, 520	5, 643	900	3, 112	948
600	13, 740	4, 186	1,000	348	106
700	9, 700	2, 955	1,013	Sea level	Sea level

d. It should be borne in mind that these tables represent average conditions, and that any altimeter (essentially a barometer) may be in error, high or low, depending upon the local departure from average.

44. Isobars.—*a.* This local departure from the average is one of the phenomena that the weather forecaster utilizes constantly. The pressure at a number of stations is entered upon a map called a synoptic chart, and the weather is analyzed from these pressures. If some of the stations are in the mountains and others near sea level, the upper stations will report a lower pressure. A common level or altitude must be chosen which is sea level. The weather observer, therefore, must correct his observed pressure by adding to it the pressure exerted by an imaginary column of air between the level of his station and sea level.

b. Once the corrected pressures are received and recorded, the forecaster can draw isobars or lines joining points on the map having the same pressure. The Army requires that isobars be drawn for intervals of 3 millibars for all recorded pressures divisible by 3. Thus isobars would be drawn for pressures of 996, 999, 1,002, 1,005 mb, etc. Figure 36 is a part of a map with a number of isobars drawn. Beginning at the left, a person naturally knows that the 1,002 isobar must lie between the pressures recorded as 1,002.2 and 999.8 and be much closer to the former. Note that these lines are drawn smoothly, but do bend rather sharply along the dotted axis. Except for bends along such fronts, isobars are continuous and gently bending, eventually closing upon each other again, just as the 999 and 1,002 do, and

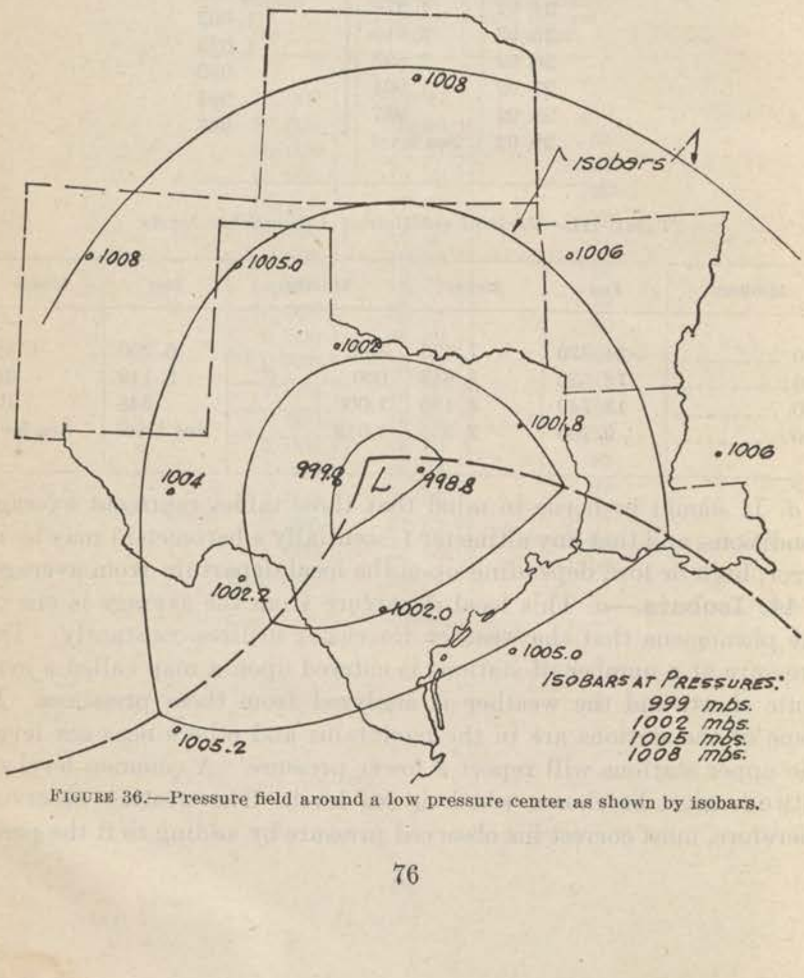

FIGURE 36.—Pressure field around a low pressure center as shown by isobars.

the 1,008 would do if carried above the limit of the chart. No isobar may branch out in a Y or fork, and separate isobars may not cross.

45. Pressure gradient and wind.—When the forecaster has drawn all the isobars, he has a quickly grasped picture of the pressure variations, or pressure field. The lines are quite similar to contour lines upon a map, and not only show the mountains and valleys or centers of low and high pressure but also give an idea of the steepness of the hill, or the pressure gradient. The latter is defined as the ratio of the change in pressure to the distance between points. A large change in pressure within a small distance would indicate a large pressure gradient, and the isobars would crowd closely together. High pressure gradients are especially watched for, because associated with such regions are high winds blowing approximately parallel to the isobars. A pilot or forecaster has a good idea of the wind speed and direction from a quick look at the isobars upon the synoptic chart, for wind speed is proportional to pressure gradient. The synoptic chart has many other features, too, which are required for a complete grasp of the weather along a route or at a station, and these will be taken up later.

46. Mercurial barometers.—*a.* Thus far the phenomena associated with pressure have been considered but no attention has been

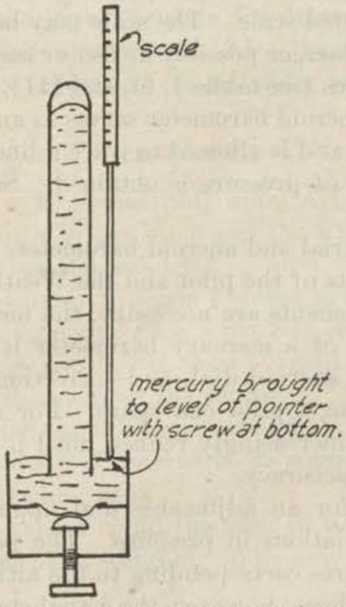

FIGURE 37.—Principle of Fortin type barometer.

paid to methods of precisely measuring pressure. A working knowledge of such instruments is useful, and absolutely essential in the case of altimeters.

b. Present-day mercurial barometers differ little in principle from Torricelli's tube. The tube is a glass cylinder filled with mercury evacuated at the top. A brass measuring scale is fixed to the glass and is used with a sliding vernier for accurate readings.

c. There are two common mercurial barometers in use, namely, the Fortin and the Kew. The Fortin barometer has a leather pouch at the bottom of the column by means of which the height of the outside mercury may always be brought to a fixed point so that the scale will read the true height of the mercury column. No such adjustment is possible in the Kew barometer, consequently, an extra source of error is introduced which must be corrected. Other corrections must be made for temperature, gravity, and latitude.

47. Aneroid barometers.—*a.* The other type of barometer in common use, the aneroid, depends upon the movement of a hollow corrugated metal box under varying pressures. The inside is airtight and evacuated, so that pressure is exerted only by the outside air against a spring inside that prevents collapse of the bellows. When the atmospheric pressure increases, it squeezes the sides closer together, and this movement is multiplied by suitable levers and indicated upon a calibrated scale. The scale may be calibrated in inches of mercury, in millibars, or possibly in feet or meters corresponding to the standard pressures (see tables I, II, and III). When calibrated in feet or meters, the aneroid barometer serves as an altimeter. If a pen replaces the pointer and is allowed to trace a line on a rotating drum, a continuous record of pressure is obtained. Such an instrument is called a barograph.

b. Both the mercurial and aneroid barometers are necessary for the different requirements of the pilot and the Weather Service. Whereever precise measurements are necessary, the mercurial type must be used. The reading of a mercury barometer is much more difficult than a glance at an aneroid dial, and corrections for the former require more time than a pilot can spare. For all these reasons the aneroid has become increasingly refined until it approaches the mercurial barometer in accuracy.

c. The necessity for an adjustable dial upon an altimeter arises because of local variations in pressure. The pointer is so adjusted as to indicate pressures corresponding to the altitudes resulting from the standard atmosphere; however, the actual state of the atmosphere seldom corresponds to the standard. Therefore, the dial is moved under the pointer until the actual pressure will cause the altimeter to read the true height at that field. For example, consider an airplane's altimeter with its zero mark set at 29.92. If at the time a plane took off from Corpus Christi the sea level pressure was found to be 30.22 inches, the pointer would indicate the plane was 300 feet below sea level because of the high pressure at that station, an increase of 0.30 inches corresponding to 300 feet. If the pilot adjusts the zero mark of altimeter setting to 30.22 inches, by effectively rotating the dial, it will read zero at take-off. If now he flies to Hensley Field, Dallas, which reports a pressure, reduced to sea level, of 29.82 inches, the pressure will be reduced upon his altimeter and will consequently read high by 400 feet. If he tries to land blind with this setting, disaster may result. Therefore, if the altimeter is reset to be 29.82 inches, it will read the true height of the station when he lands. A good habit to form is to reset the altimeter all along the route.

48. Pilot balloon ascensions and upper winds.—When a pilot is navigating it is important for him to have a close estimation of the winds that exist aloft. The direction and velocity of the upper winds are determined by the movement of ascending balloons. These rubber balloons are filled with hydrogen and will rise at a known rate. Thus the height of the balloon at any time is known. The change in position of the balloon gives the data for determining the direction and velocity of the winds at any level. Also, the direction and velocity of the winds may be estimated by watching the movement of the clouds.

PROBLEMS

1. A man exerts a 50-pound pull upon a hydraulic jack. The driving piston is 1 inch in diameter and the lifting piston 3 inches. How heavy a weight can the jack lift?

2. If the driving piston in problem 1 moves $\frac{1}{2}$ inch each stroke, how many strokes are necessary to raise a flat tire clear off the ground if it is 6 inches from the rim to the outside tread of the tire when inflated? Neglect the thickness of the rubber.

3. How heavy a man could be supported upon a pine raft 4 feet on a side and 4 inches thick? Pine weighs 30 pounds per cubic foot and water 62.4 pounds per cubic foot.

4. How much equipment could the man in problem 3 carry if the raft had been made of balsa weighing 10 pounds per cubic foot?

5. The height of a mercurial barometer on the surface is observed to read 29.95 inches. What would the barometer read 750 feet above the station?

6. If a balloon ascends at 6 feet per second and disappears in the clouds in 8 minutes, how high are these clouds?

7. Normal atmospheric pressure is 29.92 inches of mercury or 1,013 millibars. Use this relationship to convert 800 millibars to inches of mercury.

8. How many millibars correspond to 1 inch difference in mercury pressure?

9. A pilot descending from 15,000 feet altitude wants to maintain the same average pressure increase for each 5,000 feet of decreased altitude. In which altitude bracket would his rate of descent be greatest?

Section VIII

FLUIDS IN MOTION

49. Velocity of fluids.—In section VII the properties of fluids at rest were discussed. Now that expressions for the energy of any body have been developed, these formulas can be applied to the study of the flow of fluids or hydrodynamics.

a. Complete calculation of the properties of flow of fluids is very complicated. In cases dealing with incompressible fluids or with compressible fluids (gases) remaining at the same density during the flow, the calculation is much simplified. In this section it will always be assumed for purposes of simplification that the fluids have constant density. If the fluid is air, the results of this calculation will be only an approximation but for most purposes will be sufficiently accurate.

b. If there is a steady state of motion (that is, the present motion has remained the same for some finite period of time and will remain the same for some finite time to come), the amount of fluid entering some definite space must be the same as the amount of fluid leaving that same space in a unit time. If the fluid is considered incompressible, it may be said also that the volume of the fluid entering must equal the volume leaving. Consider the fluid flowing through the reducer pipe in figure 38. If some definite volume V_o enters the large end, the same volume V_o must leave the small end in the same period of time. If the fluid were compressible, and with the differences in pressure that would exist at the two points, the volumes of fluid entering and leaving would not be the same, but the mass or weight of fluid in each case would be equal. Let it be assumed here and in the rest of the calculations that the fluid is incompressible. It is easy to see that the fluid will have to move faster through the small end than through the large end. If in the large end a part of the fluid moves in one second from point P_1 to point P_2, a part of the fluid in the small end will have to move a longer distance from P_3 to P_4 so that the volume of fluid between cross sections P_3 and P_4 will be equal to that between P_1 and P_2.

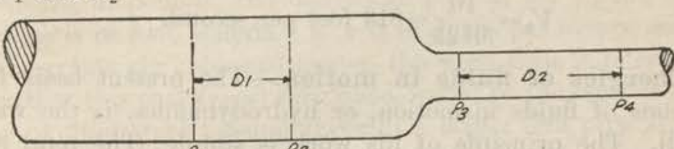

FIGURE 38.—Pipe reducer showing increase of velocity with decreased size pipe.

D_1 and D_2 will be the distance traveled in 1 second at each point; and as velocity is defined as the distance traveled in 1 second, $D_1 = V_1$ and $D_2 = V_2$ where V_1 and V_2 are the velocities of the fluid at these points. The volume in each case will be equal to the cross-sectional area of the pipe times the distance D (or V), and the equation for velocities of flow in pipes is set up accordingly.

$$A_1V_1 = A_2V_2$$

(A_1 and A_2 are cross-section areas; V_1 and V_2 are velocities of motion.)

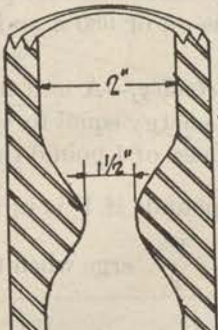

FIGURE 39.—Venturi constriction in pipe.

Example: Air flows through a carburetor with a venturi constriction (fig. 39). If 10 cubic feet of air per second enter the tube, what will be the velocities of the air at point A and at point B?

Solution: The cross-section area at point A is:

$$\left(\frac{1}{12}\right)^2 (3.141) = .0218 \text{ square feet.}$$

The cross-section area at point B is:

$$\left(\frac{.75}{12}\right)^2 (3.141) = .0123 \text{ square feet.}$$

$$V_a = \frac{\text{Volume}}{\text{Area}} = \frac{10}{.0218} = 460 \text{ feet per second.}$$

$$V_b = \frac{10}{.0123} = 813 \text{ feet per second.}$$

50. Energies of fluids in motion.—The present basis for all calculations of fluids in motion, or hydrodynamics, is the work of Bernoulli. The principle of his work is simple: The total energy carried and transmitted by any fluid will be the same at any point in its path. One type of energy may be transmitted to another, but the total will be constant if no energy is added from the outside as by a pump. If it is assumed that there is no friction converting mechanical energy into heat energy and that the fluid is incompressible, the only types of energy with which one will be concerned are those listed below:

a. Potential energy of height.—A unit mass of water will have a potential energy equal to the product of its weight and height above a reference plane. For 1 pound of water this potential energy is simply h and the energy is measured in foot-pounds. For 1 gram of water this potential energy is gh or 980 h and is measured in ergs if h is in centimeters.

b. Kinetic energy due to velocity.—A unit mass of fluid flowing by any point will have a kinetic energy equal to $\frac{1}{2}\ mV^2$, or $\frac{1}{2}\ wV^2$ in the British system. For a unit mass of 1 pound the kinetic energy $(KE)_g$ is $\frac{V^2}{2g}$ or $\frac{V^2}{64.4}$ and is in foot-pounds if V is in feet per second. For a unit mass of 1 gram, the KE is $\frac{V^2}{2}$ ergs when the velocity is expressed in centimeters per second.

c. Pressure energy of flow.—Imagine 1 pound of fluid having a volume Q flowing in the pipe shown in figure 40 which has a cross-section area of 1 square inch. The volume of this fluid flowing through will push an imaginary piston from A to B. If the fluid has a pressure of p pounds per square inch, the work done in moving this fluid will be pQ. But the volume Q is equal to the weight w of the fluid divided by d.

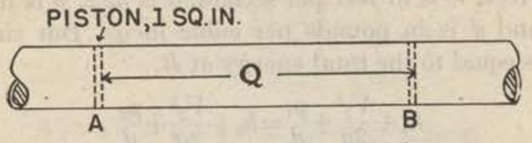

FIGURE 40.—Pressure energy of flow.

Hence the work done is $p\,\frac{w}{p}\cdot$ If pressure is in pounds per square inch, weight in pounds, and density in pounds per square inch, the work done is in foot-pounds. If p is in dynes per square centimeter and d in grams per cubic centimeter, the work done is in ergs. It is obvious that this energy, or work done, would be the same if the same volume of fluid were passing through a larger size pipe at a lower velocity, as the force on the imaginary piston would be greater for the same pressure but the distance traveled would be less.

d. Sum of these energies constant.—According to Bernoulli's law the total energy carried and transmitted by a fluid is the same at any point in its path. Therefore the total energy of a unit mass of fluid at A in the tapered pipe shown in figure 41 is the same as at B and at each point is equal to the sum of the potential, kinetic, and pressure energies at that point. The total energy in foot-pounds at A for 1 pound of fluid is

$$h_1+\frac{V_1^2}{2g}+\frac{p_1}{d}$$

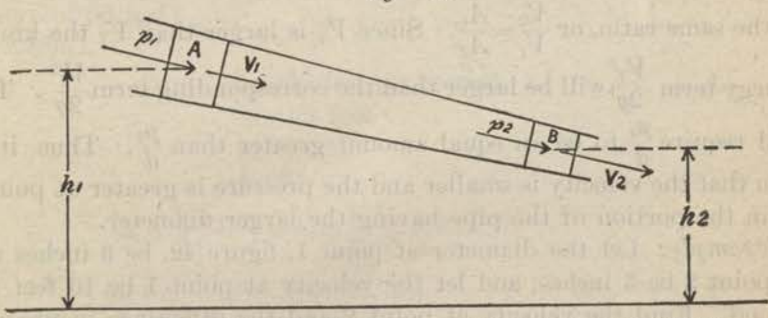

FIGURE 41.—Potential and kinetic energies at two points in a tapered pipe.

and at B:

$$h_2+\frac{V_2^2}{2g}+\frac{p_2}{d}$$

where h is in feet, V is in feet per second, g is 32.2, p is in pounds per square inch and d is in pounds per cubic inch. But since the total energy at A is equal to the total energy at B,

$$h_1+\frac{V_1^2}{2g}+\frac{p_1}{d}=h_2+\frac{V_2^2}{2g}+\frac{p_2}{d}$$

In the metric system, this equation becomes

$$h_1+\frac{V_1^2}{2}+\frac{p_1}{d}=h_2+\frac{V_2^2}{2}+\frac{p_2}{d}$$

where h is in centimeters, p is in dynes per square centimeter and V is in centimeters per second.

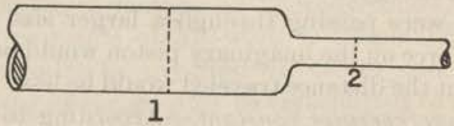

FIGURE 42.—Compound pipe.

51. Illustrations and applications.—*a*. Take the case of a fluid flowing through the compound pipe in figure 42 and consider the potential, kinetic, and pressure energies at points 1 and 2. Since the pipe is horizontal, $h_1=h_2$ and these two terms cancel in the equation. The equation of continuity (example, par. 49) requires that $A_1 V_1= A_2 V_2$ and since A_1 is larger than A_2, V_2 must be larger than V_1 in the same ratio, or $\frac{V_2}{V_1}=\frac{A_1}{A_2}$. Since V_2 is larger than V_1 the kinetic energy term $\frac{V_2^2}{2g}$ will be larger than the corresponding term $\frac{V_1^2}{2g}$. This will require $\frac{p_1}{d}$ to be an equal amount greater than $\frac{p_2}{d}$. Thus it is seen that the velocity is smaller and the pressure is greater at point 1 or in the portion of the pipe having the larger diameter.

Example: Let the diameter at point 1, figure 42, be 6 inches and at point 2 be 3 inches, and let the velocity at point 1 be 10 feet per second. Find the velocity at point 2 and the difference in pressure at points 1 and 2, assuming the fluid in the pipe to be water.

Solution: The area of a circular pipe is equal to $3.1416r^2$. Since

$$\frac{V_2}{V_1}=\frac{A_1}{A_2}$$

then

$$\frac{V_2}{V_1}=\frac{3.1416\times\left(\frac{6}{12}\right)^2}{3.1416\times\left(\frac{3}{12}\right)^2}=\frac{\frac{1}{4}}{\frac{1}{16}}=4$$

or

$$V_2=4V_1=4(10)=40 \text{ feet per second.}$$

Then

$$h_1+\frac{V_1^2}{2g}+\frac{p_1}{d}=h_2+\frac{V_2^2}{2g}+\frac{p_2}{d}$$

$$0+\frac{(10)^2}{64.4}+\frac{p_1}{d}=0+\frac{(40)^2}{64.4}+\frac{p_2}{d}$$

or

$$\frac{1{,}600-100}{64.4}=\frac{p_1-p_2}{d}=\frac{p_1-p_2}{62.4}$$

$$p_1-p_2=\frac{1500\ (62.4)}{64.4}=1{,}454 \text{ pounds per square foot}$$

difference in pressure between points 1 and 2. If p_1-p_2 is desired in pounds per square inch, divide by 144, thus obtaining 10.09 pounds per square inch.

b. In water falling freely in air the pressure is zero. The potential energy, h, decreases with fall and consequently the kinetic energy must increase to maintain the same energy content. Therefore the velocity must increase with fall.

Example: A pipe discharges horizontally with a velocity of 10 feet per second. What is the velocity of the water after falling a distance of 60 feet?

Solution:

$$V_1=10 \text{ feet per second}$$
$$h_1=60 \text{ feet}$$
$$p_1=p_2=0$$
$$h_2=0$$

$$h_1+\frac{V_1^2}{2g}+\frac{p_1}{d}=h_2+\frac{V_2^2}{2g}+\frac{p_2}{d}$$

$$60+\frac{(10)^2}{64.4}+0=0+\frac{V_2^2}{64.4}+0$$

$$V_2^2=\frac{(3864+100)}{64.4}64.4=3964$$

$$V_2=\sqrt{3964}=62.96 \text{ feet per second.}$$

c. In a waterfall the pressure will be approximately the same at the top as at the bottom; the pressure terms will cancel. The potential energy will decrease during the fall, but the kinetic energy will increase, indicating an increased velocity as expected.

Example: The stream velocity at the top of a fall is 1 meter per second. If the falls are 30 meters high, what will be the velocity of the water when it reaches the bottom?

Solution:

$$V_1 = 100 \text{ cm per second}$$
$$h_1 = 3{,}000 \text{ cm}$$
$$h_2 = 0$$
$$gh_1 + \frac{V_1^2}{2} = gh_2 + \frac{V_2^2}{2}$$
$$980\ (3{,}000) + \frac{10000}{2} = 0 + \frac{V_2^2}{2}$$
$$V_2 = \sqrt{5{,}880{,}000 + 10{,}000} = 2{,}420 \text{ cm per second}$$
$$= 24.20 \text{ meters per second.}$$

d. Several applications of the Bernoulli principle are well known. The Venturi tube (fig. 43) in a carburetor uses this principle for injecting the gasoline into the air stream. At the point of maximum construction the velocity of the air is highest and the pressure is reduced below that of the outside air, forcing the gasoline through the injection tube.

e. The Pitot tube (fig. 44) on the outside of an airplane is used for measuring air speed, and the foregoing principle applies in its use. In use, the tube is pointed into the wind or straight ahead on an airplane. The air blows rapidly by point *A* with approximately the speed of the airplane and at point *B* the air is carried into the tube.

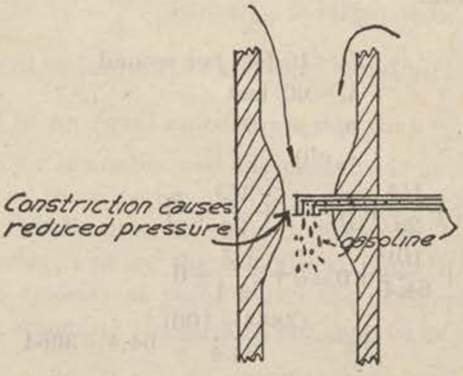

FIGURE 43.—Schematic diagram showing prinicple of carburetor.

In the simplified case assume that the tube stands still and the air is blowing by with a speed that one desires to determine. Port A is at right angles to the stream of air and therefore not subject to its impact. The air pressure on port A, and, hence, in tube P_2 is accordingly atmospheric pressure. Port B faces the air stream and receives the full impact of the air reducing its velocity to zero and building up a pressure head p_1 which is greater than atmospheric. From the difference in pressures in tubes P_1 and P_2, the velocity of the air stream can be calculated by using the following equation.

$$\frac{V_a^2}{2g}+\frac{p_a}{d}=\frac{V_b^2}{2g}+\frac{p_b}{d}$$

In this equation the potential terms have been omitted, as there is no change in elevation. V_b will be zero, V_a will be the velocity of the plane, and p_a the atmospheric pressure. Solving for V_a the equation reduces to:

$$V_a=\sqrt{\frac{2(p_b-p_a)}{d}}$$

The air-speed indicator in an airplane is a sensitive pressure measuring device which measures the difference in pressure between the two openings and which has a scale so calibrated that it will read directly in miles per hour. At high altitudes the density d of the air is reduced and consequently the air-speed indicator will ordinarily indicate a lower speed than the plane is actually traveling, since d at high altitudes is less than at the altitude for which the instrument is calibrated.

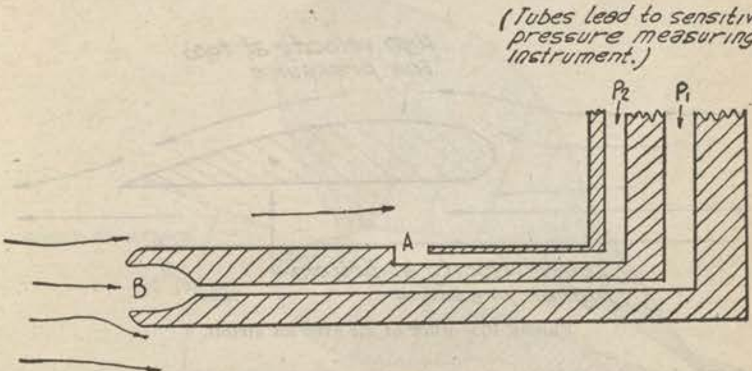

FIGURE 44.—Schematic section of Pitot tube.

Example: If the difference in pressure at A and B, figure 44, is ½ inch of mercury, how fast is the airplane traveling? Assume air density to be 0.0765 pounds per cubic foot.

Solution: Since standard atmosphere is equal to 14.7 pounds per square inch or 29.92 inches of mercury, 1 inch of mercury is equal to:

$$\left(\frac{14.7}{29.92}\right) = .491 \text{ lbs. per sq. inch} = p_b - p_a$$

Since d is .0765 pound per cubic foot, $(p_b - p_a)$ will be in pounds per square foot. This is 144 times the pressure difference in pounds per square inch, or $(144).491 = 70.704$ pounds per square foot.
Then

$$V_a = \sqrt{\frac{2g(p_b - p_a)}{d}}$$

$$V_a = \sqrt{\frac{64.4(70.704)}{.0765}}$$

$$V_a = \sqrt{59508}$$

$$V_a = 244 \text{ feet per second}$$

$$V_a = 166 \text{ miles per hour}$$

f. The lift of a modern airplane wing is developed upon the application of the Bernoulli principle. The curvature of the top surface (fig. 45) makes the air travel a longer path over the top of the airfoil than over the bottom. Since the air immediately on the top has farther to travel, its velocity is greater, and therefore the pressure is less on the top than on the bottom. Hence there is an in-

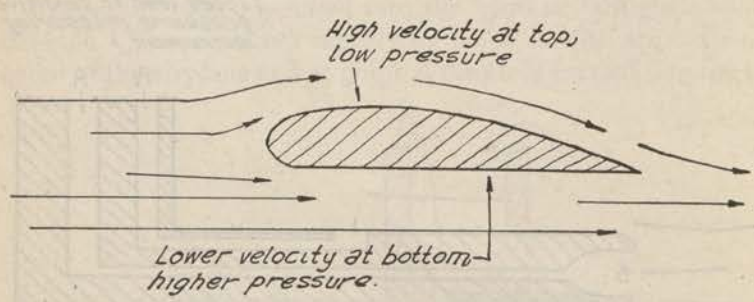

FIGURE 45.—Flow of air over an airfoil.

duced lift because of the flow of air. At low angles of attack (angle between the line of the air stream and the line from the front to the back of the wing) (fig. 45) there is practically no pressure other than ordinary atmospheric pressure on the underside of a wing with a flat undersurface. However, when the wing is tilted up (higher angle of attack) there is also an upward pressure on the underside of the wing caused by deflection of the impinging air stream as shown in the two lower illustrations in figure 46. The air flow along the fore

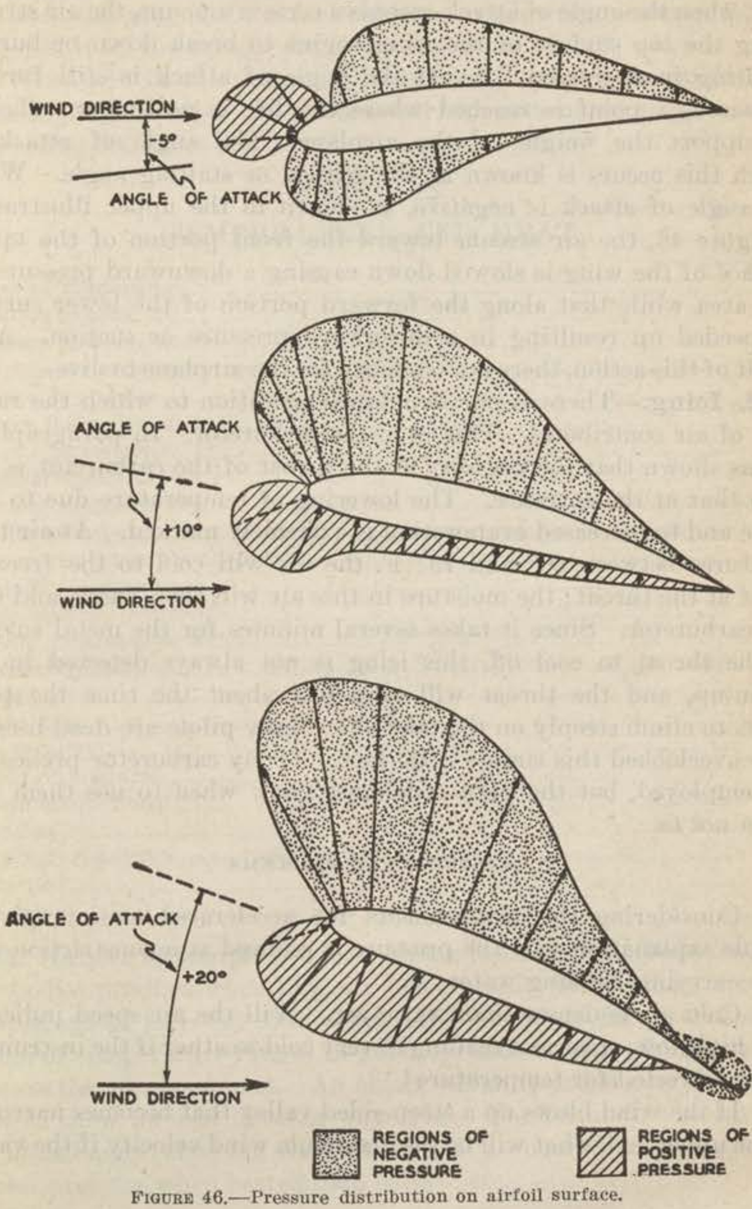

FIGURE 46.—Pressure distribution on airfoil surface.

part of the upper surface of the wing is also speeded up resulting in a still further decrease in pressure or still greater lift. Thus it is seen that lift increases with the angle of attack as is clearly noticeable when comparing the two lower illustrations in figure 46. However, when the angle of attack exceeds a certain amount, the air stream along the top surface of the wing begins to break down or burble, resulting in decreased lift. If the angle of attack is still further increased, a point is reached where the lift is no longer sufficient to support the weight of the airplane. The angle of attack at which this occurs is known as the critical or stalling angle. When the angle of attack is negative, as shown in the upper illustration in figure 46, the air stream toward the front portion of the upper surface of the wing is slowed down causing a downward pressure on this area while that along the forward portion of the lower surface is speeded up resulting in a downward pressure or suction. As a result of this action, there is a tendency for the airplane to dive.

52. Icing.—There is one dangerous condition to which the rapid flow of air contributes. This is in the carburetor. In paragraph 46 it was shown that the pressure at the throat of the carburetor is less than that at the entrance. The lowering of temperature due to this cause and to increased evaporation is extremely marked. At air temperatures between 60° and 70° F. the air will cool to the freezing point at the throat; the moisture in this air will then freeze and clog the carburetor. Since it takes several minutes for the metal surface of the throat to cool off, this icing is not always detected in the warm-up, and the throat will clog just about the time the pilot starts to climb steeply on the take-off. Many pilots are dead because they overlooked this simple little fact. Today carburetor preheaters are employed, but the pilot still must know when to use them and when not to.

QUESTIONS AND PROBLEMS

1. Considering the requirements for accelerated motion, give a simple explanation why the pressure is reduced at a constriction in a pipe carrying running water.

2. Cold air is denser than warm air. Will the air-speed indicator give high, low, or correct reading in very cold weather if the instrument is not corrected for temperature?

3. If the wind blows up a steep-sided valley that becomes narrower at the upper end, what will be the maximum wind velocity if the valley

is 3 times as wide at the mouth as at the top and the entering wind 20 miles per hour?

4. The water surface of a reservoir is 200 feet above the level of the turbine in a power plant. If water is discharged through a turbine at the rate of 100 cubic feet per second, what power could be developed if all the energy was taken out of the water?

5. What will be the difference in pressure between the static and dynamic pressure tubes of the air-speed indicator of an airplane that is traveling 300 miles per hour?

Section IX

TEMPERATURE AND HEAT

53. Nature of temperature.—All are familiar with the sensations that bodies produce when they are hot or cold. While these are unreliable except as rough indicators, they furnish a fairly consistent system of temperature ranges in good agreement with other observations on the effects of heat. An object which feels hot can always be made to show its heat in other ways also. For instance, a metal rod is a little longer when hot than when cold; a quantity of gas exerts a greater pressure when heated than before; etc.

54. Definition of heat.—*a*. The supply of heat cannot be weighed; therefore it cannot be a substance (as was once thought), but must be related in some way to motion.

b. When heat is applied to a body, it increases the energy of that body; and since no change can be detected in either the kinetic or the potential energy of the body as a whole, it appears that the energy must have been given to the molecules of which the body is made. Molecules are known to possess both kinetic and potential energy. This is true for the molecules which have been expanded by heat, for work must have been done upon the molecules to separate them in opposition to the forces of cohesion. Heat is a form of energy which in gases is practically the kinetic energy of molecules, and which in solids and liquids also includes potential energy due to expansion.

c. When a gas is confined to a vessel and the vessel is heated, the gas molecules striking the heated side of the vessel in their incessant motion rebound with greater speeds. These molecules then strike others, and so on until the entire gas is heated. When one end of a metal rod is placed in a fire, the entire rod becomes warmer as the heat is gradually conducted along it. The kinetic theory of matter explains this phenomenon as the result of the progressive transference of molecular kinetic energy from one molecule to another throughout the rod.

55. Definition of temperature.—*a*. The application of heat to a body causes an increase in its temperature unless there is a change of state. The term "temperature" is used to express how cold or how hot an object is; "cold" implies a low temperature and "hot" implies a high temperature with reference to the surroundings. A more definite idea of temperature can be realized by considering what occurs when a hot body is brought into contact with a cold one; for example, a hot steel rod plunged into cold oil. The rod becomes cooler and the oil warmer, an indication that the hot body gives up some of its energy to the cold one. This process continues until a state of thermal equilibrium is reached, and this condition signifies that the same temperature prevails throughout. Consequently, temperature is that property of a substance which determines whether heat will flow from it or toward it when it is placed in contact with some other body.

b. Terms such as "hot," "cold," "warm," and "cool," although used in ordinary speech, do not express accurately the temperature of a substance, and this fact has led to the adoption of certain thermometric scales.

56. Measurement of temperature.—*a*. A thermometer is any type of instrument made for the measurement of temperature. Precisely, it measures its own temperature which is made to agree with what it is desired to measure. All sorts of thermometers depend upon heat effects (changes in dimensions, pressure, electrical resistance, heat radiation, etc.), but these are so numerous that only a few types of thermometers will be discussed in this study.

b. The action of the liquid, solid, and gas thermometers depends upon expansion by heat; for a liquid thermometer it would be the difference of expansion of the liquid and the glass. When a substance is being heated, the agitation of its particles pushes them a little farther apart because of the increased vigor of their impacts. Solids show but a small change. A few alloys shrink with increase of temperature, but this is unusual. Evidently no single explanation of thermal expansion is adequate for all cases.

57. Thermometer scales.—Galileo is credited with the invention of the first thermometer. His instrument, however, measured only temperature differences. Later, Hooke proposed that the melting point of ice should be taken as a standard on which to found a scale of temperature. Still later it was discovered that two fixed points were necessary for a successful scale. Consequently, the boiling point of water was taken for the other fixed point. Various fixed points were tried, but the boiling and freezing points of water were established as a standard.

a. Fixed points.—(1) The lower fixed point on the thermometric scale, called 0° C. or 32° F., is the temperature at which pure ice and water can remain in equilibrium without any change in their relative amounts.

(2) The upper fixed point on the thermometric scale, called 100° C. or 212° F., is the temperature existing in the steam above boiling water and under standard atmospheric pressure (1013.2 millibars).

b. Centigrade and Fahrenheit.—(1) The centigrade scale, devised by Anders Celcius, Swedish astronomer, is universally used for scientific measurements. The Fahrenheit scale, named after the German physicist Gabriel Fahrenheit, is used largely for engineering and household purposes in England and the United States.

TEMPERATURE SCALES

Boiling point of water	F. 212°	C. 100°
Melting point of ice	32°	0°
Number of divisions between fixed points	180	100

(2) It is frequently necessary to convert temperatures from one scale to the other. In this process it must be observed that on the

Fahrenheit scale there are 180 divisions, while the centigrade scale has only 100 divisions for the same temperature range.

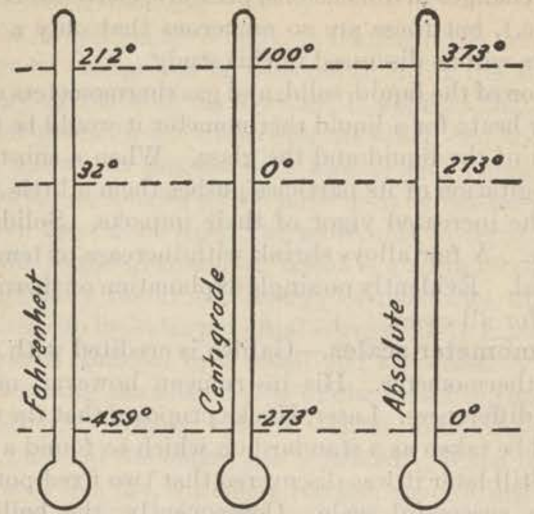

FIGURE 47.—Comparison of temperature scales: Fahrenheit, centigrade, and absolute.

For conversion from centigrade to Fahrenheit temperatures the following formulas will be useful:

$$T_f = \frac{9T_c}{5} + 32 \text{ and}$$

$$T_c = \frac{5}{9}(T_f - 32)$$

(3) On the "absolute" or Kelvin scale, zero degrees is the lowest temperature theoretically obtainable. That is, if all the heat energy were taken from a body, the temperature of that body would be absolute zero. This value would correspond to −273° C. or −459° F. Absolute zero may also be described as that point where both the temperature of a body and the quantity of heat which it possesses will be zero, or that point where molecular motion ceases.

58. Mercury thermometer.—This thermometer consists of a thick-walled glass tube with a very fine central hole down its axis drawn as uniformly as possible and sealed to a thin-walled bulb, usually cylindrical. The top of the tube is sealed off when the tube contains nothing but mercury. The positions of the mercury at 0° C. and 100° C. are marked off, and then the space between is graduated. The scale may be extended beyond the fixed points if necessary. Other liquids may also be used in thermometers; but as mercury possesses many favorable properties, it is used extensively. Some of these properties are the following: Freezing point −38.7° C., boiling point +357° C., high specific gravity, low vapor tension, and a uniform rate of expansion.

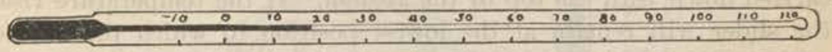

FIGURE 48.—Mercury thermometer.

59. Alcohol thermometers.—Alcohol and some other liquids have an advantage over mercury in their greater coefficient of expansion and smaller surface tension, but they are seldom used for accurate thermometers. Since the freezing point of alcohol is −117° C., which is lower than that of mercury, it is used frequently in thermometers for measuring low temperatures.

60. Maximum thermometers.—A maximum thermometer is a device used for recording the maximum point reached by the end of the mercury column. There are two types of maximum thermometers. In the first, a small metal index (usually iron) is pushed ahead of the expanding mercury column. When the mercury column contracts, the highest temperature is indicated by the position of the lower end of the iron index. In the second type, a constriction is made in the bore of the tube near the bulb, and at this point the mercury breaks. When contraction occurs after the maximum temperature has been reached, the mercury in the tube will not return through the constriction. Thus, the highest temperature for any period of time is indicated by the top of the mercury column. In either type the thermometer must be set before a maximum reading for a given period of time may be obtained.

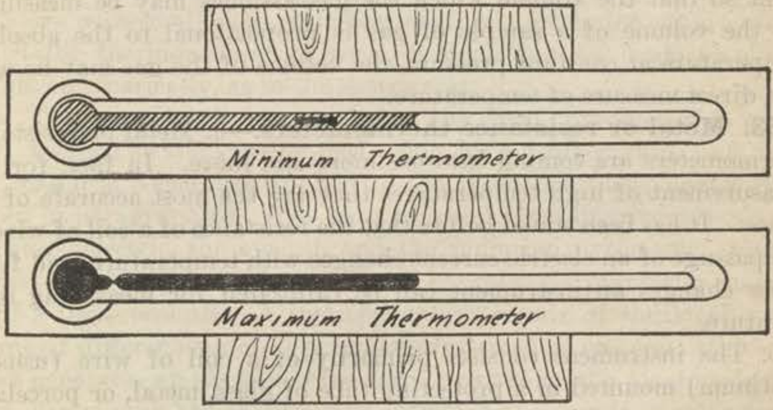

FIGURE 49.—Maximum and minimum thermometers.

61. Minimum thermometers.—A minimum thermometer is an instrument that records the lowest temperature in a given period of time. It is made of glass and alcohol. Within the alcohol in the tube is a small slider. When the temperature drops, this slider is carried down with the top of the alcohol. If the temperature rises, the slider will remain at the lowest position to which the alcohol surface dropped, the alcohol flowing past the slider as the temperature rises.

62. Gas thermometer.—*a.* Galileo discovered that gases expanded with increased temperature, and one of the first thermometers based on this principle was invented by him. There are two types of gas thermometers. In one, the gas is allowed to expand under constant pressure and the volume is measured. In the other, the volume is kept constant and the changes in pressure are noted. Here the latter will be discussed.

b. In figure 50 the bulb *A* containing the gas is connected to *C* by a small glass tube *B*. The flexible tube *CDE* is attached to an open glass tube *F*. The tube *DEF* is then filled with mercury. The volume of the gas in the bulb is held constant by adjustment of the height of the tube *F* so that the mercury surface at *C* is always at the same position. The height of the mercury surface in the tube *F* is a measure of the pressure of the gas in the bulb and therefore also a measure of the temperature of the bulb, pressure being proportional to absolute temperature at constant volume. When properly calibrated, this device operates as an accurate and reliable thermometer.

c. There is a similar instrument in which the pressure is kept constant so that the volume which the gas assumes may be measured. As the volume of a sample of gas is proportional to the absolute temperature at constant pressure, the volume of the gas may be used as a direct measure of temperature.

63. Metal or resistance thermometers.—*a.* Metal or resistance thermometers are coming into use more and more. In fact, for the measurement of high temperatures they are the most accurate of all types. It has been stated before that the resistance of a coil of wire to the passage of an electric current changes with temperature, and from these changes an instrument can be calibrated for measuring temperature.

b. The instrument consists primarily of a coil of wire (usually platinum) mounted in a protecting tube of glass, metal, or porcelain.

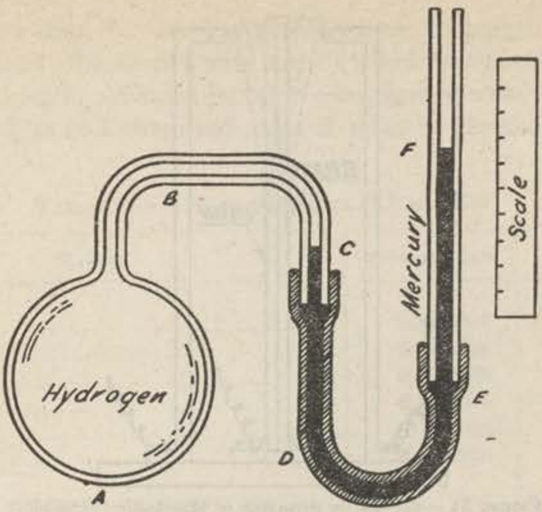

FIGURE 50.—Gas thermometer.

A Wheatstone Bridge is connected in the circuit, and from the resistance reading, the temperature may be calculated.

c. Metal thermometers offer several distinct advantages over other types. They are very durable and reliable. They give reliably accurate readings over a great range of temperature. They may be used either for indicating or for recording at a distance from the actual thermometer. Because of these advantages the metal resistance thermometer is being used more and more in industrial and scientific applications.

64. Bimetallic thermometer.—If two thin strips of different materials are fastened together and one end is held fixed, the free end will move with small changes in temperature. Such devices are used as metallic thermometers; or their motions may be made to close circuits automatically, as in the thermostat.

65. Thermoelectric pyrometer.—The word "pyrometer" is generally applied to devices for measuring high temperatures and for that reason is sometimes applied to the resistance thermometer described in paragraph 63. The most common types of pyrometers are the thermoelectric, the optical, and the radiation pyrometer. Only the first will be discussed here. The thermoelectric pyrometer makes use of a thermocouple. A thermocouple is a pair of electrical conductors of different material permanently joined at one end. Such a device generates an electromotive force or voltage, the magnitude of which varies with the temperature to which the couple is subjected.

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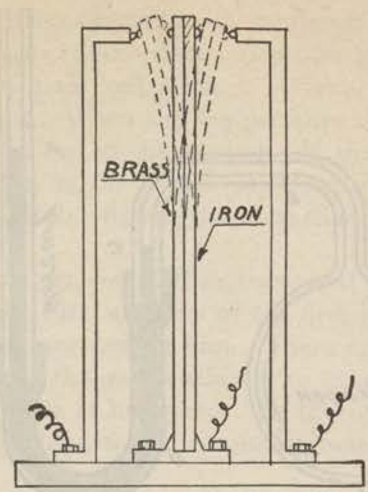

FIGURE 51.—Schematic principle of bimetallic thermostat.

A sensitive galvanometer or millivoltmeter is connected by long leads to the free ends of the thermocouple and calibrated to read in degrees of temperature. The thermocouple itself is delicate and is inclosed in a protecting tube. Like the resistance thermometer, the thermoelectric pyrometer may be used for indicating or recording temperatures at a distance from the place where the thermocouple is placed.

66. Thermal expansion of solids.—A common method of measuring the expansion of solids due to change in temperature is to heat a rod of the material and observe the change in length by means of a micrometer. The change in length depends upon the kind of material, the change in temperature, and the length of the rod. The total expansion divided by the length of the rod gives the expansion per unit length. If this is divided by the number of degrees change in temperature, the quotient is the change in length per unit of length per degree change in temperature. This is known as the coefficient of linear expansion. It may be given for a change of 1° C. or 1° F. The coefficient for the Fahrenheit scale is 5/9 the value of the coefficient for the centigrade scale, since 1° C.=9° F. If K is the coefficient, L_o the original length of the rod, T_o the initial temperature, T the final temperature, E the change in length and L the final length, then—

$$E=L_oK(T-T_o).$$

or

$$L=L_o+L_oK(T-T_o).$$

If T is greater than T_0, this gives an increase in length; and if T_0 is greater than T, the second term on the right is negative and gives a decrease in length. K must be for the centigrade scale if T is centigrade and if T is in Fahrenheit units K must be for the Fahrenheit scale.

TABLE IV.—*Linear coefficients* (K) *of solids*

Material	K for centigrade	K for Fahrenheit
Iron	0. 000011	0. 000006
Aluminum	0. 000025	0. 000014
Platinum	0. 000009	0. 000005
Brass	0. 000018	0. 000010
Glass (sodium)	0. 0000085	0. 0000047
Glass (lead)	0. 000003	0. 0000017

67. Calorimetry.—The process of measuring heat quantities is called calorimetry. When two bodies of different temperatures are placed in good contact with each other, the hot body gives up heat and the cold body takes on heat until both reach the same temperature. This reaction may be stated thus: "Heat lost by one body equals heat gained by the other body, provided no heat is gained from, or given to, the surroundings."

68. Unit of heat.—*a. In the metric system.*—In this system the unit for measuring heat is the calorie. It is defined as the quantity of heat required to raise the temperature of 1 gram of water from 14.5° C. to 15.5° C.

b. In the British engineering system.—In this system the unit of heat is called the British thermal unit or Btu. It is defined as the quantity of heat required to raise the temperature of 1 pound of water from 59° F. to 60° F. One Btu=252 calories, approximately.

c. Mechanical equivalent of heat.—Heat is energy and so the calorie and Btu are in reality units of energy. The number of units of mechanical energy required to produce one unit of heat energy is called the mechanical energy of heat and is denoted by the letter J. In the metric system

$$J=4.187 \text{ joules per calorie}$$

or 4.187 joules of mechanical energy can produce one calorie of heat. In the British engineering system—

$$J=778 \text{ foot-pounds per Btu}$$

Example: If a 30-gram bullet moving 1,000 meters per second is imbedded in a block of wood, how many calories of heat energy will appear?

Solution: The entire kinetic energy of the bullet will be converted into heat energy.

$$KE=\frac{mV^2}{2}$$

V is 100,000 centimers per second
m is 30 grams

$$KE=\frac{30\ (100{,}000)^2}{2}=150{,}000{,}000{,}000 \text{ ergs}$$

$$15\times10^{10} \text{ ergs}=15\times10^3 \text{ joules}$$

$$\frac{15000}{J}=\frac{15000}{4.187}=3{,}582 \text{ calories}$$

69. Specific heat.—*a.* The specific heat of a substance is the ratio of the number of calories of heat required to raise the temperature of 1 gram of the substance 1° centigrade to that required to raise the temperature of 1 gram of water from 14.5° C. to 15.5° C. The specific heat of the substance is therefore numerically equal to the number of calories of heat required to raise the temperature of 1 gram of the substance 1° C. since 1 calorie is required to raise the temperature of 1 gram of water from 14.5° C. to 15.5° C. The definition in the British engineering system is similar and specific heat in that system is numerically equal to the number of Btu's required to raise the temperature of 1 pound of the substance 1° F, since 1 Btu is required to raise the temperature of 1 pound of water from 59° F. to 60° F. Specific heat is a ratio and has the same value for either the metric system or the British engineering system. The specific heat of a substance is not a true constant but varies with temperature and generally average values are used.

b. The specific heat of water (which is 1.0) is higher than that of most other substances. For this reason, oceans and lakes change temperature more slowly than adjacent land masses. From night to day, the temperature of an ocean surface seldom changes more than 1° or 2°.

70. Heat capacity.—*a.* The heat capacity of a body is the number of calories required to raise the temperature of the body 1° C. It is therefore equal numerically to the product of the mass of the body and its specific heat. This definition applies to the cgs system of units. In the British system, heat capacity is the number of

Btu's required to raise the temperature of the body 1° F., and is equal to the product of the weight of the body in pounds and its specific heat.

b. Let Q be the quantity of heat required, m the mass of the body, s the specific heat of the substance, and T the change in temperature. Then—

$$Q = m \cdot s \cdot T$$

Example 1: 50 grams of lead in being raised from 20° C. to 100° C. will absorb 50×0.031×80=124 calories.

Example 2: 50 grams of lead are cooled from 200° C. to 50° C.; the heat lost will be 50 × .031 × 150 = 232.5 calories.

c. In the British engineering system, weight, w, is used instead of mass: then—

$$Q = w \cdot s \cdot T$$

where Q is in Btu, w in pounds, and T in degrees Fahrenheit.

Example: If 50 pounds of iron are raised from 50° F. to 150° F., the heat absorbed will be 50 × .113 × 100 = 565 Btu.

71. Method of mixtures.—*a.* If two substances of different temperatures are mixed, an equilibrium temperature will be reached by the mixture. For instance, if a ball of hot iron is placed in a container of cold water, the water plus the container will gain heat, and finally the mixture will have the same temperature.

b. If m_1 represents the mass, s_1 the specific heat, T_1 the temperature of one body; m_2 the mass, T_2 the temperature, s_2 the specific heat of the liquid; and T_m the temperature of the mixture, the following expression is true:

Heat lost=heat gained

$$(m_1) \cdot (s_1) \cdot (T_1 - T_m) = (m_2) \cdot (s_2) \cdot (T_m - T_2)$$

Problem: How much heat is required to raise the temperature of 100 grams of tin from 20° C. to 200° C.?

$$\begin{aligned} Q &= ms(T_1 - T_2) \\ &= 100 \times 0.060 \times 180 \\ &= 108 \text{ calories} \end{aligned}$$

Problem: 100 grams of iron at 200° C. are placed in a copper calorimeter containing 200 grams of water at 20° C. (The calorimeter weights 130 grams and is at the temperature of the water.) Find the temperature of the mixture:

$$\text{Heat lost} = \text{heat gained}$$
$$100\ (0.113)\ (200 - T_m) = 200\ (1)\ (T_m - 20) + 130\ (.093)\ (T_m - 20)$$
$$2260 - 11.3\ T_m = 200\ T_m - 4000 + 12.09\ T_m - 241.8$$
$$223.39\ T_m = 6{,}501.8$$
$$T_m = 29.1^\circ \text{ C.}$$

c. In the British engineering system a similar formula is used:

$$\text{Heat lost} = \text{heat gained}$$
$$w_1 \cdot s_1 (T_1 - T_m) = w_2 \cdot s_2 (T_m - T_2)$$

Example: 10 pounds of iron at 300° F. are placed in an aluminum vessel weighing 10 pounds which contains 30 pounds of water at 50° F. The vessel has the same temperature as the water. Find the temperature of the mixture.

Solution:

$$\text{Heat lost} = \text{heat gained}$$
$$10\ (0.113) \cdot (300 - T_m) = 30\ (1)\ (T_m - 50) + 10\ (.21)\ (T_m - 50)$$
$$339 - 1.13\ T_m = 30\ T_m - 1500 + 2.1\ T_m - 105$$
$$33.23\ T_m = 1{,}944$$
$$T_m = 58.5^\circ \text{ F.}$$

72. Transmission of heat.—There are three ways by which heat energy may be transferred from one place to another: radiation, convection, and conduction. Each performs a significant role in the heating of the atmosphere.

73. Radiation.—*a*. Radiation is the process by which energy is transmitted through space without the presence of matter. Heat and light are transmitted from the sun in this manner at the velocity of light, which is 186,000 miles per second. It is unchanged in quantity and quality until it is intercepted by matter. The solar radiation which comes to the earth and which plays such an important part in our weather is given the special name of "insolation."

b. Radiation is thought to be a wave disturbance analogous to the waves which travel over a water surface. The characteristics of a radiation wave are the period and the wave length. Radiant heat and light are alike, not only in that they travel at the same speed but also in that they can both be refracted by lenses and prisms. These and other facts prove that radiation waves are of exactly the same nature as light waves. Light consists simply of radiation waves, which affect the eye, and are between 0.0004 and 0.00076 mm in length.

74. Radiation, absorbtion, and reflection.—There is a direct relationship between radiation, absorption, and reflection. It has been found that a body which is a good radiator is also a good absorber. The hotter the body, the more rapidly radiant energy is sent out.

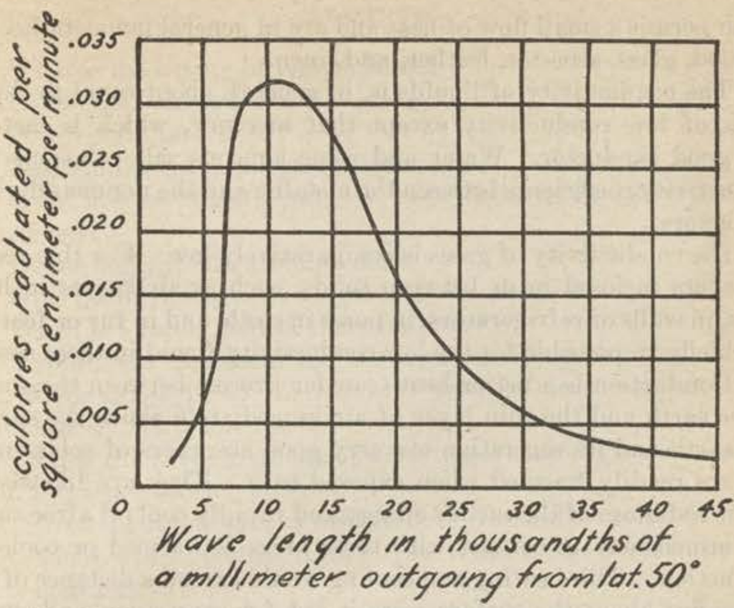

FIGURE 52.—Radiation from the earth, showing intensity as a function of wave length.

Since every body is radiating (unless it is at absolute zero), every body must also be absorbing. An easy way to prove that there is a close connection between the absorbing power and the radiating power of an object is to heat a piece of white china, with dark markings, in an oven. At ordinary temperatures the markings look dark because they absorb more light, but at high temperatures they look bright against the china because they radiate more. The reflecting power of a surface is the ratio of the radiant energy reflected from the surface to the energy incident upon it. The reflecting power of a surface is also different for different substances; that is, a polished silver surface will reflect more than a polished iron surface.

75. Conduction.—*a.* Conduction is the flow of heat through matter unaccompanied by any motion of the matter; in other words, the transfer of heat from molecule to molecule. The rate of flow from the body of higher temperature to the body of lower temperature is dependent upon the temperature difference. Heat will be conducted faster if the temperature difference is greater. The rate of flow of heat, other conditions being equal, also depends upon the material through which it must flow; substances are roughly divisible into "good conductors" which permit, under given conditions, a large flow of heat and which in general are metallic, and "poor conductors" which permit a small flow of heat and are in general nonmetallic, such as wood, glass, asbestos, leather, and linen.

b. The conductivity of liquids is, in general, about equal to that of solids of low conductivity except that mercury, which is metallic, is a good conductor. Water and some aqueous salt solutions have conductivity coefficients between the metallic and the nonmetallic solid conductors.

c. The conductivity of gases is comparatively low. For this reason, air layers inclosed in or between solids, such as air spaces in house walls, in walls of refrigerators, in pores in cloth, and in fur or feathers, are chiefly responsible for the low conductivity found in these cases.

d. Conduction is a major heat transfer process between the surface of the earth and the thin layer of air immediately above the surface. The earth and its vegetation are very good absorbers of solar energy and are readily warmed when exposed to it. They are likewise efficient radiators of the earth's energy and rapidly cool off after sunset. The atmosphere in contact with these areas is warmed or cooled by conduction. This heating and cooling would extend a distance of only a few feet above the surface were it not for convection and surface turbulence, which continually bring fresh air into contact with the surfaces. Thermometers placed in the surface of the soil and a few feet above the surface show a large difference in temperature, the air temperature lagging behind that of the soil. This poor conducting property of the air contributes to the formation of the temperature inversion near the ground and often causes the ground fogs observed early in the morning.

76. Convection.—Convection is the transport of heat by moving matter, for example, by the hot air which can be felt rising from a hot stove. In connection with weather, convection refers to the upward or downward movement of a limited portion of the atmosphere, the movement having been induced by thermal action. Gases upon being heated, expand and become less dense. When the atmosphere is heated at the equator or any localized area, it is pushed aloft by the colder, heavier air in its neighborhood, thus carrying this surface heat to higher elevations. Cumuliform clouds and dust whirls are visible evidence of these vertical convections. Horizontal convection also occurs in the local and general wind systems of the earth as a result of unequal surface heating and cooling.

QUESTIONS

1. What is the nature of temperature?
2. Define heat; temperature.
3. How is heat measured?
4. Explain the principle of a thermostat.
5. What are the "fixed points" of a thermometer and how are they determined?
6. Define and explain absolute zero.
7. Give the advantages of a mercurial thermometer.
8. When is alcohol used in thermometers?
9. Explain the maximum and minimum thermometer.
10. Name one type of thermometer used in measuring very high temperature. Why is it used?
11. Name the three methods of heat transfer and give an example found in nature of each method.
12. From the standpoint of heat radiation and absorption (a) What color should winter clothes have? (b) What finish should the sides of a teakettle have?
13. Why should steam radiators be installed on the cold sides of a room?
14. Would you expect bumpier flying conditions over land at night or in midafternoon? Over the ocean? Explain briefly.
15. If a door is opened between a warm and a cold room, in what direction will a candle flame placed at the top of the door be blown?
16. The earth's atmosphere has been likened to a greenhouse. Explain why higher temperatures can be expected inside the greenhouse than in the outside air.
17. Why does the fleece lining of a winter flying suit help keep one warm?

PROBLEMS

1. Mercury solidifies at $-38.8°$ C. and vaporizes at $356.7°$ C. Express these temperatures on the Fahrenheit scale.
2. At what temperature are the readings of a Fahrenheit and a centigrade thermometer the same numerically?
3. Find the centigrade temperatures corresponding to $10°$ F. and $60°$ F.
4. A steel tape which is correct at $60°$ F. is used to measure a bridge at a temperature of $100°$ F. The bridge measured 1,000 feet long. What was the error in measurement due to the expansion of the tape?

What is the correct length of the bridge? The coefficient of expansion of the steel tape is 0.00000645.

5. The steel cables of a suspension bridge are 2,000 feet long when measured at 80° F. in summer. What will be their length in winter if the temperature of the cables is −10° F.?

6. A brass meter bar is found to be 0.007 centimeters longer than an iron one at 25° C. At what temperature will they be the same length.

7. What will be the temperature of 1 liter of water at 30° C. if 500 calories of heat are added to it?

8. What will be the temperature of 1 cubic foot of water at 40° F. if 2,500 Btu are added to it?

9. An iron bath tub weighing 120 pounds contains 4 cubic feet of water. Both the water and the tub are at a temperature of 45° F. How much boiling water must be added to raise the temperature of both water and tub to 85° F.?

SECTION X

HEATING OF THE ATMOSPHERE

77. Source of the earth's heat.—*a.* The sun is the source of all terrestrial energy that has any practical significance for man. It is a body 800,000 miles in diameter and has a surface temperature of about 5,800° C. or roughly 6,100° A. It radiates energy at the tremendous rate of 60,000 horsepower from every square yard of its surface. The earth 93,000,000 miles away, receives this energy at the rate of about 1 horsepower per square yard.

b. The energy which comes to the surface of the earth by conduction from the earth's interior and that which comes from the planets and stars of outer space is small in comparison. The unequal amounts of solar energy absorbed by unit areas over the earth, from the equator to the poles, and Nature's method of equalizing this energy give rise to all our wind movements, cyclonic systems, thunderstorms, precipitation, etc. In this chapter is discussed how the sun's energy is received and distributed by the atmosphere.

78. Factors governing insolation received.—*a.* The amount of insolation that any particular area of the earth receives is dependent on several different conditions. One of the most important of these conditions is the angle of inclination. The more nearly overhead the sun is, the greater will be the insolation.

b. The distance from the earth to the sun varies from 91,500,000 miles in January to 94,500,000 miles in July. This periodic variation causes 7 percent more energy to arrive at the earth in January than in July, and will have a tendency to make the winter temperature

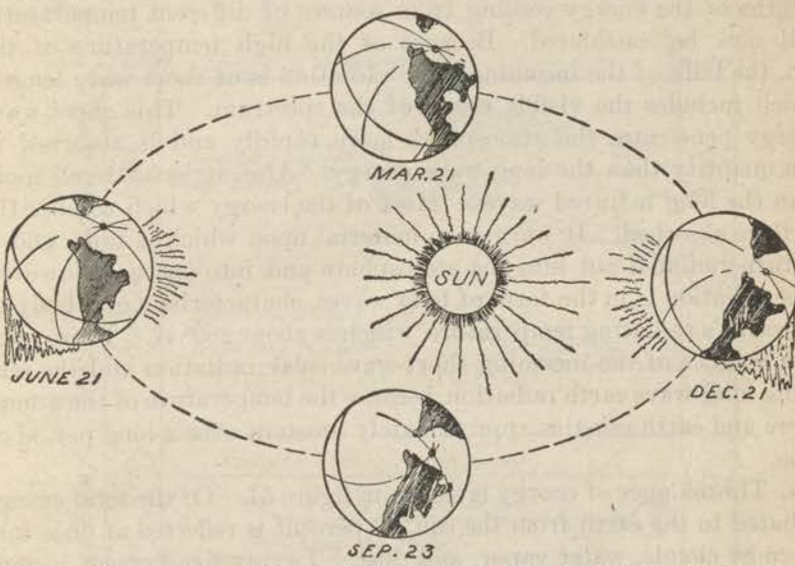

FIGURE 53.—Position of the earth with relation to the sun at different seasons.

higher and the summer temperature lower in the Northern Hemisphere. The reverse effect would be observed in the Southern Hemisphere. The moderating effect of the large water bodies of the Southern Hemisphere, however, make it difficult to observe any particular difference in the annual range of temperatures of the two hemispheres.

c. At the outer reaches of our atmosphere, insolation is coming in at the rate of 1.94 calories (approximately 2.0) per square centimeter per minute, and this value is known as the solar constant. It is equivalent to 1.5 horsepower per square yard. It has been observed that the solar constant varies over a period of years by as much as 2 percent and that the period of its variation agrees somewhat with the sun-spot cycle. The direct effect upon the world weather of this change is not known, but certainly some effects exist and in time will be known and used in long range forecasting and in the study of world weather trends.

d. Not all of the sun's energy that is directed toward the earth, reaches it. A great amount is reflected back by clouds. The amounts of cloudiness, averaged for the entire earth for the whole year, has been found to be 42 percent. This amount will be used to show the transmission and absorption of the earth's atmosphere in figure 54.

79. Terrestrial and solar radiation.—*a.* The difference in wave lengths of the energy coming from sources of different temperatures will now be considered. Because of the high temperature of the sun, the bulk of the incoming solar radiation is of short wave length, which includes the visible range of the spectrum. This short-wave energy penetrates the atmosphere more rapidly and is absorbed in less quantity than the long-wave energy. Also, it is scattered more than the long infrared waves. Most of the energy which reaches the earth is absorbed. It warms the material upon which it falls, and is in turn radiated out into the atmosphere and into space. However, this radiation is in the form of long waves, characteristic of a body of the earth's radiating temperature, which is about 280° A. There must be a balance of the incoming short-wave solar radiation and the outgoing long-wave earth radiation, because the temperature of the atmosphere and earth remains approximately constant over a long period of time.

b. This balance of energy is shown in figure 54. Of the total energy radiated to the earth from the sun, 33 percent is reflected at once into space by clouds, water vapor, and dust. Twenty-five percent is scattered radiation through the atmosphere; of this amount 9 percent is returned to outer space and 16 percent is reradiated to the earth. It will be noted that the 33 percent reflected by the clouds and the 25 percent scattered in radiation through the atmosphere will leave 42 percent of the sun's energy bound directly for the earth's surface. Of this 42 percent, the atmosphere will absorb 15 percent before the energy reaches the earth. Thus only 27 percent of the sun's total energy strikes the earth directly. But it will be recalled that of the scattered radiation in the atmosphere 16 percent is reradiated to the earth. The final total received and absorbed by the earth is, then, 43 percent, or the sum of the direct radiation from the sun and the reradiation from the atmosphere. The 15 percent absorbed by the atmosphere and the 43 percent absorbed by the earth are used to warm the lands and water; produce evaporation from soil, ocean, and clouds;

melt snow; and produce the photosynthesis in plant life. Of the 43 percent absorbed by the earth, 8 percent is radiated directly into space, 16 percent is radiated to the atmosphere and is absorbed, and 23 percent is transmitted to the atmosphere by water vapor and convection. Of this 23 percent transmitted to the atmosphere, 4 percent is again returned to the earth by downward convection currents. The atmosphere radiates the same amount of energy which it receives. If this were not the case, there would be a building up or a lowering of the temperature of the atmosphere, a phenomenon which is known not to be true.

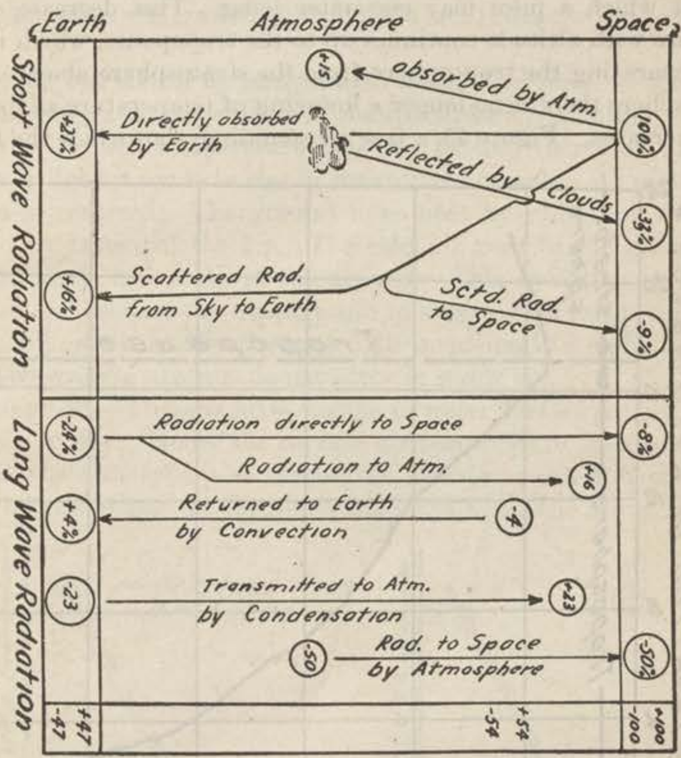

FIGURE 54.—Balance of heat gained and lost by the earth and its atmosphere.

c. This whole process is well illustrated in the principle operative in a greenhouse, where short waves penetrate the glass roof and warm the soil and vegetables. The warmed interior radiates long heat waves to which the glass roof is opaque. The greenhouse is, therefore, warmed to a much higher temperature until by conduction and radiation a heat balance is established with its surroundings.

80. Normal lapse rate.—*a.* All pilots have probably at one time or another noticed that as they rise in altitude the temperature of the air decreases. If the amount of temperature decrease with increase in altitude were averaged for a great many cases, it would be found that the air temperature usually falls off 3.6° F./1,000 feet increase in elevation (equal to 6° C./km). This is called the *normal lapse rate.* As an example consider air over the North Pacific Ocean. If the surface air temperature is 68° F., the air temperature at 10,000 feet will be 32° F. ($3.6°/1{,}000 \times 10 = 36°$, the temperature drop at 10,000 feet). Similar computation is useful in determining the elevation at which a pilot may encounter icing. This decrease of temperature with altitude continues up to the tropopause, which is a surface separating the troposphere from the stratosphere above. In the stratosphere there is no longer a lowering of temperature as the elevation increases. Figure 55, a free air sounding, shows how the temper-

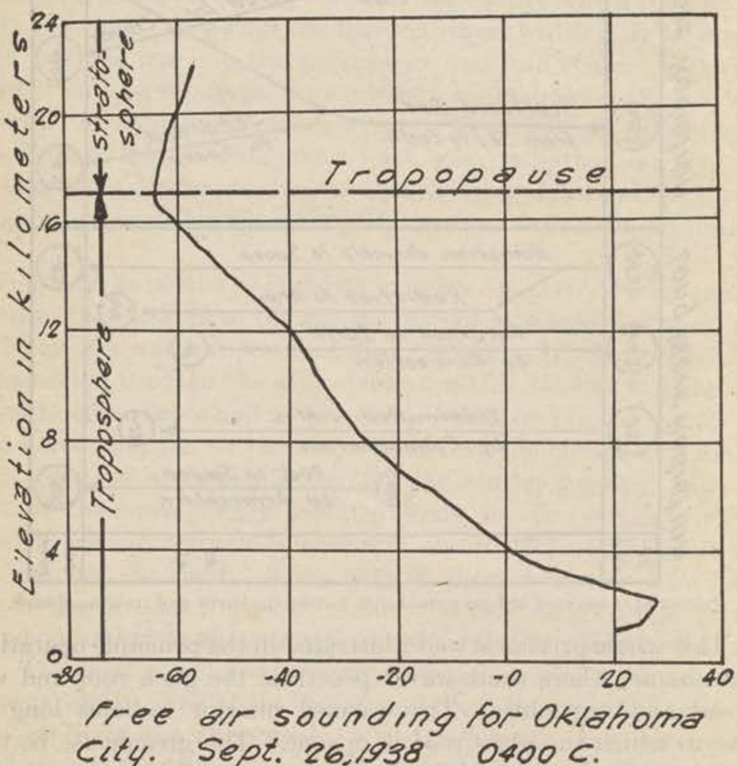

FIGURE 55.—Temperature of the upper atmosphere at night.

ature drops off with increase in altitude up to the tropopause; then the temperature no longer decreases with increase in altitude.

b. As has already been pointed out, different parts of the earth, such as the equatorial regions, are heated more than other parts, such as the polar regions. Since the atmosphere tends to get the same temperature as the surface, we find cold air masses over the poles and warm air masses over the equator. The cold air is more dense and hence will form a high pressure area; whereas the warm air, being less dense, will form a low pressure area. It is these differences in pressure that cause the movement of air masses with their resultant winds. The high pressure will tend to push down to neutralize the low pressure areas.

81. Daily variation in temperature.—*a. Over land.*—Figure 56 shows the changes in temperature in the atmosphere from night to day. During the day the temperature near the ground increases, and as warm air is light it tends to rise in convective currents. At night the condition is reversed. The ground loses heat by radiation, cooling off the lower layers of the air. The cold air next to the ground is heavy and tends to remain at the ground. This condition is called an "inversion" because the temperature increases with height instead of decreasing, as is usually the case. An inversion is a stable condition, and convective currents do not occur in stable air.

b. Over ocean.—There is little change in water surface temperature from night to day. Hence the surface air temperature does not vary much, but the atmosphere at the higher elevations can still cool off at night by radiation. If the upper air cools while the lower air re-

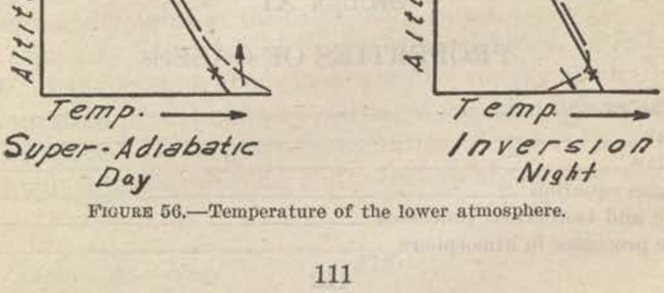

FIGURE 56.—Temperature of the lower atmosphere.

mains at the same temperature, the effect is similar to heating from below, though no actual heating has taken place. Under such conditions the air becomes unstable and convective currents may arise in the same way as over the land, where actual heating occurs from below. Thunderstorms are a result of convective instability and consequently occur over the ocean chiefly at night.

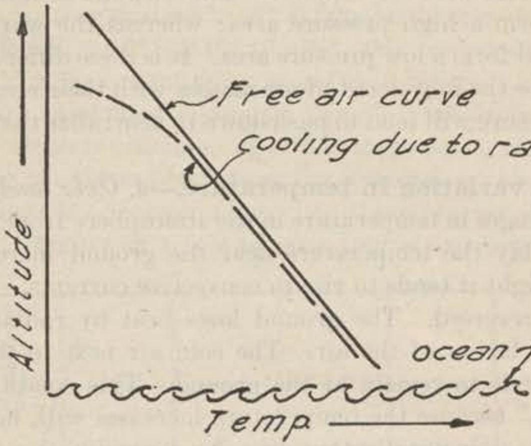

FIGURE 57.—Cooling of the air over the ocean.

QUESTIONS

1. Explain why the atmosphere receives more heat indirectly from the earth than it receives directly from the sun.

2. Should bumpier flying conditions be expected over land at night or in the afternoon? Over the ocean? Explain briefly.

3. If the surface air temperature over the Atlantic Ocean is 70° F., how high could one fly before getting into subfreezing air?

4. The earth is closer to the sun in the winter than in the summer. Why, then, are winters in the Northern Hemisphere colder than the summer months.

SECTION XI

PROPERTIES OF GASES

82. Kinetic theory.—*a. Molecular structure of a gas.*—Present-day theories of the structure of gases are based on a great many different methods of investigation. The kinetic theory, described below, seems to explain best all the experimental evidence of the properties of gases. This theory presupposes that a gas is composed of a great many tiny molecules, each a unit in itself, separated by distances of free space relatively large compared with the size of the molecules. These molecules have almost no attraction for each other and move with high velocity in purely random motion. The only important interference with this motion is the frequent collision of the molecules with other molecules and with the sides of the container which holds the gas. These molecules are extremely small, and very large numbers of them are present in any normal quantity of gas. For example, 29 grams of air, 32 grams of oxygen, or 18 grams of water vapor each contain 6.06×10^{23} molecules (606 followed by 21 zeros).

b. Pressure in gases.—It is easy to see that a great number of collisions occur between these molecules and any solid wall. Each individual collision causes a small impulse against the wall, but the collisions occur with such great frequency that there is a continuous effect of force against the wall perpendicular to its surface. This force is called the pressure of the gas, and every gas exerts a pressure in some degree, even when highly rarefied. The pressure of the gas against any wall will depend upon the number of collisions per second, upon the mass of the molecules, and upon the velocity of their movement.

83. Boyle's law.—*a.* From experience it is known that any gas is compressible to some extent, and this compression is accomplished only by exerting some force on the gas (that is, increasing the pressure). Boyle's law mathematically expresses the relationship between pressure and volume: *In any sample of gas the volume is inversely proportional to the pressure if the temperature is held constant.* This may be expressed by the equation:

$$p_1V_1 = p_2V_2$$

p_1 and V_1 are known pressures and volumes; p_2 and V_2 are some other pressure and volume at the same temperature.

b. This may be explained by the kinetic theory, as follows: A decrease in the volume of a given quantity of gas results in a higher concentration of molecules by causing a specified number to occupy a smaller space. This higher concentration of molecules must of necessity result in more collisions and therefore higher pressure.

84. Charles' law.—According to the kinetic theory of gases, the temperature of a gas is determined solely by the kinetic energy of its molecules. This means that the molecules are going faster at higher temperatures than at lower temperatures. An increase of velocity means that the molecules are going to strike the walls harder than before and, furthermore, that there are going to be more collisions. At a temperature of absolute zero the velocity of the molecules is zero. As the temperature increases, the motion of the molecules increases in such a way that the average of the kinetic energies of all the molecules in a given mass of gas is directly proportional to the absolute temperature. This results in an increase in pressure exerted by the gas if the volume of the sample is held constant and the temperature is increased. The relationship between pressure and temperature is expressed mathematically by Charles' law:* *In any sample of gas at constant volume, the pressure is directly proportional to the absolute temperature.* In equation form this would be:

$$p_1T_2=p_2T_1$$

or

$$\frac{p_1}{T_1}=\frac{p_2}{T_2}$$

p_1 and T_1 are some known pressure and absolute temperature; and p_2 and T_2 are some other temperature and pressure. These temperatures are based on the absolute scale where 0° absolute corresponds to −273° centigrade or −459° Fahrenheit and 300° absolute with correspond to 27° centigrade or 80.6° F.

Example 1: If air is admitted to a telescoping cylinder at atmospheric pressure (14.7 pounds per square inch), what will be the total pressure on the air if its volume is reduced to one-fifth the initial volume and the air cooled to its initial temperature.

Solution: Since the temperature is the same, apply Boyle's law. So—

$$p_1V_1=p_2V_2$$

$$14.7\ V_1=p_2\ (1/5\ V_1)$$

$$p_2=5\ (14.7)=73.5 \text{ pounds per square inch.}$$

A pressure gage reads the difference between the total pressure and atmospheric pressure. Therefore the pressure-gage reading in the preceding solution would be 73.5−14.7 or 58.8 pounds per square inch.

* Sometimes called Gay Lussac's law.

Example 2: Automobile tires frequently blow out because of the increased pressure caused by heating due to fast driving. If a tire shows a gage pressure of 30 pounds per square inch at night when the temperature is 30° F., what will be the gage pressure if the tire reaches a temperature of 120° F. the next day?

Solution: In this example the temperature changes but the volume is approximately constant so that the air obeys Charles' law. Therefore—

$$p_1T_2=p_2T_1$$

The initial temperature T_1 is the absolute temperature which is +459°+30°=489° F. above absolute zero. The final temperature T_2 is 459°+120°=579° F. above absolute zero. Absolute pressure, which is equal to the gage pressure plus atmospheric pressure, must be used in the formula. Therefore $p_1=30+14.7=44.7$ pounds per square inch.

$44.7(579)=p_2(489)$

$p_2=52.9$ pounds per square inch absolute pressure or

$52.9-14.7=38.2$ pounds per square inch gage pressure.

85. General gas equation.—Boyle's and Charles' laws are the bases for a general equation of state for gases. This may be expressed as follows:

$$pV=mRT$$

As before, p, V, and T are the total unit pressure, the volume, and the absolute temperature, respectively. m is the mass of the gas, and R is a number whose value has been determined for every known gas. This number is always the same for any one type of gas, but each gas has its own R. If R is known for any gas, it is possible to determine the pressure, the volume, or the temperature if all the other elements of the equation are known. In any given sample of gas, m and R are constant, and the equation may be set up as follows:

$$\frac{p_1V_1}{T_1}=\frac{p_2V_2}{T_2}$$

p_1, V_1, and T_1 are the pressure, volume, and temperature of a sample of gas. p_2, V_2, and T_2 are any other conditions in the same gas sample.

Example: In the preceding example of the gasoline engine assume that the gas exploded at the compressed position and the temperature changes from 20° C. to 1,000° C.

Solution:

$p_1 = 14.7$ lb. per sq. in., atmospheric pressure

$T_1 = 20° + 273° = 293°$ A.

$T_2 = 1000° + 273° = 1{,}273°$ A.

$V_2 = \frac{1}{5} V_1$ from the data

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

$$\frac{14.7 V_1}{293} = \frac{p_2(\frac{1}{5} V_1)}{1273}$$

$$p_2 = \frac{5(14.7)1273}{293} = 319.3 \text{ pounds per square inch}$$

This is the absolute pressure and the gage pressure is 319.3 −14.7 or 304.6 pounds per square inch.

86. Adiabatic and isothermal processes.—*a.* According to Boyle's law, the pressure of a gas is inversely proportional to its volume if the temperature is held constant. Figure 58 is a chart showing how the pressure of a gas will increase with a decrease in volume if the temperature is held constant. On the curve for the temperature of 0° C., it may be seen that when the volume is reduced to one-tenth of that at the far right-hand side, the pressure has increased 10 times. The same relation will hold at any other temperature, provided that this temperature is held constant during the volume change. It should be noted also that at the higher temperature the pressure is higher for the same volume. Such a change in volume and pressure at a constant temperature is called an *isothermal* process.

b. Ordinarily, when a gas is compressed the temperature does not remain constant, but increases. If a compression or expansion is carried out in such a way that there is no heat added to or taken away from the gas, the process is called *adiabatic*. This is different from the isothermal process in that heat must be added or subtracted during the isothermal process to keep the temperature constant. Almost any rapid expansion or compression is approximately adiabatic. Adiabatic compression of a gas is always accompanied by an increase in temperature, and adiabatic expansion causes a cooling effect. In Diesel engines air is rapidly compressed to a small fraction of its original volume, and the temperature is increased thereby so greatly that fuel sprayed into the gas will spontaneously ignite. The decrease in pressure on the upper surface of an airplane wing in flight may cause a temperature decrease on that surface of as much as 7° C. The student has probably noticed that air which is allowed to escape from an automobile tire is very cold on the fingers because of a rapid adiabatic expansion upon release from the tire.

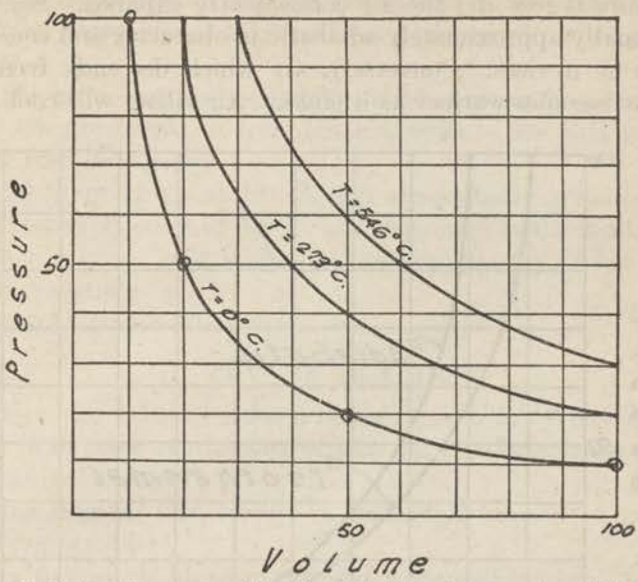

FIGURE 58.—Variation of pressure with volume of a gas at temperature of 0° C., 273° C., and 546° C.

c. The increase in temperature with adiabatic compression is caused by the simple fact that work is being done on the gas to compress it and thereby there has been an addition of energy to the gas which can only result in an increase in its temperature. Figure 59 shows the relationship between adiabatic and isothermal compression of a gas. On the right-hand side of the diagram the same sample of gas is taken as in figure 58. As the volume is reduced by compression (moving left on the curve) it is found that the pressure increases to 10 times its former value when the volume has been reduced to only one-fifth its initial value. This is due to the fact that the temperature has reached twice its former value at this point. Mathematically the relationship between pressure and volume may be expressed as follows:

$$p_1 (V_1)\gamma = p_2 (V_2)\gamma$$

p_1 and V_1 are the pressure and volume before the change and p_2 and V_2 are their values after the change. γ * is an exponent which depends upon the type of gas. Its value for air is about 1.4.

*γ is the Greek letter *gamma* and is universally used to designate this exponent.

87. Adiabatic processes in atmosphere.—Very often air in the atmosphere undergoes a great deal of lifting. At higher elevations the pressure is less and the air consequently expands. Such expansion is usually approximately adiabatic in character and consequently air cools as it rises. Conversely, air which descends from higher elevations becomes warmer as it sinks. Air rising will cool approxi-

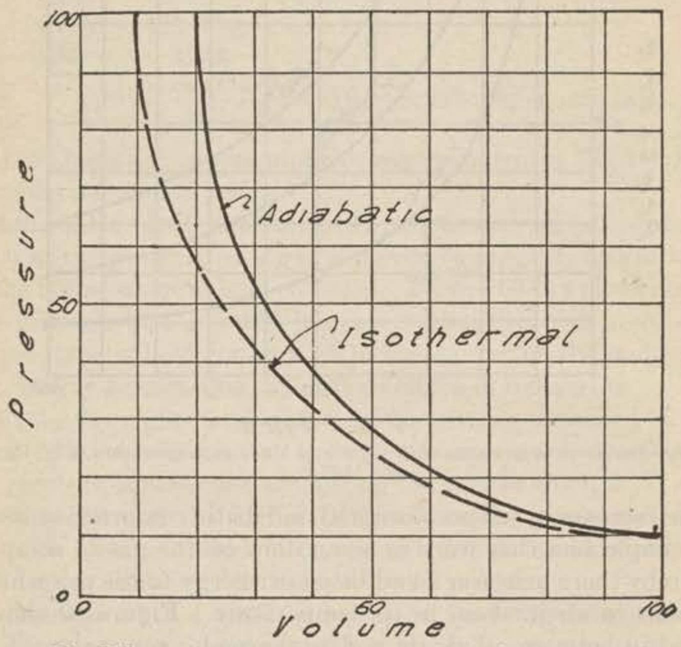

FIGURE 59.—Difference between adiabatic and isothermal compression of a gas.

mately 3° C. for every 1,000 feet. This partially accounts for the fact that pilots find air at high elevations colder than at the ground. Such cooling is very pronounced and is usually sufficient to cause the water vapor in the air to condense and form clouds with a lift of the air of only 1,000 or 2,000 feet. The formation of clouds and precipitation in the atmosphere is almost always a result of this condensation. In storms some of the air is forced to rise and expand adiabatically. Clouds form in this air as a result of the cooling.

QUESTIONS AND PROBLEMS

1. What is an adiabatic process?
2. What is an isothermal process?

3. If a paper bag containing 50 cubic inches of air is cooled from 100° C. to 0° C., what is the final volume?

4. If the same bag at original conditions is compressed with the hands until a gage reads 3 pounds per square inch, what is the new volume?

5. If the same bag has a capacity of 50 cubic inches, and 10 more cubic inches are forced in from outside, what is the final pressure as would be read by a gage?

6. If 20 liters of air at 10° C. and atmospheric pressure are first raised to a temperature of 50° C. and expanded isothermally to twice the former volume, what is the final total pressure? What would be the gage pressure?

7. In the adiabatic equation:

$$p_1 (V_1)\gamma = p_2 (V_2)\gamma$$

assume that the value of γ for a certain gas is 2. What will be the pressure if 10 cubic centimeters of this gas is adiabatically expanded to 14 cubic centimeters?

8. If the original temperature in example 7 were 27° C., what was the final temperature?

9. Very dry air is blowing up over a mountain range 10,000 feet high. A weather station on the windward side at an elevation of 5,000 feet reports a temperature of 0° C. What would be the temperature at the top of the ridge? At a station on the other side at sea level?

10. The volume inclosed by the fabric covering of an airfoil is 100 cubic feet. Small holes or vents are provided in the lower surface of the airfoil to permit the escape of air. How many cubic feet of air will flow out of the airfoil while the airplane is rising from the earth (atmospheric pressure 14.7 pounds per square inch) to an altitude at which the atmospheric pressure is 10 pounds per square inch? (Ignore change in temperature.)

11. If no provision had been made for the escape of air from the interior of the airfoil mentioned in problem 10, how much force would the difference in atmospheric pressure exert on the lower surface of the airfoil if its area is 75 square feet?

12. Air at atmospheric pressure of 14.7 pounds per square inch contains 21 percent oxygen. What would be the oxygen content in percent of a sample of air at an altitude where the atmospheric pressure is 8 pounds per square inch?

13. Of the 14.7 pounds per square inch pressure exerted by the atmosphere at sea level, 3.09 pounds per square inch is the pressure exerted by its oxygen content. What will be the oxygen pressure at an altitude where the atmospheric pressure is 8 pounds per square inch?

SECTION XII

CHANGE OF STATE

88. Matter in three states.—There are three states of matter: gaseous, liquid, and solid. In the preceding chapters these three states have been mentioned separately, but transformation of matter from one state to another was not considered. Most inorganic substances in one state can be made to exist in the other states under proper conditions of temperature and pressure. Mercury is ordinarily liquid under normal conditions. Yet it freezes at –39° C. and boils at 360° C. Alcohol boils to vapor at 76° C. and freezes at –117° C. Also substances which are ordinarily solid can be melted to liquid. At sufficiently high temperatures, solids may even be vaporized. Gases under the proper conditions of temperature and pressure can be liquefied and solidified. Air can be made into liquid, and even into a solid. In general, then, most substances can be made to exist in any of the three states by proper regulation of pressure and temperature.

89. Three states of water.—Water may exist in the atmosphere in any of its three states; gas, liquid, and solid.

a. Gas.—Gaseous water is found mixed with the air in the form of water vapor. This water vapor, or moisture, in the atmosphere is picked up by evaporation as the air moves over water sources such as oceans, rivers, and lakes. The amount of moisture in the air is variable, depending upon the character of the earth's surface over which the air has moved.

b. Liquid.—Liquid water in the atmosphere is found in the form of clouds and rain, formed by condensation of water vapor. Condensation is the transformation from the gaseous to the liquid state.

c. Solid.—The solid form of water (ice) is found in the atmosphere in the form of ice clouds, snow, hail, etc. Ice may be found as a transformation either from the liquid state (freezing) or directly from the gaseous state (sublimation).

90. Transformation between the three states.—By increasing the temperature it is possible to melt ice into liquid water, or evaporate liquid water to water vapor; conversely, by lowering the temperature it is possible to condense water vapor to liquid water, or freeze liquid water into ice. What are these processes, especially with respect to temperature and energy? Suppose we have 1 gram of ice at −5° C., a thermometer to measure the temperature, and a heat source whose output (in calories) can be accurately measured.

a. Raising temperature of ice.—The heat source is applied and the temperature is raised from −5° C. to 0° C. Two and one-half calories are required to warm the ice from −5° C. to 0° C., or 0.5 calories for each degree centigrade rise in temperature. The specific heat of the ice, then, is .5 calories per gram per degree C. If the ice is cooled from 0° C. to −5° C., 2½ calories are given off. To increase the temperature of a substance is to add energy to it; to cool a substance is to remove energy from it.

b. Change of state from solid to liquid.—The heat source is again applied, and ice at 0° C. melts to liquid water at 0° C. The melting of the ice takes 80 calories. As the temperature does not rise during this process, the 80 calories of heat are required for the change of state alone. Conversely, when 1 gram of water freezes to ice, 80 calories are given off. This 80 calories of energy emitted by freezing or absorbed by melting is called the *latent heat of fusion*. Latent means hidden; 1 gram of water at 0° C. has 80 calories that will be released when the water is frozen.

c. Raising temperature of water.—The heat source is again applied, and the temperature of the water is raised from 0° C. to 100° C. Raising the temperature 100° C. requires 100 calories. If a temperature change for water is to be accomplished, calories (or energy) must be added to or taken from the water. The change in temperature is a direct change in energy.

d. Change of state, liquid to gas.—The heat is again applied and the liquid water at 100° C. is changed to water vapor at 100° C. This evaporation requires 540 calories. Since the temperature does not rise during this process, the 540 calories are required for the change of state. Conversely, when 1 gram of water vapor is condensed to liquid water, 540 calories are given off. This energy, 540 calories, required for this change of state, is called the *latent heat of vaporization or condensation.* There are many examples of condensation and evaporation in the atmosphere. The air picks up its moisture from the evaporating lakes, oceans, and rivers. This moisture is then mixed through the lower atmosphere by turbulence. Warm air can hold more moisture than cold air, but any air can be cooled to a temperature where the moisture or water vapor in that air will condense. This temperature is known as the dew point. In the atmosphere warm, moist air is lifted up over mountains or colder air masses, or is driven upward as a result of the sun's having heated the surface of the earth. As this air is lifted, it cools adiabatically and condensation will occur when the temperature reaches the dew point. Condensation will produce clouds and may even produce precipitation. Dew forms on the ground at night, because the earth's surface cools and reaches the condensation temperature, the dew point. Frost forms the same way

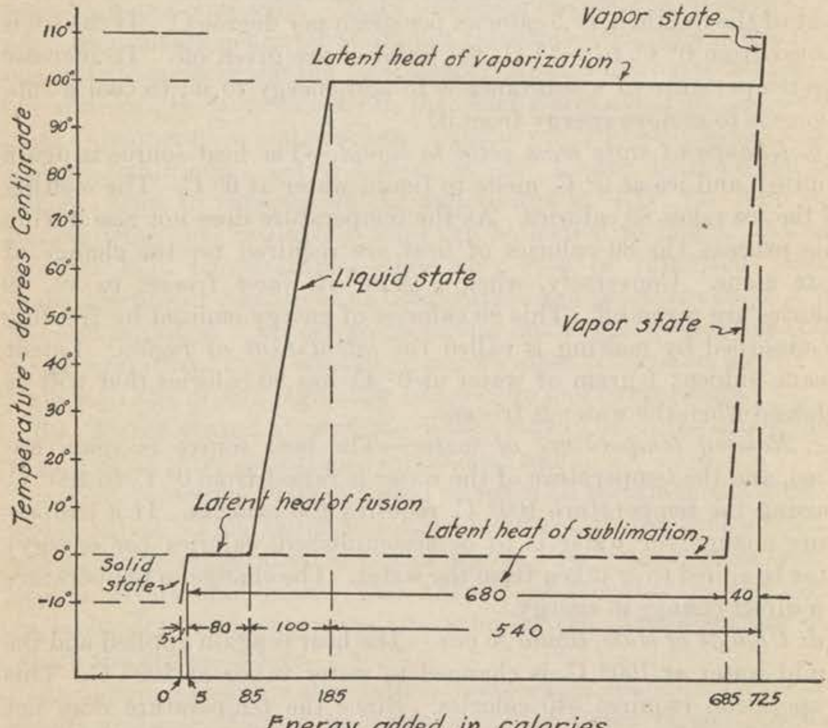

FIGURE 60.—Energy relationships in changes of temperature and changes in state of water.

except that the air is below the freezing temperature so that the water vapor is frozen directly to ice, or frost.

e. Explanation of boiling.—In the normal vaporization of water, the vapor above the surface will exert a pressure which depends upon the temperature. At low temperatures this pressure is small; but at a temperature of 100° C. the vapor pressure will be 14.7 pounds per square inch, equal to standard atmospheric pressure. At a temperature of 100° C. bubbles of pure water vapor can form within the fluid against the atmospheric pressure without. When bubbles of vapor form in this way and rise to the surface we have the familiar process of boiling. At high altitudes, where the atmospheric pressure is reduced, boiling can take place at lower temperatures because less vapor pressure is required to form bubbles.

f. Raising temperature of water vapor.—The heat is again applied and the temperature of the water vapor is changed from 100° C. to 110° C. Raising the temperature 10° C. requires 4 calories of heat; consequently, the specific heat of water vapor is 0.4.

g. Energy diagram.—Figure 60 is a diagram showing the energy relationships in changes of temperature and changes in state of water.

h. Sublimation.—Certain substances in the solid state pass directly into the gaseous state, or conversely, gases may pass directly to the solid state. This process is known as sublimation. Dry ice is a good example. Solid carbon dioxide goes directly to CO_2 gas without ever liquefying. Iodine and ice will also readily sublime. When ice at 0° C. sublimes to water vapor, 680 calories per gram are absorbed. The eighty calories which would ordinarily be needed to melt the ice and the 600 calories which would be needed to boil the water at 0° C. are added together to equal the amount needed to sublime the ice to vapor. When the vapor sublimes to ice, 680 calories are given off. In the atmosphere the sublimation process plays an important part in producing rain, as will be explained in section XIII.

i. The foregoing was worked out with a gram of water, the centigrade temperature scale, and the calorie as the unit of heat. A similar problem worked in the British engineering system of units would use 1 pound of water, the Fahrenheit temperature scale, and the Btu as the unit of heat. The specific heats of ice, water, and water vapor are the same in both the metric system and the British system of units, since they are ratios and the heat unit in each system is the heat required to raise the temperature of 1 unit mass or weight of water 1° on the corresponding temperature scale. However, the latent heats of fusion, vaporization, and sublimation are not ratios and are numerically different for the two systems of units. The latent heat of fusion in the British system is 144 Btu, which means that 144 Btu are absorbed by a pound of ice by melting or emitted by a pound of water in freezing. Similarly, the latent heat of vaporization is 970 Btu in the British system and the latent heat of sublimation is 1,224 Btu.

91. Supercooled water.—It is possible under certain conditions to cool water to temperatures below 0° C. without freezing into ice. Water in this state is called supercooled. If such water comes into contact with even a very small ice crystal, or is violently disturbed, freezing will take place rapidly, a sufficient portion of the water freezing to raise the temperature to 0° C. For instance, water at −5° C. requires 5 calories per gram to bring the temperature to 0° C., and these 5 calories will be obtained from the latent heat of fusion of 5/80 or 1/16 of this water, which be almost instantly frozen. Icing of aircraft occurs when the supercooled droplets in the atmosphere freeze on account of the violent disturbance produced by impact with the plane.

92. Effect of pressure on fusion.—The normal melting point of pure substances depends upon the pressure at which melting occurs. An increase in pressure will lower the melting point of a substance which contracts on melting, such as ice. If the substance expands on melting an increase in pressure will raise the melting point.

93. Freezing point of solutions.—If salt is dissolved in water the freezing point of the solution is lowered. Thus ice in a strong solution of common salt will have its melting point lowered to about −15° C. and the ice remains at this temperature until it is all melted by heat absorbed from surrounding objects. Thus the old ice-cream freezer froze the cream by extracting heat from it to melt the ice in the brine solution surrounding it.

94. Boiling point of solutions.—The boiling point of a pure liquid is always raised by dissolving a nonvolatile substance in it, such as sugar. If the substance dissolved is volatile it may either raise or lower the boiling point. Thus alcohol dissolved in water lowers the boiling point below that of the water and also lowers the freezing point of the water. For volatile mixtures, the boiling point may be raised above that of both of the constituents. Nonvolatile dissolved substances (solutes), however, raise the boiling point in proportion to the mass of solute added. For equal gram-molecular weights of solute in a given quantity of solvent all nonvolatile solutes raise the boiling point approximately the same amount.

PROBLEMS

1. What would be the final temperature of a mixture of 1 liter of water at 20° C. and ¾ liter of water at 45° C.?

2. What would be the final temperature of a mixture of 100 grams of ice at −12° C. and 60 grams of water at 25° C.?

3. What is the final temperature of a mixture of 10 pounds of ice at 20° F. and 20 pounds of water at 60° F.?

4. If 2 grams of superheated water vapor were passed into a 4-liter bucket of water at 20° C., how warm would the water get if all the vapor were absorbed by the water and the vapor was originally at 120° C.?

5. Suppose that into a calorimeter containing 100 liters of water at 40° C. were dumped 5 kilograms of ice at 0° C. and 2 liters of water at 0° C. What would be the final temperature of the mixture?

6. How much ice at 0° C. would be required to lower the temperature of 100 grams of water at 35° C. to 10° C.?

7. Assume that the cold water in a shower is 15° C. and that the hot water is 85° C. Suppose that a shower is to be taken at 40° C. What would be the ratio of hot to cold water flowing into the shower nozzle?

8. What would be the final temperature of a mixture of 20 pounds of water at 120° F., 5 pounds of water at 32° F., and 10 pounds of ice at 28° F.?

9. Find the temperature of the folowing mixture: 10 pounds of ice at 20° F., 20 pounds of water at 40° F., and 5 pounds of water vapor at 250° F.

10. Give to the nearest degree the final temperature of the following mixture: 50 grams of ice at 0° C., 30 grams of water at 15° C., and 3.3 grams of water vapor at 130° C.

11. An airplane flies through a supercooled cloud at −2° C. and picks up ice by impact with the water droplets. What percentage of each drop will have to freeze in order to bring the ice and water to 0° C., which is the only temperature at which water and ice can remain in equilibrium?

12. An airplane flies through a cloud at −10° C., and picks up ice on impact. What percentage of each drop will freeze in bringing the water and ice to equilibrium at 0° C.?

13. In problem 9 how much of the remaining water at 0° C. must evaporate in order to freeze the rest of the water?

14. At high altitudes, water boils at less than 212° F. May anything be added to the water to raise its boiling point; if so, what?

Section XIII

WATER IN THE ATMOSPHERE

95. Physical states.—Water is found in all three of its physical states in the atmosphere. As discussed in section XII, these three states are solid, liquid, and gaseous. At all levels at which tests can be made, water vapor may be found in any sample of air. The amount may vary considerably, but some is always present. Clouds and precipitation may be composed of either ice or liquid water, depending on their elevation, temperature, and history. Clouds consisting only of ice particles exist at very high altitudes, but in very cold weather may occasionally be found close to the surface of the earth. Clouds with temperatures of 0° C. or higher are always water clouds. Both types of clouds are composed of extremely fine droplets of liquid water or particles of ice which because of their minute size remain suspended in the air.

96. Water vapor.—*a.* Water vapor is a gas which in most respects acts very much like other gases. As long as its concentration does not exceed certain limits it obeys the normal gas laws. When mixed with air it is normally unnoticeable, being colorless, odorless, and tasteless. Its density at a given temperature and pressure is only five-eighths that of air. Being colorless, it is invisible because it contains no particles which can reflect light. Steam jets are visible because of tiny particles of liquid water which have condensed from the vapor state.

b. When dry air passes over a water surface, a process called evaporation takes place wherein water leaves the surface and becomes mixed as a gas within the air. The reverse process of condensation takes place when air which is moist (that is, it contains a large amount of water vapor) comes into contact with a cold surface and water vapor leaves the air and deposits as liquid water or dew on the surface. In the free atmosphere, condensation takes place by the formation of small droplets on nuclei such as particles of sulfur trioxide or salt. When there are a large number of these drops in the air, this air is called a cloud or fog.

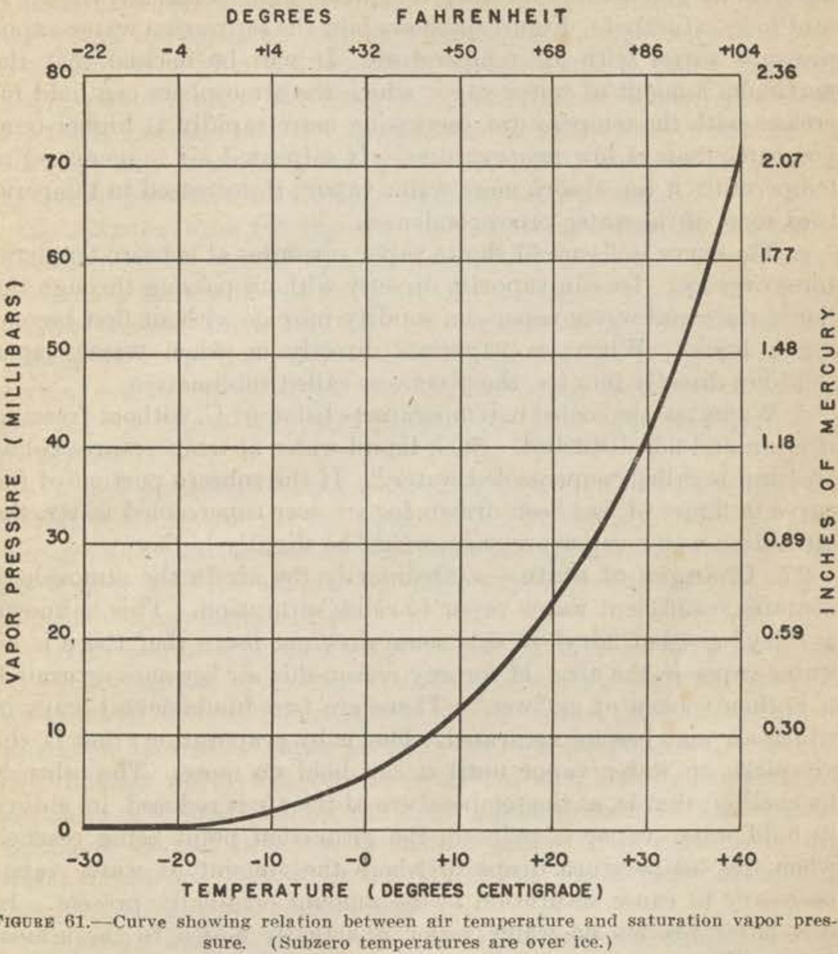

FIGURE 61.—Curve showing relation between air temperature and saturation vapor pressure. (Subzero temperatures are over ice.)

c. Atmospheric pressure, as previously stated, is the sum of the pressures exerted by those gases which compose the atmosphere—nitrogen, oxygen, carbon dioxide, argon, water vapor, etc. If it were possible to take some humid air at atmospheric pressure p, confine it in an air-tight container, and then remove all the water vapor, it would be found that the pressure inside the container dropped by a relatively small amount p. This small pressure p was the pressure exerted by the water vapor and is what is known as vapor pressure. It is generally measured in millibars.

d. There is a limit to the amount of water vapor which the air can hold at any given temperature. When this limit is reached the air is said to be saturated. Figure 61 shows how the saturation water-vapor pressure varies with air temperature. It will be noticed that the maximum amount of water vapor which the atmosphere can hold increases with the temperature, increasing more rapidly at higher temperatures than at low temperatures. If saturated air is increased in temperature it can absorb more water vapor; if decreased in temperature, some of the water vapor condenses.

e. The curve in figure 61 shows vapor pressures at subzero temperatures over ice. Ice can vaporize directly without passing through the liquid state and water vapor can solidify into ice without first becoming a liquid. When ice vaporizes directly or when water vapor solidifies directly into ice, the process is called sublimation.

f. Water may be cooled to temperatures below 0° C. without freezing if clean and not disturbed. Such liquid water at temperatures below freezing is called "supercooled water." If the subzero portion of the curve in figure 61 had been drawn for air over supercooled water, the saturation water-vapor pressures would be slightly higher.

97. Changes of state.—*a.* Ordinarily the air in the atmosphere contains insufficient water vapor to cause saturation. This is known as "dry" air, but "dry" in this sense does not mean that there is no water vapor in the air. If for any reason this air becomes saturated, it is then spoken of as "wet." There are two fundamental ways in which air may become saturated. One is by evaporation; that is, the air picks up water vapor until it can hold no more. The other is by cooling; that is, as the temperature of the air is reduced, its ability to hold water vapor is reduced, the saturation point being reached when the temperature drops to where the amount of water vapor necessary to cause saturation is the amount originally present. In this latter process no water vapor is actually added to the atmosphere. Either process or a combination of the two may cause atmospheric air to become saturated, cooling usually being the direct cause. Evaporation is, of course, a very important process in weather, but it seldom alone produces saturation.

b. Saturation of the atmosphere is a very important phenomenon and is the direct cause of all precipitation such as rain, snow, or drizzle. Saturation first forms clouds which with further cooling may give precipitation. The cooling necessary for saturation may be caused in several different ways. Lifted air will expand adiabatically and be cooled thereby. Warm air may be cooled by passing over colder ground. The first condition will produce clouds and perhaps rain, and the second condition may produce fog. If the air is moist and warm, condensation will form small water droplets; but if it is dry and cold so that the saturation temperature is below freezing, sublimation will occur and ice clouds or ice fog will form. If a cloud is already present and the temperature is raised, the water or ice particles will evaporate and the cloud will disappear because at higher temperatures the air can hold more water vapor.

98. Expressions for the amount of water vapor in the air.—As shown in the preceding paragraphs, for any temperature there is a limit to the amount of water vapor that may be present in the air. Usually the amount is less than this maximum, and it is often important to know the amount which is present in order to predict certain weather phenomena. In the following paragraphs several methods for expressing quantitatively the air's water vapor content are explained:

a. Vapor pressure.—Vapor pressure has already been defined as the partial pressure exerted by water vapor in the air. If the vapor pressure and temperature are known it is a simple matter to use the gas laws to find the amount of water vapor present in any known volume or in any sample of air.

b. Dew point.—The dew point is defined as that temperature to which any sample of air must be cooled (keeping the total pressure constant) in order to be brought to the saturation point. Because of the unique saturation vapor pressure for each temperature, it may be seen that air which will become saturated at a definite temperature will have a unique amount of water vapor present at the original conditions as well as at the saturation point. Dew point is a very useful expression because it quickly shows the amount of cooling necessary before condensation begins.

c. Specific humidity.—Specific humidity may be defined as the mass of water vapor per unit mass of air and is generally measured in grams of water vapor present in 1 kilogram of air. If there is no condensation or evaporation, the specific humidity of any sample of air will remain constant, even though the pressure, temperature, or volume of the sample changes.

d. Relative humidity.—Relative humidity is the ratio, usually expressed in percent, of the actual amount of water vapor present to that which the air could hold if the air were saturated at that tem-

560696°—43——9

perature. If the vapor pressure of some sample of air is 2 millibars and an inspection of the graph in figure 61 shows that at that temperature the saturation vapor pressure is 4 millibars, then the relative humidity is 50 percent.

e. Absolute humidity.—Absolute humidity is defined as the weight of water vapor present in a given volume of air; for instance, it may be expressed in grams of water vapor per cubic meter of air. It is not a conservative property like specific humidity, as there will be a change in its value when there is expansion or compression.

99. Methods of measuring humidity.—There have been devised no really accurate indicating meters for humidity, but there are in use several fairly convenient devices which give results sufficiently accurate for most purposes. Three of these devices are described below.

a. Wet and dry bulb thermometers.—(1) Two thermometers are used in this method; one is a normal thermometer for measuring the temperature of the air, and the other is equipped with a moistened wick around the bulb. With good air circulation around the thermometers the wet bulb will normally cool to a temperature below that of the dry bulb. Because of the energy required for evaporation, there is a cooling effect which depends upon the rate of evaporation. If the air is nearly saturated, the rate of evaporation is small, and the wet bulb will have a temperature close to that of the dry bulb. In very dry air (that is, air with low relative humidity) there is rapid evaporation, and the wet bulb may be several degrees cooler than the dry bulb. A set of tables must be used to convert these two temperatures into an expression for humidity.

(2) Several different instruments have been devised using the above principle, but the one in most common use is the sling psychrometer. The device consists of the two thermometers attached rigidly together and the combination attached at the top end to a handle arranged so that the thermometers may be whirled vigorously about. The whirling provides the ventilation necessary to give accurate wet bulb readings. In use, the wick is wet with pure water and the device is whirled about. After the wet bulb has dropped in temperature as far as it will, the two readings are taken and the table is consulted to determine the dew point, relative humidity, or vapor pressure. More complicated devices on the same principle may use a fan to provide the necessary ventilation. A drawing of the sling psychrometer is shown in figure 62.

b. Hair hygrometer.—A human hair, after it has been cleaned of its natural oils, has the property of absorbing water from the air and thereby increasing its length. The amount of water absorbed and the

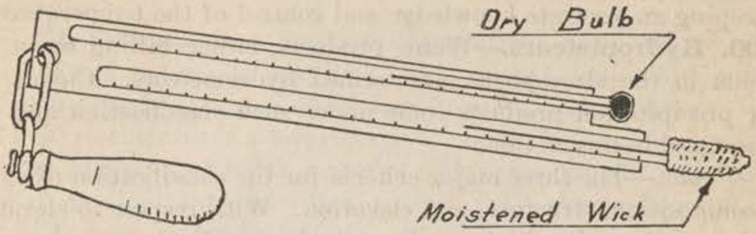

FIGURE 62.—Sling psychrometer.

degree of lengthening depend upon the relative humidity. The amount of this lengthening is not very great, but mechanical linkages may be used for magnification of the movement. A needle may be used to indicate the relative humidity on a scale. A drawing showing an arrangement for an indicating hair hygrometer is shown in figure 63.

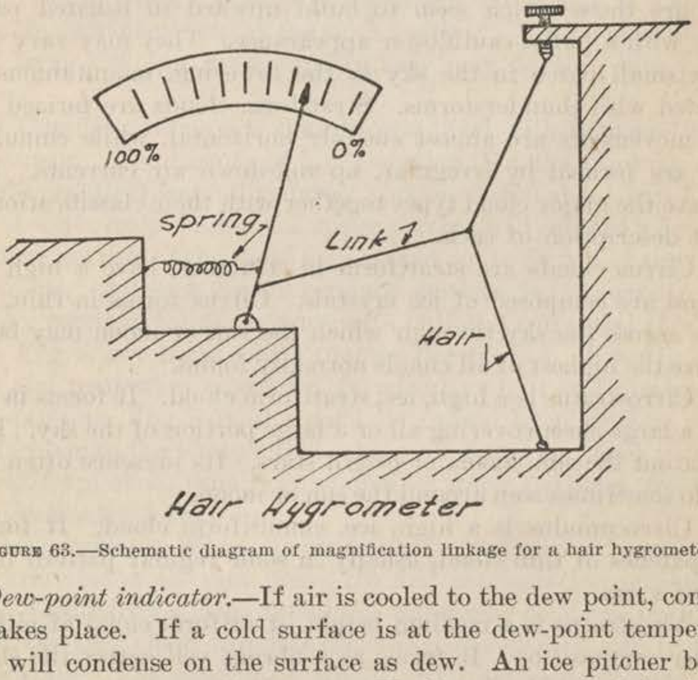

FIGURE 63.—Schematic diagram of magnification linkage for a hair hygrometer.

c. Dew-point indicator.—If air is cooled to the dew point, condensation takes place. If a cold surface is at the dew-point temperature, water will condense on the surface as dew. An ice pitcher becomes wet on the outside for this reason. The instrument used for indicating the dew point consists of a shiny, metallic surface which may be cooled to any desired temperature. The temperature at which the surface first becomes fogged with dew is the dew point. In practice the device is not convenient to use because of the difficulties in determining just when the dew first forms and because of the difficulties in keeping an accurate knowledge and control of the temperature.

100. Hydrometeors.—Water products, either falling or in suspension in the atmosphere, are termed hydrometeors. Clouds and their precipitation products come under such classification and will be discussed in this section.

a. Clouds.—The three major criteria for the classification of clouds are composition, structure, and elevation. With respect to elevation, clouds may be either high, medium, or low. High clouds have elevations of their bases above 20,000 feet; medium clouds, between 6,500 and 20,000 feet; and low clouds, below 6,500 feet. With respect to composition, clouds may be made up of tiny particles of ice, liquid water, or both. With respect to structure, clouds may be classified as stratiform or cumuliform. Stratiform clouds are of a sheetlike structure formed in layers of large horizontal extent. Cumuliform clouds are those which seem to build upward in isolated patches, usually with a puffy, cauliflower appearance. They may vary in size from a small patch in the sky to the towering, mountainous mass associated with thunderstorms. Stratiform clouds are formed in air whose movements are almost entirely horizontal, while cumuliform clouds are formed by irregular, up-and-down air currents. Listed below are the major cloud types together with their classifications and a short description of each.

(1) Cirrus clouds are stratiform in structure, have a high elevation, and are composed of ice crystals. Cirrus forms in thin, wispy streaks across the sky through which the sun or moon may be seen. They are the highest of all clouds normally found.

(2) Cirrostratus is a high, ice, stratiform cloud. It forms in a thin veil as a large sheet covering all or a large portion of the sky. It does not blot out the sun, moon, or bright stars. Its presence often causes the halo sometimes seen around the sun or moon.

(3) Cirrocumulus is a high, ice, cumuliform cloud. It forms in small patches of thin cloud, usually in some regular pattern like the scales of a fish.

(4) Altostratus is a medium height, stratiform cloud of either ice or water composition. It forms as a fibrous veil across the sky and may or may not hide the sun or moon. It may cause a precipitation of light rain or snow.

(5) Altocumulus is a medium height, cumuliform cloud of either ice or water composition. It forms a layer of flattened globular masses often arranged in some regular pattern across the sky. It may cause a precipitation of light rain or snow. A mackerel sky is caused by altocumulus.

(6) Nimbostratus is a low, stratiform cloud composed of either ice or ice and water. It is a thick, dark, ragged cloud which gives a continuous precipitation of either rain or snow, perhaps heavy.

(7) Stratocumulus is a low elevation, cumuliform, water cloud. It forms in a layer of globular masses or rolls across the sky with limited vertical development but often packed very closely together. It ordinarily gives no precipitation.

(8) Stratus is a low, stratiform, water cloud. It is usually not very thick and has a light gray color. Usually it is a local cloud which forms at night and disappears in the day. The precipitation, if any, will be a drizzle.

(9) Cumulus is a low elevation, cumuliform, water cloud. It forms in scattered dense white masses with a cauliflower appearance and flat, horizontal bases. It usually forms in the daytime as a result of convective currents set up by the sun's heating. When cumulus clouds are of large size and grow rapidly they may develop into cumulo-nimbus.

(10) Cumulo-nimbus is a cumuliform cloud with immense vertical development. The base is of low elevation, but the top may extend to 20,000 or 30,000 feet. The lower portion of the cloud will be composed of water droplets, but the upper portion will contain ice crystals. The upper portion of the cloud may spread out to form a characteristic anvil shape. All such clouds produce showers, but in extreme cases they may result in thunderstorms with hail and torrential rain.

(11) Fog is any cloud which touches the ground. Usually it is of a local and temporary character, forming at night and disappearing in the daytime. Fog is most commonly caused by nighttime cooling of surface air to the temperature where condensation takes place. It is a stratiform cloud usually composed of water particles, though ice fogs occasionally form.

b. Precipitation.—When air containing water vapor is cooled to a temperature below the dew point, the first condensation products are clouds. Ordinarily a large amount of water may condense in this way without the tiny cloud droplets becoming of sufficient size to fall as precipitation. The process by which precipitation is formed is not too well understood, but it is generally conceded that particles large enough to fall as rain will not ordinarily be formed unless the upper levels of the cloud are at temperatures below freezing. It is known that the vapor pressure of ice is less than that of supercooled water at the same temperature. As condensation ordinarily occurs in air which is being lifted, some liquid water will usually be found at levels where the temperature is below 0° C., together with newly formed ice particles. Because of the difference in vapor pressure between these two kinds of water, it is thought that there is a rapid transfer of water from one to the other by evaporation of the supercooled water and sublimation onto the ice particles. In this way the ice particles could grow rapidly in size and soon become large enough to fall downward. After the first large particles are formed, many changes may take place, and the conditions of the air through which the particles must fall will determine the kind of precipitation which will finally reach the earth. Several of the different forms which precipitation may take are described in the next few paragraphs, together with a short description of the processes required for their formation:

(1) Rain is simply a fall of large drops of liquid water. The original ice particle melts in warmer air below and may increase in size by picking up more water in the clouds below. Raindrops have a diameter greater than $\frac{1}{50}$ of an inch.

(2) Drizzle is a fall of very small particles of liquid water. The particles must have a diameter of less than $\frac{1}{50}$ inch and will fall with velocities of less than 10 feet per second. Drizzle does not require freezing temperatures for its formation and is usually the only type of rain which can fall from water clouds.

(3) Freezing rain and freezing drizzle is simply rain or drizzle which falls through a layer of cold air so that the particles become supercooled. Freezing rain or drizzle causes glazing because it freezes upon impact with objects in the open.

(4) Snow is a fall of white or translucent ice crystals. It is formed by direct sublimation from water vapor.

(5) Sleet is a fall of grains or pellets of ice. It is formed by the freezing of rain when it falls through a cold layer of air below.

(6) Hail is a fall of ice balls or stones of a size which varies from $\frac{1}{5}$ inch to 2 inches or more in diameter. Hail may be either transparent ice or layers of opaque snow and ice. Hail is formed almost exclusively in thunderstorms and requires violent upward currents of air for its formation. It is very hazardous to aircraft and is one of many reasons why thunderstorms should be strictly avoided by pilots.

(7) Snow pellets are falling grains of a snowlike structure, crisp

but easily compressible; they rebound upon striking the ground. Snow pellets form in upward air currents and are often found with showers.

TABLE V.—*Saturation vapor pressures and saturation specific humidities at various temperatures*

Temperature		Saturation vapor pressure (millibars)	Saturation specific humidities at sea level (grams per kilogram)
Centigrade	Fahrenheit		
−20	−4	1.27	0.77
−10	14	2.86	1.76
−5	23	4.21	2.59
0	32	6.11	3.77
5	41	8.27	5.36
10	50	12.28	7.58
15	59	17.05	10.50
20	68	23.38	14.40
25	77	31.68	19.50
30	86	42.45	26.10
35	95	56.23	34.60
40	104	74.10	45.60
45	113	95.84	59.10

At temperatures below freezing, these values apply to supercooled water. For ice, the values will be slightly lower.

QUESTIONS AND PROBLEMS

1. Why does warm, moist air cause more discomfort than warm, dry air?

2. If air with a relative humidity of 50 percent is expanded adiabatically, will the following quantities increase or decrease? vapor pressure; relative humidity; specific humidity; absolute humidity; dew point.

3. If air in the free atmosphere at 25° C. has a dew point of 20° C., describe what will occur if the air is slowly cooled to −10° C.

4. If laundry is hung out to dry at temperatures below freezing, what process is responsible for the disappearance of the water?

5. At a temperature of −5° C., which will transform into vapor more quickly, supercooled water or ice? Assume similar conditions for each.

6. If air in a small chamber has a temperature of 25° C. and a dew point of 15° C., what is the approximate vapor pressure?

7. If air has a specific humidity of 5.25 grams per kilogram, at what temperature would the relative humidity be 50 percent?

8. If air has a dew point of 50° F., what will be the relative humidity if the air is at a temperature of 104° F., 77° F., 68° F., and 50° F.?

9. If air has a temperature of 20° C. and the relative humidity is 52°, approximately how much water will condense if the temperature is reduced to 0° C.?

10. A kilogram of air is saturated with water at normal pressure and then expanded to twice its former volume. If during this process the temperature is reduced from 25° C. to 0° C., how many grams of water will be condensed?

INDEX

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