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ELEMENTARY LESSONS

IN

HEAT.

BY

S. E. TILLMAN,

PROFESSOR OF CHEMISTRY, UNITED STATES MILITARY ACADEMY.

FOURTH EDITION.

REVISED AND ENLARGED.

FIRST THOUSAND

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PREFACE TO THIRD EDITION.

THE preface to the first edition of this book read as follows:

" These lessons have been prepared to meet the necessities of a very short course of study at the Military Academy in this branch of physics, a course so short that it can command for study and recitation only about seventy hours from the cadets.

" In selecting the material, I have been guided by the consideration of what is applicable to the subsequent courses of study at the Academy and also of what is essential and most useful for the student to know. In the arrangement I have kept in view facility of acquirement and thorough understanding, and, accordingly, the logical connection of the facts and principles set forth.

"In the exposition of the subjects treated, I have aimed at clearness and conciseness, and have omitted detailed descriptions of investigations and of apparatus as entirely as is consistent with the foregoing objects. Most of the experimental illustrations described or referred to are such as can be performed in the lecture-room."

The preface to the second edition contained this statement:

" In the use of the book experience has shown that many of the subjects touched upon are pregnant with suggestions to the pupils, and there is a great temptation to treat them more fully; but the object for which the lessons were prepared and the time that can be devoted to them, as stated in the preface to the first edition, are barriers to a more extended treatment, or to a different apportionment of space to the subjects treated."

The same necessities, conditions and objects as set forth in the above extracts have been the governing factors in this revision for the third edition, and they have prescribed the same limitations and general treatment as in the previous editions.

A number of changes, for the sake of simplicity or greater clearness, have been made both in the figures and in the text of the second edition.

The chapters relating to meteorology have been, in large part, rewritten, and the author is entirely indebted to the published papers of Prof. F. H. Bigelow, U. S. Weather Bureau, for new and interesting matter in this science. The publications of Prof. Bigelow have shown the necessity for a modification of Ferrel's view of the general circulation of the atmosphere, and they contain a new theory of cyclones, more satisfactory in conception and in much more perfect accord with observations than the generally accepted condensation theory. This new explanation of the cyclone is here adopted instead of that given in the second edition.

There are appended to this edition a few tables, valuable for use or reference.

S. E. Tillman.

West Point, May 15, 1901.

PREFACE TO FOURTH EDITION.

The conditions which produced the previous editions of this book and which have limited its scope and governed the treatment of the subject are briefly given in the preface to the third edition which preface is retained herein.

The conditions referred to are still such that no material changes in the book have been made, except that a short general description of steam turbine engines has been introduced.

S. E. T.

West Point, N. Y., July 1, 1907.

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CHAPTER I.

THERMOMETRY.

We are all familiar with the sensation of warmth, and the words *hot* and *cold* are associated in our minds with different degrees of warmth. *Heat* is the agent which produces these sensations, and should not be confused with the sensations themselves. *Heat* is a form of energy, and probably consists in the energy of motion of the molecules of bodies. This motion is not of visible parts of matter, but of the molecules,—of parts too small to be observed separately.

Heat produces in a body a series of different states or conditions recognized by our sense of heat, and associated in our minds with different degrees of warmth, indicated by the terms *hot, warm, cool, cold,* etc. In science, any one of the states of a body with respect to sensible heat is called its temperature, and the words *hot, cold,* etc., in popular use, are the names of temperatures. Since the state of a body may vary continuously from very hot to very cold, there is an indefinite number of intermediate states or temperatures. We may give names to any number of particular temperatures and indicate any other by its relative place among these. By the temperature of a body, therefore, is specified relatively how hot it is.

Heat and Temperature.—It is very essential in beginning this subject to have distinct ideas of Heat, the agent, and Temperature, the effect. Without at present considering the ultimate nature of heat, we may say that we know it to be a property of matter, a form of energy, communicable from one body to another, so as to diminish the quantity of heat in one and increase that in the other, and, in addition to the changes of condition in bodies which heat produces, and which we call *temperatures,* it produces other obvious changes, as changes of *dimensions,* and in gases changes of *pressure,* and changes of *state of aggregation,* as in melting solids or volatilizing liquids.

Temperature has reference to the states or conditions of a body as regards *sensible* heat, these states usually, but not always, varying when heat is added to or taken from a body. Two unequal weights of the same body may be at the same temperature, but contain very unequal quantities of heat, as may also two equal weights of different bodies; thus, a pint and a gallon of water at the same temperature will contain very different amounts of heat, as will also a pound of iron and a pound of mercury. The temperature of a body always determines whether, as regards other bodies, heat will flow from or to it; thus, from a small piece of metal at high temperature, heat will pass to any amount of metal, however large, at a lower temperature, though the larger mass might contain a much greater quantity of heat. Temperature is one of the effects of heat; it is the state of a body with respect to its power of communicating heat to other bodies.

It would probably be more correct to say that temperature determines whether more heat flows from a body than to it, as all bodies are probably giving out and receiving heat, but in unequal quantities, depending upon their own temperatures and that of surrounding bodies. This unequal transfer of heat always takes place whenever bodies at unequal temperatures are in communication with each other, and continues until an equilibrium of temperature is established. If no excess of heat over that received passes from one body to another, there will be no change in either, as regards heat, and such bodies are said to be at the same temperature.

Expansion.—Although our sensations give us indications of varying temperature, they are not sufficient for the accurate comparison of the states of bodies, all of our sensations being modified by subjective causes. This is readily perceived by placing one hand in cold and the other in hot water for a little time, then by dipping both hands in lukewarm water it will appear warm to one hand

and cold to the other. Accompanying variations of temperature in bodies there are usually other variations in the properties of bodies, some of which are abrupt, as the melting of ice and the boiling of water ; other variations are continuous, the most general of which is the expansion or change of volume which bodies undergo with change of temperature. The volume of most substances, under specified conditions, increases continuously as the temperature rises, and decreases as the temperature falls, though there are exceptions to the rule. This effect of heat on bodies, accompanying change of temperature, may be illustrated by the following experiments.

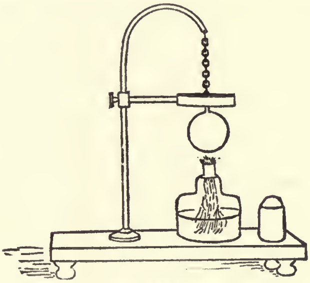

Fig. 1.—Gravesand's Ring.

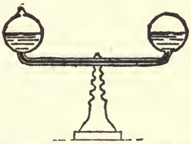

Fig. 3.—Expansion of Gases.

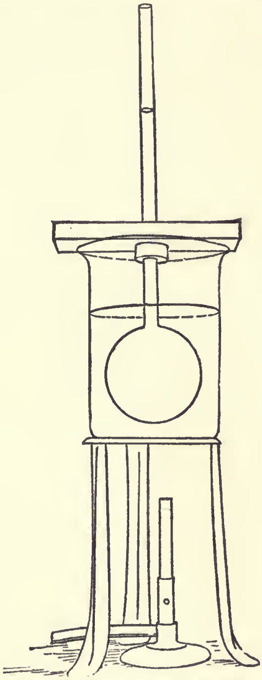

Fig. 2.—Expansion of Liquids.

Solids.—Take a ring through which a metal sphere when cold just passes, as in Fig. 1. Heat the sphere, and it will no longer pass through the ring : during a rise of temperature its volume has increased. Let the sphere be cooled by immersion in water : it will again pass through the ring, its volume decreasing with fall of temperature.

Liquids.—Let a quantity of liquid contained in a glass bulb with a narrow neck be heated (Fig. 2): the liquid will rise in the neck, showing an increase of volume. The liquid descends slightly at the beginning of the operation, owing to the fact that the bulb is warmed and increases in volume before the liquid expands sensibly. When the liquid is warmed it expands also, and as it rises in the neck we conclude that it expands more than the glass.

Gases.—Any gas confined in a vessel, as in Fig. 3, may, by the application of very little heat, as when the hand is applied to one of the bulbs, be made to occupy a sensibly larger volume.

Thermometer.—This most general effect of heat on bodies—the changes of volume accompanying changes of temperature—furnishes us with a means of estimating temperatures which depends upon the properties of matter and is independent of our own senses. This means consists in measuring the change of volume in a body produced by heat and accepting this change to be the same as the change of temperature. Any arrangement for measuring or comparing temperatures may be called a thermometer. When such an arrangement is at the same temperature as the surrounding medium, it of course indicates both its own temperature and that of the surrounding medium. Under such conditions, therefore, thermometers measure or indicate the temperatures of the surrounding medium.

The most common form of thermometer is the mercurial. It consists of a capillary glass tube terminating in a bulb or reservoir. The bulb and a portion of the tube are filled with mercury. As the temperature varies the level of the mercury in the tube will rise or fall. These variations in the volume of the mercury measure the temperature.

The *principle* of the construction of a mercurial thermometer is simple, but the *construction* of an accurate thermometer is a very delicate operation.

The Tube.—It is evident that the tube should be of as uniform bore as possible. This may be tested by introducing a short column of mercury into the tube and moving it successively forward through its length. If these lengths are unequal, the tube is not of uniform bore. If these different lengths be marked on the tube they will indicate equal volumes, and the tube is thus *calibrated.*

Introduction of Mercury.—When a suitable tube is obtained, one end is closed and expanded into a bulb, usually by blowing, and the other end is drawn out somewhat expanded and left open. The bulb is then cautiously heated, and the open end inserted into a cup of mercury (Fig. 5); the mercury rises in the tube as the latter cools, replacing the air which was expanded and driven out by the heat. By alternately heating and cooling the bulb, with the instrument upright (Fig. 4), a considerable portion of the mercury descends to the bulb. By now boiling the mercury in the bulb the vapor of mercury drives out the air and completely fills the tube, and while in this condition the open end of the tube is plunged into the vessel of mercury. As the tube cools and the vapor of mercury condenses, the atmospheric pressure causes the liquid mercury to completely fill the tube and bulb. The thermometer thus filled is then heated until so much mercury is driven out by expansion that the remainder in the tube stands at the point required at common temperatures. This being adjusted, the heat is again applied until the mercury fills the tube, and while thus filled the tube is sealed by fusion with a blow-pipe. The retraction of the mercury in cooling leaves a vacuum, which is essential to the perfection of the instrument.

Fig. 4.

Fig. 5.—Introduction of Mercury.

Reference Points.—We now have an instrument which would indicate temperatures, but to make its indications comparable with similar instruments we must adopt for all at least two common points of reference. For these points of reference, or standard temperatures, it has been agreed to adopt the freezing and boiling points of water, or, more correctly, the temperature of a mixture of ice and water under ordinary pressure, and the temperature of steam from water boiling under definite pressure. These two phenomena are found always to give the same temperatures, they are easily reproduced and maintained, and are consequently our most important temperature references.

These two points are found by noting the level of the mercury in the tube when subjected to the conditions indicated in Figs. 6 and 7. In the first case the instrument is surrounded by melting ice contained in a perforated vessel to allow the escape of the water produced; in the second case it is surrounded by steam from boiling water, a small manometer tube being used to show that the pressure of the steam is the same as that of the air, or that the steam is not generated faster than it escapes.

These two points being marked on the tube, it only remains to divide the interval between them into equal parts, to indicate degrees. The number of these divisions is arbitrary, and they are continued both above and below the fixed points.

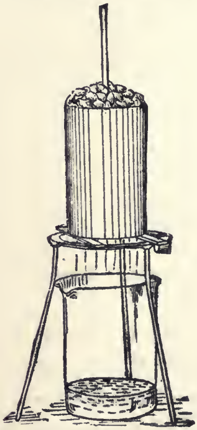

Fig. 6.—Freezing-point Apparatus.

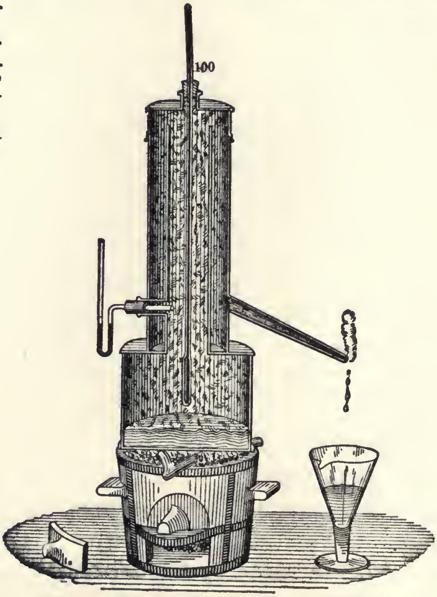

Fig. 7.—Temperature of Boiling Water.

Thermometric Scales.—The most common scales are—

1. *The Centigrade.*—In which the distance between the fixed points is divided into 100 equal parts, the melting point of ice being

at the zero of the scale, and the boiling point of water at 100. This scale is sometimes called the Celsius scale.

2. *The Fahrenheit.*—In which the interval between the freezing and boiling points is divided into 180 equal parts, the melting point being at 32 and the boiling point at 212, so that on this scale the zero point is 32 degrees below the melting point.

3. *The Réaumur.*—This scale has 80 divisions between the fixed points, the zero being taken at the melting point and 80 marking the boiling point.

The scales with their reference points are indicated in Fig. 8. On all the scales the numbers below the zero point are distinguished by the negative sign.

A little consideration enables us to find equivalent readings on the other scales when that of any one is given. It is evident that equal intervals of temperature on the scales are to each other as the numbers 180, 100, and 80, or 9, 5, and 4. Since the zero on the Fahrenheit scale is 32° below the freezing point, this number must be subtracted from the Fahrenheit reading to get the interval from the freezing point; $\frac{5}{9}$ or $\frac{4}{9}$ of this interval will then be the corresponding reading on the Centigrade and Réaumur scales, respectively; $\frac{9}{5}$ and $\frac{9}{4}$ of the Centigrade and Réaumur readings, respectively, will give the corresponding *interval* from the *freezing point* on the Fahrenheit scale, to which must be added 32, to give the corresponding Fahrenheit reading. To convert the readings of the Centigrade and Réaumur scales no explanation is necessary.

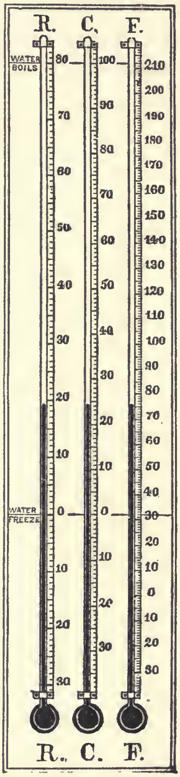

FIG. 8.—THERMOMETER SCALES.

The rules for the conversion of the scales are expressed in the following equations, in which C, F, and R denote equivalent readings:

$$C = \tfrac{5}{4}R = \tfrac{5}{9}(F - 32),$$
$$F = \tfrac{9}{5}C + 32 = \tfrac{9}{4}R + 32,$$
$$R = \tfrac{4}{5}C = \tfrac{4}{9}(F - 32).$$

Sensitiveness of Thermometers.—The power of the instrument to detect slight differences of temperature will evidently be measured by the length of the degrees, which will vary with the expansibility of the substance used and the capacity of the bulb directly and the area of the cross-section of the tube inversely.

The quickness of action depends upon the rapidity with which the substance employed in the thermometer comes to an equilibrium of temperature with the surrounding medium; and this depends upon the nature of the substance (its conducting power and specific heat), and requires that the bulb be small in at least one dimension and the glass of the bulb thin.

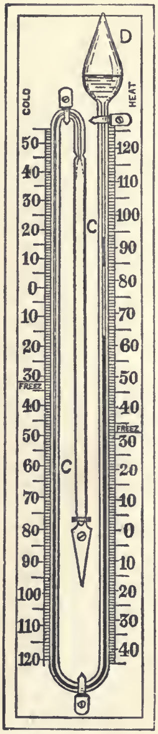

Fig. 9.—Six's Thermometer.

Advantages of Mercury.—Mercury is usually chosen for a thermometric substance, because of its uniformity of expansion within certain limits, and because of the great interval between its freezing point (− 39° C.) and its boiling point (357° C.). It is opaque and easily seen in the tube, it fulfils the conditions of good conduction and small specific heat, it does not wet or adhere to the glass, and it can be easily obtained pure.

Alcohol Thermometer.—Other liquids may be used in thermometers, and, for temperatures near to and below the freezing point of mercury, alcohol is often employed because of its very low freezing point (− 130° C.). The expansion of alcohol is not so uniform as that of mercury, and, if an alcohol thermometer be graduated throughout by comparison with a mercurial thermometer, its degrees will be longer as we ascend the scale.

Maximum and Minimum Thermometers.—Besides the temperature at a particular instant, it is often desirable to know the highest or lowest temperature to which an instrument has been exposed. Maximum and minimum thermometers are used for this purpose, and they are "self-registering."

Six's (Fig. 9) is a common form of such an instrument in popular use, and is both a maximum and a minimum thermometer. It consists of a glass tube bent twice upon itself, as shown in the figure. Alcohol fills the bulb *C* and a portion of the tube to the left; another portion is occupied by a column of mercury, which extends around the lower bend and partly up the tube on the right; the remainder of the tube and a portion of the bulb *D* is occupied by alcohol; the other portion of *D* is occupied by air. The mercury column is in contact with the alcohol at both extremities, and, when by an elevation of temperature the alcohol in *C* expands, it shoves the mercury column before it. The highest points reached in the right and left limbs of the instrument by the ends of the mercurial column are indicated by two indices, held in place by springs just strong enough to keep them from slipping by their own weight. The expansion of the air in *D* causes the mercury column to follow the alcohol during contraction. It is readily seen from the figure that the maximum temperature is recorded on the right scale, and the minimum on the left. The indices must in part be composed of iron or steel, so that they can be brought to the surface of the mercury by a magnet. The alcohol in the right limb of the tube prevents the index from rusting.

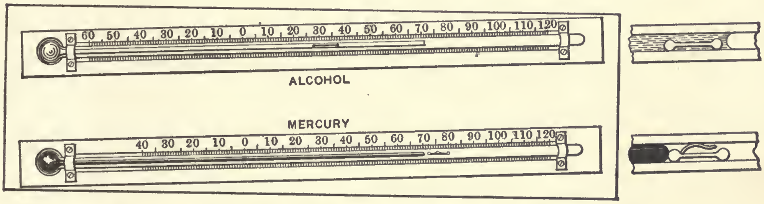

FIG. 10.—RUTHERFORD'S MAXIMUM AND MINIMUM THERMOMETERS.

Rutherford's maximum and minimum thermometers are distinct instruments, though often mounted together, as in Fig. 10, both being placed horizontally. The liquid of the minimum is alcohol, and has immersed in it a small index of glass or enamel. To set the instrument it is inclined until the forward end of the index slides to the end of the liquid column. During the expansion of the liquid the index remains stationary, the liquid moving by it; but during contraction the end of the liquid column does not pass the index but pulls it back. The forward end of the index thus marks the degree of contraction of the liquid, and hence the minimum temperature reached.

The liquid of the maximum thermometer is mercury, and the tube contains an iron or steel index outside the mercury. This index is pushed before the mercury during expansion and is left behind during contraction. The back end of the index marks the limit of expansion, and therefore the maximum temperature experienced. The instrument is set by bringing the index back to the mercury, and this is usually done with a magnet.

Phillips's Maximum Thermometer.—In this instrument the index is a part of the mercurial column itself, separated from the main body of the liquid by a little air, as shown in Fig. 11.

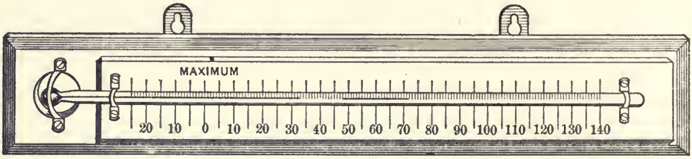

FIG. 11.—PHILLIPS'S MAXIMUM THERMOMETER.

Another form of maximum thermometer is that of Negretti, shown in Fig. 12. The bore of the tube is diminished at *a*; during expansion the mercury is forced through at *a*, but during contraction the part of the column past the obstruction does not return. To set this instrument the detached column must be shaken past the contraction until the bulb is filled and the column continuous.

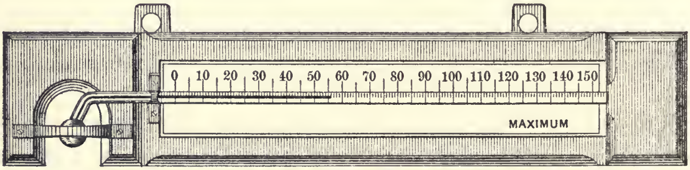

FIG. 12.—NEGRETTI'S MAXIMUM THERMOMETER.

Air Thermometers.—Air or other gas may be used as a thermometric fluid, and such instruments will measure temperatures through a very wide range. They may be constructed either upon the principle that the volume of the gas, at constant pressure, varies directly with the temperature, or that, if the volume be kept constant, the pressure varies in the same way. Such instruments are the most accurate of all thermometers, and will be again alluded to.

Metallic Thermometers.—Thermometers depending upon the expansion of solids by heat have been made. For domestic purposes a very convenient thermometer of this kind is now widely used in this country. It is made by the "Standard Thermometer Company," Peabody, Mass. Its great convenience centres mainly in the large dial-face, upon which the temperature is indicated by a pointer. These faces are as much as eight inches in diameter, and the temperature can be observed from a distance of fifteen feet. In the largest and best forms a ribbon three-sixteenths of an inch wide, composed of two strips of metal soldered together (apparently brass and steel), is closely wound into a cylindrical spiral two inches long and five-eighths of an inch in diameter. One end of this spiral is rigidly attached to a fixed support, and the other is made fast to the centre of a brass octant, the octant itself being mounted on an axis passing through the middle point of its bisecting radius. The rim of the octant is cut into cogs, which work into the teeth of a smaller wheel. The axis of the smaller wheel projects in front of the dial-face and carries the pointer. The winding and unwinding of the ribbon, due to contraction and expansion, by this gearing transmit motion to the pointer.

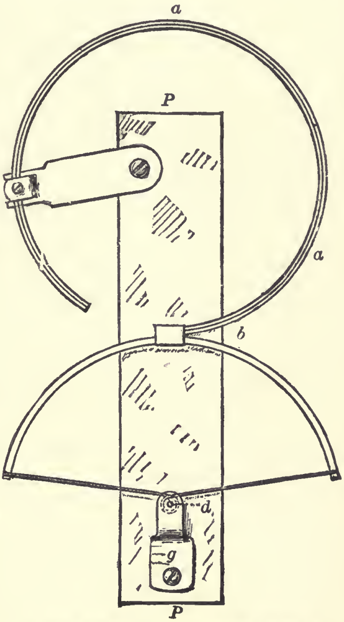

FIG. 13.—METALLIC THERMOMETER.

The actuating part of a simpler form made by the same company is shown in Fig. 13, in which *a* is a circular compound metal ribbon with one end attached to the semicircular brass hoop *b*. From the ends of this hoop a small cord passes to and several times around the axis *d*, whose back end abuts against the supporting strip *g*. The axis passes through the frame-plate *P* and through the dial-plate in front of it, and its other end carries the pointer. Since the cord is so wound that it cannot slip, it is evident that expansion or contraction in the ribbon produces rotation in the axis and corresponding motion in the pointer. Owing to the care exercised in the adjustment of these instruments, they compare favorably in accuracy with ordinary mercurial thermometers, and are far more convenient. Much older forms of metallic thermometers, very similar in principle to the above, have long been made, but have not come into general use.

Pyrometers.—Other instruments are also constructed for measuring very high temperatures, as those of furnaces, and are called Pyrometers. Wedgwood's pyrometer acts by the measurement of the contraction in a piece of baked clay when heated. Other instruments of this class depend for their action upon the expansion of a metal rod (iron, platinum, etc.), contained in an infusible cylinder, the expansion giving motion to an indicator of some kind.

CHAPTER II.

DILATION OF BODIES.

Coefficient of Expansion.—It has been stated as a general though not universal law, that, when the temperature of a body is increased (other conditions being unchanged), its volume is also increased, and the reverse. The temperature and volume vary simultaneously, and the *quantity* which expresses the average numerical relation between the variations of volume for each unit of temperature, and the original volume taken at a standard temperature, is the mean coefficient of cubical expansion.

Thus, let a substance, whose volume is v, at a standard temperature t, assume a volume v_1 at a temperature t_1; then the change of temperature is $t_1 - t$, the corresponding change of volume in terms of original volume is $\frac{v_1 - v}{v}$, and the quotient $\frac{v_1 - v}{v(t_1 - t)} = \alpha$ is the *mean* coefficient of cubical expansion between the temperatures t_1 and t.

The coefficient of cubical expansion of a substance is made *specific* by defining it as the ratio which the increase in unit volume bears to the unit of volume when the temperature of the unit is raised from 0° C. to 1° C. In other words, if in the equation

$$\alpha = \frac{v_1 - v}{v(t_1 - t)}$$

we make $v = 1$, $t_1 = 1°$ C., and $t = 0°$ C., α becomes the specific coefficient of expansion. If the body is homogeneous and it be raised to the same temperature throughout, it is unnecessary to consider the unit of volume.

The coefficient of cubical expansion of any substance *at any temperature* is the ratio which the increase of volume bears to the original volume when its temperature is raised one degree. The expression for the mean coefficient of expansion between t_1 and t, $\alpha = \frac{v_1 - v}{v(t_1 - t)}$, becomes the expression for the coefficient of expansion at temperature t when $t_1 - t$ is made equal to unity.

If, instead of considering the increments of volume produced by heat, we estimate the increase in length or superficial area, the corresponding increments become the coefficients of linear and superficial expansion, respectively.

The coefficient of linear expansion at any temperature is the ratio which the increment in length of the body bears to the original length, when the temperature is raised one degree. As in cubical expansion, if no temperature is specified, reference is had to the increase in length between 0° and 1° C.

It will be inferred from the foregoing definitions that the variations in the dimensions of bodies are not always exactly proportional to variations of temperature, and such is found to be the case: at high temperatures the coefficients of expansion increase slowly as the temperatures rise.

Solids.—Since the change of dimensions in solids for a change of one degree in temperature is very small, the *mean coefficient* of expansion, the *specific coefficient,* and the coefficient at a particular temperature for moderate ranges of temperature, may be taken for ordinary considerations to be the same. It is usually the first that we determine. Thus, the ratio which the increase of length in a bar of metal between 0° and 1° C. bears to the original length at 0° is taken as the $\frac{1}{100}$ of the ratio between 0° and 100° C. Supposing l_0 and l_{100} to represent the lengths of the rod at 0° and at 100°, respectively, we have $\frac{l_{100} - l_0}{l_0} = 100\alpha$, or $\alpha = \frac{1}{100} \frac{l_{100} - l_0}{l_0}$, the coefficient of linear expansion. The coefficient of expansion of solid metals is sensibly constant from 0° to 100° C., but above that point it becomes irregular.

Relation between Cubical and Linear Expansion.—In general, homogeneous uncrystallized bodies expand in such manner that the figures at different temperatures are similar, or expand equally in all directions. In such cases the cubical expansion for small changes of temperature is approximately three times the linear. For, suppose the body to be divided into any number of cubes, and let v represent the volume of a cube whose edge may be taken as unity. After expansion the length of an edge will be $1 + l$, and the volume will become $(1 + l)^3$ or $1 + 3l + 3l^2 + l^3$. If l is so small that higher powers than the first may be omitted without material error, we have the cubical expansion equal to $3l$; that is, three times the same fraction of the volume that the linear expansion is of the length. If the body does not expand equally in all directions, let a, b, and c denote the expansion of the three conterminous edges at right angles to each other, then the volume in expanding will become $(1 + a)(1 + b)(1 + c)$ or $1 + a + b + c + ab + ac + bc + abc$; and if a, b, and c are very small, as is usually the case with solids, their products may be omitted, and the cubical expansion, for small changes of temperature, is in all cases approximately equal to the sum of the expansions of length, breadth, and thickness expressed in terms of the volume.

Considering in the same way the expansion in area, it is readily seen that the surface expansion is twice that of the linear in isotropic bodies, and in other bodies it is equal to the sum of the expansions in length and breadth expressed in terms of the surface.

Force Exerted in Expansion.—The force which is required to change the volume of a solid by a certain amount is the same as that which the solid would exert during a change of temperature sufficient to produce the same change in its volume. It has been calculated that a bar of wrought-iron of square cross-section, four inches on a side, would exert a pull of sixteen tons if its ends were secured and its temperature should fall 15° F. Consequently, in all structures where metal is largely used, and which are subjected to considerable changes of temperature, it is indispensable to make provision for these changes of dimension. The force of contracting metal is frequently made use of to straighten up walls which have settled and inclined. This is done by securing bars of iron in a heated state to the walls so that the force of contraction in cooling is exerted to pull them together.

The amount of linear expansion of glass in passing from 0° to 100° C. is $\frac{1}{1168}$, and of platinum it is $\frac{1}{1167}$. The fact that these two substances expand so nearly equally enables us to fuse a platinum wire into a glass tube without fear of breakage on cooling.

There are some interesting exceptions to the law that the volumes of bodies increase with the temperatures, and the statement that a body recovers its original volume when it returns to its original temperature is not absolutely correct. The time and manner of cooling a body in many cases influence the volume assumed: this fact will be brought out as we proceed.

Liquids.—Since liquids must be retained in vessels, and since the volumes of these vessels change with the temperature, it is evident that a change of volume in the liquid is complicated with the change in the vessel. The actual change of volume of the liquid, independent of variations in the containing vessel, is the *real* or *absolute* dilation of the liquid; the *apparent* dilation is affected by the dilation of the vessel. The expansions of liquids are, in general, much greater than those of solids, and much less uniform, increasing more rapidly as the temperature rises.

The absolute dilation, between 0° and 100° C., of alcohol, water, and mercury, is given in the following table:

Alcohol expands	$\frac{1}{9}$
Water expands	$\frac{1}{21}$
Mercury expands	$\frac{1}{55}$

Mercury.—The rate of expansion of mercury increases as the temperature rises. The expansion from 0° to 20° is more than double that from 0° to 10°, and that from 0° to 100° is more than ten times that to 10° and more than twice that to 50°. The expansion of mercury, however, is less variable than that of any other substance that is liquid at ordinary temperatures, and the increased expansibility between 100° and 200° in the thermometer is nearly compensated for by the expansion of the glass.

Water.—Water exhibits a striking peculiarity in its variations of volume during change of temperature, a peculiarity which has most important influences. If fresh water be taken at common temperature and cooled down, its volume diminishes until the temperature falls to about 4° C. After this a further reduction of temperature causes expansion, which continues until the freezing-point is reached, when there is a sudden and violent enlargement. At the temperature of 4° C. water is at its maximum density, and increase or reduction of temperature has the same effect upon its volume.

This peculiarity of water is easily illustrated by an arrangement which indicates the changes of volume as the temperature is changed. A moment's consideration will show that this property of water has a most beneficial effect in nature. In cold weather bodies of fresh water are cooled at the surface, contraction of volume with increased density takes place, the heavier surface water descends and the warmer rises to replace it. This circulation continues until the entire body of water falls to 4°, after which any further cooling expands the water and the colder water remains at the surface. The freezing of the surface water then further protects the remaining mass of water from other reduction of temperature.

The *gradual* expansion of water between 4° and 0° must be distinguished from the *sudden* enlargement in freezing. Many other bodies, in common with water, possess this latter property. The sudden expansion of water due to freezing exerts an enormous pressure. The bursting of water-pipes by freezing too often illustrates this force. The freezing of the water absorbed by and taken into the crevices of rocks is a potent agent of their disintegration. The beautiful columnar effect produced by the freezing of certain damp soils is familiar to all, and is often very destructive to newly-sprouted cereals. Iron shells filled with water may be burst by subjecting them to cold enough to freeze the water.

Sea-water has no point of maximum density above its freezing point, but contracts as it cools until it solidifies at − 2.6° C.

Gases.—In gases the coefficient of expansion is much larger than in solids or liquids, and much more nearly uniform at different temperatures. Let us take v_0 to indicate the volume of a gas at 0° C., and v_t the volume at any other temperature $t°$; then, if the pressure be the same at the two temperatures, the variation of volume is expressed by the equation

$$v_t = v_0(1 + \alpha t),$$

which experimental law is called the law of Charles or Gay-Lussac, in which α is the mean coefficient of expansion between 0° and $t°$. α has been shown to be practically the same for all temperatures within the range of the mercurial thermometer; it is not only the same at different temperatures, but is the same for different gases. Its value is approximately .00366 or $\frac{1}{273}$ of the volume at 0° C. for each degree centigrade, nor is it affected by the elastic force or pressure of the gas. Although α is thus *practically* constant for all gases, under all pressures, and at all temperatures, it is not absolutely so: there are very slight variations in different gases and in the same gas at different pressures, the greatest deviations being in case of gases most easily condensed.

From this experimental law of Charles, which may be written

$$v_t = v_0 + \frac{t}{273} v_0 ,$$

it is seen that a gas expands or contracts $\frac{1}{273}$ of its volume at 0° C. for each change of one degree in temperature on that scale; therefore if its temperature were reduced to $-273°$ C., and the law of volumetric change did not vary, the volume of the gas would be reduced to zero. This temperature, 273° below 0° C., is called the absolute zero of temperature, and temperatures reckoned from this point are called *absolute temperatures.* Since the absolute zero is 273° below the zero ordinarily used, it is evident that absolute temperatures in C. degrees can be obtained from common centigrade readings by adding 273 thereto. By transferring to the F. scale it will be seen that the coefficient of expansion on this scale is $\frac{1}{460}$ (exactly $\frac{1}{459.4}$) of the volume at 0° F. It thus appears that the absolute zero on this scale is 460° below 0° F., and, accordingly, absolute temperatures in F. degrees may be obtained by adding 460 to the common F. readings.

From the expression for the law of Charles,

$$v_t = v_0(1 + \alpha t),$$

we can readily find what a volume of a gas at one temperature becomes when its temperature is changed.

If the volume of a gas is given at 0° C., the volume at any other temperature may be directly obtained by substituting in the formula the values of v_0, t, and α; if t is below zero, it has the negative sign. Thus, required to know what 200 cubic inches of a gas at 0° C. will become at 20° C.

$$v_0 = 200; \quad t = 20; \quad \alpha = \frac{1}{273}.$$

Hence the volume required,

$$v_t = 200\left(1 + \frac{20}{273}\right).$$

If the volume of a gas is given at a temperature other than 0° C., as for instance at t, and then the volume at another temperature, as t_1, is desired, we have, first,

$$v_0 : v_t :: 1 : 1 + \frac{t}{273},$$

and also

$$v_0 : v_{t_1} :: 1 : 1 + \frac{t_1}{273};$$

hence,

$$v_t : v_{t_1} :: 273 + t : 273 + t_1.$$

If the temperatures are given on the Fahrenheit scale, the coefficient of expansion is $\frac{1}{460}$, the volume at 0° F. being the standard, and the change of volume will be determined by the following relation :

$$v_t : v_{t_1} :: 460 + t : 460 + t_1.$$

From these considerations we see that, with pressure constant, the volume of a gas varies as its absolute temperature. The coefficient of expansion being constant, it follows that it is at any temperature numerically equal to unity divided by this temperature expressed on the absolute scale.

Another experimental law is that of Boyle, sometimes designated as Mariotte's law, which asserts that the volume of a gas is inversely proportional to the pressure when the temperature remains constant, or, under these conditions, the product of pressure and volume is constant and it may be written $pv =$ constant.

From a combination of Charles' and Boyles' laws two important deductions may be made.

Let P_0 and V_0 be corresponding pressure and volume of a mass of gas at 0° C. Suppose the pressure be kept constant and that the temperature of the gas be changed to $t°$, then, by Charles' law, the new volume will be $V_0 (1 + at)$; since the pressure has not changed it is still P_0.

Keep t constant and change the pressure to P_t; the corresponding volume may be represented by V_t. Corresponding sets of volumes and pressures at $t°$ are then P_0 and $V_0 (1 + at)$ and P_t and V_t. Applying Boyle's law to these we have

$$P_t V_t = P_0 V_0 (1 + at),$$

which being of exactly the same form as the original equation for Charles' law shows that the product of the pressure and volume of a gas will vary as the absolute temperature.

Make $V_t = V_0$, which imposes the condition of varying the pressure of the gas with the temperature without changing the volume, and the equation reduces to

$$P_t = P_0 (1 + at),$$

which shows that volume constant the pressure of a gas will vary as the absolute temperature.

If we assume the formula $P_t V_t = P_0 V_0 (1 + at)$ to hold for all temperatures, it is evident that the first member becomes 0 when in the second member $t = -273$; that is, under the assumption that the laws of Charles and Boyle are accurate at all temperatures the pressure or volume disappears at $-273°$ C. This is the point at which a gas would cease to have volume or cease to exert pressure on the walls of the enclosing vessel, and would be the absolute zero of temperature. This location of the absolute zero is substantiated by determinations independent of the properties of particular substances.

Air Thermometers.—From what was said in regard to measuring temperatures by ordinary thermometers, it is evident that we really measure the apparent expansion of some liquid in a tube. It is obvious that we may make the indications of any number of these thermometers, containing different liquids, agree at two fixed temperatures; but if the intervals between these fixed points on the different instruments be divided into the same number of equal parts, and all the instruments be plunged into a bath at intermediate temperature, no two, in general, will indicate precisely the same temperature, nor would they at temperatures beyond the fixed points, for different liquids expand not only by different amounts, but by amounts which are not proportional. If all the instruments contain the *same* liquid, and have been carefully made, their indications for temperatures between and beyond the fixed points will be identical, but as yet we have no reason for assuming that one liquid gives more correctly the temperature than any other.

In case of permanent gases,* expanding under constant pressure, this discordance is much less, so that, if we have a series of thermometers containing permanent gases, and their envelopes are of the same material, and they all have a common volume under a common pressure at 0°, they will also have a common volume under a common pressure at 100°, or at any other temperature. This fact would indicate that for measuring temperatures by differences of volume gases are superior to liquids. Moreover, the expansion of gases is much greater than that of liquids, so that the expansion of the containing vessel is much less important than with liquids.

Convection of Heat in Fluids.—From the action of heat in dilating bodies it is evident that, if the different parts of a liquid or gas are unequally heated, the warmer portions will be more expanded and become less dense, while the cooler portions, being more dense, will descend, thus establishing convection currents.

The warming of water is thus readily brought about if the vessel containing it be heated at the bottom, for the convection currents just described are produced, and a circulation established which may be rendered visible by coloring matter, cotton-seed, or other floating particles placed in the water. The mass of water is thus heated by the different parts alternating in position and coming successively near the source of heat, and by the commingling of the warm with the cold water.

Warming Buildings by Hot Water.—This is a useful domestic application of the principle above stated. A common and simple arrangement for warming buildings is shown in Fig. 14. It consists of a boiler heated by a furnace fire. From the top of the

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* By permanent gases are here meant those which are remote from their condensing points, and most nearly in the condition of a "perfect gas," or one which will exactly fulfill Boyle's law. Molecular theories lead to the conclusion that for perfect gases the coefficients of expansion would be equal. Actual experiment shows that the more highly rarefied the gases are, the more nearly they approach to perfect gases ; and the more they are compressed, and the more nearly they approach their condensing points, the more they depart from the condition of "perfect gases."

boiler a pipe, as shown, leads to a reservoir in the upper story of the house, a second pipe leads from this reservoir into another

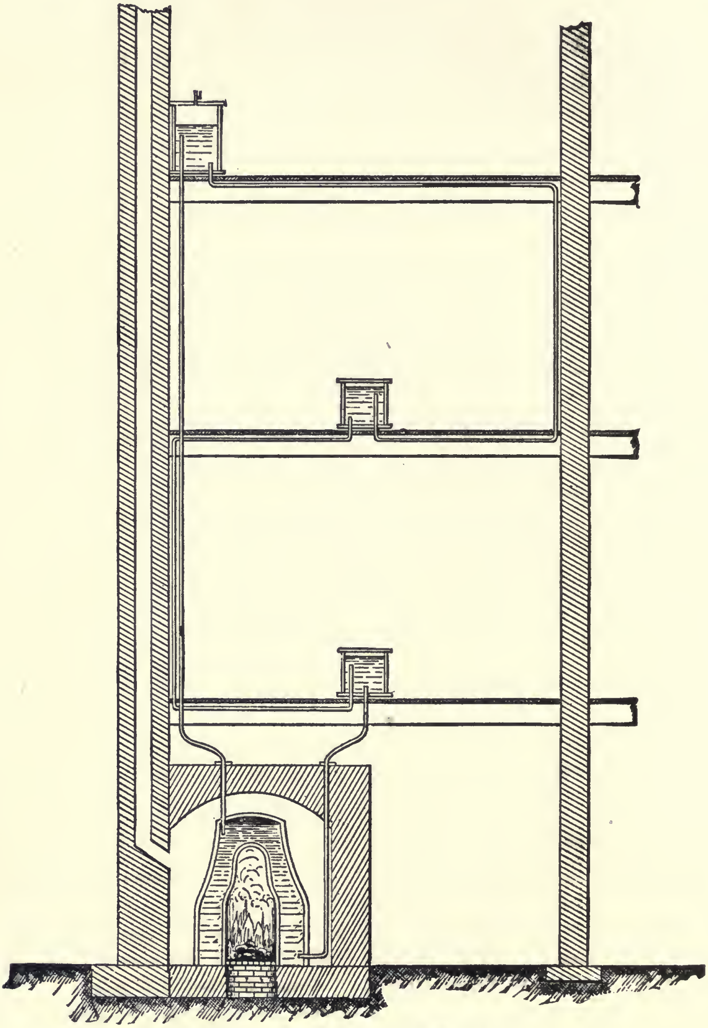

FIG. 14.—WARMING BY HOT WATER.

reservoir in the story below, and thence to a third, and finally enters the boiler at the bottom.

The boiler, pipes, and reservoirs are all filled with water except a small space at the top of the upper reservoir, which is left to give room for the expansion of the liquid. When the liquid is heated it is evident that a current will flow upward by the pipe from the top of the boiler and return by the one at the bottom. The great *specific heat* of water, a property which we shall define subsequently, renders heating by this method very regular.

On American railways the passenger coaches are frequently heated on this same principle, a strong solution of salt being used instead of pure water, which avoids the liability to freezing at the temperature at which it would ordinarily occur.

Draught of Chimneys.—The expansion of air by heat produces the draught, which for equal cross-section will depend mainly upon the height of the chimney and the difference between the temperature inside and outside. It is because of this latter condition that the draught is not so good when the fire is first lighted; it also explains why, if the temperature of the room is kept constant, the draught is better in cold weather than in warm. The location of the chimney in the building would have an important influence in this respect, as would also the form and area of the cross-section of the chimney.

In ordinary chimneys and fireplaces it is desirable that the air which enters the chimney should pass as much as possible through the burning fuel, thus serving the purposes of combustion and being itself raised in temperature. The fireplace should not, then, be too wide nor the opening above the fire too high. The blower facilitates combustion in grate-fires by accomplishing the above desiderata.

The custom, first suggested by Rumford, of placing inclined plates at the sides and top of the fireplace is a good one, both to guide the air to the fire and to reflect and radiate the heat into the room.

In an ordinary fireplace (Fig. 15) about seven-eighths of the heat from the burning fuel passes up the chimney, so that it is not an economical means of heating, but, on the other hand, it is the most healthy, as it produces a constant change of atmosphere in the room, thus insuring ventilation, which is not at all accomplished in heating by hot water.

The waste of heat is greatly reduced when the chimney is centrally situated, in which case as the heated gases escape up the shaft they warm the contiguous rooms through which it successively passes.

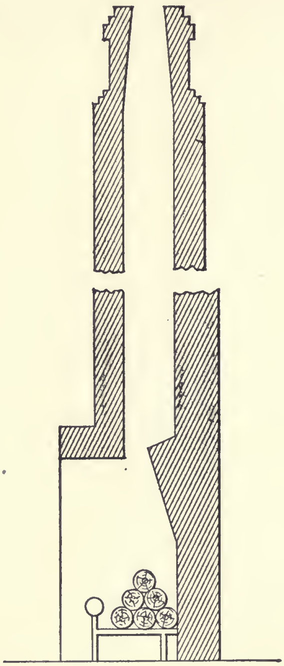

FIG. 15.—COMMON FIREPLACE.

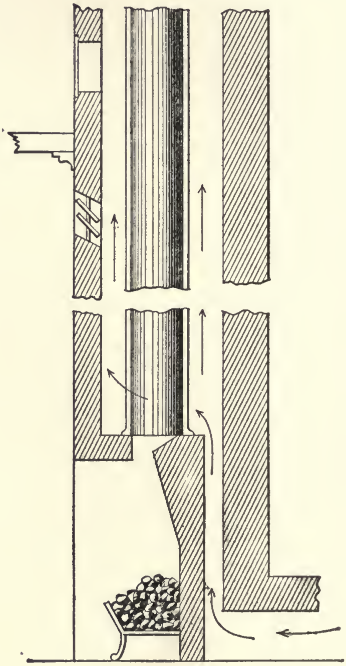

FIG. 16.—VENTILATING FIREPLACE.

This waste is still further prevented in the so-called ventilating fireplaces (Fig. 16), now frequently made, especially on the continent of Europe. In these fireplaces the flue of the chimney is not formed by a single passage-way left in the wall. The flue and its walls form a sort of pipe (the flue frequently is a cast-iron pipe) which passes up within the walls of the building, but separated from them by an open space. In this open space around the flue-shaft air from the exterior circulates and is warmed by the heat of the flue-shaft; at suitable points above, this warm air is admitted into the rooms of the building.

Heating by Stoves.—Stoves constitute a far more economical means of heating than fireplaces; from eight-tenths to nine-tenths of the heat produced by the fuel can be given out to the rooms by closed stoves, such as are frequently used. The amount of air which passes per hour through these stoves for the combustion of anthracite coal is not over one-tenth the volume of the space warmed, so that the entire air of this space would only change once in ten hours. A common chimney and fireplace properly constructed remove in one hour five times the whole contents of the room it is intended to warm.

In addition to these disadvantages stoves cause great differences in the temperatures which prevail at different heights. Stoves of cast-iron, too, at red heat permit the passage of gases, especially hydrogen and carbon monoxide, the latter of which exercises poisonous effects on the occupants of the room. Stoves of sheet-iron or porcelain are far preferable as regards this defect.

Warming by Hot Air.—This method of warming also depends upon the dilation and rarefaction of air by heat. In this method the external air is led into a chamber heated by a furnace, or it may be that the air in the chamber is made to pass over pipes heated by water or steam. From this heating chamber conducting channels or pipes lead to the apartments to be heated.

Ventilation.—Many of the most successful methods of ventilation depend upon these same principles of rarefaction by heat, the general idea being to produce at some point an upward current of air by heat and then have pure air introduced to takes its place. The upward draught should be arranged to carry off the foul air and to produce a complete renovation of the air of the space to be ventilated. From what has been said it is evident that some of the methods of heating accomplish a more or less perfect ventilation, especially the open fireplace. In general, however, in workshops and large buildings other special arrangements have to be resorted to. In private dwellings chimneys are very beneficial ventilators, with or without fires. In mines this method of ventilating by draught is frequently adopted. By building fires at the bottom of one or more shafts, ascending columns of air are produced, and fresh air is admitted at other points and made to circulate through the different compartments of the mine before it can reach these exit shafts. Ventilation is also accomplished by mechanically forcing air through the compartments to be ventilated.

CHAPTER III.

CALORIMETRY.

As has already been stated, heat produces effects of various kinds on bodies: it usually changes the temperature, generally alters the volume and pressure, and sometimes changes the state of a body from a solid to a liquid, or a liquid to a gas.

Calorimetry has for its object the measurement of quantities of heat, and any of the measurable effects of heat may be used for that purpose; the most convenient, however, is the alteration of temperature produced in a known weight of a given substance by the communication or abstraction of the heat to be measured.

Unit of Heat.—In estimating quantity of heat by the change of temperature it produces, the *unit of heat,* or *thermal unit,* is taken as the amount of heat necessary to raise a unit mass of water, taken at a standard temperature, through one degree centigrade. Since the unit of mass is not the same in all countries, the thermal unit also varies. In this text the pound measures the unit of mass.

There is no general agreement as to the standard temperature at which the water is to be taken, but we shall suppose this standard temperature to be 15.5° C. or 60° F.

Necessary Principles.—The calorimetrical measurements most necessary to be made are those for determining the quantities of heat given off or absorbed by bodies when their temperatures change through certain intervals or when they change their states of aggregation. We are here concerned with the former.

1st. All that is assumed in these measurements is that, if it takes a certain quantity of heat to produce a certain temperature effect in a given portion of a homogeneous substance, the same amount of heat will produce the same effect in another equal portion, or that the heat required to raise the temperature of two pounds of a substance through a certain interval is twice as great as that required to raise one pound of the same substance through the same interval.

2d. Another principle employed, the truth of which is established by experiment, is that the heat given to a body to cause it to pass through a series of states, as regards temperature and volume, is the same as that given out by the body in cooling and passing in reverse order through the same states.

We cannot, however, assume that the quantities of heat required to raise the temperature of a body through *equal* intervals are always the same, for it may require a different amount of heat to raise the temperature of the body from 5° to 10° than from 40° to 45°.

Thermal Capacity.—If a quantity, Q, of heat be taken from or given to a body and produce in it a change of temperature $t°$, then $\frac{Q}{t}$ is called the *mean thermal capacity* of the body between the initial and final temperature.

From the definition of the unit of heat it is evident that the thermal capacity of a quantity of cold water is numerically equal to its mass expressed in pounds; and the thermal capacity of any other body is numerically equal to the weight of water, in pounds, which would have the same thermal capacity. This quantity of water is also called the *water equivalent* of the body.

Specific Heat.—In the above expression $\frac{Q}{t}$, if the unit of mass be taken and $t = 1$, the expression indicates the thermal capacity of the unit of mass, or the *specific heat* of the body. We may define the specific heat of a body *as the amount of heat, expressed in thermal units, which must be transferred to or from a unit mass of the body, taken under specific conditions, in order to raise or lower its temperature one degree.*

From what precedes, it is evident that m pounds of a substance in changing its temperature through t degrees will take up or give out a quantity of heat equal to mst, where s denotes the mean specific heat of the body between the initial and final temperatures.

Determination of Specific Heat.—*By Mixtures.*—Let us take a known weight m of a substance whose specific heat is desired, and heat to a known temperature t, and then mix it with a known weight n of water at a lower known temperature t', at or near zero. If we suppose that there is no external loss or gain of heat, we have a means of determining specific heat, for the heat taken from the hot body is given to the water; and if we let θ denote the common temperature first reached by the mixed liquids, and x the required specific heat, we shall have

$$mx(t - \theta) = n(\theta - t'),$$

from which x becomes known.

This method is applicable to the case of any two bodies at different temperatures that can be brought to the same temperature by an interchange of heat between themselves only, even though literal *mixing* cannot be accomplished. Thus a solid may be immersed in a liquid. Nor is it necessary to use only water: any liquid whose specific heat is known may be used.

This method, though convenient, is not accurate, for the theoretical conditions assumed cannot be realized, and there must be some external loss or gain of heat.

Method of Melting Ice.—The determination of specific heat by this method consists in finding the amount of ice, at the freezing point, melted by a known weight of a substance, heated to a known temperature. If the amount of heat necessary to convert ice into water is known, we can then find the specific heat of the body operated upon.

Method of Cooling.—Specific heat may also be estimated by comparing the times the bodies occupy in cooling through the same number of degrees.

In the following table are given the average specific heats of the substances named, between 15° C. and 98° C., as determined by Regnault:

Water	1.0080	Copper	0.0952
Charcoal	0.2414	Silver	0.0570
Aluminium	0.2143	Tin	0.0562
Sulphur (native)	0.1776	Mercury	0.0333
Iron	0.1138	Platinum	0.0329
Nickel	0.1086	Gold	0.0324
Zinc	0.0955	Lead	0.0314

In general, the specific heats of solids and liquids increase as the temperature rises, and the specific heat of a body in the liquid state is greater than in the solid. With solids there is generally found a decrease of specific heat with an increase of density.

Great Specific Heat of Water.—No solid or liquid substance (with one exception*) has been found to have as great a specific heat as water; and among the gases whose specific heats have been determined, that of hydrogen alone exceeds that of water. The specific heats of ice and steam are about one-half, and that of the atmosphere and the solid parts of the earth's crust about one-fourth, that of water. With the two exceptions named, water, therefore, absorbs or emits in its changes of temperature more heat than other substances that have been experimented upon. The quantity of heat required to raise a pound of water from 0° to 100° C. is sufficient to raise thirty pounds of mercury through the same interval, and would raise one and two-thirds pounds of silver from 0° to the fusing point, 1037° C. It will be found that this property of water plays an important part in nature, and is frequently utilized for heating buildings and for other domestic purposes.

Specific Heat of Gases.—The determination of the specific heat in the case of gases is attended with greater difficulty than in the case of solids and liquids, both from an experimental and a theoretical point of view. The measurement of the specific heat of a gas may be made either at a constant pressure or a constant volume; the specific heat at a constant pressure is always the greater; the two specific heats are simply connected in the case of perfect gases. The experiments of Regnault established the following facts in regard to gases:

1st. The specific heat of a given weight of the more permanent gases does not vary with the temperature or density of the gas. The specific heat of a given volume of such gas accordingly varies as its density.

2d. Equal volumes of the more non-condensable elementary gases have the same specific heats, when compared under the same temperature and pressure.

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* The experiments of Dupré (Phil. Trans. 1869) appear to prove pretty conclusively that the specific heat of a mixture of alcohol and water is greater than that of water, until the mixture reaches a strength of 36 per cent. of alcohol.

The specific heat of carbon dioxide was found to vary with the temperature, and only oxygen, hydrogen, and nitrogen among the elementary gases conformed to the second law.

The following table gives the specific heats of the gases named, according to Regnault, pressure being constant and the specific heat of water taken as unity:

	For equal Weights.	or equal Volumes.
Atmospheric air	0.2377	0.2374
Oxygen	0.2175	0.2405
Nitrogen	0.2438	0.2368
Hydrogen	3.4090	0.2359
Aqueous vapor	0.4805	0.2989
Carbon monoxide	0.2450	0.2370
Carbon dioxide	0.2169	0.3307
Olefiant gas	0.4040	0.4160
Marsh gas	0.5929	0.3277
Ammonia gas	0.5084	0.2996

The volumes of the gases are referred to an equal volume of air, the specific heat of the volume of air being referred to an equal weight of water.

The specific heat of a body in a liquid state is generally greater than that of the same body in either the solid or the gaseous state. The following table shows this relation between the specific heats of the substances named in the different states—temperature given on Fahrenheit scale:

SUBSTANCE.	SOLID.		LIQUID.		GAS.	
	Specific Heat.	Temperature. Between	Specific Heat.	Temperature. Between	Specific Heat.	Temperature. Above
Ice	0.5050	− 22° and + 32°	1.0000	32° and 68°	0.4805	212°
Bromine	0.0843	−108° and − 4°	0.1060	10° and 118°	0.0555	
Tin	0.0562	32° and 212°	0.0637	482° and 662°		
Lead	0.0314	32° and 212°	0.0402	662° and 842°		
Alcohol			0.5475		0.4534	
Carbon bisulphide			0.2352		0.1569	
Ether			0.5290		0.4797	

CHAPTER IV.

PRODUCTION AND CONDENSATION OF VAPOR.

Vaporization.—*Vaporization* is a general term applied to any process by which a liquid is converted into a vapor. When the change takes place from the surface without visible disturbance of the liquid, it is called *evaporation*. Under ordinary atmospheric conditions most liquids undergo this change. Evaporation does not occur at a particular temperature only, but takes place over a wide range of temperature. At very low temperatures evaporation is insensible for many substances, if it takes place at all.

Some solids change to the vaporous state without passing through the liquid state: in these cases the process is called *sublimation*. Ice, snow, and camphor are examples.

Vapors and gases are the terms used to designate the aeriform bodies into which liquids pass by vaporization. The distinction, as the terms are generally employed, is that gases are vapors more difficult to condense, and under ordinary conditions are always aeriform, while vapors may exist under ordinary conditions as solids or liquids. A more exact distinction will appear later, p. 38.

Vapors, thus limited, under ordinary conditions have properties such that it is necessary to consider them separately from gases. The formation of vapors and their elastic force are subjects of much importance.

Maximum Pressure and Density of Vapors in Vacuo.—The elastic force and other properties of a vapor may be observed in such an arrangement as is shown by Fig. 17. A glass globe is connected by a rubber tube with a U-shaped glass tube containing mercury, called a manometer. The air is first exhausted from the globe and its tube-connection. Of course, the mercury ascends in the left and descends in the right branch of the glass tube as the exhaustion is perfected; if all the air is taken from the globe, the level of the mercury in the two tubes will differ by the height or the barometer column. A little liquid is then admitted into the globe through the stopcock *R*, which is so arranged as to admit the liquid without admitting air.

As soon as the liquid is passed through the stopcock the mercury in the left branch of the manometer descends, and, as no liquid appears in the globe, we conclude that the liquid is immediately converted into vapor, and that the vapor presses down the mercury. As we continue to introduce the liquid the mercury column descends more and more, but finally it ceases to descend, and any additional liquid introduced will be left unevaporated in the tube attached to the globe.

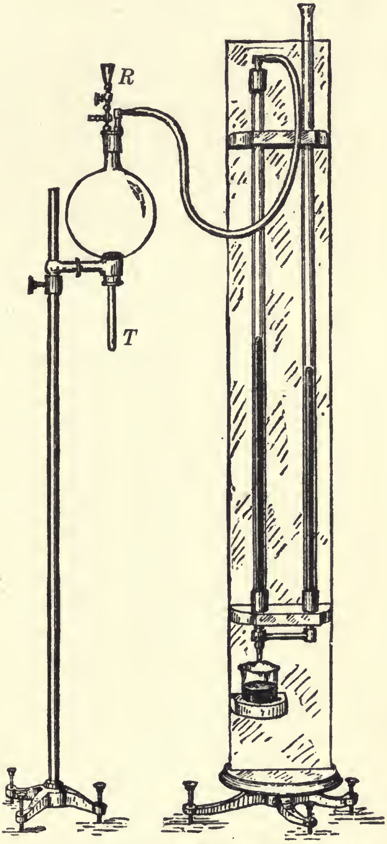

FIG. 17.—VAPOR DENSITY AND PRESSURE.

If now the temperature of the globe be increased, more of the liquid will be evaporated and a greater pressure indicated by the manometer. Further experiment will continue to show that the amount of the liquid evaporated and the pressure exerted will depend upon the temperature of the space. We are thus enabled to conclude that the amount of vapor which passes from a liquid *in vacuo* and the pressure exerted by the vapor in a given space are limited, and vary with the temperature. This pressure of the vapor in contact with its liquid, being the greatest possible for the temperature, is called its *maximum pressure,* and under such conditions the space is said to be saturated.

The maximum density for any temperature is that state of density which the vapor cannot exceed without becoming liquid.

It can be shown that the vapor of a saturated space is at its maximum density because it is impossible to diminish the volume occupied by the vapor without liquefying a portion of it. If the vapor be not at its maximum density and its volume be decreased, temperature remaining constant, an increase of pressure and density will take place until the point of maximum density is reached. These effects of change of volume may be roughly illustrated by having a barometer-tube, with the usual vacuous space above the mercury, inverted in a deep cistern of mercury, as shown in Fig. 18. Let a small amount of ether, not sufficient to saturate the vacuous space, be introduced into the tube. The column of mercury will descend, due to the elastic force of the vapor. If we now shove the tube down into the cistern, we shall see the mercury descend more, due to the increased elastic force of the vapor, while the volume occupied by the vapor decreases, and its density accordingly increases. The reverse effect is observed if the tube be lifted up. After the tube has been shoved down a certain distance, the mercury column no longer descends, showing that the pressure of the vapor does not increase. As soon as this point is reached, liquid ether appears on the surface of the mercury. We then know that the space above the mercury is saturated. So long as this is the case it matters not whether we raise or depress the tube; the height of the mercurial column is constant, showing that the pressure of the saturated vapor remains constant in the two cases.

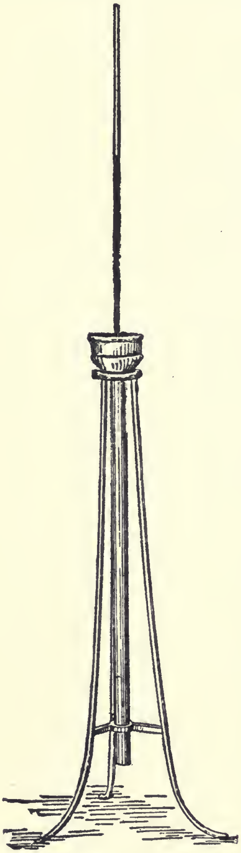

Fig. 18.—Effect of Pressure on Ether Vapor.

It has been seen that the maximum density and pressure are dependent upon the temperature, and increase rapidly as the temperature rises. In order, therefore, to saturate a given space, a greater quantity of vapor is required as the temperature rises. This is illustrated in the case of water vapor by the following table, in which is given the elastic pressure of such vapor at saturation at different temperatures, with the corresponding weights contained in a cubic foot of saturated space.

Temperature F.	Elastic Pressure in inches of barometer.	Weight of Vapor in cubic foot in grains.
0°	.045	0.54
10°	.071	0.84
20°	.109	1.30
30°	.167	1.97
40°	.246	2.86
50°	.360	4.09
60°	.517	5.76
70°	.732	7.99
90°	1.407	14.81
100°	1.913	19.79

Vapor which is at less than its maximum density is called *superheated* vapor, because it can be obtained by heating vapor at maximum density at lower temperature.

Fig. 19 represents graphically the rate at which the maximum density of aqueous vapor increases with the temperature between *a* and *b*. The horizontal distances proportional to temperature are laid off on the base line *ab*, and the corresponding vertical lines at every fifth degree are proportional to the masses of vapor necessary to saturate the spaces at the temperatures. It is noticed that the curve, *ac*, of vapor density becomes steeper as the temperature in-

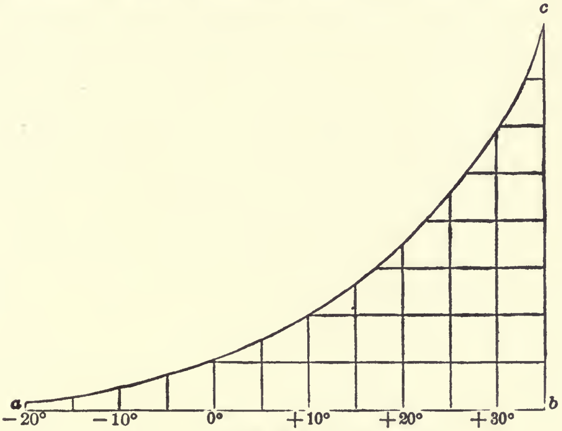

Fig. 19.—Curve of Vapor Density.

creases, showing that the amount of vapor for saturation increases more rapidly at high than at low temperature.

No general formula has been deduced which will express the relation between the pressures and temperatures in the case of saturated vapors. The many experiments on saturated aqueous vapor, the most celebrated of which are Regnault's, have suggested numerous empirical formulæ which may be used for that purpose in the case of steam. As nearly all recent works on steam give tables showing the relations between pressures, temperatures, and volumes, such formulæ are now seldom necessary.

Mixture of Gas and Vapor in a Confined Space.—If the experiment with the apparatus (Fig. 17) be repeated without exhausting the air, the results finally obtained are the same as with the exhausted receiver.

The only effect of the air is to retard the production of the vapor, but the evaporation goes on until the pressure is the maximum pressure due to that temperature. The more dense the gas which is present, the greater the retardation. *In vacuo* the vapor passes very rapidly to the state of maximum density. The above deductions were given by Dalton in two laws, which may be stated as follows:

1st. The quantity of vapor which can be contained in a given space, or the ultimate pressure of a saturated vapor, is dependent only on the temperature. It is the same whether or not the space contain other gas.

2d. When a space containing other gas is saturated with vapor, the pressure of the mixture is the sum of the pressure due to the vapor and the gas separately.

This second law applies whether the vapor be saturated or not, and is a particular case of the more general law,—that each gas in a mixture of gases and vapors exerts in a confined space the same pressure as if the others were absent.

It may be well to here state again directly the following inferences from the facts of the above paragraphs. The greatest pressure and density that a vapor can have at any temperature is when it is in a state of saturation for that temperature. Vapors in contact with their liquids in a confined space soon pass to saturation, for the temperature and any diminution of volume by increase of external pressure, or any decrease of temperature, will cause condensation of a part of the vapor.

Condensation of Vapors.—1. Since a vapor in the saturated state is at its maximum density for the temperature, it is evident that, if the volume of such vapor be decreased without change of temperature, a portion of the vapor corresponding to the decrease of volume will be condensed, and the remaining portion will be at the maximum density and pressure.

2. Since the maximum density and pressure of a vapor in a confined space depend only upon the temperature, if the temperature of a saturated space be lowered and the volume kept constant, both density and pressure of the vapor will fall to correspond to the lower temperature, and as much vapor will be condensed as corresponds to the difference of maximum density at the two temperatures.

It is thus seen that both extraneous pressure and reduction of temperature are effective in condensing vapors, and they may be employed separately or conjointly. The same means are employed in the condensation of gases.

Critical Temperatures.—Andrews was the first to show that there probably exists for each gas or vapor a temperature above which no amount of pressure can liquefy it: this temperature is called the critical temperature.

Below the critical temperature sufficient external pressure will bring the vapor to its maximum density, after which further diminution of volume will liquefy it without increase of its pressure, as already pointed out.

Continuity of Liquid and Gaseous State.—Below their critical temperatures, under sufficient pressure, all gases and vapors are liquid; above that temperature they are gaseous; and if the pressure be kept up between the two temperatures the transition is unrecognizable.

All ordinary liquids have their critical temperatures, above which no amount of pressure will keep them in the liquid state.

The critical temperature of hydrogen is believed to be about − 204° C., while that of chlorine is + 140° C. The critical temperature of water vapor is still much higher, approaching a low red heat.

Liquefaction and Solidification of Permanent Gases.—Until 1877 a number of gases had resisted all attempts to liquefy them, and hence were designated as *permanent gases*, among which were oxygen, hydrogen, and nitrogen. In the latter part of 1877 and the first part of 1878 oxygen was also liquefied by combining great pressure with great cold. This result was accomplished at about the same time by Cailletet, of France, and Pictet, of Switzerland, acting independently of each other, and thus verified Andrews's law as to *critical temperature.* Pictet thought that he had succeeded in liquefying hydrogen also, but it is now believed that he was mistaken. This gas has now been liquefied, the temperature employed being below — 205° C. Nitrogen has also been liquefied, its critical temperature being — 146° C. The critical temperature of oxygen is —113° C. Both oxygen and nitrogen have been solidified. When near their condensing points these gases, like vapors, depart widely from the laws of Boyle and Charles.

These considerations furnish us with a basis for a slight distinction between gases and vapors. Below the critical temperature the substance is a vapor, above the critical temperature a gas. In the latter condition it obeys very nearly the laws of Boyle and Gay-Lussac until greatly compressed; in the form of vapor it departs more widely from these laws.

Conditions Affecting Rapidity of Evaporation.—Some substances evaporate much more rapidly than others, and are then said to be more volatile; for instance, alcohol and ether evaporate much more rapidly than water. The rapidity of evaporation is subject to the following laws:

1st. It increases directly with the temperature and with the extent of evaporating surface.

2d. It increases the more nearly the evaporation takes place in a vacuum.

3d. It increases with the rapidity with which the vapor is removed from over the liquid.

The third law is evidently a consequence of the second, and both the second and third flow from principles stated in the paragraphs relating to the pressure and density of vapor.

The evaporation of water takes place on an enormous scale in nature, and supplies the moisture to the air which again descends as rain. Without this circulation the present conditions of life could not prevail.

Besides this quiet transformation into the vaporous state, which has been called evaporation, there are other forms of vaporization which we will now describe.

Ebullition or Boiling.—When a liquid is heated in an open vessel, the evaporation first goes on quietly and the liquid steadily rises in temperature. After a time very minute bubbles are given off: these are bubbles of air. Soon after, at the bottom of the vessel and at other parts most exposed to the heat, bubbles of vapor are formed and ascend, decreasing in size as they move upward, and disappear before reaching the surface, being condensed by the colder upper layers of water. The collapsing of these bubbles produces the *singing* of liquids before they boil. Finally the bubbles increase in number and grow larger as they ascend until they burst at the surface. The liquid is thus kept agitated and gives off vapor much faster; it is then said to *boil* or be in a state of *ebullition.* These phenomena may be readily observed in a glass vessel such as is represented in Fig. 20.

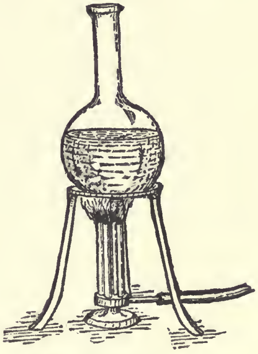

FIG. 20.—BOILING LIQUID.

Laws of Ordinary Ebullition.—Experiment enables us to state the following laws of ebullition:

1st. Under the same pressure there is a definite boiling point for every liquid. The boiling point is then a specific property of the liquid, and is a physical character of importance in distinguishing liquids which otherwise resemble each other.

The following table gives the boiling points of the liquids named, under common atmospheric pressure:

Ammonia	−34° C.
Common ether	37°
Carbon bisulphide	48°
Alcohol	79°
Distilled water	100°
Turpentine	130°
Glycerin	290°
Sulphuric acid (concentrated)	338°
Mercury	357°

2d. When ebullition has commenced the temperature of the liquid remains constant (pressure constant), however much heat be applied.

The liquid must be kept thoroughly stirred, to avoid small fluctuations of temperature The temperature of the vapor is more constant than that of the liquid; hence with water we employ the vapor in determining the boiling point on the thermometer. The constancy of temperature during ebullition explains why vessels of easily fusible metal may be exposed to the action of a hot fire provided they contain water, for they cannot be heated much above 100° until the water has evaporated. That the temperature remains constant during ebullition, notwithstanding the continued application of heat, will be explained subsequently.

3d. The pressure of the vapor given off during ebullition is equal to that of the external medium.

This law has been verified in the case of the atmosphere by a very simple arrangement, shown in Fig. 21. A barometer-tube is bent, near the closed end, to a U-shape. The shorter limb of the tube is filled with mercury, except a small space occupied by water. The mercury extends around the bend a little way up the longer branch. Under ordinary conditions the mercury in the shorter limb will stand higher than that in the other. But let the water in the shorter limb be brought to the boiling temperature by immersing the tube in the steam from boiling water, as shown in Fig. 21. The steam from the water in the shorter limb presses the mercury down until its level is the same in both limbs, showing

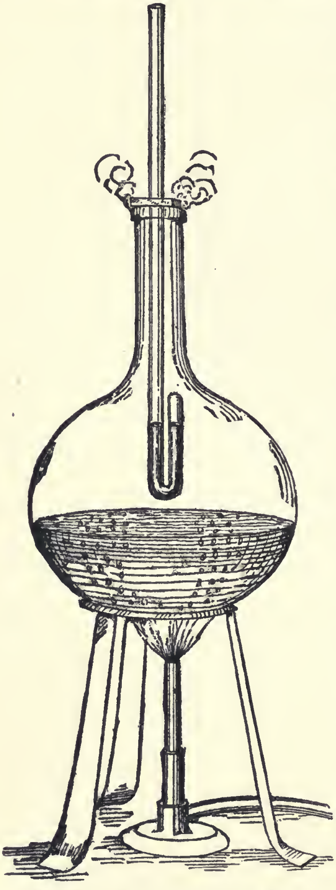

FIG. 21.—VAPOR PRESSURE FROM BOILING WATER.

that the pressure in the shorter limb is exactly equal to the atmospheric pressure in the longer limb.

Boiling Point.—A liquid is in ebullition when it gives off vapor at the same pressure as that to which the free surface of the liquid is exposed, and the boiling point is the *lowest* temperature at which ebullition can occur.

In ebullition the elastic bubbles of vapor formed below the surface of the liquid have to withstand the weight of the liquid above them and the pressure of the atmosphere. In order to escape from the liquid they must in addition overcome the cohesion of the liquid and, at the sides, the adhesion to the vessel. The first element of pressure diminishes as the bubble rises, and at the surface of the liquid the pressure to which it is subjected is reduced to that of the atmosphere. There is thus evidently a greater pressure on the bubbles of vapor formed lowest in the liquid. From these considerations we can anticipate several means of varying the boiling point: the most evident is by pressure.

Effect of Pressure on the Boiling Point.—Ebullition, like fusion, under constant pressure, commences and continues at a constant temperature. As all substances increase in volume upon vaporization, we should expect that increase of pressure would raise the boiling point, and the reverse, and experiment shows this to be the case. Water may be made to boil at any temperature between 0° and 100° by sufficiently diminishing the pressure to which it is subjected. The boiling point of water is associated in our minds with a fixed temperature because it usually boils under atmospheric pressure, and the variations of atmospheric pressure are comparatively small. It is also evident from the foregoing that there is a slight difference of temperature in the different layers of the same liquid, owing to difference of pressure.

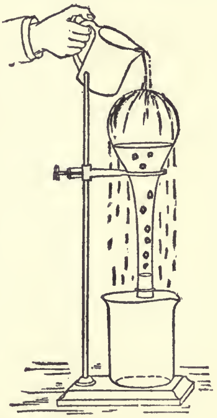

FIG. 22.—BOILING BY COLD.

Diminished Pressure Illustrated.—A little water is boiled over a lamp in a glass flask until the air is driven out. A closely-fitting cork is then inserted, and at the same time the lamp removed.

When ebullition has ceased, it may be renewed for a considerable time by pouring cold water on the flask above the liquid. A Florence flask is very convenient, and may be inverted when removed from the lamp and held by the neck, as in Fig. 22. The cold water condenses the vapor above the liquid and thus diminishes the pressure upon it. In this experiment a fragile vessel is likely to be crushed when the vapor is condensed. The experiment is often called the *culinary paradox.*

On the other hand, by increasing the pressure on the free surface of the liquid, by its own vapor or otherwise, the boiling point may be raised at pleasure.

Other Causes Affecting the Boiling Point.—1. The nature of the vessel also influences the boiling point; the boiling point is different in metallic and glass vessels, being higher in the glass. In this case the water may be heated to 105° or 106° without boiling; then there is a violent escape of steam, and the temperature of the water falls nearly to the normal boiling point, and remains tranquil until the temperature again rises and the phenomenon repeats itself. This intermittent formation of vapor produces what is known as "bumping" in heated liquids, and may be largely mitigated by scraps of metal or a drop of mercury, or a piece of charcoal weighted down.

2. When water has been largely deprived of air and other gases by boiling or otherwise, its boiling point is considerably raised. When ebullition commences there is much more rapid generation of steam than usual, with reduction of temperature. Water has thus been heated from 30° to 80° above its boiling point without passing into vapor.

3. When salts are dissolved in liquids, the general effect, as shown by Magnus and others, is to raise the temperature of ebullition and also of the vapor emitted. Regnault showed that the temperature of the vapor from such solutions soon falls to the temperature of vapor disengaged from pure water under the same conditions. From moderately pure water, for practical purposes it may be assumed that the vapor is at the same temperature as though the water were pure. The steam emitted from saline solutions generally gives pure water, but common salt is often carried over from salt water.

When a liquid, under given conditions, is vaporized by ebullition, the rapidity of vaporization is directly proportional to the heat received.

Applications Resulting from Variations of Boiling Point.—From the connection between the boiling point and the pressure exerted upon the free surface of the liquid result many useful applications, among which may be mentioned—

The Measurement of Heights by the Boiling Point of Water.—Instruments for this purpose are called *Thermo-barometers* or *Hypsometers,* and consist of a little boiler heated by a spirit-lamp and terminating in a tube, with an opening at the side for the escape of the steam. A delicate thermometer is supported in the centre of the tube, and projects slightly above so as to allow the temperature of ebullition to be read. The thermometer is entirely surrounded by the steam, but does not touch the liquid. (See Fig. 23.) When the liquid boils, the pressure of its vapor is equal to the atmospheric pressure. The pressure of aqueous vapor at different temperatures has been determined and tabulated. By observing the boiling point and referring to the table, we get the vapor pressure for that temperature, and accordingly the pressure of the atmosphere, from which the height is computed. An approximation is at once obtained by using Soret's formula,

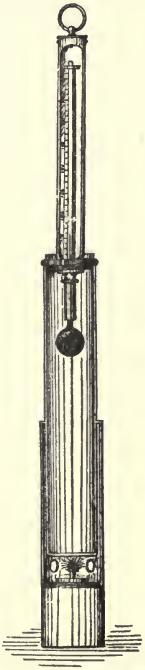

FIG. 23.—THE HYPSOMETER.

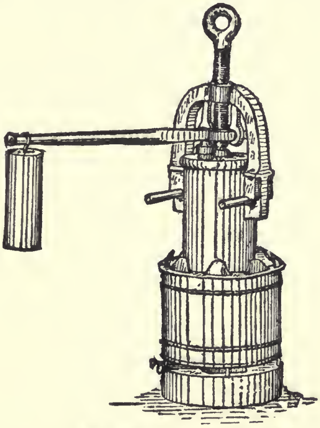

FIG. 24.—PAPIN'S DIGESTER.

which gives a decrease of 1° C. in the boiling point for each 968 feet in altitude. The boiling point being thus lowered as we go upward, the dwellers above particular elevations are unable to perform certain culinary operations in the open air, and are compelled to adopt means for raising the boiling point.

Papin's Digester.—The principle most generally employed for raising the boiling point is illustrated in Papin's Digester (Fig. 24), and is a simple application of increase of pressure. The digester is a strong metallic vessel in which the water may be heated. The only opening to the vessel for the escape of the vapor is closed by a valve pressed down by a weight. The pressure on the valve can thus be varied, and the vapor cannot escape until its pressure lifts the valve. The pressure on the surface of the liquid and the temperature of boiling may thus be varied and regulated.

It is evident that this principle may be applied equally at all levels, and it frequently is, whenever it is desired to heat water above the ordinary boiling point, as in the extraction of gelatin from bones, etc. The reverse principle of lowering the boiling point by diminishing the pressure is frequently made use of to evaporate rapidly solutions which cannot bear a high temperature, by keeping them in a space exhausted of air and vapor. An important and useful application of the principle is made in the manufacture of sugar, the liquid being slowly evaporated in vacuum pans.

Distillation.—Distillation is the boiling or vaporization of a liquid and the condensation of the vapor evolved. It enables us to separate liquids from solids in solution, and to partially separate liquids which rise in vapor at different temperatures. The apparatus (Fig. 25) employed is called a *still,* and consists of a vessel *a,* for heating the liquid, called a *retort,* and one for condensing the vapor, called the *condenser,* and a receiver *b.* The condenser is sometimes in the shape of a spiral tube, *w,* and is then called *the worm* (Fig. 26). The condenser or worm is kept cool by immersion in running water or otherwise, so that the vapor is there condensed and the distilled liquor collects in the *receiver* or flows from the worm. It is evident that, if the air be excluded and the vapor rapidly condensed, the distillation will take place at reduced temperature.

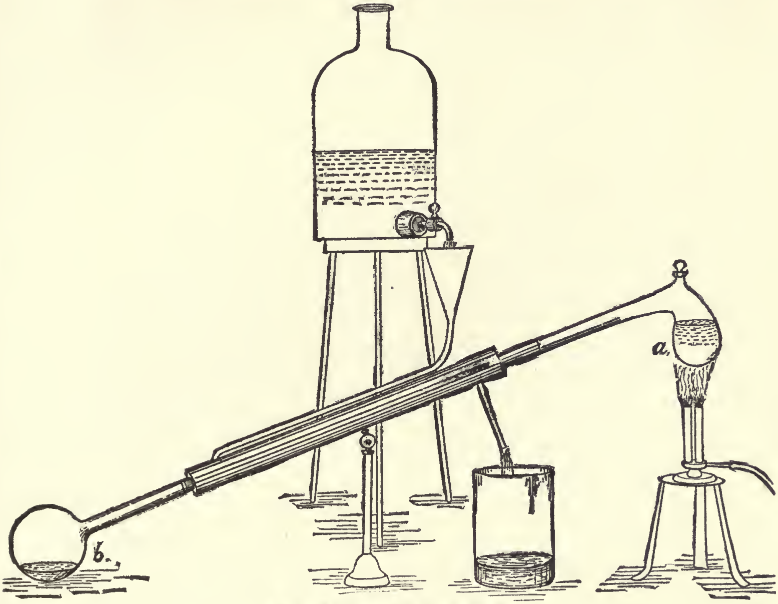

FIG. 25.—LIEBIG'S CONDENSER.

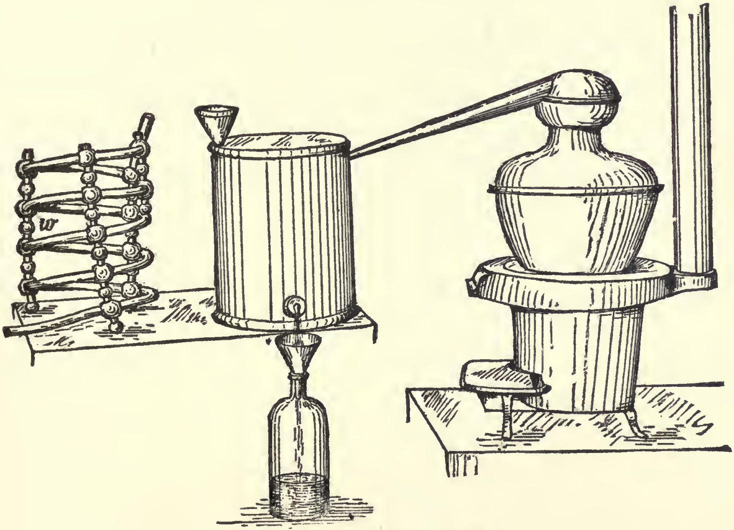

FIG. 26.—STILL WITH WORM.

Spheroidal State.—There is a peculiar action of liquids when dropped upon highly-heated metallic surfaces which may be conveniently considered here, being a case of evaporation though not of ebullition. If water be sprinkled upon a highly-heated metallic or other smooth surface, it does not adhere to the surface, but assumes an ellipsoidal form, spins around, and moves about. The liquid in this condition is separated from the surface by a cushion of its own vapor, and its temperature is found to be below the boiling point. In this condition the liquid is evaporated less rapidly than when the surface of the metal is at lower temperature.

That the liquid remains below the boiling point is due to the evaporation which takes place and to the fact that, not being in contact with the plate, it is heated by radiation. The form is the consequence of cohesion among the molecules as modified by external forces, gravity and atmospheric resistance.

It is possible that all liquids are capable of assuming this state but at different temperatures, dependent upon the liquid and the nature of the surface. In this state they do not wet the surface of the plate. If the plate cools below the particular temperature for the liquid, it flattens out and evaporates rapidly away with ebullition.

We may partially reverse these phenomena by putting a highly heated metallic ball into a liquid. For a time the liquid will be kept out of contact with the ball by a cushion of vapor produced by the heat of the ball.

We can, too, understand how the moist hand of a man has been plunged into molten metal with impunity; it could not be done in a liquid at lower temperature, such as boiling water.

These phenomena were first examined by Leidenfrost more than a century ago, and have since been studied by other physicists, mainly Boutigny.

Freezing of Water and Mercury in a red-hot Crucible.—The fact that a liquid assumes the spheroidal state at a temperature below its boiling point enables us to explain the seeming paradox of freezing water or mercury in a hot crucible. Thus Boutigny poured liquid sulphurous acid, whose boiling point is −10° C., into a white-hot platinum crucible. The liquid assumed the spheroidal state, and water dropped upon it was immediately frozen. Mercury has been similarly frozen by using liquid nitrous oxide, whose boiling point is − 70° C. The liquids thus frozen do not touch the heated ladle.

CHAPTER V.

CHANGE OF STATE.

Latent Heat.—It has been mentioned that other effects than change of temperature may be produced by giving heat to or taking it from a body. The heat which produces changes in bodies other than change of temperature is called *latent heat.*

Liquefaction.—*Latent Heat of Fusion.*—Most solid bodies when heated sufficiently high change their state from solid to liquid. Some bodies pass gradually from the solid state through a semi-solid state to the liquid form, others pass abruptly from the solid to the liquid state; the following remarks apply to the latter class.

This change is called *fusion* or *melting,* and the temperature at which it takes place is called the fusing or melting point, and is constant for the same substance when the pressure is constant. The temperature of the solid remains constant from the time the fusion commences until it is finished, though heat must be constantly applied to continue the melting. The heat thus transmitted to a body without producing any other effect that we know of, except a change of state, is called the latent heat of fusion.

The latent heat of fusion of a particular substance is specified by taking a unit weight of the substance, and may be defined as *the amount of heat expressed in thermal units necessary to melt or fuse a unit weight of the substance starting at the temperature of its fusing point and under atmospheric pressure.*

If we had a perfectly uniform source of heat, such that a pound of water at 0° C. placed over it would have its temperature raised 5° per minute, in a little less than sixteen minutes the temperature of the water would be 79°. The same weight of ice at 0° C. receiving the same quantity of heat would be converted into liquid, but would not have its temperature changed. The entire heat is consumed in changing the state of the ice, but does not affect its temperature, and consequently could not be detected by a thermometer. So far as temperature is concerned this quantity of heat produces no effect, and hence is called latent heat.

Determination of Latent Heat of Fusion.—*a.* This determination may be made by a method similar to the "method of mixtures" for specific heat determination. Thus, if we mix i pounds of ice at 0° C. with w pounds of water at $t°$ and find the resulting temperature, as soon as an equilibrium is reached, to be $\theta°$, we can find the latent heat of fusion as follows:

The units of heat lost by the water are

$$w(t - \theta),$$

and are spent partly in melting the ice and partly in raising the temperature of the water produced from 0° to $\theta°$; then, if we denote by x the latent heat of fusion, we shall have

$$w(t - \theta) = ix + i\theta,$$

from which x may be found.

b. If any other liquid than water be used, we must know its specific heat s, and of any other solid than ice we must know its fusing point T and its specific heat s' in the liquid state; the above formula will then become

$$sw(t - \theta) = ix + is'(\theta - T),$$

in which the first member is the heat lost by the liquid, and the second the heat employed in melting the solid and raising the temperature of the liquid produced from $T°$ to $\theta°$. In the above cases the solid operated upon is supposed to have been at the temperature of fusion at the beginning of the operation, but this is not necessary if we know also the specific heat of the solid body and suppose it constant up to the fusing point. If we start with a solid body below the fusing point, say at t'', and suppose s'' to be its specific heat, the above equation will then become

$$sw(t - \theta) = is''\ (T - t'') + ix + is'(\theta - T),$$

in which the first member is the heat lost by the liquid and spent in raising the temperature of the solid to fusing point, fusing it, and then raising the temperature of the liquid from the fusing point to $\theta°$.

c. For substances which have high melting points, a known weight in the molten state may be enclosed in a small vessel and immersed in the liquid ; then if its initial temperature, the temperature of fusion, and the specific heat of the body in the liquid and in the solid state be known, its latent heat may be determined.

In all these cases it is assumed that the specific heat of the liquid between the initial and final temperature is constant, and the same assumption is made in regard to the solid between the initial temperature and the fusing point. It is also assumed that the entire heat given out by the warmer body is transferred to the other, or that there is no loss of heat. None of these assumptions is accurate, and the determinations are subject to slight error. In *c* above it is also assumed that the same amount of heat which is absorbed in converting a solid into a liquid is given out when the liquid is converted into a solid. This can, however, be demonstrated.

The fusing points and latent heats of several substances are given in the accompanying table :

	Melting Point.	Latent Heat.
Mercury	— 39° C.	2.82
Ice	0	79.00
Tin	235	14.20
Lead	332	5.40
Zinc	433	28.10
Silver	1000	21.00

The latent heat of ice is greater than that of any other substance named in the table; it is 14 times as great as that of lead and 28 times that of mercury. Ice is more difficult to melt, and water more difficult to freeze, than any other substance, each being at the freezing or fusing point. These properties are of great importance in nature, retarding both freezing and thawing.

Latent Heat of Solution.—The conversion of a solid into a liquid by solution is frequently accompanied by a disappearance of heat or reduction of temperature. This reduction of temperature is consequent to the change of state from solid to liquid. This same result is generally observed during solution whenever there is no chemical action between the solid and liquid. Thus the sweetening of coffee by sugar is also a cooling process, and a fall of from 20° to 25° may be obtained by dissolving ammonium chloride in water.

Solution takes place over a wide range of temperatures, and nearly all substances are more soluble at high temperatures, though there are exceptions. There is accordingly no definite point of solution corresponding to the point of fusion.

Solidification or Congelation.—Solidification or congelation is the process by which a body passes from the liquid to the solid state,—the reverse of fusion. In fusion heat becomes latent or produces no effect on the temperature; in congelation the same amount of heat reappears or becomes evident by its effect on temperature. The same number of thermal units which have been communicated to a body without affecting its temperature in fusion will be given to the surrounding medium by the body in solidifying. In the one case addition of heat to the body did not affect its temperature ; in the other the temperature of the body is not affected, although it gives up heat to the surrounding media.

All liquids are capable of being solidified. Like fusion, with a few exceptions, the change takes place abruptly. The temperature of congelation or the freezing point is the *highest* temperature at which solidification can take place, and is the same as the fusing point of the body when solid. It is possible, however, to preserve substances in the liquid state at lower temperatures. In case of water this result has been accomplished by simply subjecting to cold, vessels of water perfectly protected from agitation and dust. Despretz also cooled water in narrow tubes to – 20° C. without freezing. Dufour also obtained similar results by suspending water in a liquid of the same specific gravity and with which it would not mix.

A liquid thus reduced to a temperature below its freezing point is in general partially solidified by the slightest agitation or by the contact of any solid particles. Particles of its own solid are sure to produce the result.

When congelation commences under these conditions, it continues until the heat given out during solidification raises the entire mass of liquid to the freezing point. This may be easily shown by experiment on water. A small vessel containing water in which a thermometer is immersed may be cooled 10° or 12° below the freezing point ; if freezing be then brought about by a shock to the vessel, the thermometer rises rapidly to 0°. Congelation continues until the heat liberated by the water frozen raises the temperature of the remaining liquid to 0°.

Knowing the mass of water involved and the temperature to which it is reduced, it is evident that the quantity of ice that will be formed when congelation sets in may be computed.

The freezing of water is sometimes employed to moderate the reduction of temperature in small conservatories, or other confined spaces.

Change of Volume in Solidification.—Most substances contract in solidifying, but there are some exceptions, as water, bismuth, cast-iron, etc. This property of bodies is very important, enabling some of them to be used in castings.

The expansion of water in freezing is about $\frac{1}{12}$ of its volume, and the enormous mechanical force exerted thereby has already been referred to. This increase of volume also renders ice lighter than water, and it consequently floats at the surface.

Effect of Pressure on the Freezing and Melting Points.—Substances which expand in freezing have their freezing points lowered by pressure. Prof. J. W. Thomson was led to this conclusion by theoretical considerations, and it has been verified by several experimenters. It has also been shown that substances which contract in freezing have their freezing points raised by pressure.

Mr. T. J. Bottomley beautifully illustrated the effect of pressure in lowering the melting point of ice by resting a block of ice on two supports a short distance apart, and slinging over the ice a copper wire to the ends of which weights were attached. The weighted wire gradually worked its way through the ice and fell to the floor, but the block was not cut in two,—the path made by the wire was filled by the formation of new ice as the wire advanced.

Latent Heat of Vaporization.—The process of vaporization has been already defined, and bodies which do not volatilize under ordinary conditions can usually be made to do so by the application of heat. Almost all bodies can be heated high enough to convert them into the gaseous state, if not decomposed before assuming this state. Generally in assuming the gaseous state a solid passes through the liquid state, though, as already stated, there are some which pass directly to the gaseous state.

A law exactly similar to that accompanying fusion universally affects the gaseous condition. The change from a solid or liquid state to a gas is accompanied by the absorption of sensible heat, and the reverse change by its disengagement.

Many gases are absorbed or dissolved in large quantity by liquids and thus are liquefied, or at least greatly condensed, and heat is evolved during this condensation ; and during the reverse operation, when the gas passes out of the liquid, heat disappears. All gases have, however, been brought to the liquid state proper.

The amount of heat which disappears in passing to the gaseous state varies with the temperature at which the change takes place, and is exactly equal to that given out when the gas is condensed or returns to the original form, provided both changes are effected at the same temperature. The heat absorbed by a liquid during conversion into vapor or gas is called the latent heat of vaporization.

The amount of heat necessary to convert a pound of water at 100° C. into steam at 100° is 537 units ; that is to say, the heat necessary to evaporate one pound of water at 100° is sufficient to raise 537 pounds of water one degree in temperature. This same amount of heat reappears in the condensation of the pound of steam at 100°; that is to say, a pound of steam at 100° by its condensation to water would raise 5.37 pounds of water from 0° to 100° C. The latent heat of steam at 100° C. is 537. The latent heat of the vapor of water decreases as the temperature rises. Vapors of other liquids have less latent heat than steam. The accompanying table gives the latent heats of the vapors named at the boiling points of their respective liquids under atmospheric pressure. The third column gives the approximate volumes of vapor, under atmospheric pressure, given off from one volume of each of the liquids at their boiling points.

	Boiling Point. C.	Latent Heat. C.	Volume of Vapor from one Volume Liquid.
Water....................	100°	537	1696
Alcohol....................	78°	202	528
Carbon bisulphide.........	46°	87	420
Ether......................	35.5°	90.5	298
Ammonia *...............	– 38.5°	259	850 †

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* Principles of Chemistry, vol. I. p. 246, Mendeléef.

† These numbers, taken in connection with the specific gravities and specific heats of the liquids, and the ready solubility of ammonia in water, have suggested the possibility of using it in competition with steam for driving engines. If equal weights of ammonia and water be converted into vapor at 100°, the volume of the ammonia vapor is slightly greater than that from water.

Latent Heat of Aqueous Vapor.—We have stated above that the heat given out in the condensation of a vapor is equal in amount to that absorbed in its vaporization, provided both changes take place at the same temperature. If they do not take place at the same temperature, these amounts are not equal.

The results of Regnault's labors in connection with the subject of latent heat have established the following facts in regard to aqueous vapor:

The quantity of heat required to convert a pound of water at 100° C. into vapor at the same temperature is 537 thermal units. If we start with the water at 0° C., raise it to 100° C., then vaporize it without change of temperature, the total will be 637 thermal units. It is this total amount which it is most important to know in the applications of heat in the arts.

In general, if we denote by Q the total amount of heat required to raise the temperature of a unit weight of water from 0° to $T°$, and vaporize it at that temperature, the value of Q is given by the formula:

$$Q = 606.5 + 0.305T. \quad \ldots\ldots\ldots\ldots \quad (a)$$

From what is said above we see that, if we denote by λ the latent heat of vaporization at T, we will have

$$Q = \lambda + T,$$

and by substituting this value of Q in (a) we have

$$\lambda = 606.5 - 0.695T,$$

from which it appears that the latent heat of water decreases as the temperature rises.

By considering the slight variation of the specific heat of water with change of temperature, Regnault found the latent heat of vapor of water to be at 0° C. 606.5, at 100° C. 536.5, and at 200° C. 464.3. Watt was aware of the decrease of the latent heat of steam with increase of temperature, but he thought that the sum of the two remained constant. The above numbers added in indicated pairs show that there is considerable error in Watt's idea.

Latent Heat of Expansion.—When a gas expands, heat must be communicated to it in order to keep its temperature the same: this may be called the latent heat of expansion. If the gas be compressed by external force, its temperature will be increased.

In all these cases in which *heat* is said to become latent it must be kept in mind that there is no loss of *heat energy*. Heat when applied to bodies produces several effects, one of which is *usually* a change of temperature; if it produces other effects and no change of temperature, it is called *latent*. These other effects above given are fusing solids, vaporizing liquids, expanding gases. The heat applied has altered the relations of the particles of the body, probably by changing their positions; and, when these particles assume their original relations, that other effect of heat, *temperature*, is observed.

Utilization of Latent Heat.—There are many practical applications which depend upon the foregoing laws involved in the change of state of bodies. The thermic effects accompanying the changes of state of water are also very important.

Freezing-Mixtures.—Common freezing-mixtures are efficient because of the heat absorbed in the liquefaction of solids. In all such mixtures there is at least one solid substance which is reduced to the liquid state by the action of the others, thus producing a fall of temperature proportional to the latent heat of fusion of the substance. When two solids or a liquid and solid are brought together and produce a mixture which is liquid, cold will be produced unless there be strong chemical action between the bodies. One of the most common of such mixtures is that of snow and salt, in which both the snow and the salt are brought to the liquid state with a reduction of temperature to 0° F. Powdered crystallized calcium chloride and snow will produce a much greater cold (−40° C.). The mere solution of bodies in water, when unaccompanied by energetic chemical action, will produce marked fall of temperature. Thus the solution of nitre or ammonium chloride or ammonium nitrate in water at ordinary temperature will produce a fall of from 15° to 25° C.

Cold by Evaporation.—The latent heat of evaporation can in many ways be taken advantage of to produce cold. Those liquids which evaporate most rapidly produce the greatest reduction of temperature. If the hand be moistened with alcohol or ether, a decided sensation of cold is experienced; with water the effect is less marked, because it evaporates more slowly.

Leslie's experiment consisted in showing that water could be frozen by the cold resulting from its own evaporation. A thin metallic vessel (Fig. 27) containing a little water was placed over a vessel containing strong sulphuric acid, the whole being placed under the receiver of an air-pump. As the air is exhausted the water evaporates more and more rapidly, the vapor of water being absorbed by the sulphuric acid, and ice soon forms on the surface. To make this experiment a success it is necessary to remove the vapor of water as fast as it is formed, which is difficult to do with the arrangement given, for the absorbing power of the sulphuric acid diminishes as the surface layer becomes diluted by the vapor first escaping, and the vapor more remote from the acid is only imperfectly absorbed. Air-pumps are now constructed which at each stroke force the vapor drawn from the water into reservoirs of sulphuric acid, and insure the success of the experiment.

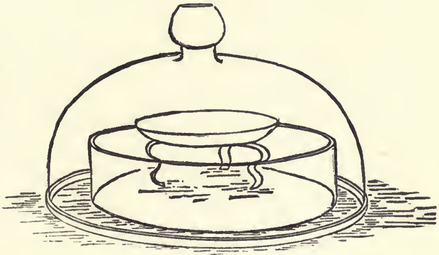
Fig. 27.—Leslie's Experiment.

Wollaston's Cryophorus.—This instrument is sometimes used to show the freezing of water by its own evaporation. It consists of a U-shaped tube (Fig. 28) with a bulb at each end, and is partly filled with water, the air having been expelled by hermetically sealing the tube while the liquid was in a state of ebullition. When an experiment is to be made, all the liquid is passed into one bulb and the other is plunged into a freezing-mixture. The cold condenses the vapor from the water and thus facilitates evaporation until ice appears on the surface of the liquid.

When other liquids more volatile than water are employed much more intense cold can be produced. Water contained in a thin tube dipped into a glass containing ether may be frozen by causing the ether to evaporate rapidly by agitating it with a current of air from a pair of hand-bellows. Mercury may be frozen by liquid sulphurous acid, which is much more volatile than ether.

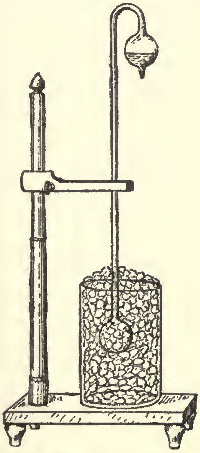
Fig. 28.—Wollaston's Cryophorus.

Ice-Machines.—Most machines for the artificial preparation of ice depend for their action upon the cold produced by evaporation. In Carré's machine the evaporation takes place from liquid ammonia, the vessel of water to be frozen being surrounded by the ammonia. The vapor of the evaporating ammonia passes into a second vessel containing water, by which it is greedily absorbed and thus removed from over the evaporating liquid. By applying heat to the second vessel the ammonia may be again driven out of the water and condensed in the liquid state in the first, and the operation repeated.

In many other machines in this country the evaporating liquids, which are usually ammonia or some of the more volatile petroleum compounds, are condensed by pressure and cold and then allowed to evaporate through a series of pipes immersed in a strong solution of salt. The salt solution is thus cooled to such a degree that vessels of water placed in it are quickly frozen. The vapor of the evaporating liquid as it passes into the pipes is continually pumped out and returned to the condenser in a liquid state.

Liquid carbonic acid, when permitted to escape from a vessel through a narrow orifice, evaporates so rapidly that a portion of the vapor freezes and falls as snow. Faraday, with this carbonic-acid snow dissolved in ether and placed under the receiver of an air-pump, obtained a temperature of − 166° F.

Alcohol has been solidified by Wroblewski and Olszewski by adopting the method, first suggested by Cailletet, of using liquefied ethylene as the means of producing cold. The boiling point of this substance under atmospheric pressure is between −102° and −103° C., and the temperature produced by boiling it *in vacuo* is lower the more perfect the vacuum. The above-named experimenters obtained a temperature of −136° C. by means of it. They determined that carbon bisulphide solidified at −116° C., and alcohol became viscous at about −129° C. and solidified to a white mass at −130.5° C. The critical temperature of oxygen is lower than the boiling point of ethylene in air, and it commenced to liquefy at −131.6° under 26.5 atmospheres.*

Heating by Steam.—The large amount of heat given out by steam in condensing, and its rapid circulation even under slight pressure, have led to its use as a means of heating.

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* Comptes Rendus, April 16, 1883.

The steam is generated in boilers and conducted by iron pipes to the building to be heated. The circulating pipes should be so arranged as to secure an expeditious return of the water from the condensed steam to a receptacle from which it may be again forced into the boiler. This may be accomplished by giving the pipes an inclination in the proper direction.

Irregularities in the fires under the boilers affect very quickly the circulation of steam. When the fires are too low the steam condenses along the pipes, circulation largely ceases, and a partial vacuum exists. When the fires become hot again the steam rushes into the pipes of the ordinary construction and, meeting the water, hurls it forward violently, producing very disagreeable noises and sometimes cracks in the pipes. These disagreeable noises, and the fact that the steam-heaters do not of necessity enforce ventilation, are the main objections to this method of heating.

CHAPTER VI.

HYGROMETRY.

Hygrometry in its broadest sense is that branch of science which has for its object the measurement of the humidity of substances. Hygrometry, however, is generally restricted to the measurement of the amount of aqueous vapor in the air, on account of the paramount importance of this branch of the subject.

Absolute Humidity. — The condition of the air as regards *moisture* depends both upon the *temperature* of the air and the amount of *aqueous vapor* present.

The *actual amount* of vapor present in a given amount of air is expressed by the term *absolute humidity.* This amount may increase or decrease considerably with the temperature without affecting our sensations of dryness or moisture.

Relative Humidity.—Our sensations of moisture and dryness, and the terms *humid* and *moist* in ordinary language, nearly correspond to the meteorological term *relative humidity,* and depend upon the condition of the air as regards saturation. In warm weather the air is generally *drier* than in cold, though the actual amount of vapor present is greater. This is because the capacity of air for vapor is greater at higher temperature.

Since a cubic foot of air will contain as much vapor as a cubic foot of space without air, we may define relative humidity as *the ratio of the mass of vapor present in a space to the mass which would saturate the space at the actual temperature.*

Since aqueous vapor follows approximately Boyle's law, the pressures will be directly as the densities, and we may also define the relative humidity as *the ratio of the actual vapor pressure to the maximum vapor pressure for the temperature.*

If the *absolute* humidity remain constant, the *relative* humidity will vary in the opposite direction to the temperature until saturation is reached, and the dryness and moisture of the atmosphere will, in the main, vary in the same way. Relative humidity is usually expressed as a percentage.

Dew-Point.—In general the atmosphere is not saturated with vapor, and if it be continually cooled the density of the vapor will increase until it reaches a maximum, and any further reduction of temperature will cause a portion of the vapor to liquefy. The temperature at which saturation is reached is called the *dew-point.*

Hygroscopes.—These instruments give simply indications as to the relative humidity or dryness of the air. Their construction depends upon a property, common to nearly all organic substances, of changing their dimensions by absorbing moisture as the air becomes damp and giving it off when dry. During these changes variations of volume occur, which may be used to indicate the hygrometric condition of the air. The result of absorption of moisture is generally increase of volume, and, if the body be composed of twisted fibres as are ropes and cords, the increase of length may not be sufficient to counterbalance the increase in cross-section of the fibres, and such bodies grow shorter when wet.

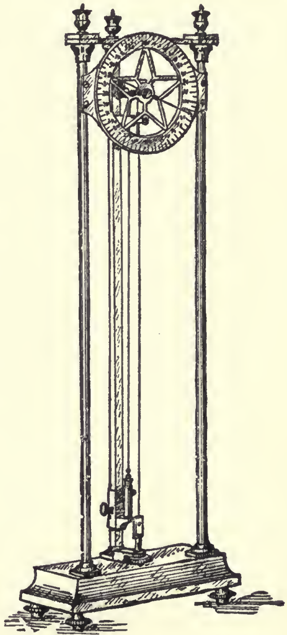
Fig. 29.—Saussure's Hygrometer.

Saussure's Hygrometer.—This is but a hygroscope in which a hair, deprived of grease, is made to move a needle by its contraction, and when the hair expands the needle is moved in the opposite direction by a weight. The weight keeps the hair always taut. Except in the very cold climates of Russia and Siberia this instrument is simply a *hygroscope,* but there it is used as an instrument of observation, because of the difficulty of making observations at such low temperatures with the hygrometer proper. One form of the instrument is shown in Fig. 29.

To the class of hygroscopes belong many of the chimney ornaments in popular use for "weather indicators." One of the most common forms is that in which the figure of a man or woman is made to step out from a toy house, depending on the dampness or dryness of the air. Another form is that in which a monk is made to draw a cowl over his head when the air is damp. Certain chemical substances will change color by loss and gain of moisture, and they can be used to give indications of the moisture present in the air.

Hygrometers.—Instruments intended to furnish accurate information as to the state of the air in regard to moisture are called *hygrometers.*

They may be divided into three classes:

1st. Hygrometers of condensation, or dew-point hygrometers.

2d. Hygrometers of evaporation, or wet and dry bulb hygrometers, also called psychrometers.

3d. Chemical hygrometers, which directly measure the weight of vapor in a given volume of air.

Dew-Point Hygrometers.—The principle of this class is illustrated when a body cools in a moist atmosphere, as when a glass of water in damp air is cooled by dropping in fragments of ice. As the vessel is cooled the layer of air in contact with it is also cooled, and finally moisture makes its appearance on the outside of the vessel, and the temperature at which this occurs is the dew-point, which may be known from a delicate thermometer immersed in the vessel.

Dines's Hygrometer is a good one of this class, and consists of a small flat chamber covered with thin black glass. (Fig. 30). This chamber contains a delicate thermometer, and is connected by a

FIG. 30.—DINES'S HYGROMETER (SECTION).

pipe with a reservoir of water, which is gradually cooled by dropping in ice. The chamber also has a discharge-pipe through which the water flows when the chamber is full. The water is admitted to the chamber by turning a stopcock, and, after filling, the chamber overflows through the waste-pipe. As soon as the dew is seen on the black glass, the thermometer is read and the stopcock turned off. When the moisture disappears the thermometer is read again, and the mean of the readings gives the dew-point.

Daniell's Hygrometer.—This instrument consists of a bent glass tube with a bulb at each end. (Fig. 31.) It contains only ether and the vapor of ether, the air having been expelled in the making of the tube. One of the bulbs, *A*, is made of blackened glass, and that limb of the tube also contains an enclosed thermometer. To use the instrument the whole of the ether is passed into the bulb *A*, and the other bulb, which is surrounded by muslin, is moistened externally with ether. The evaporation of this ether from the muslin causes a condensation of the vapor of ether on the inside of this bulb, with a diminution of pressure. This difference of pressure produces a transfer of vapor from *A* to *B*, with renewed evaporation from the surface of the ether in *A*, and a reduction of temperature in this part of the instrument. The moment the dew appears on the blackened surface of the bulb, the temperature of the enclosed thermometer is read. If the temperature is again read at the moment of disappearance of the dew, the mean of the two readings will give the dew-point more accurately than either separately.

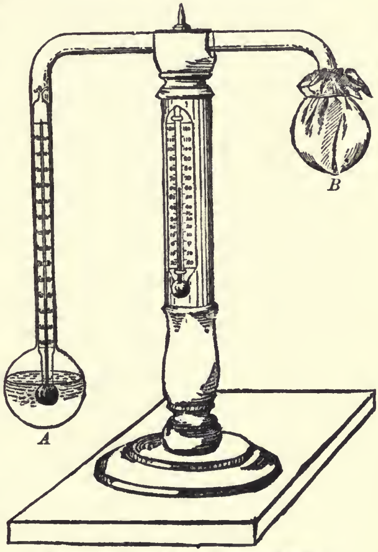

FIG. 31.—DANIELL'S HYGROMETER.

The temperature of the air is given by a thermometer attached to the stand of the instrument.

Regnault's Hygrometer.—This instrument (Fig. 32) consists of two glass tubes, *A* and *B*, terminating at the bottom in polished silver cups which are nearly filled with ether. A thermometer passes through the stopper of each tube and has its bulb dipping into the ether. The tube *B* has also two smaller glass tubes, *c* and *d*, passing through its stopper. The lower end of the tube *c* dips well into the ether, and the upper end is open to the external air. The tube *d* passes through the stopper but does not extend to the ether. The outer end of this tube is connected by a rubber tube to a cylindrical vessel, *V*, which is closed at one end by a stopcock. This vessel when filled with water constitutes the aspirator. To make an observation with this instrument, both stopcocks are opened, and, by the escape of the water from the aspirator, air is drawn from the tube *B*, and the external air passes through the tube *c* to supply its place. This inflowing air produces agitation in the ether, causing evaporation and consequent reduction of temperature, and at the same time tends to preserve a uniform temperature throughout the ether.

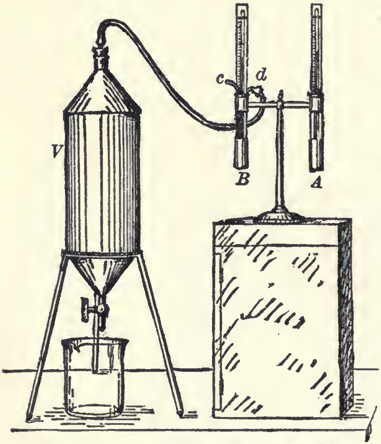

FIG. 32.—REGNAULT'S HYGROMETER.

When the temperature of the ether has been thus sufficiently lowered, a deposit of dew will take place upon the silver surface, which is more readily seen by contrast with the other cup. The reading of the enclosed thermometer at the first appearance of the dew on the silver gives the dew-point. The mean of its readings at the appearance and disappearance of the dew is usually taken as the correct temperature. The thermometer in the other tube indicates the temperature of the air. Neither in this instrument nor in Daniell's can the indications be too *high* if the thermometers are accurate and the readings correct, but they may be too low.

Alcohol may be used in this instrument instead of ether, which is an important advantage, since the boiling point of ether is so low (36° C.) that it is difficult to preserve it in hot climates. The agitation of the liquid and the fact that it is contained in a silver or good conducting holder are both important advantages over Daniell's hygrometer.

When the dew-point is known, the humidity may be determined, as will appear from the following considerations:

If a mixture of air and vapor be subjected to changes of temperature, pressure, or volume, and none of the vapor be condensed, both constituents will be affected alike, since they both obey Boyle's law and have the same coefficient of expansion. In such a mixture, if a change of volume and temperature occur at the same time as in cooling, the pressure of each constituent and the total pressure will all be increased or decreased alike. In other words, the pressure of each constituent and the total pressure will each be multiplied by the same factor. Now, if the total pressure remains the same during a change of volume and temperature of such a mixture, the constituent pressures will also remain unchanged. The total pressure does remain the same (that of the atmosphere) when there is free communication between the altered air and the general atmosphere; consequently the constituent pressures are the same.

It therefore follows that cooling the air down to the dew-point does not alter the vapor pressure. The actual vapor pressure in any portion of air is, therefore, equal to its maximum pressure at the dew-point.

The dew-point might also, therefore, be defined as the temperature at which vapor at its maximum density would have the same pressure as that in the air at the time.

If we know the dew-point, we can find at once from tables of vapor pressure the pressure of the vapor in the air; and if we have the temperature of the air, we can find from the same tables what the pressure would be at saturation for that temperature. The ratio of the former to the latter is the relative humidity.

Under the assumption that aqueous vapor has the same coefficient of expansion as air, and equally obeys Boyle's law, it follows that the ratio of the density of aqueous vapor to that of the air at different temperatures and pressures is constant. This ratio, as determined by Gay-Lussac, Regnault, and others, may be taken as .623, and it may be considered as constant within the ordinary range of temperature and pressure which exist in the atmosphere.

Aqueous vapor is therefore .623 ($\frac{5}{8}$ nearly) as heavy as air at the same pressure and temperature. This same fraction (to within $\frac{1}{1000}$) for the density of aqueous vapor, referred to air at the same pressure and temperature, is given by the law of volumes. The above relations give the means for the determination of the absolute humidity or actual amount of vapor in the air; for the weight of the unit of volume of air at the standard pressure and temperature has been very accurately determined. This weight, as adopted by the International Bureau of Weights and Measures, for a cubic foot of air at 32° F. and under 30 inches pressure is 566.53 grains. From the constants above given, the weights in the table on page 35 are computed. The tables of vapor pressure adopted by meteorologists are those made by Regnault.

Hygrometers of Evaporation.—*The Psychrometer, or Wet and Dry Bulb Hygrometer.*—This instrument consists of two precisely similar thermometers mounted at a short distance from each other. The bulb of one is covered with muslin and kept moist by capillary action through a string leading from a vessel of water. (See Fig. 33.) The vessel should have only a small surface of liquid exposed, should be placed some distance from the thermometer, and should be at such level as to keep the muslin well moist but not dripping wet.

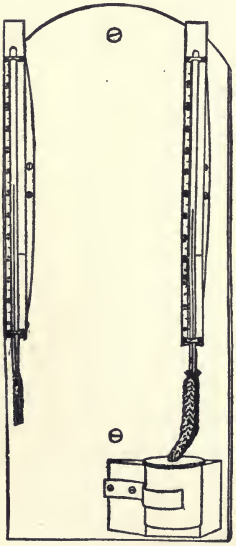

Fig. 33.
The Psychrometer.

When the temperature of the air is below freezing, the covered bulb must be dipped into the water and removed, and the water adhering to the bulb allowed to freeze. The evaporation then takes place from the shell of ice.

The observations in both cases consist simply in noting the reading of the thermometers.

The difference of reading between the two thermometers will evidently be greatest when the air is driest. The facility of observation with this instrument at ordinary temperatures, and in extremely dry regions where the hygrometers of condensation act with difficulty, has brought it into very general use.

For meteorological observations in the field, as distinguished from observations at permanent stations, and for hygrometric observations in connection with barometric hypsometry in the various surveys conducted in this country, the psychrometer is indispensable.

Empirical tables have been constructed by a comparison of the simultaneous readings of the psychrometer and Daniell's hygrometer, taken at Greenwich and other places for a series of years. These tables give a ready means for determining the dew-point from the observations of the psychrometer.*

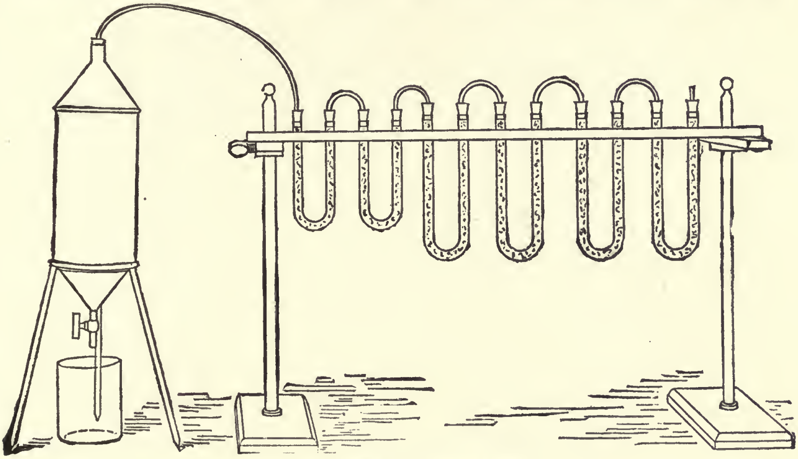

Fig. 34.—Chemical Hygrometer.

For many years it has been attempted to construct a rational formula for determining the dew-point from the observations of the psychrometer, but it has been very difficult to eliminate uncertain assumptions from the data necessary to the solution of the problem. Some of the recent formulæ are however satisfactory.

Chemical Hygrometer.—This apparatus (Fig. 34) consists simply of an aspirator filled with water and connected at its upper

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* See note, p. 166, Appendix.

extremity with a series of U-tubes containing pumice soaked in sulphuric acid. The water is allowed to flow out of the aspirator by the lower stopcock; the air which enters the aspirator to replace the water is obliged to pass through the tubes and leaves the moisture in them. The moisture from the air is left in the first tubes; the last tube is to absorb any moisture which might pass backward from the aspirator. The increase of weight in the tubes evidently gives the weight of moisture which was in the air admitted, the volume of which is known by the volume of water which has escaped.

CHAPTER VII.

CONDUCTION.

WHEN any portion of a metallic body is subjected to a higher temperature than other portions, there is at first a gradual rise of temperature in the surrounding parts, which is more rapid near the source of heat. After a time the temperatures of the different parts of the body cease to rise, and remain constant so long as the source of heat and other conditions are unchanged.

These effects can only occur by the transference of heat from part to part of the body through the intermediate parts. This transfer of heat through contiguous matter, leaving always particles nearer the source at higher temperatures than others more distant, is called conduction, but there are two stages in the process.

1. Variable Stage—Diffusivity.—When any part of the body as above stated is first subjected to a higher temperature, there is a gradual and continuous rise of temperature in all the adjoining portions. This variable stage is known by changes of temperature in the body, and therefore depends not only upon the heat transmitted from portion to portion of the metal, but also upon its specific heat. In this case it is evident that, since the temperature of each portion of the metal rises, a part of the heat transmitted to any particle is not passed onward but remains in the particle, as is evidenced by the increase of temperature. This transfer of heat, with accompanying partial consumption in elevating the temperature of the medium of transfer, measures the *diffusivity* or *thermometric conductivity.* It varies directly with the transferring power of the metal, and inversely as the specific heat per unit of volume.

2. Permanent Stage of Conduction.—The source of heat and other conditions remaining constant in the case supposed, the temperatures of all parts of the body after a time cease to change and remain constant. By air-contact and radiation all the surface particles of the warm metal are still giving off heat, and since their temperatures do not fall, heat is still being transferred to them from the source. Since the temperature of none of the particles changes, though constantly receiving heat, it follows that every particle transfers just as much heat as it receives. This is the permanent stage of conduction, and the facility of transfer in this state is what is usually referred to as *conducting power*, though, as we have just shown, conduction in general must also involve thermometric conduction or diffusivity. We shall hereafter, in this discussion, for brevity, use the term conductivity to refer to the permanent stage only. It is independent of the specific heat of the body.

Determination of Conductivity.—One definition of temperature has been given as "the state of a body or portion of matter with respect to its capacity to communicate heat to other matter." Conduction is the process by which heat is communicated to contiguous matter, and to determine *conductivity* we must measure the flow of heat in a unit of time, in the permanent state, due to the difference of temperature which produces it.

The *conductivity* of a body is usually defined as the amount of heat which flows through a plate of unit area and of unit thickness in a unit of time when there is a unit difference of temperature between the sides. If we had a plate of unit area, of unit thickness, and could keep a unit difference of temperature between the sides, and should then determine the quantity of heat passing through it in a given time, we should have an obvious means of determining its *conductivity*. But, for reasons which will subsequently appear, this simple and direct means of determining the flow of heat, and thereby the conductivity, cannot be employed.

The measure of the passage of heat by conduction after the body has reached the permanent state has to be made in a more indirect way. One of the simplest methods and most important in practice is by observation of the permanent distribution of temperature in a cylindrical mass of the body, one end of which is subjected to a constant source of heat while the rest of the surface is cooled by exposure to lower temperature.

This method, employed by Forbes with iron, will make plain the principles involved. A bar of iron, mounted as in Fig. 35, was kept at a constant temperature at one end, molten lead being used for the purpose. The bar, in the experiment here described, was 8 feet long and of square section 1¼ inches on a side. The entire surface of the bar, except the heated end, was exposed to the air. Holes were drilled in the bar and thermometers inserted at different points, metallic connection between the bar and the thermometer-bulbs being secured by inserting a few drops of mercury or amalgam.*

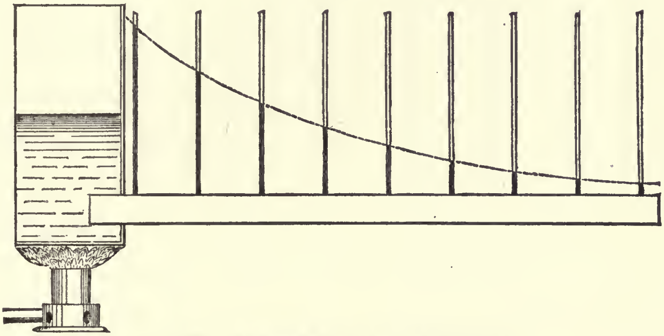

FIG. 35.—DETERMINATION OF CONDUCTIVITY.

After a sufficient lapse of time the bar arrived at the permanent state, and the thermometers showed a gradual decrease of temperature from the heated end outward. The farther end was not sensibly raised in temperature. It is evident that by this means the distribution of temperature along the bar could be obtained. If we deduct the temperature of the atmosphere from that of the various points of the bar, we shall know the excess of temperature of these points of the bar above that of the atmosphere. These numbers may be used as the ordinates of a curve which will indicate the excess of temperature along the bar, above that of the atmosphere, the axis of the bar forming the axis of abscissas. This

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* General considerations of the problem of conduction demonstrate that the temperature is practically the same throughout each cross-section of the bar.

curve will represent this excess the more accurately the greater the number of points at which the temperature of the bar is determined. The curve will intersect the axis of the bar at the point at which the temperature of the bar is the same as that of the atmosphere,—at the point at which the effects of the source of heat cease to be felt in the bar.

Let *CDB,* Fig. 36, represent such a curve of temperature. Since the bar has reached the permanent state, it is clear that all the heat which crosses any section, as *ef,* passes into the air by radiation and convection. We shall know then the amount of heat which is conducted across any section, *ef,* of the bar, in any time, if we can determine the amount of heat given off in the same time from the portion of the bar beyond that section.

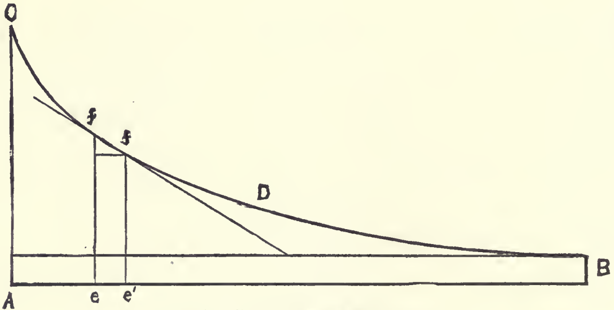

FIG. 36.—CURVE OF TEMPERATURE.

By actual experiment on a similar bar, heated to a high temperature and subjected to the same atmospheric conditions as the first, the determined rate of cooling would enable us to calculate the amount of heat lost by this bar, per unit of length, per unit of time, at each temperature within the range employed. This knowledge would enable us to calculate the loss in a given time in any portion of the other experimental bar, since we know the stationary distribution of temperature in it from the curve of excess. This was the method adopted by Forbes.*

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* Forbes determined the heat given out by his second bar in cooling by the fall of temperature in the bar itself; and by calculating the specific heat of the bar per unit of volume (from the specific gravity and specific heat) he obtained the actual quantity of heat given out.

By thus being able to determine the heat given off in any time by any assigned portion of the bar, we are enabled to know the quantity of heat which passes in the same time through any section; and by comparing this quantity with the rate of diminution of temperature per unit of length along the bar as shown by the temperature curve, we ascertain the conductivity of the bar at the temperature of the section, or the flow of heat due to the difference of temperature which produces it.

In this comparison of the flow of heat with the decrement of temperature, it is *assumed* that the flow of heat is, *first*, directly proportional to the difference of temperature between the sides of the section considered, and, *second*, inversely to the distance between them. This first assumption is in accord with all experiments for small differences of temperature, and is probably true at all temperatures, but neither it nor the second assumption has been fully verified by experiment. Péclet's* experiments are sometimes quoted as a verification, but they cannot be fairly taken as such.

Making this assumption, and denoting by Q the quantity of heat which flows through any section, x its thickness, v and v' the temperatures of the two sides, s the area of the section, and t the time, we may write generally

$$Q = ks\frac{v - v'}{x}t,$$

in which k is the conductivity and depends on the material experimented with; and if s and t equal unity we have

$$Q = k\frac{v - v'}{x}.$$

Now, by reference to the temperature curve it is seen that $\frac{v - v'}{x}$ is the tangent of the angle which the downward slope of the temperature-curve makes with the axis of the bar. From the above we have

$$k = \frac{Q}{\frac{v - v'}{x}}.$$

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* Annales de Chimie et de Physique, tome 2, 3me série.

This value of k, by Forbes's method, is given entirely in terms obtained by experiment, and, if the sections of the bar could be taken *continuously,* we might write

$$k = \frac{Q}{\frac{dv}{dx}},$$

in which $\frac{dv}{dx}$ is the rate of decrement of the temperature along the bar, or the tangent of the temperature gradient at any point, but, since such a continuous result can only be obtained by computation, the value of k must depend partly on the assumptions above given.

It is, however, to be observed that conductivity *must* be determined by the quantity of heat which passes, and that this can only depend upon the *nature* and *dimensions* of the body and the *difference* of temperature between its parts, and these *all* enter the expression for the value of k, and that, although this value depends partly on the assumptions given above, it is at the same time possible from the experimental values of Q, $\frac{v - v'}{x}$ (or passing to the limit $\frac{dv}{dx}$) to ascertain the correctness of the assumptions themselves, and also to ascertain whether k varies with the temperature. It is plain that by using different substances their conductivity may be similarly determined.

It will now be evident why the direct method of determining absolute conductivity, suggested by the definition, cannot be followed. The curve of temperature within a body is determined by the mutual influences of the temperature conditions to which all the different parts of the body are subjected, and it is entirely impossible to fix arbitrarily the temperatures of different parts of a body by bringing these parts into contact with other bodies at different determined temperatures. Under the influence of the first body the temperatures of the applied bodies are changed, which change is further increased by their action on *each other* through the medium of the first body, so that the temperature of no *two* parts of a body at different temperatures can be fixed arbitrarily, but must be known from experiment. If the applied temperature conditions to which a body is subjected are permanent, it will itself reach the permanent state, and its temperature curve can then be known by experiment only.

The expression
$$Q = ks\frac{v - v'}{x}t,$$

is frequently said to give the flow of heat through a substance when the conductivity is k, the area s, thickness x, and the time t, when the two sides are *kept* at the temperatures v and v' and when there is no heat lost *laterally.* This last condition may be practically attained by having the area so great that the lateral loss is insignificant when compared with that which passes transversely, or the lateral loss may also be made insignificant by proper coverings. The other condition of the problem is clearly impossible: the faces cannot be *kept* at v and v', but will *assume* temperatures depending upon the temperatures of the bodies contiguous to and near them. The discussion of such a problem is accordingly not only useless but misleading, and has caused a great deal of confusion in the discussion of this subject. A proper statement of the relations implied in the above equation is that it gives the quantity of heat which flows through any section whose area is s, and thickness x, in the time t, when the two sides of the section *assume* the temperatures v and v' under the conditions of the experiment. The conductivity through any section under these conditions being determined, the conductivity through a *given* thickness, with a *given* difference of temperature between the sides, must be computed from the assumptions already referred to.

Determination of Diffusivity.—If one part of a body be subjected to periodic variations of temperature and the periodic variations at other points be observed, the *diffusivity* of the body may be calculated. The explanation of the method is not deemed appropriate in the present work.

When the diffusivity is known and the specific heat per unit of volume also known, the conductivity is given.

Absolute and Relative Conductivity.—The absolute conductivity of wrought iron, from the determinations of Forbes,* Tait,† Angström,‡ and Neumann,§ may be taken as 0.20. The absolute conductivity of copper, from the determinations of the two experi-

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* Phil. Trans. R. S. E., vol. xxiii.

† R. S. E., 1878.

‡ Phil. Mag., September, 1863.

§ Annales de Chim. et de Phys., 3me série, tome 66.

menters last named, may be taken as 1.0. In the above numbers the C. G. S. scale is employed, and, considering copper, is equivalent to saying that heat sufficient to raise a gramme of water one degree C. in temperature will pass through a plate of the metal one centimetre square and one centimetre thick in one second of time, when the two surfaces differ in temperature by one degree, the copper having reached the permanent stage as above described.

The conductivity of iron was found to diminish as the temperature increased, and according to Tait it is at a minimum somewhere about red heat. According to the same authority, iron is an exception in this respect, the majority of the metals improving in conductivity with rise of temperature. The following table gives the approximate relative conductivities of the metals named, copper being taken as 100:

Copper	100	Tin	19.8
Silver	135.9	Lead	11.5
Gold	72.1	Platinum	8.7

The absolute conductivity of copper being known, we may from this table of relative conductivities calculate the absolute conductivities of the other metals.

From the absolute conductivities, the diffusivities may be computed by dividing by the thermal capacity per unit of volume. Denoting the absolute conductivity by k, and the thermal capacity per unit of volume by c, the diffusivity is $\frac{k}{c}$; c is obtained by multiplying together the specific heats and specific gravities of the respective metals.

Conductivity of Solids.—As a class the solids are the best conductors, and among these the metals stand first, stone second, and wood third.

The difference in the conducting power of substances explains many familiar phenomena. If we enter a room the temperature of which is below that of our bodies, and place the hand upon different articles in the room, different sensations of cold will be experienced; on the other hand, if the temperature of the room be above our own temperatures, some of the bodies will appear warmer than others, though in each instance the bodies in the room are at one temperature,—that of the room. In the first case it is the better conductors which feel colder, and in the second they feel warmer, the difference being due to the facility with which they take heat from and give it to our bodies.

The knowledge of the relative conducting powers of substances is important in many practical applications. In our houses the material and thickness of the walls must be considered both for economy and comfort. The walls should be of non-conducting material, both for keeping them warm in winter and cool in summer. Wood and brick are poorer conductors than stone.

Conducting Power of Liquids.—With the exception of mercury and molten metals, liquids are very poor conductors. This can be shown in a very simple way by heating the upper part of a column of liquid and observing the variations of temperature below, which will be exceedingly slow and scarcely perceptible. Water may be placed in a test-tube over a piece of ice held down by a small weight, and the upper portion of the tube may be heated and the water boiled for a considerable time without melting the ice below. Of a large number of substances liquid at ordinary temperatures, Guthrie determined that water had the greatest conducting power.* The absolute conductivity of water as determined by Bottomley is greater than that of wood, and about $\frac{1}{500}$ that of copper.

Conducting Power of Gases.—The conducting powers of gases are very feeble and difficult of measurement. It is, however, possible, assuming the kinetic theory of gases, to calculate conducting powers with perhaps more accuracy than they can be determined by experiment. We know that all gases are exceedingly bad conductors, and wherever gases are enclosed in small cavities so as to prevent their circulation, the system produced is a bad conductor. This is the cause of the feeble conducting power of furs, eider-down, felt, and loose woollen and cotton cloths. Materials of this kind when used for clothing are warm because they prevent the escape of heat from the body. If a garment of down or fur be pressed flat so as to remove the air, it will be a much better conductor and less warm.

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* Trans. R. S. 1869.

The snow which often covers the earth in cold climates has air nearly immovably imprisoned within its flakes, and is an excellent non-conductor of heat. Snow thus often protects the rootlets which would otherwise freeze and prevent perennial vegetation. The conducting power of hydrogen is superior to that of other gases, and about seven times that of the air, and that of the air is about $\frac{1}{20000}$ that of copper.

Notwithstanding the poor conducting power of gases and liquids, we know that they can be cooled and warmed very readily. This is due to the fact, already mentioned, that they expand by heat and rise, while the colder fluid descends, and thus are established the *convection currents* previously discussed.

From the above principles it is evident that, if a fluid be heated at the upper surface or cooled at the lower, variation of temperature away from these surfaces will take place very slowly. An air-space is thus often made an immense protection to upper rooms from the sun's heat.

CHAPTER VIII.

RADIATION.

In conduction a transfer of heat takes place between contiguous particles of matter. *Radiation* is the process by which a transfer takes place between bodies not in contact. Thus considered, radiation consists of three distinct phenomena,—emission, transmission, and absorption; and three bodies are concerned,—the body *from* which the heat passes, that *through* which it passes, and that *to* which it passes.

Radiation Distinct from Conduction.—In conduction the spread of heat to points remote from the source can only take place by the warming of the intervening medium, so that any portion of the medium is at higher temperature than all other portions more distant from the source. In radiation no elevation of temperature of the intervening medium seems essential to the transfer of heat to distant bodies. Radiation takes place through many bodies without sensible elevation of temperature, though all bodies are probably slightly heated.

Conduction is a gradual, while radiation is an almost instantaneous process. The heat radiated from a hot body to another may be instantly cut off by a screen, and resumes its full intensity as promptly upon the removal of the screen. By conduction heat travels from the *hotter* to the *colder* parts of the medium, whatever the direction be; by radiation, in a homogeneous medium, the heat travels in straight lines.

General Properties of Radiant Heat.—It is now generally believed that both radiant heat and light are the results of a vibratory motion which is transmitted through space in undulations or waves by an all-pervading medium called luminiferous ether; and before considering radiant heat in relation to the physical properties of particular substances, we shall give some of the most important general properties of radiant heat as determined by experiment.

1. Radiant heat travels through a vacuum or homogeneous medium (with an exception to be named) in straight lines, as can be readily shown by means of opaque screens.

2. From a heated point it would be emitted in straight lines equally in all directions; hence the heat energy which in a given time falls on a given area is inversely proportional to the square of the distance of the area from the radiating point. The velocity of propagation of radiant heat has not been *directly* measured, but there is the strongest possible reason for believing it to be the same as that of light.

3. Radiant heat is reflected from a polished surface, and the direction of the reflected ray is determined by fixed laws:

FIRST.—The reflected ray lies in the plane of incidence.*

SECOND.—The reflected and incident rays make equal angles with the normal to the surface at the point of incidence.

Owing to the inequalities of even the finest polished surfaces, a portion of the reflected heat makes with the normal an angle different from the incident ray. This irregular reflection is called *diffusion* of heat, and must be distinguished from the phenomenon designated under conduction by the term *diffusivity.*

4. In addition to the part of the heat which is regularly and irregularly reflected from the incident surface, a certain quantity usually, probably always, penetrates the second medium: of the quantity thus entering the body a certain proportion is always *absorbed.* In general, if the incident heat is not normal to the surface of the second medium, the portion which penetrates it will undergo *refraction* or be bent out of the original direction, and the refracted ray will lie in the plane which contains the incident ray and the normal to the surface at the point of incidence.

Theory of Exchanges.—Before proceeding to describe more in detail the phenomena attending the radiation of heat, it will be well for the student to understand what is meant by the Theory of Exchanges. This theory asserts that all bodies are constantly

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* The plane of incidence is the plane passing through the incident ray and the normal to the surface at the point of incidence.

giving out heat by radiation, at a rate depending upon their substance and temperature, but independent of the substance and temperature of the bodies surrounding them; and that whether the body remains at the same temperature or alters its temperature depends upon whether it receives as much heat from other bodies as it yields up to them. This theory is now generally received, and, while affording explanation of many phenomena, it has also suggested new truths which have afterwards been experimentally verified.

The theory is frequently called Prévost's theory, after its author. It has been developed by De la Provostaye, Desains, Kirchhoff, and Balfour Stewart. The last named has made a very satisfactory discussion of the theory in his Elementary Treatise on Heat, but it cannot be sufficiently condensed for insertion here. The comprehension of the theory will facilitate the conception of many of the principles subsequently involved, and it will conflict with none. Indeed, the theory is sustained by all experimental investigation of the subject of radiant heat.

The general properties of radiant heat thus far given indicate its similarity to light, but the analogy is still more striking when the more special phenomena attending the radiation of heat are compared with the corresponding optical phenomena. Some of these we now proceed to give.

Light and Heat Spectra of Bodies.—If a beam of sunlight be made to fall obliquely upon the side of a glass prism whose edge is vertical, two phenomena will be observed. The *direction* of the beam will be changed in passing through the prism, and it will no longer be *white* light, but will be separated into its constituent colors. If we should try this experiment in a darkened room and place behind the prism a screen, we should find an oblong space on the screen illuminated by the various colors, as indicated in the diagram Fig. 37. All these colors would be bent out of the original direction of the beam, the red least and the violet most. In this case the colored space is called the *solar spectrum*, and if it be formed from

Fig. 37.—Order of Colors in Spectrum.

any other body it is the spectrum of that body. The spectrum thus formed is but a series of overlapping colored images of the slit or opening through which the beam of light passes, due to the unequal refraction of the different colors. The spectrum may also be formed by a reflecting diffraction-grating, this grating consisting of a system of close equidistant parallel lines ruled on glass or polished metal. Such a spectrum is generally designated as a *normal spectrum*, and in it the positions of the colors are determined by the corresponding wave-lengths.

In the normal spectrum the maximum heating effect does not coincide with the maximum light effect, the former being in the orange-yellow and the latter in the yellow. These positions vary slightly with the extent of the earth's atmosphere through which the heat and light pass, and consequently with the altitude of the sun. The above-given are for the sun in the zenith. The heating effect is found throughout the spectrum and for a short distance beyond the violet and *far* beyond the red end.

We thus see that the grating which produces the light spectrum also produces a heat spectrum, extending throughout the light spectrum and beyond on both sides, the maximum of the heat effect being near the red of the spectrum. With the spectra of the other luminous bodies results are observed analogous to those here given for the solar spectrum.

Refraction of Heat.—From the distribution of heat in the spectrum as above described, the bending of the heat rays out of their original course, or *refraction*, is clearly implied. Melloni first showed in a more direct way that heat from a non-luminous source was capable of refraction. By using a lens and prism of rock-salt between the non-luminous source of heat and the *thermopile*,* he showed conclusively that the heat could be bent out of its course and concentrated to a point in the same manner as light. Forbes showed that the refrangibility of non-luminous heat was less than that of luminous rays. All lenses for kindling by the sun's heat depend upon the property of refraction.

Reflecting Power.—The reflecting power of a surface is measured by the proportion of the incident heat which is regularly

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* The thermopile is an instrument giving electrical indication of very slight changes of temperature, and capable of detecting very small quantities of heat.

reflected from it. This property of substances has been investigated by Leslie, Melloni, Desains, and De la Provostaye. The first named determined the relative reflecting power, taking brass as a standard ; the three last named determined the absolute power. It was shown by Desains and De la Provostaye that for diathermanous substances, or such as permit heat to pass through them, the reflecting power increased as the angle of incidence was increased. For metals, which do not transmit heat, the reflecting power varied very slightly with the angle of incidence, and after the angle had reached about 75° a further increase caused a decrease in reflecting power. They also show that the reflecting power varied with the source of heat. These phenomena are entirely analogous for light.

Some of the results of the experimenters last named are here given ; the source of heat was luminous, an oil lamp being used.

Silver-plate	0.97	Speculum metal	0.86
Gold	0.95	Zinc	0.81
Brass	0.93	Iron	0.77

Burning Mirrors.—This reflecting power is made use of in all burning mirrors, and the construction of such mirrors depends upon the laws of reflection already referred to, and may be used to verify them. All rays either of heat or light falling upon a properly constructed concave mirror from a direction parallel to its axis are reflected to its focus. Tschirnhausen's mirror which was constructed in 1687 was about six and a half feet in diameter, and was capable of fusing copper and silver. Instead of curved mirrors, plane movable ones may be so arranged as to converge their reflected rays to a point and thus produce a powerful effect. Such was the reported arrangement by which Archimedes is said to have destroyed the Roman fleet in the siege of Syracuse.

Irregular Reflection of Heat.—The irregular reflection of heat which is designated diffusion, and probably resulting as previously described, is often felt very strongly from a white wall or other white surface exposed to the direct rays of the sun. That this heat cannot be due to radiation from the heated surface is shown by the fact that it instantly attains its maximum, instead of rising gradually as it would if it were radiated from the body. Moreover, the heat thus diffused from bodies in direct sunlight always agrees in properties with the heat from a highly-heated source, which could not be the case if it were radiated from the body at its actual temperature. The irregular reflection of heat and of light take place in the same manner, and the laws in the two cases so far as they are known are analogous.

Emissive Power.—It is a familiar fact that the hotter a body is the more heat it emits, but temperature is not the only condition which affects the quantity emitted. It was observed by Leslie in 1804 that different substances have very different emissive powers even at the same temperature, and he compared the emissive powers of various substances by a method similar but less perfect than the one now to be described.

Melloni determined the relative emissive powers of a number of substances for dark heat by means of the thermopile (already referred to) and a cube filled with water kept at the boiling point, and having its different faces covered with differences substances. The relative emissive powers of the different substances were given by the electrical currents produced in the thermopile when the respective faces of the cube were allowed to radiate heat to it, these currents being indicated by the deflections of a galvanometer needle in circuit with the pile.

By similar means De la Provostaye, Desains, Tyndall, and others have also made determinations of this power in different bodies. The relative emissive powers of the non-metallic substances named below are from the determinations of Leslie and Melloni. Those of the metals were determined by Desains and De la Provostaye.

Lamp-black	100	Polished silver	2.5
White lead	100	Gold-leaf	4.3
White paper	98	Copper foil	4.9
Crown glass	90	Polished platinum	9.2

It was found that the radiating power of the same substance varied with the condition of the surface, whether it was polished, rough, or tarnished. In general, the more dense and compact the surface of the body, the smaller its emissive power, and polishing only seemed to diminish the emissive power when it affected the density of the surface layer.

The thickness of the radiating layer was also found to exert an influence on the quantity of heat emitted at a given temperature from such substances as were perceptibly transparent to heat and therefore gave off heat from particles below as well as at the surface. For bodies which are practically opaque to heat, as metals, the effect of variation of thickness was imperceptible.

Absorption of Radiant Heat.—When radiant heat falls upon a body, whatever portion of it is not regularly or irregularly reflected penetrates the substance of the body; this penetrating portion may be partially transmitted through the body without affecting its temperature, or it may be partially or wholly taken up in the body with increase of temperature. The portion which is stopped in the body is called *absorbed heat.* In bodies which are opaque to heat absorption like emission is a surface action, but in diathermanous bodies it takes place below the surface. Experiment proves that different substances have different absorbing powers, and that those which have the greatest emissive powers have also the greatest absorbing powers: the correspondence is not only general but exact; the numbers which express the radiating powers also express the absorbing powers, and what affects the one affects the other. It is also found that the absorbing power of the same substance varies with the source of heat. From the above statement in regard to the relation existing between the reflected heat and that which penetrates the body, it is evident that a good absorber must be a bad reflector and a good reflector a bad absorber of heat; and experiment proves such to be the case. The numbers which have been given for the emissive powers also indicate the relative absorbing powers of the same substance.

Diathermancy, or the Transmission of Heat.—We have above stated that of the heat which falls upon a body a portion is reflected, regularly or irregularly, and the remainder enters the body. The portion which enters the body may be entirely absorbed, or partially absorbed and partially transmitted. *Diathermancy* refers to the power which bodies have of transmitting heat: it corresponds to the property of transparency for light.

It has long been known that some of the heat from an intensely luminous source, as the sun, could pass through certain transparent substances, as glass, but it was not known that this was the case with heat from a non-luminous or feebly luminous source. Pictet was the first to establish the fact of diathermancy for radiant heat in general, and Prévost proved that it could not possibly be due to absorption and subsequent radiation by showing that such heat passed through ice. Many investigations have been made as to this property of bodies, and some of the more important conclusions are here given.

Effect of Source of Heat.—As a general rule, the same substance transmits unequal quantities of heat when the source of heat is varied, the amount increasing with the temperature.

The following table, from the results of Melloni, shows the proportion transmitted, out of 100 rays, from the different sources:

SUBSTANCE.	SOURCE OF HEAT.			
	Locatella's Lamp.	Incandescent Platinum Wire.	Copper at 400°.	Copper at 100°.
Rock-salt	92	92	92	92
Calcium fluoride	78	69	42	33
Plate-glass	39	24	6	0
Selenite	14	5	0	0
Alum	9	2	0	0
Ice	6	0.5	0	0

Rock-salt is seen from the table to transmit the same proportion from each source, and Melloni concluded that it was perfectly diathermanous; but it has since been shown that such is not the case, and that, though its absorbing power is in general small, it is still perceptible, and in particular cases, yet to be referred to, it is very great.

Influence of the Nature and Thickness of the Material.—From the list given in the table (which is from a much more extended one), it is seen that from the *same* source the transmitting powers of different substances are very different, and that for substances equally transparent to light, as rock-salt and alum, the transmitting powers are greatly different. The transmission of heat and light, then, in general are apparently not connected, and one cannot be taken as a measure for the other; but it should here be stated that, if the transmission from a distinct and separate portion of the spectrum be considered, then a substance which is transparent to the light (say *red*) of that portion also transmits the heat of the same portion.

With successive strata of the same material and thickness, in general the amount transmitted by the first, in proportion to the amount falling upon it, is less than with the succeeding strata; or we may say that a plate of given material in general exercises a sifting effect upon the rays of heat, and that such sifted rays are then better fitted to pass, and do pass with less obstruction, through a plate of the same material. The effect of varying thickness is in general as stated, but Masson and Jamin have shown that, if the heat of a separate and distinct portion of the spectrum be passed through successive strata of the same thickness and material, the amount transmitted decreases in a geometrical progression as the thickness increases in arithmetical progression. This simple law for the absorption of the solar heat by the earth's atmosphere was assumed more than a century ago, and has until recently been generally employed to determine the *solar constant*,—that is, the amount of heat which would fall in a unit of time upon a unit of area normally exposed at the earth's surface if there were no atmosphere. The recent extended and valuable labors of Prof. Langley have conclusively shown that the earth's atmosphere exerts a remarkable sorting power upon the solar rays, and that the above simple law is inapplicable to the case.

Prof. Tyndall showed that a solution of iodine in carbon bisulphide, though very opaque to light, permitted heat to pass in great quantity.

Absorptive and Emissive Powers of Gases.—It has been determined by Tyndall that the absorptive powers of elementary gases for heat from sources at low temperatures are less than those of compound ones; oxygen, hydrogen, and nitrogen, in the quantities experimented upon, exert an almost inappreciable effect, while olefiant gas (C_2H_4) exerts about one thousand times as much. The absorptive power increases with the density, but, in case of high absorptive power, not proportionally to it. The same lack of connection between transparency for light and for heat was observed in the case of gases as has been referred to in the case of solids.

Thus ammonia, which was quite transparent to light, was black or opaque to heat, while chlorine allows heat to pass more freely though much less transparent to light.

The absorptive power of vapors or the more readily condensable gases was even greater than that of the more permanent compound gases: thus the power of ammonia was greater than that of olefiant gas, and carbon bisulphide and alcohol had still higher powers. The most important of Tyndall's conclusions refer to the vapor of water, which, weight for weight, transcends all other gases or vapors in heat-absorbing power, so much that, according to him, though amounting on the average to less than one-half of one per cent. of the whole atmosphere, it exerts an absorbing action many times greater than the air through which it is diffused.*

Tyndall also examined the emissive power of gases, and found, as in the case of solids, that the best absorbers were also the best radiators.

Prof. Langley has demonstrated that the earth's atmosphere exerts a much greater absorbing power on the solar rays than was formerly supposed, so much so that something more than one-third of this energy is absorbed by the atmosphere when the sun is in the zenith. According to him, the amount of heat which would fall upon a normally exposed surface of a square centimetre area at the earth's surface in a minute if there were no atmosphere is three calories,—that is, it would raise one gramme of water three degrees in that time. This is probably the most accurate determination yet made of the *solar constant.*

Prof. Langley has also shown that, contrary to the general opinion, the longer waves of solar heat are more readily transmitted by the earth's atmosphere than the shorter ones, and, consequently, the dark solar heat more readily than the luminous. In such greater proportion are the shorter waves absorbed that if one could be above our atmosphere the sun would be blue.

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* The determinations of Magnus make the absorbing power of water vapor much less than that given by Tyndall. The results of Magnus's determinations are supported by the investigations of Hoorweg and Dr. Buff, and it now seems certain that Tyndall greatly overestimated the action of water vapor. An account of the last-named experiments may be seen in Pogg. Annalen der Physik., Bd. clv., clviii.

Laws of Cooling.—In determining the emissive powers of substances as described, it is evident that what was measured was not the *actual amount* of heat emitted in a given time, but, according to the theory of exchanges, merely the difference in the rate of exchange between the radiating body and the surrounding objects, including the thermopile. If the pile gives back as much heat to the radiating body as it receives from it, no matter how much this might be, the method of observation described would indicate no emission whatever. By varying the temperature of the pile it is evident that the indicated emissive power could be made to vary while the absolute quantity of heat emitted was the same, or by varying the temperature of both body and pile the indicated emissive power would remain unchanged while the actual quantity of heat emitted would change. It is plain, then, that the emissive powers thus determined establish no apparent relation between the temperature of the radiating bodies and the absolute amounts of heat emitted.

Law of Dulong and Petit.—To ascertain whether such relation existed, Dulong and Petit determined the rate at which the same body cooled *in vacuo* when its initial temperature exceeded that of the enclosure by different known amounts. They concluded that the rate of cooling in a given time depends not only upon the difference of temperature between the radiating body and the surrounding objects, but also upon its absolute temperature, and that the rate of cooling for a constant excess of temperature increases in a geometrical progression as the temperature of the enclosure or surrounding bodies increases in an arithmetical progression, and that the ratio of the progression is constant whatever be the excess of temperature.

From the above relations Dulong and Petit were enabled, in accord with Prévost's theory, to express the dependence of the rate of cooling of a heated body upon its temperature and its excess of temperature over that of the enclosure.*

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* The form of the equation is $B = C(a^{t+\theta} - a^{\theta})$, in which B is the rate of cooling; C is a constant depending upon the mass, extent of surface, specific heat and emissive power of the body; a is the ratio of the rate of cooling when the temperature of the enclosure is 1° to the rate when it is 0°, the excess being the same in the two cases; θ is the temperature of the enclosure; and t the excess of temperature of the heated body above the enclosure.

It was supposed by Newton that the rate of cooling of a heated body was directly proportional to its excess of temperature over that of surrounding bodies, and this statement constitutes Newton's law, but from the above experiments it is seen not to be true in general. However, Newton's law is sensibly accurate for small differences of temperature between the body and enclosure, and for differences not exceeding 15° or 20° corresponds very closely with the formula when the temperature of the enclosure is constant.

This law of Petit and Dulong was deduced in 1817.* Since that time experiment has shown that the law does not hold for all temperatures of the radiating body. Ferrel has recently shown that the same is true of the expressions of the law of radiation as given by Stefan (1879) and Weber (1888), and that for higher and lower temperatures a change is necessary in the value of the constants in the expression of the law for ordinary temperatures.

Interference, Polarization, and Diffraction.—In addition to the analogous phenomena attending the radiation of heat and light already referred to, there are others even more important in establishing the exact relation between heat and light and the exact nature of heat energy. We here merely name these phenomena.

Interference.—There are methods by which two rays or beams of light can be made to produce darkness; this phenomenon is designated interference of light. Two beams of dark heat can also be made to interfere so that the thermic effect of the *two* beams is less than of one.

Polarization.—It is also known that a ray of light after passing through a properly prepared plate of tourmaline will pass through a similar plate when held in a certain position, but not otherwise. This modified ray is said to be polarized. There are many other ways of polarizing light with results similar to the above. Heat may be polarized in the same way as light.

Diffraction.—When light passes, under certain circumstances, *by* an opaque body or *through* a narrow aperture, certain luminous effects are produced out of the direct line of the rays. Exactly similar phenomena have been observed with heat, and hence we see that heat can be diffracted as well as light.

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* Ann. de Chimie, ii., vii., p. 337.

It may here be added that the phenomena just mentioned are the strongest supports of the theory that radiant heat and light are the results of a vibratory motion of an elastic medium, and that the vibrations take place in directions perpendicular to that in which the undulations advance,—that is to say, in a direction transverse to the direction of the ray.

Distinction between Radiant Heat and Light.—From the fore going facts of this chapter, the marked analogy between radiant heat and light is evident, and, without further detailing their common characteristics, we may add that all their known properties point to the conclusion that there is no difference of a fundamental kind between them. On the contrary, all investigations combine to prove that radiant heat and light are the results of the same physical agent, the distinction between them being subjective rather than objective. This *agent* is now universally believed to be the moving molecules or particles of the body in which the phenomena of heat and light are observed to exist, and the condition of bodies as regards heat and light depends entirely upon the vibratory motion of their molecules. We have seen from the action of the grating that rays exist of refrangibilities much greater and less than those, which compose the light spectrum, and with the normal spectrum, the least refrangible rays extend far outside the red, while the most refrangible are beyond the violet. As has been observed, the greatest heating effect at the earth's surface is near the red, but Langley has shown that above the earth's atmosphere, owing to the greater absorption of the more refrangible rays, this maximum is transferred towards the violet. The more refrangible rays at the violet end of the spectrum and beyond have the property of acting more readily upon certain salts of silver, and the chemical effect is here a maximum. The physical distinction between these different parts of the spectrum is believed to be one solely of wave length. The dark spectrum beyond the red and violet is but the natural prolongation of the luminous one, and is caused by wave lengths which do not affect the visual organ, while those lengths which produce light do affect it. When the heat-wave length is greater than 0.000812 of a millimetre, and a little less than one-half this length, it ceases to produce luminous effect, though the heating effect in the first instance and the chemical effect in the second are very marked.

Prof. Langley has shown that the invisible heat spectrum, of greater wave length than red light, is many times the width of the visible spectrum,—as much as twenty times. The longest heat-wave length recognized ten years ago was 0.0015 millimetre, but the above-named physicist has succeeded in measuring lengths, from the sun as well as from other sources, of 0.03 millimetre.

A body at a low temperature emits only dark heat. As the temperature rises, the emission of dark heat becomes more energetic, and at the same time more refrangible rays are given off; the luminosity, to the human eye, begins when the red rays appear and goes on to include rays of other colors. Only bodies at the highest temperature give out waves of all lengths. Generally speaking, the rays which constitute the visible spectrum are the more transmissible, the extreme rays being most readily absorbed; but this is not always the case, for, as we have already stated, rock-salt is nearly as transparent to the ultra-red from the sun as it is for light, and a solution of iodine in carbon bisulphide is very transparent to the ultra-red and opaque to luminous ones. Rock-crystal, pure qnartz, is very transparent to the ultra-violet rays. The departure from this law in the case of the earth's atmosphere has already been noted.

It is also seen from the foregoing facts that the same substance stops the heat and light rays of the different parts of the spectrum unequally, and it has also been noted that certain bodies entirely stop the polarized beam. The peculiarity of heat, whether of polarization or wave length, which causes different rays to be unequally absorbed is termed *quality*. The increasing temperature of a body, besides developing rays of increasing refrangibility or of different wave lengths, also increases the quantity of each particular refrangibility, so that the higher the temperature the more energetic the radiation of every degree of refrangibility.

In conclusion, it may be accepted that heat and light are but varieties of the same physical agency; that light is heat which affects our sense of sight, while dark heat does not thus affect us.*

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*Melloni asserted this fact as far back as 1843, but it was not generally accepted as such until quite recently.

Selective Emission and Absorption.—The accepted view as to the nature of the heat agent enables us to connect together the various phenomena which come under this head. According to this view a hot radiating body is one whose molecules are in rapid vibration, and different bodies have different periods of vibration, which periods alter with the temperature, so that shorter periods are included at higher temperatures, and these vibrations are communicated to the luminiferous ether and propagated by it in undulations in all directions. Those conditions of a body which promote the transfer of its vibrations to the ether constitute it a good radiator, and the conditions which enable a body to take up the vibrations from the ether make it a good absorber. If the particles of a body can execute vibrations of only certain periods, they can take up or give out only that particular vibration; hence we have a conceivable explanation of selective absorption and emission.

A direct consequence of these principles is that bodies are opaque to their own radiation. Thus Stewart has shown that rock-salt, which is nearly transparent for most sources of heat, is nearly opaque if another piece of rock-salt be the source of heat. Glass readily absorbs heat of low refrangibility, such as is emitted by non-luminous bodies, but allows the luminous heat (light) to pass almost uninterruptedly. Accordingly, glass when heated emits abundantly non-luminous heat, but very little light. Red glass absorbs green light, but if it be heated to a high temperature it will give out in the dark the same color.

It has been shown by experiment that any bodies whatever, placed in a highly-heated furnace and allowed to acquire the temperature of the furnace, will not alter the light emitted from it. The bodies when cold may be opaque or transparent, colored or colorless, yet all will exhibit the same color in the furnace,—that of the furnace itself. This is explained when we remember that a body which absorbs certain kinds of rays emits the same on its own account, so that the radiation which it sends to the eye is partly its own and partly that transmitted from the coals behind, and the total is exactly the same as that which comes from other portions of the fuel. With an opaque body (such as polished platinum) this totality will be in large part due to reflected heat, but the result will be the same in kind and amount as that from the coals. If these bodies be taken out of the furnace, they will, in the dark, while hot, exhibit the tints due to their own emissions. A black body in such an enclosure would have the same tint as the others, but, being both non-reflective and nearly opaque to visible emanations, all its light is proper to itself, and, if taken out of the furnace into the dark, it would exhibit the tint of the enclosure.

The vibrating periods of gases are more sharply defined than those of solids or liquids, and they exhibit a more perfect equality of selective radiation and absorption. The vapor of sodium stops completely that portion of light which corresponds to a definite shade of yellow produced by its own combustion, and thus produces a dark line in the yellow of the solar spectrum.

Summary and Conclusions.—From the facts of this chapter we are enabled to draw the following conclusions:

In general, good radiators are good absorbers of heat and bad reflectors. Absorption and radiation are both surface actions in the case of bodies which, like lamp-black, are nearly opaque to heat, except of the greater wave lengths; metals are also practically opaque. In diathermanous bodies radiation and absorption go on in the interior also, so that a thick plate absorbs more heat than a thin one, and, at the same temperature, radiates more.

Bodies when cold absorb the same kind of rays that they give out when hot. Lamp-black is the most perfect absorber and radiator, it being devoid both of reflecting and diffusive power. Its absorbing power is also most nearly independent of the source of heat. It absorbs all rays nearly alike, the luminous as well as the dark ones. Lamp-black is accordingly taken as the standard surface of absorption, absorbing in the greatest degree every variety of ray which falls upon it.* It is consequently, also, when hot, the typical radiator, giving out the maximum amount of heat which any substance at the same temperature could possibly give out; moreover, it gives out the maximum amount of each kind of heat that can be given out by any body at that temperature. A heated body at first gives off obscure rays, but as the temperature rises a proportion of luminous rays are emitted; the ratio of the luminous to the obscure heat rays is in the case of all ordinary sources small.

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* Prof. Langley has recently shown that, for the greater wave lengths which he has succeeded in detecting, lamp-black is nearly transparent.

Tyndall showed that with the electric light this ratio was only one-tenth. Langley showed that of the radiant energy from an ordinary Argand gas-burner only 2.4 per cent were light, and when the energy consumed in heating the air by convection currents is considered, it is probable that less than 1 per cent of the total energy of the burner appears as light. All colored substances owe this element of their beauty to their partial behavior with reference to the different visible rays, and the popular impression which attributes warmth to the red and orange tones correctly, though probably unconsciously, expresses a physical fact.

We see also that a body may be a good reflector of luminous heat (light) and an excellent absorber of dark heat; white lead is a body of this kind. Domestic utensils, as tea- and coffee-pots, which are intended to retain heat, are more efficient when they have polished metallic surfaces; while the outside of stoves should be black, and apparatus for heating by radiation should not be of polished metal, as is frequently the case with hot-water apparatus. Fireplaces should be lined with fire-brick to radiate heat into the room, at the same time keeping up the temperature of the fire. Glass screens transmit the light from the fire but intercept the larger part of the dark heat; glass for the same reason is efficient in conservatories.

Radiation and conduction are the only processes by which heat as such ever leaves a body, and while there is, as we have pointed out, a distinction between the processes, their ultimate effect is the same,—viz., to reduce all bodies to the same temperature.

CHAPTER IX.

THERMO-DYNAMICS.

Thermo-dynamics is that branch of science which treats of the relations of heat to other forms of energy.

We are here principally concerned with the relations between heat and mechanical effect. That heat can be made to produce work is a fact familiar to all. Indeed, heat is through engines the most important source of mechanical power that we possess.

Many familiar facts also supply us with illustrations of the production of heat by the expenditure of mechanical energy. Some examples are here given.

Heat by Friction.—The common method of lighting a match by friction is one of the simplest illustrations of this conversion of mechanical energy into heat. Formerly the American Indians, by rapidly rotating a small rod of wood while pressing it firmly against a depression in another piece, managed to ignite fine dry shavings and thus kindle their fires. Other savages are said to accomplish a similar result in a similar manner.

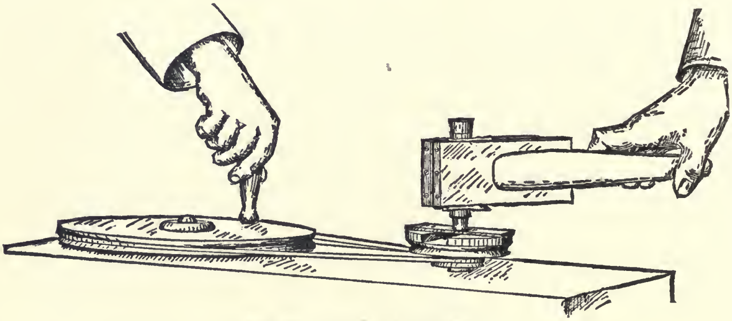

Fig. 38.—Heat by Friction.

An experiment of Tyndall's illustrates the same principle. He mounted a small tube (Fig. 38), so that it could be rapidly rotated about its axis; when filled with water and closed by a cork and rapidly rotated, while pressed between two pieces of wood covered with leather, the cork was blown out by the steam developed by the heat due to the friction.*

In the year 1798 Count Rumford published results of experiments as to the large amount of heat produced by friction in the boring of cannon. He called attention to the fact that the source appeared "evidently to be inexhaustible," and argued that anything which could under the conditions be thus furnished without limitation could not be a "material substance." And he declared it "extremely difficult if not impossible to form a distinct idea of anything capable of being excited and communicated in the manner that heat is communicated in these experiments, except it be motion."

Sir Humphry Davy in 1799 showed that two pieces of ice could be melted by rubbing them together *in vacuo* at a temperature of 0° C., and he concluded that "Heat is motion, and its laws of communication are the same as those of the communication of motion."

The energy expended in compressing the air in a fire-syringe may be made to develop heat enough to inflame the vapor of carbon bisulphide and produce light. To accomplish this a piece of cotton may be moistened with carbon bisulphide and placed at the bottom of the syringe (Fig. 39); the piston may then be inserted, and if suddenly shoved down a flash of light will be visible.

The evident production of heat in the above case was formerly accounted for by supposing that the capacity of the gas for heat was diminished by pressure, and that the heat which it contained was thus enabled to raise it to a higher temperature, the pressure thus serving to squeeze out the *caloric*, and hence a development of heat. The same idea was appealed to for an explanation of the development of heat in a piece of soft iron, when rapidly pounded while resting upon an anvil. These explanations were based upon the belief that heat was a material substance, and it

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* A mixture of water and alcohol will accomplish the result with less work.

was held that these and all similar phenomena could be explained as depending upon altered distribution without any production of heat.

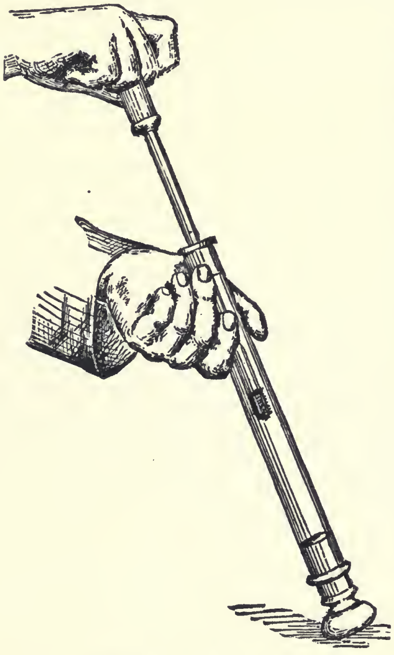

FIG. 39.—FIRE-SYRINGE.

Rumford, in the experiments above given, attempted to show that this explanation was insufficient, by proving that the metal shavings from the bored gun had the same *capacity* for heat as the metal in bulk. Had he shown this conclusively, his experiments would have been fatal to the material view of heat; but, although he showed that the heat developed was out of all proportion to what might be expected by such view, he failed to consider that his metal chips were in a different physical condition from the metal of the gun, and, for his experiments to have been conclusive, they should have been the same.

Davy's experiments, as above given, were entirely conclusive as to the immateriality of heat, but, like Rumford, his failure to consider that the ice and water produced were in different physical conditions made his reasoning less conclusive. Rumford was so impressed with the idea that heat was not material that he sought to determine the ratio of heat to the work necessary to develop it. Notwithstanding these suggestive experiments of Rumford and Davy, the material view of heat was almost universally entertained until about 1840.

The idea that heat and mechanical energy are definitely convertible seems to have been entertained by a number of men at about this time. Séguin in France in 1839, Mayer in Germany in 1842, Colding in Denmark in 1843, and Joule in England in 1843 to 1849 made and published determinations of the mechanical equivalent of heat. So far as the others were concerned, each of these philosophers may be said to have been independent and original in the investigations here referred to.

To Joule, however, must be given the credit of having first established exact numerical quantitative relations between mechanical energy and heat, thereby causing the general acceptance of the mechanical theory of heat.

Mechanical Equivalent of a Unit of Heat.—The unit of heat has been already defined (p. 27), and to determine the amount of energy necessary to be expended in producing this heat was the object of Joule's experiments. Joule's method of experiment was to cause the mechanical energy of a descending weight to produce friction between iron plates, or to agitate different liquids (water and mercury) by means of a paddle-wheel. In the first case, of friction between iron plates, the plates were enclosed in a cast-iron vessel filled with mercury. The heat developed was measured by the rise of temperature in the liquid agitated, and, in the case of the iron plates, by the rise in the surrounding mercury. The weight was allowed to descend many times and the mechanical work thus expended accurately computed. As accurate corrections as possible were made for all losses of heat by radiation, conduction, rigidity of cords, and friction outside the calorimeter, etc. The thermometers were capable of indicating variations of $\frac{1}{200}$ of one degree F.

The conclusions of Joule were :

1. That the quantity of heat produced by the friction of bodies, solids or liquids, is proportional to the force expended.*

2. That the quantity of heat necessary to raise the temperature of 1 pound of water (weighed *in vacuo* between 55° and 60° F.) 1° F., requires for its evolution the expenditure of the mechanical energy represented by the fall of 772 pounds through a distance of 1 foot.

These experiments were made at Manchester, England, and although the foot-pound does not denote exactly the same energy at all points of the earth's surface, the variation is not greater than the probable error of the determination ; we may therefore say that the energy comprised in one pound-degree Fahrenheit

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* We should now say *energy* expended.

is 772 foot-pounds. For a centigrade degree this number would be 1390.

If we take for units the kilogramme-degree C. for heat, and the kilogramme-metre for work, this number becomes 424, since a kilogramme is 2.205 pounds and a metre 3.281 feet. For the gramme-degree C. and the gramme-centimetre it is 42,400.

These numbers are known as Joule's Equivalents in the respective systems. Joule's recent determinations (1878) do not sensibly change this number, and it is probably correct to within $\frac{1}{300}$ of its own amount (Rankine).

Prof. Rowland, of the Johns Hopkins University, has also determined the mechanical equivalent by using Joule's method of agitating water by a paddle-wheel. The apparatus devised by Prof. Rowland could hardly be surpassed in the perfection of arrangement necessary to accurate results. The advantages of Rowland's arrangement as compared with Joule's can only be fully appreciated from a full description, such as cannot be here given. The mean difference between Rowland's and Joule's determinations, when the latter's temperatures were reduced to those of the air thermometer, amounts to only 1 in 430. Prof. Rowland's determinations showed conclusively that the specific heat of water decreased with an increase of temperature, and his value for the mechanical equivalent of a unit of heat when water is taken at the temperature of 60° F. is 778.9. Prof. Rowland thinks that subsequent experiments will not change his results more than 1 in 500. At 15.5°, the equivalent temperature on the centigrade scale, the number is 1402.

There are other methods for determining the mechanical equivalent, and the agreement of all the results is now deemed conclusive that equal quantities of mechanical energy always correspond to the same amount of heat.

The measurement of the work done by heat, or the inverse of Joule's problem, was first accomplished by Hirn in 1862. His results, when the mechanical difficulties of the problem are considered, are completely confirmatory of Joule's.

When heat is measured as a *quantity*, it should be remembered that the temperature or condition of the body in which it exists is immaterial. The mechanical equivalent of a definite amount of heat is always the same, no matter what the temperature of the body in which it exists. The heat, however, is more available for conversion into mechanical energy when at a high temperature.

First Law of Thermo-Dynamics.—A correct expression for the relation between heat and mechanical energy constitutes the First Law of Thermo-dynamics. It is expressed by the equation $W = JH$, in which W denotes work, J Joule's equivalent, and H heat units.

When heat is admitted to be a form of energy and the theory of the conservation of energy is accepted, the truth involved in the above expression is axiomatic, and it is but a particular case of transmutation of energy. Work is not energy, but rather the operation or process by which energy is transmuted. The amount of work is measured by the energy transmuted, which is always left behind in some other form.

This transmutation of heat into mechanical energy and of mechanical energy into heat is so familiar that it barely needs to be referred to. All steam-boats, cars, steam-pumps, power engines, etc., derive their useful motion and work from the heat energy of the burning coal in their furnaces. In these same cases we find the energy of the moving parts by friction and concussions producing heat.

Heat Consumed in Expansion.—When a gas expands without having to overcome external resistance, that is, without doing external work, its temperature is not sensibly changed ; but when it does external work its temperature falls. A gas which develops mechanical power in expanding can only be kept at a constant temperature by the addition of heat to it, and the heat necessary to be thus added is nearly, though not exactly, the thermal equivalent of the work done by the gas during expansion; the approach to equality being the nearer, the nearer the gas approaches the condition of a perfect gas. Consequently, if a gas does work without transfer of heat to or from it, the thermal equivalent of the work must disappear as heat. It is thus evident why it was necessary to make a distinction between the specific heat of a gas at constant volume and at constant pressure. The work done by a gas on expanding against uniform hydrostatic or pneumatic pressure may be computed by multiplying the increase of volume by the pressure per unit of area.

Thermic Engines.—In all forms of thermic engines work is obtained by means of expansion produced by heat in some elastic fluid, the expansive force usually acting on a piston travelling in a cylinder. Of the heat received from the source by the fluid a fraction only can under any circumstances be converted into mechanical work. A portion is lost by conduction through the parts of the apparatus, another portion remains in the fluid when it escapes into the air or condenser, and a third portion has disappeared and ceased to exist, for the time being, as heat. The heat thus converted or utilized bears to that received from the source a simple relation depending only upon the temperatures of the source and refrigerator. The second law of thermo-dynamics refers to this relation, and one of its expressions may be made in this form: *No part of the heat of a material object by the action of natural processes alone can be converted into mechanical energy except by allowing the other part to pass from that body into other bodies at a lower temperature.*

In the conversion of heat into mechanical energy by engines, or doing work by means of heat, the expanding fluid (as air in the hot-air engine, or steam in the steam-engine) is called the working substance. In order that the process may be continuous, it is evident that the action of the machine by which the conversion is accomplished must be periodic; that is to say, after a series of changes all parts of the machine must return to the same relative positions and conditions as at the beginning; and to facilitate the conception here desired, the condition of the working substance at the end of the operation will be taken the same as at the beginning. A series of operations by which this result is accomplished is called a *cycle.* If the working substance is not in exactly the same condition at the end of the cycle as at the beginning, we should have to know the energy involved in the change of condition before we could estimate the other work involved in the cycle.

To determine the law governing the performance of work by the conversion of heat into mechanical energy, recourse is had to a conception of Sadi Carnot set forth in 1824, and brought into renewed prominence by Prof. (now Sir William) Thomson in 1848. Carnot's machine is an entirely imaginary one and impossible of construction, and used only for scientific illustration and deduction; but by describing an ideally perfect engine he brings out the points to be kept in view in the construction of possible engines in any case. This ideal engine is usually known as Carnot's reversible engine.

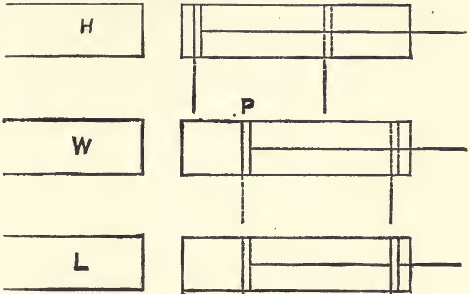
Carnot's Cycle.—The conception is as follows:

Suppose we have a cylinder, with piston *P* (Fig. 40), containing air as the working substance, though we might take any other. The walls of the cylinder and the piston are absolute non-conductors and non-absorbers of heat, the bottom of the cylinder is a perfect conductor and without specific heat; heat to and from the cylinder can only pass through this bottom. *W* is a body which is a perfect non-conductor and non-absorber of heat, *H* and *L* are bodies at temperatures which remain constant during the operation, that of *H* being higher than that of *L*.

Let us suppose that the cylinder stands on *W* and the piston is any distance above the bottom, and the working substance (which we will hereafter for brevity indicate by *ws*) at the temperature of *L*.

1st Operation.—Let the piston be depressed until the temperature of *ws* rises to that of *H*.

FIG. 40.—CARNOT'S ENGINE.



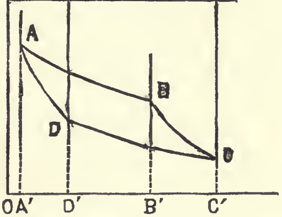


FIG. 41.—GEOMETRICAL ILLUSTRATION.

2d Operation.—Now transfer the cylinder to the hot body *H*, and allow the piston to rise: the expansion of *ws* tends to produce a fall of temperature; but this is prevented by heat flowing in through the perfectly conducting bottom of the cylinder, and *ws* expands at the temperature of *H* and the piston ascends through a certain distance.

3d Operation.—Now move the cylinder back to *W* and allow the piston to rise, and let *ws* expand until its temperature falls to that of *L*, then stop the expansion.

4th Operation.—Now transfer the cylinder to the colder body L and depress the piston. The temperature of *ws* would rise, but it is prevented by the heat flowing through the bottom of the cylinder into L. When the piston is depressed to the point at which we commenced in the first operation, let the cylinder be transferred to W. Everything will now be exactly as it was in the beginning, and, with the imagined arrangement, the operation can be repeated indefinitely, a cycle being completed each time these operations are gone through with.

Work done during the Cycle.—During the cycle there were two elevations and two depressions of the piston. During the elevations work was done *by ws* (working substance), measured by the average pressure on unit of area in each case multiplied by the distance through which the piston moved; during the depressions work was done *upon ws,* measured in each case in the same way Since the piston at the end of the cycle is in the same position as at the beginning, the sums of the elevations must be equal to the sums of the depressions: and since the elevations took place at the higher temperature, the average pressures during the elevations must have been greater; therefore, the work done *by ws* during the elevations must have been greater than that done *upon* it during the depressions. As these operations can be continued indefinitely, we have a means of obtaining useful work.

Transference of Heat during Cycle. — From the conditions imposed upon our ideal engine, it will be seen that there was no transference of heat to or from the cylinder, except during the second and fourth operations. During the second operation heat was taken from the hot body, and during the fourth heat was given to the cold body.

Results and Conclusions.—At the end of the cycle everything is, so far as we are able to discover, exactly as at the commencement; more work has been done *by* the substance than *upon* it, and a certain quantity of heat has been taken from the hotter body and a certain quantity transferred to the colder body. The principle of the conservation of energy, which cannot be shaken by any evidence yet available to us, teaches that the useful work (the excess of work done *by* over that done *upon ws*) must arise from some expenditure of energy. With our present knowledge the only conceivable source is the heat taken in during the second operation, and therefore we conclude that the heat taken in during the second operation is greater than that given out during the fourth by an amount equivalent to the useful energy.*

If W represent the useful energy obtainable from the engine, and Q the heat communicated to it at the higher temperature, $\frac{W}{Q}$ measures the efficiency of the engine; or if Q' equal the heat given out by *ws* at the end of the operation, the efficiency may be written

$$\frac{Q - Q'}{Q},$$

or the efficiency of the engine may be defined as *the ratio of the heat converted into work to the whole amount which enters the engine.*

Geometrical Illustration.—The above cycle of operations may be illustrated geometrically as follows:† In our cylinder the distance between the piston and the bottom of the cylinder is always proportional to the volume of the working substance; now let, in the diagram (Fig. 41, p. 101), A', B', C', and D' be the positions of the piston at the end of each operation, and O the bottom of the cylinder, and let AA', BB', CC', and DD' be perpendiculars proportional to the pressures at these points.

At the end of the fourth operation and at the beginning of the first, the piston is at D'. During the first operation the volume is decreased and the pressure increased, the piston moving to A'. The work done during the compression is equal to the mean pressure

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* Carnot thought that the useful energy was due to the loss of temperature by the heat. He thought that the energy of a given quantity of heat was greater when it existed in a hot body than when in a cold one. We now know that the mechanical energy of a given quantity of heat is the *same*, no matter at what temperature it exists.

† The diagram is known as the "indicator diagram," and is very convenient for representing and explaining to the eye the working of a fluid of variable volume. It is not deemed necessary here to fully describe the principles of this method of indicating the working of a fluid. The statements referred to in connection with the diagram are susceptible of easy proof.

exerted on the piston multiplied by the distance $A'D'$. The mean pressure is somewhere between A and D, and the product is the area $AA'D'D$; the work is proportional to the area and may be represented by it. In the same way it follows that the work in the 2d, 3d, and 4th operations may be represented by the areas $A'ABB'$, $B'BCC'$, and $C'CDD'$, respectively.

The work done *by ws* during the whole expansion is represented by the area $A'ABCC'$, that done *upon ws* during compression is represented by the area $A'ADCC'$, and the difference or balance of useful work is represented by the area $ABCD$. It is likewise provable that the area $A'ABB'$ described under the circumstances is proportional to the heat imparted to *ws* during the 2d operation, and the area $D'DCC'$ is proportional to the heat given out by *ws* during the 4th operation, and that heat has disappeared represented by the area $ABCD$, which is the representation of the work done; the ratio

$$\frac{ABCD}{A'ABB'}$$

on the diagram represents the efficiency of the engine.

Principle of Reversibility.—This hypothetical engine of Carnot's is also reversible,—that is to say, all the operations described may be performed in the reverse order, as follows:

Referring to Fig. 41, let us begin at the temperature of the colder body L and volume OD' (on diagram), let the cylinder be placed on L and allow expansion from volume OD' to OC'; *ws* (working substance) will receive from L a quantity of heat. Let the cylinder then be transferred to W and the piston compressed until the volume is OB'; *ws* would then have the temperature of H. Now transfer the cylinder to H and press the piston to volume OA'; during this operation *ws* will give out a quantity of heat to H. Lastly, transfer the cylinder to W and let expansion occur to OD'; *ws* will then be in its original state. Now, by considering the *diagram*, and remembering that the areas marked out are proportional to the work done during the motion of the piston and also to the transfers of heat during the 1st and 3d operations, it is seen that more work is done *upon ws* than *by* it, and that more heat is communicated to H than was taken from L. The same fact is evident when we consider that the work done *upon ws* is during the *compression* of the piston, and that *by* it during the *elevation,* and that the former takes place at the higher temperature.

With such an engine we see that it is possible to transfer heat from a body at a lower to one at a higher temperature, but that such result can only be accomplished by the expenditure of mechanical energy. If we accept this as the only means of such transfer (and our experience compels us to deny every other), it can be readily shown that the efficiency of a reversible engine is the greatest that can be obtained with a given range of temperature.* No engine, therefore, could be more perfect than a reversible one; hence, reversible engines being perfect, they all convert the same proportion of the heat received into mechanical energy when working between the same temperatures of source and refrigerator, no matter what the working substance be. It can be further shown, from the principles of the indicator diagram, that the quantity of work can only be increased by increasing the quantity of heat taken in, or with the same quantity of heat by increasing the difference between the temperatures of the hotter and colder bodies which diminishes the amount given out.

Absolute Temperatures.—The conceptions of Carnot, as Sir W. Thomson † has pointed out, give also the conception of a scale of temperatures the definition of which is independent of the nature of any particular substance. From the above principles it is seen that *quantities of heat* and *intervals of temperature* are the only elements upon which the useful work of a perfect engine depends, and, if the quantity of heat taken in by the working substance be constant, the useful work depends only upon intervals of temperature between the source and refrigerator. If the intervals of temperature in different cases then be so divided that the number of divisions is proportional to the quantities of heat converted into useful work, then these divisions will be as definite and absolute as are our measurements of quantities of heat.

On a scale with such divisions or degrees the numbers of degrees between different intervals would be proportional to the

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* See foot-note on page 119

† Cambridge, P. S. P., June, 1848.

amounts of useful work done by a perfect engine when working through these intervals and taking in the *same* quantity of heat each time. Now, if the temperature of the hotter body be fixed and the quantity of heat taken in be fixed, the useful work done depends only on the temperature of the lower body or refrigerator. If the temperature of the refrigerator be so determined that the useful work done shall be equal to the total heat received, we could not possibly have more work than this from that amount of heat; consequently such a point would be the absolute zero, and we would be precluded from a negative temperature on such a scale.

In terms of such a scale as just described the efficiency of a perfect engine can be shown to be equal to $\frac{T - T'}{T}$, or

$$\frac{Q - Q'}{Q} = \frac{T - T'}{T},$$

in which Q is the quantity of heat taken in, Q' the quantity given out, and T and T' the absolute temperatures of the source and refrigerator respectively. From the above we have

$$\frac{Q}{T} = \frac{Q'}{T'};$$

or, absolute temperatures may be defined as such as are proportional to the quantities of heat taken in and given out by perfect engines.

From the above considerations it is seen that in order to construct a scale of absolute temperatures it is only necessary to determine the maximum amount of mechanical energy that a given quantity of heat (say one unit) is capable of giving out during its transmission from a body at one temperature to another at a lower temperature; that is, the same amount as would be given out by a perfect engine between these temperatures. The discussions of Carnot's ideal engine have shown what physical properties, capable of experimental determination in certain working substances, are necessary to obtain this amount of work.* By taking the number

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* The experiments necessary to be made on the working substance for the determinations of the quantities of heat taken in and given out by a perfect engine have not been successfully made, but in a different way the absolute dynamical scale has been compared with the so-called absolute scale of the air thermometer. (See Maxwell's Theory of Heat.)

of degrees between the temperatures considered the same as that by any of our ordinary scales, it is evident that the size of our absolute degrees will be equal to the mean value of the degree on the scale used. The comparison of the absolute thermo-dynamic scale with that of the air thermometer shows them to be almost exactly the same, the absolute zero on the two scales is within a fraction of a degree centigrade of the same point, when the absolute thermo-dynamic degrees are so taken as to make 100 between the freezing and boiling temperatures of water.

In concluding this discussion of Carnot's cycle, it may be well to add that in practice the cycle is not usually completed, the same portion of the working substance not being made repeatedly serviceable. At a certain point of its expansion the working substance may be discharged into the atmosphere and a fresh portion taken in to supply its place. In the case of steam, when a condenser is used, the water produced is returned to the boiler, but here the regularity of the cycle is broken by the abrupt condensation of the steam before it has done all the work of which it is capable. In general a portion of the useful work in engines has to be sacrificed to avoid a greater loss in establishing a complete cycle. Besides this loss of useful work there is loss of heat at every stage of the operation by radiation and conduction. But, discarding these sources of loss and assuming a perfect engine, it will be seen from the expression for the efficiency

$$E = \frac{T - T'}{T},$$

that only a small fraction of the heat taken in is converted into mechanical energy; for, suppose we have an engine working under a pressure of 130 pounds per square inch, this would require a temperature of 185° C., which reckoned from the absolute zero would be 458° for the upper temperature, and if the engine be non-condensing the lower temperature would be 373° on the absolute scale; these numbers in the expression above give

$$\frac{458 - 373}{458} = 0.19 \text{ nearly.}$$

Steam-Engine.—We shall now explain the elementary principles of the reciprocating steam-engine and describe the essential parts.

The earliest application of the principle for accomplishing useful work is said to have been made by Savery, an English mining engineer, about 1697. He invented a machine by which the pressure of steam was made to force water from a receiver up through an ascending pipe, and then by condensing the steam, by the application of cold water to the outside of the receiver, more water was forced by atmospheric pressure into the receiver and the operation repeated. This was really a steam-pump, and was to a limited extent used in draining mines.

Papin, the inventor of the digester (page 44) and of the safety-valve, was the first to conceive the idea of making steam move a piston and thus communicate motion to mechanism. He constructed in 1690 a working model which consisted of a vertical cylinder with a piston and a little water beneath it. By converting the water into steam the piston was forced up, and upon condensation of the steam the atmosphere forced the piston down. Papin's cylinder was also the boiler, and the condensation was brought about by removing the cylinder from the fire and cooling it.

Newcomen, Savery, and Cawley, in 1705, combined the cylinder and piston with the separate boiler, and condensed the steam by injection of cold water into the cylinder. The descent of the piston was produced by the atmosphere, and hence the engine is generally referred to as Newcomen's atmospheric engine.*

In 1763 and 1764 James Watt, while repairing a model of Newcomen's engine (belonging to the University of Glasgow, and still preserved there), perceived the defects of the machine, and conceived the idea of improving it. In 1769 his first patents were taken out. His first improvement consisted in the introduction of a separate vessel for the condensation of the steam. In the second improvement he substituted the pressure of steam for the atmospheric pressure which caused the downward stroke in Newcomen's engine; the upward stroke was effected by means of a counterpoise, the steam pressing equally on the two sides of the

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* Arrangements for automatically operating the valves of an engine were devised by Newcomen and Savery and are shown in a cut of an engine erected by them in 1712. Desaguliers in his Experimental Philosophy, vol. II, 1743, claims this improvement for a boy, Humphrey Potter, 1713, but the above fact disproves the claim.

piston. This engine succeeded Newcomen's, and is known as the *Single-Acting Engine,* because only the down-stroke is produced by the steam. It is still frequently employed, because of the simplicity of its arrangements. It was not long before Watt perfected his engine by employing steam to produce both strokes. This is the characteristic of the *Double-Acting Engine,* and the improvements since Watt's time have been of detail rather than principle. Early attempts at steam navigation had been made before, but it was first established on a commercial basis in 1807 by Fulton on the Hudson River, New York. Fulton's vessel was driven by an engine made by Boulton and Watt.

Double-Acting Engine.—The principle of this engine is very simple, and will be understood from the figure (Fig. 42). The steam is admitted from the boiler to the top and bottom of the cylinder by the pipes a and b, and escapes from the cylinder to the condenser through the pipes c and d. If the stopcocks a and d are open while b and c are closed, it is evident that the steam from the boiler will force the piston in one direction; and then, if a and d be closed and b and c be open, the piston will be driven in the other direction. By suitable connections with the rod of the piston, this alternate motion can be converted into one of rotation.

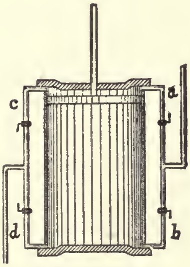

FIG. 42.—DOUBLE-ACTING ENGINE.

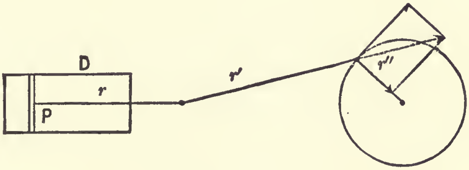

FIG. 43.—PISTON CONNECTIONS.

The principle by which this rectilinear motion of the piston is converted into circular motion is shown in the diagram (Fig. 43), in which D is the cylinder, P the piston, r the piston-rod, r' the connecting-rod, and r'' the crank. It will be seen from the figure that at the beginning and end of the stroke in this arrangement the piston-rod, connecting-rod, and crank are in the same right line, and pressure on the piston at these positions will not turn the crank either way. These positions of the piston are called the *dead points.* The momentum of the wheel or machinery to which the crank communicates motion carries it beyond these points, and the motion is continued.

Arrangements for Admitting Steam.—In the above simple description we have supposed the cocks to be operated by hand, but the opening and closing of steam-passages is really effected automatically, and the distribution of steam is regulated by valves. The arrangement of the simplest form of slide-valve is shown in the figures (Figs. 44 and 45). The steam, instead of entering the cylinder direct, first passes into the steam-chest *C.* Besides the opening for the admission of steam in the chest, not shown in the figure, there are three other holes called *ports;* two of these, *a* and *a'*, communicate with the cylinder at the opposite ends, and the other, *H,* communicates with the condenser. *D* is the slide-valve, and in this case is exactly the length contained between the outer edges of the steam-ports, and its faces are just sufficient to cover the widths of the steam-ports. In Fig. 45, when the valve is at the upward part of its stroke, the steam is admitted to the lower part of the cylinder from the chest and escapes into the condenser from the upper part through the port *a'* and *H*; the reverse is the case when

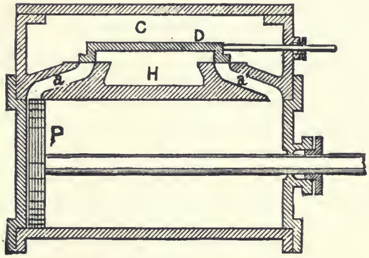

FIG. 44.—SLIDE-VALVE CENTRAL.

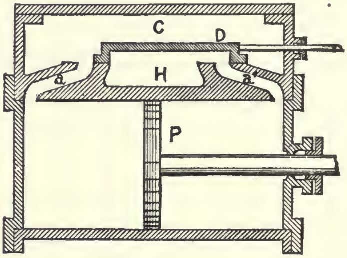

FIG. 45.—SLIDE-VALVE UPWARD.

the valve is down. The slide-valve is moved automatically by the engine itself by means of an eccentric or other arrangement.

An eccentric is a species of crank. A simple form consists of a circular piece of metal *e* (Fig. 46), called the eccentric. This is traversed by the shaft of the engine in a point other than the centre. The eccentric is firmly attached to and revolves with the shaft. This eccentric turns inside a ring of metal, which ring is rigidly connected to the frame-rod *T*. It is evident that the rotation of the shaft will cause a reciprocating motion in *T*, which by suitable gearing can be made to move the valve. The distance from the centre of the eccentric to the centre of the shaft is called the eccentric radius.

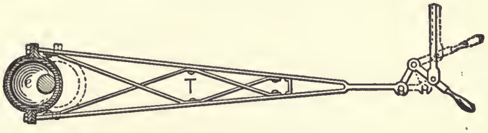

Fig. 46.—Simple Eccentric.

The simple D-valve just described, for illustrating the principle of valves, is in common use in the smaller types of land engines and locomotives, but there are many other forms and arrangements of valves more advantageous in larger engines.

The double-ported slide-valve, the piston-valve, and the cylindrical valves of the Corliss engine are examples of these, but their description is not appropriate to this book.

Modification of D-Valve for Expansive Working.—By the simple valve just described, and when the radius of the eccentric is at right-angles to the crank, steam is admitted on one side of the piston during the *whole* length of the stroke; and the port to the condenser, or *exhaust* on the other side, is also open during the same time. In such an arrangement steam of the same density and pressure acts on the piston during the entire stroke, and steam only begins to be admitted to the cylinder as the valve moves from its central position (Fig. 44), and the steam is completely exhausted from the cylinder on the side of the piston toward which motion takes place, because the exhaust on that side is open all the while the piston moves in that direction.

In practice these features do not exist. The steam is cut off comparatively early in the stroke, and acts by expansion during the remainder of it; the exhaust is also closed before the end of the stroke, so that the steam left in the cylinder is compressed and acts like a cushion before the advancing piston, and the arrangement is such that steam is admitted just before instead of just after the beginning of the stroke.

These first two objects are usually accomplished by increasing the width of the faces of the valve, as shown in Fig. 47; the width added to the outside is called outside lap, the other the inside lap. By such an arrangement the admission and escape of steam is cut off earlier than with a valve without lap, and the expansive action of the steam is secured on the driving side of the piston and the cushioning effect on the other.

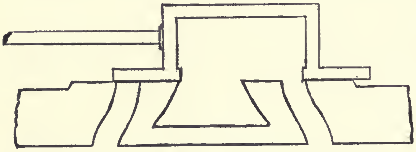

FIG. 47.—VALVE FOR EXPANSIVE WORKING.

In working expansively, the part of the stroke at which the cut-off occurs varies considerably,—sometimes at half-stroke, sometimes at one-quarter, and sometimes at one-fifth of the stroke. The above is not the only way of regulating the amount of expansion.

The amount by which the admission steam-port is open at the commencement of the stroke is called the *lead*, and is brought about by the proper adjustment of the positions of the crank and the radius of the eccentric.

The above arrangement is usually sufficient for ordinary engines which work in one direction, but, where engines have to be frequently reversed, other arrangements have to be adopted. The method usually employed is known as Stephenson's link-motion, though there are others in use. Without describing in detail this arrangement, we may say that it consists of two eccentrics oppositely placed on the shaft, and the slide-valve rod can be shifted from one to the other by means of a link and the valve thus be made to obey either eccentric, and this change reverses the engine. When the link is kept half-way between the two eccentrics, the valve remains in its central position, no steam is admitted, and the engine stops. By varying the position of the link, the distribution of the steam can be entirely modified. Locomotive engines and most engines needing frequent reversals are regulated in this way, not being fitted with governors.

Governors.—To prevent variations in the speed of the engine when the load is varied, a contrivance called a governor is made use of. It usually acts by opening or closing the *throttle-valve* which regulates the admission of steam into the steam-chest. The simplest form of governor is that invented by Watt, and its description will serve to illustrate the principle. It consists of two metal balls attached to inclined arms which are jointed to the upper end of a vertical axis. Two rods are jointed to the arms and to a collar which embraces the axis. The axis is rotated, through gearing, by the main shaft. When the engine is at rest the balls hang down as in the figure (Fig. 48). The balls fly out as the velocity of rotation increases, the collar is raised and by means of levers acts on the throttle-valve.*

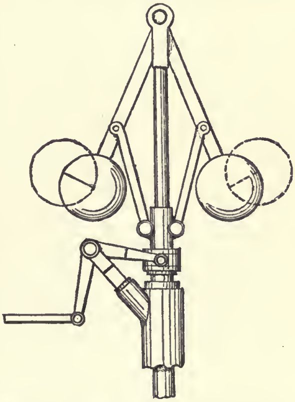
FIG. 48.—CENTRIFUGAL GOVERNOR

The forms of governors are many, and owing to the size of parts in large engines, steam governors are frequently employed. The governor proper acts upon a steam cylinder, and this actuates the regulating machinery.

Fly-Wheels.—It has already been seen that at the *dead* points the steam only presses the crank-axle against its bearing and exercises no rotary effect on the shaft; the turning effort varies from nothing at these points to its maximum value when the crank is nearly at right angles to the connecting rod. Other causes, as the variations in the steam-pressure, the weights of the piston and connecting rods, also cause variations in the driving power, which produce variations in the velocity of rotation. The effect of variations in the resistance to be overcome in producing the same results has already been referred to. Sudden changes in the velocity of rota-

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* The governors, instead of acting on the throttle-valve as above described, are often arranged to act by link-motion directly on the expansion-gearing of the slide-valve.

tion are injurious to the mechanism of the engine because of the shocks they produce.

The object of the fly-wheel is to prevent these irregularities of motion. It is a large, heavy wheel, with the mass collected as much as possible about the rim. It receives a rotary movement from the engine. When the driving power is in excess of the resistance all the moving parts of the engine acquire increased velocities, but the large moment of inertia of the fly-wheel prevents a sudden increase of velocity and absorbs a large proportion of the excess of energy, a small change in the angular velocity of the fly-wheel corresponding to a large amount of energy. The energy thus absorbed by the fly-wheel is restored to the rotating parts when the resistance is in excess of the driving power, and thus tends to keep the rotation of the shaft uniform. The size of the fly-wheel is usually made such that the difference between the greatest and least velocities shall not exceed about one-thirtieth of the mean velocity for ordinary machinery and about one-fiftieth for fine machinery.

It will be observed that the governor never acts until the change of velocity occurs which it is designed to control, but the fly-wheel resists all change from its beginning.

In the above description we have supposed a single cylinder. Two or more cylinders may be made use of, coupled to the same shaft by cranks making angles with each other, so that the rotary effort is very nearly the same in all positions of the shaft. Variations in velocity of rotation, due to variations in rotary effort on the crank, can be thus nearly obviated. Locomotive engines are supplied with two cylinders, and their cranks are at right angles to each other. The variations in rotary effort may also be largely overcome in the next form of engine.

Compound Engines.—These are among the most efficient means of preventing the condensation which so generally occurs when steam is worked under high pressure and expansively, and they have the mechanical advantage of nearly equalizing the strain on the piston throughout the stroke.

In these engines the total expansion of the steam is divided between two or more cylinders, so that the extreme range of temperature due to expansion in any one cylinder is greatly diminished. The successive cylinders increase in diameter, and, when the pressure is very great, as in many modern marine engines, three and even four cylinders are used, giving rise to triple and quadruple expansive engines.

In compound engines there may be only one crank used, in which case the two pistons are connected with the same rod, giving rise to *tandem* engines. When there is more than one crank, they may or may not make angles with each other. If there is but one crank or the cranks are in the same plane, the pistons of the different cylinders rise and fall together.

One of the simplest arrangements for showing the principles of the compound engine of two cylinders is seen in Fig. 49. In the upward stroke the steam is admitted below in both cylinders, coming from the boiler to the small or high-pressure cylinder, and exhausting from the upper part of this to the lower part of the larger one. During the downward stroke the steam is admitted at the upper ends of the cylinders from the same sources. The high-pressure cylinder exhausts into the larger one, and it exhausts into the condenser.

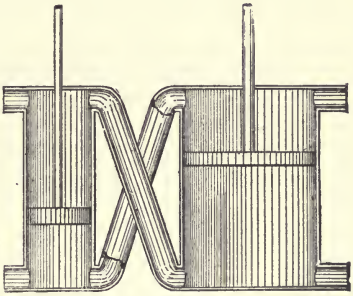

FIG. 49.—COMPOUND ENGINE.

Compound engines have been adopted for several lines of ocean steamers, where it is important to obtain as much work as possible from a limited quantity of fuel.

Boilers.—The essential parts of all boilers are the same, and consist of a furnace in which the fuel is burned, a chimney to produce draught and carry away the products of combustion, a receptacle to hold the water to be evaporated, and a space for the steam when generated; also fittings to supply the boiler with water and conduct the steam away from it and for indicating the quantity of water present and the pressure of the steam.

The simplest form of boiler consists of a cylinder partly filled with water, the furnace being exterior to and below the cylinder. But such forms are now seldom seen. The modern forms of boilers are numerous and quite different, depending upon the conditions under which they operate and the duties to be performed. The objects aimed at are great strength in the boiler, economy in heating, and large evaporating surface for the production of steam. The importance of this last object has very generally led to the adoption of forms in which either the hot gases pass through numerous channels entirely surrounded by water, or the water and steam circulate in tubes which are in the midst of the flame and gases ; the latter class is called *tubular* boilers. In certain cases facility in repairing and cleaning is of great importance.

Pressure-gauges and Safety-valves.—The *pressure-gauge* is used to show the pressure of the steam within the boiler at any time. It is connected with the interior of the boiler, and usually indicates on a dial-plate the pressure in pounds per square inch.

The *safety-valve* is a circular valve seated on the boiler, and when the pressure of the steam exceeds the pressure on the valve it is lifted and the steam escapes. These valves may be loaded directly, or the load may be transmitted by a lever, or the valve may be pressed down by a spring, the tension of the spring being varied by a screw.

Causes of Explosion.—Properly adjusted safety-valves afford protection against the danger of explosion from gradual increase of pressure, but they are not always efficient when there is a sudden generation of steam. There are several causes to which a sudden evolution of steam may be due.

If the water falls too low in the boiler, the different parts may be so highly heated that when fresh water is admitted it is rapidly converted into steam by contact with the metal. Arrangements are made to guard against this contingency by having two cocks, one a little above and the other a little below the level at which it is desired to maintain the water. One of these when open should emit steam and the other water. A stout glass tube opening into the boiler, both above and below the water level, and extending upward on the outside constitutes a *gauge* to show the amount of water in the boiler.

The incrustations of boilers due to the impurities of the water used may be the cause of a violent generation of steam. This crust is a bad conductor, and the portion of boiler covered with it may become overheated, when, if by cracking or peeling off of the crust the water reaches the heated metal, there is rapid evolution of steam, but this occurrence could only produce explosion when the limit of pressure was already nearly reached.

Another cause of explosion is probably found in that property of water by which the temperature of its boiling is raised when it is deprived of air; when such water reaches its boiling point, it bursts into steam with explosive violence. Such danger is to be apprehended when a boiler after use is allowed to cool and again brought into action without the addition of fresh water.

The most frequent cause of explosion is probably the *weakening* of the boiler due to natural causes, and can only be guarded against by inspections and tests.

Feeding Apparatus.—The water of a boiler is replenished by means of force-pumps or injectors or both.

Pumps.—Pumps for forcing water into the boiler may be driven by the engine itself or by a separate engine, the first method being more generally adopted.

Giffard's Injector.—The injector is an instrument which converts the energy of the heat in the steam into mechanical energy without the aid of any mechanism whatever. The injector is now in very general use. The method of its operation will be understood from Fig. 50. *A* is a section of the boiler, *B* a pipe leading from the steam-space and terminating in a nozzle, *C* is a pipe leading from the water-tank, *F* a pipe connected with the boiler through the valve *G*, opening inward. When the cock at *B* is turned, the steam rushes out of the cone *E*, carrying the air with it, and producing a partial vacuum in the tube *C*. The water from the tank then rushes up the tube *C*, surrounding the nozzle and condensing the escaping steam. The particles of condensed steam communicate their motion to the water particles by contact with them, and the combined mass is delivered at high velocity into the feed-pipe *F* and through the valve *G* to the boiler.

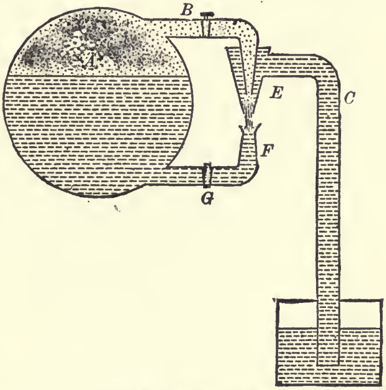

FIG. 50.—FEED INJECTOR.

It at first sight appears strange that steam should be able to overcome its own pressure and force water into the boiler against itself, but the principle of action of the injector may be grasped by considering the velocities with which steam and water would escape from the same boiler. Without discussing the laws of gaseous flow it will be sufficient to know that the velocity of efflux of steam, in ordinary boilers, is many times greater than that of water from the same boiler,—from twelve to twenty times as great. If we conceive this steam to be condensed just as it reaches the end of the pipe B, the resulting particles of water would travel forward with the velocity already acquired, and if these minute particles could by any means be gathered into a continuous stream, this stream would have the velocity of the escaping steam and would more than overcome any opposing stream of water, of equal cross-section, escaping, as such, from the boiler. This condensed steam has velocity enough to impart considerable energy to a portion of the surrounding water, and the combined mass is still able to enter the boiler. In explanation of the action it should be remembered that the water which is forced in is less in volume than the steam which issues, so that, while the exchange produces an increase of mass in the contents of the boiler, it involves a diminution of pressure as well as a fall of temperature.

Condensers.—The *condenser* is an apparatus into which the steam is discharged when it has done its work, and where it comes into contact with a spray of cold water, or else with a large extent of metallic surface one side of which is cooled by water. In this apparatus the steam is suddenly condensed and gives up its heat to the water; at the same time the air in the water is disengaged owing to the small pressure in the condenser. This air would exert a backward pressure on the piston if it were not removed. For this purpose a pump is fitted to the condenser which removes both the air and the water.

When the steam does not come into direct contact with the water, it is called surface-condensation. A series of pipes cooled by water may be used for this purpose. The steam thus condensed yields distilled water, which may be returned to the boiler and repeatedly used. Such condensers possess special advantages for marine engines.

Classes of Reciprocating Engines.—Engines may be classified in various ways:

1. As regards their use, as stationary, marine, locomotive, etc.

2. As to the mode of action, as condensing, non-condensing, expansive, non-expansive.

3. As regards the manner in which the motion of the piston is communicated to the other parts of the machinery, as by a simple connecting-rod, or by a beam.

4. As to the manner in which the heat energy of the steam is transformed into the rotary motion of the machinery, as by reciprocating motion of the piston or by direct rotation.

In this country the terms *low* and *high pressure* are simply used to designate engines working below and above a certain pressure, respectively, usually fifty pounds. Neither here nor elsewhere do these terms any longer denote definite distinctions.

Oscillating Engines.—An oscillating engine is one in which the cylinder is mounted on trunnions, generally near the middle of its length, and on which it is capable of oscillating through a small arc, so as to adapt itself to the various positions of the crank, to which the piston-rod is directly connected. The steam is admitted from the boiler through one trunnion, and passes out at the other through the exhaust-pipe to the condenser. The valve-chests are on the sides of the cylinders and oscillate with them. Such engines are economical of space and weight. They are of common use in river-boats on the continent of Europe and also in Canada, and are used upon some of the ferry-boats between New York and Brooklyn.

Under the third class the method of transmitting the reciprocating motion of the piston by means of a walking-beam is generally adopted on river steamers in the United States.

[*Note to p.* 105.]

If a reversible engine "B" is not the most efficient, let us suppose that we have one "A" of greater efficiency. Let B take heat from the source and perform the work W; let A run B backward: the heat taken *from* the source by B will then be restored *to* it; by the supposition A can do more work than W, say W''; therefore in running B backward there will be an excess of work equal to $W'' - W$.

Since A requires no more heat than B this operation might be indefinitely repeated with an excess of work each time equal to $W'' - W$ and still there would be no change of temperature in the source, no loss of heat. A production of work without loss of heat is inconceivable and contrary to the fundamental supposition.

Turbine Engines. — A turbine engine is one in which the energy of expanding steam is employed to produce direct rotation in a wheel and shaft. The possibility of thus producing direct rotation was recognized before the Christian era and the principle of action was applied in the Aeolipile of Hero 120 B.C. This piece of apparatus involved the principle of one class of modern turbines, the *reaction* turbine. The turbine of Branca, of Loretto, Italy, 1629, involved the principle of another class, the *impulse* turbine, but it is only within the past twenty-five years that the steam turbine has come to be considered as a practical form of prime motor. The turbine engine is a closer approximation to the ideal than any other form.

We know from the principles of thermodynamics already discussed that the useful work of an ideal engine would depend only upon the quantity of heat taken in and the interval of temperature between the source of heat and the condenser. If the temperature of the condenser be fixed the useful work will depend upon the quantity of heat taken in, and the temperature of the source. In all steam engines the temperatures of the source and the condenser are fixed within certain limits, and the greater amount of useful work is obtained by having the temperatures as far apart as possible.

This same statement may be made in the more usual form as follows: The potential energy of the steam is derived from the heat of the furnace, this heat first converts the water into steam, then increases its temperature and pressure: it is the energy due to the pressure and temperature of the steam that is available for useful work in the engine. The larger portion of the thermic energy from the furnace, both the specific and latent heat of the steam, is retained by the exhaust steam and given up in condensation, and is not available for work in the engine. It is therefore evident that a greater proportion of the thermic energy from the furnace will be available the higher the temperature and pressure at which the steam enters the engine and the lower the temperature and pressure at which it leaves the engine.

The rotation in turbines may be brought about either by the *impulsive* action of the steam particles, moving with velocities acquired during the expansion of the steam from one pressure to another, or the rotation may be due to the *reaction* of the steam expanding to lower pressure, or it may be due to both impulse and reaction. The action of the steam turbines is similar in principle to that of the water turbine, the motion of the turbine or wheel in each being due to the velocity of flow, or pressure, or both, of the entering fluid. The greater difficulty of operating steam turbines efficiently as compared with water turbines is due to the great difference in velocities with which steam and water move under equal pressures. The velocity of a jet of water, escaping into the air and driven by a pressure of 150 lbs. per sq. inch is nearly 150 feet per second, while steam escaping under the same conditions has nearly twenty times this velocity. Steam turbines are often run with boiler pressure from 150 to 200 lbs and the condensers at a high vacuum (27″ to 28″), under which conditions the steam velocity acquired in expanding from boiler to condenser pressure would be over 4,000 feet per second.

In an efficient steam turbine the pressure and temperature of the steam should be as high as practicable, the energy thus stored should be as fully as possible converted into mechanical rotation. This stored energy of the steam may be developed either by first converting it *fully* into the kinetic energy of a moving jet of steam and then transforming this energy of motion into work of rotation, or the stored energy may be only partly developed as kinetic energy of motion and partly as the energy of pressure due to expansion exerted while the flow is taking place.

The simplest illustration among successful turbines of the first method of transformation is shown in the De Laval turbine. In this turbine the steam expands from the pressure of supply to that of the exhaust by a single step. This expansion takes place in properly shaped nozzles and converts the available energy of the steam into mass-velocity. Issuing from the nozzles in the proper direction the rapidly moving jet impinges upon concave vanes located around the periphery of the turbine. Fig. 51 shows a section of a nozzle and a part of the periphery of the wheel with eight of the vanes included. Fig. 52 shows a perspective of the wheel with several nozzles.

The conditions for most efficient action in a turbine wheel are that the fluid must enter the wheel without impact and leave it without velocity; that is, the fluid must give up its entire momentum to the wheel. The condition that the fluid shall leave the wheel without velocity requires that the velocity of the fluid relatively to the wheel at the point of discharge shall be equal to the velocity of the wheel at that point and in the opposite direction; to accomplish this result with a single wheel, the vanes of the wheel must move with very nearly half (47%) the speed of the entering fluid. In such a case it is evident that the velocity parted with by the steam in passing over the vanes is twice that of the vanes. There should be no sharp deflections to suddenly change the direction of motion of the steam and as little friction as possible between the steam and vanes.

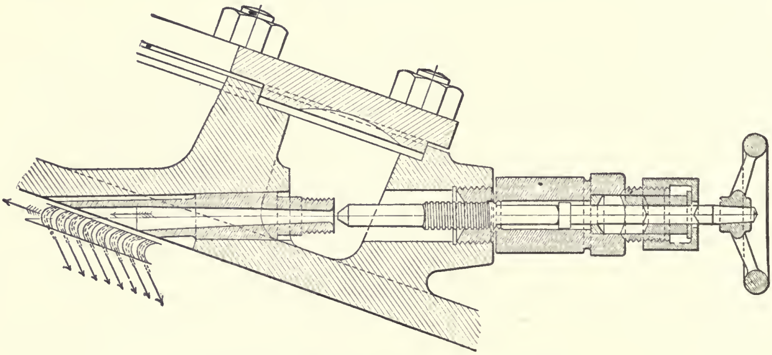

Fig. 51.—De Laval Nozzle and Blades.

The condition for best efficiency, that the vanes must move with half the speed of the impinging steam, coupled with the advantages of working from high to low pressure imposes great speed in the De Laval turbine, where there is a single wheel and the expansion from the pressure of admission to that of exhaust takes place at one step. A speed as high as 1380 feet per second has been attained in a 300 H.P. turbine of this class, the revolutions per minute reaching 10,000 and the diameter of the wheel 30″. The speed of rotation in other types has reached as much as 30,000 per minute. These great speeds are made possible by a flexible shaft which protects the bearings and foundations from the vibrations due to a want of balance. The shaft of a 150 H.P. engine of this pattern is only one inch in diameter. To make use of such high speed in the rotor, gearing is necessary to transmit reduced motion to the machine to be driven.

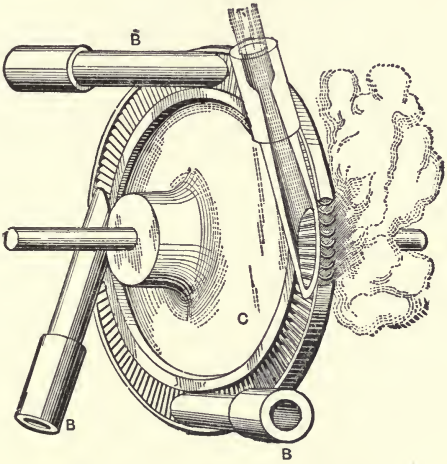

Fig. 52.—The De Laval Wheel.

This and similar turbines, whenever the energy impressed upon the motor is derived entirely from the mass velocity of the steam and not from the pressure of expansion, are called *impulse* or *velocity* turbines.

The Curtis turbine which has come into great prominence in the U. S. since 1900 is also an *impulse* turbine. It is, however, a *many stage* turbine, this is to say, that the steam does not expand by a single step from the pressure of supply to that of exhaust, but the expansion takes place by stages. In the first stage the acting steam is expanded from the boiler pressure to a certain fraction of the range between the boiler and exhaust pressure; in the second stage through a fraction of the remaining pressure, and so on for the other stages. It is evident that in each stage of expansion only a part of the potential energy of the steam is converted into mass velocity and it consequently moves with proportionally lower speed; a satisfactory velocity of the vanes or the peripheral speed of the wheel is accordingly much less than when the expansion takes place through greater range of pressure. In this form

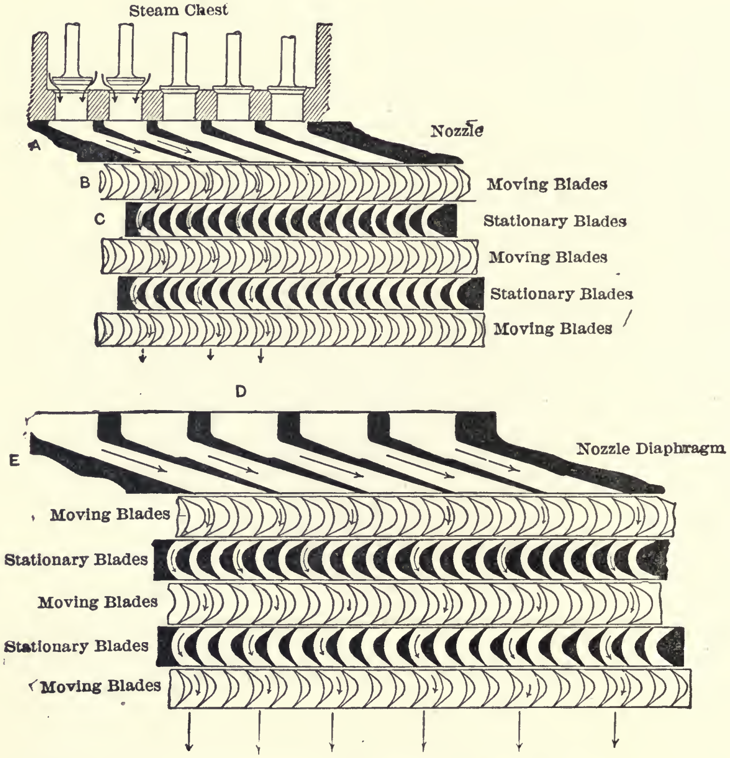

FIG. 53.—Nozzles and Buckets, Curtis Turbine.

of turbine the velocity of the steam acquired by expanding between any two pressures is not all given up, as in the De Laval engine, by action on the vanes of a *single* wheel, but after actuating the vanes of one wheel by giving to it a portion of its momentum, the steam passes through stationary vanes or blades which change its direction and bring it to bear at the desired angle upon the vanes of a second movable wheel, so that the steam gives up an additional portion of its momentum to this wheel; the steam may be then redirected and brought to impinge upon a third or even fourth wheel.

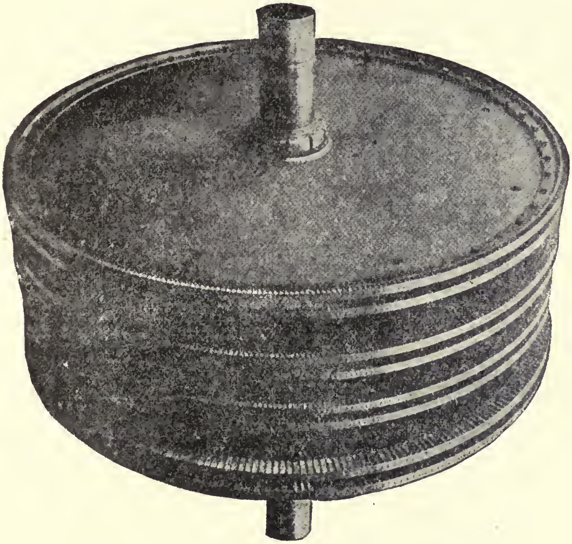

Fig. 54.—Rotor of 4-Stage Curtis Turbine.

The steam in each expansion stage parts with a portion of its momentum in passing over each row of vanes, and the speed of the vanes or wheels may be reduced in proportion to the number of wheels and still all the momentum be extracted from the steam.

We may then say that the Curtis turbine has three or four pressure stages in each of which the pressure is constant for that stage; each pressure stage is sub-divided into two or three (maybe more) velocity stages, both the pressure and velocity stages serve to diminish the necessary speed of rotation and still retain efficiency.

The successive actions in the Curtis turbine may be stated as follows: The steam passes at the pressure of the chest into a set of nozzles at lower pressure in which it expands, acquiring full velocity, and strikes at the proper angle against the vanes of the first movable wheel in this stage chamber. Passing from the vanes of this first wheel, the steam flows through and is redirected by stationary guide blades on the vanes of a second movable wheel, then through another set of fixed directing guide blades on to another movable wheel, and so on over all the wheels of this chamber. After leaving the last wheel of this chamber the steam collects in a shallow reservoir, formed by a steam-tight diaphragm which separates the first pressure chamber from the second. From this reservoir the steam passes into another set of nozzles at lower pressure leading to the second chamber. It acquires the full velocity due to expansion from the pressure of the first chamber to that of the second and is directed against the vanes of the first movable wheel in this chamber; passing from the vanes of this wheel, the steam has its direction changed by the fixed guide blades so as to impinge at the proper angle upon the vanes of the second movable wheel and so on through the other guide blades and wheels of this chamber and into the reservoir or diaphragm space adjoining the third chamber. Precisely similar expansion and action takes place through the remaining stages, the number of expansions, of course, depending upon the number of pressure stages. In the Curtis turbine the wheels are of the same diameter and being upon the same axis have the same angular velocity. This demands that the steam velocities developed in each set of nozzles shall be the same and the ratio of expansion in each set is arranged to accomplish this result. Fig. 53 shows a diagram of the vanes and nozzles in a two stage Curtis turbine. The movable vanes are, of course, attached to the periphery of the rotating wheels, the fixed vanes or blades are attached to the walls of the cylinder which encloses the rotor. Fig. 54 shows the rotor of a four stage Curtis turbine with enclosing cylinder removed.

The Parsons turbine engine is another of the more important of these engines. It differs from the two above described, in that the energy of the steam is transmitted to the movable wheels both by the impulse of motion and by expansive action. In this engine the expansion from one pressure to another does not take place in the nozzles before coming into contact with the turbines, but the expansion is taking place while passing over the fixed and movable blades. A general idea of the principle employed in actuating the engine will be obtained from the diagram, Fig. 55, in connection with the following description:

The engine consists of an enclosing cylindrical case from the interior circumference of which project rings of fixed guide-blades. This case increases in diameter by successive steps toward the low pressure end. Concentrically within the case is mounted the shaft with outwardly projecting vanes. The rings of movable and fixed blades are sandwiched in between each other, the former extending nearly to the outer case and the latter in nearly to the shaft. The section of these vanes is similar to that shown of the Curtis vanes. The whole may be considered to constitute a large number of turbine wheels increasing in diameter toward the exhaust. It is clear that the volume of the steam increases in passing through each barrel or drum of the cylinder as does also its velocity. The movable vanes are so set and shaped throughout the cylinder as to receive the benefit of the increasing velocity as the steam strikes them. There are small chambers, *A′ B′ C′*, at the shoulders of the rotor between consecutive drums into which the steam emerges after leaving the last set of vanes of the preceding drum. There the steam is brought, relatively speaking, to rest before it is directed by the next set of guide blades on to the first set of moving vanes in the next drum. The steam therefore expands gradually by small increments through the different drums before it reaches the exhaust. In different sized engines

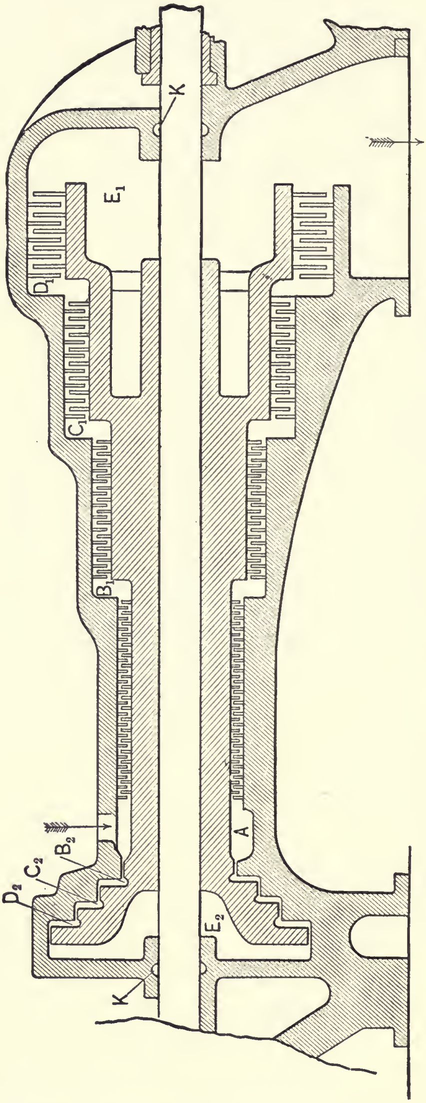

FIG. 55.—Sectional Diagram of 1,000 K. W. Turbo-Generator (not to Scale).

the number of successive rings of blades may vary from 40 to 400, and when the steam leaves the last ring of vanes the expansion has been completed. The pressure falls not only through the guide-blades but in passing over the movable vanes, so that the pressure stages in this engine are as numerous as the rows of vanes both fixed and movable. The steam velocity increases toward the lower pressure end of each drum and from drum to drum, accordingly there is an increase of velocity of the steam throughout the turbine. To meet the conditions, already stated, as to the desirable speeds of the driving fluids and vanes, the diameters of the moving wheels in the low pressure drums are greater than in the high pressure.

Steam turbines, of which the principal forms have been briefly described have since 1895 been steadily replacing the reciprocating engines for certain classes of work. They are especially adapted to operating electric generators where high rotary speed is desired. The difficulty of securing satisfactory efficiency in turbine engines while diminishing the speed of rotation has been overcome in recent improved forms to such an extent as to permit the use of turbines in large ocean steamers.

The Carmania of the Cunard line is a vessel of 31,000 tons displacement (672 feet long) and is driven by three turbine engines. The revolutions of the shaft are 180 per minute, much the largest number ever used in any vessel of great size. To accomplish this result it must be so arranged that the velocity of the steam in passing from ring to ring of vanes is much less than in higher speed turbines, and this is brought about by a large number of *rings* of movable and fixed vanes. The total number of guiding and propelling vanes in the Carmania's turbines is over 1,100,000. There is building for the same company a vessel 760 feet long and of 88 feet beam, which is to be driven by four turbines aggregating an indicated H.P. of 70,000. The Parsons turbine is the only form that has yet been applied to the propulsion of ocean craft.

CHAPTER X.

TERRESTRIAL TEMPERATURES, AERIAL AND AQUEOUS METEORS.

TERRESTRIAL TEMPERATURES.

Temperature of a Place.—The temperature of a place is determined by the readings of a thermometer placed a few feet above the ground and protected from rains, the solar rays, and all direct radiation, but freely exposed to the air.

Mean Temperature of a Place.—The mean temperature of a place is obtained by taking a series of thermometric observations separated by equal intervals of time, and dividing the sum of these observed temperatures by their number. The greater the number of observations, the more accurate the result.

If the series be extended at equal intervals over the day, the result will be the mean for the day. The mean of the maximum and minimum readings for the day is often taken for the mean of the day, but this is usually above the true mean. A convenient and close approximation to the daily mean may be obtained by taking the mean of the readings at 7 A.M., 2 P.M., and 9 P.M.

The sum of the daily means, divided by the number of days in the month, gives the monthly mean, and the sum of the monthly means, divided by the number of months in the year, gives the annual mean temperature. The sum of the daily means throughout the year, divided by the number of days in the year, gives a more accurate annual mean.

Effect of Altitude on Temperature.—In the normal condition the temperature of the atmosphere decreases as the altitude increases at the rate of about 1° F. for every 300 feet, when the mean annual temperature is considered. The temperature of the crust of the earth increases at the rate of about 1° F. for every 53 feet of descent below the surface. This interior heat has no perceptible effect upon the temperature of the air.

Isothermals are lines drawn on a map through all points which have the same temperature, and unless otherwise stated reference is had to mean annual temperature, but of course isothermals may be drawn for months or seasons. The general trend of these lines is in an east-and-west direction around the earth, but temperature is influenced by so many local causes that they are seldom parallel to the equator. Their directions with reference to the parallels are modified by the proximity of places to large bodies of water, by the direction of ocean currents, by the prevailing direction of the winds, and by the altitude and configuration of the land areas. Places near the sea have higher winter and lower summer temperatures than places of the same latitude and altitude in the interior of continents. Since temperature is the most important element in climate, the same influences which affect temperature affect climate. *Ocean* and *insular* climates are more uniform than continental climates.

AERIAL AND AQUEOUS METEORS.

These phenomena are so dependent upon heat agencies that a brief outline of the more important and common of them is deemed appropriate here.

AERIAL METEORS.

These include all the phenomena resulting from the motions of the atmosphere relatively to the earth. Such motions are called winds. All winds are primarily due to differences of pressure in the atmosphere, and these may be due to differences of temperature, differences in the amount of aqueous vapor present, and (to a slight extent) to differences of density. The main cause of winds, however, is the difference of temperature, which also produces difference of density. Without the differences of temperature which exist over the earth's surface, it is probable that the earth's atmosphere would be in a quiescent condition.

GENERAL OR PLANETARY CIRCULATION OF THE ATMOSPHERE.

Owing to the permanent differences of mean temperature on the earth's surface caused by differences of latitude, the air over the tropical regions is warmer than that over the northern and southern regions. This warm air being more expanded ascends and flows over above both to the north and south, while cold air flows in toward the equator from both sides below.

In this connection it should be borne in mind that while unequal pressure is necessary to produce motion in the air, this inequality of pressure need not prevail at all levels, for while the total pressure in two regions at different temperatures may be the same at one level, this equality of pressure cannot exist at any other level within these regions. The reason for this is that, since the density of the warm air is less, the decrease of pressure for a given increase of height is greater in the cold than in the warm region, consequently in the cold region the pressure is greater below and less above the level of equal pressure. An interchange of air will therefore take place between two such regions, the winds blowing in opposite directions on the two sides of the surface of equal pressure. If the level of equal pressure be at the earth's surface, the interchange will still occur, for the excess of pressure at all points above the surface in the warm area will cause the upper air to flow from that region, this will diminish the total pressure at the earth's surface in the warm region, and consequently the lower air will move from the cold to the warm region. It is evident from the statements above made that the conditions necessary to an interchange of air between the tropical and polar regions of the earth are always present and operative, and the winds thus produced constitute the general circulation.

The principle which causes the general circulation has frequent application in the production of local winds. It may be readily illustrated by placing a candle near the top and another near the bottom of a door connecting two rooms at different temperatures. When the door is opened, the flame of the upper candle will be blown toward and that of the lower will be blown from the cold room.

The general circulation which would result from the temperature distribution due to latitude alone is materially modified and complicated by the arrangement of land and water and by the varying rotational velocities of the earth's surface as we pass from the poles to the equator, thus giving rise to the wind systems that actually exist.

FERREL'S VIEW OF THE GENERAL CIRCULATION.

The theory of the general or planetary circulation of the atmosphere which, with some modification, has met with most general acceptance by meteorologists was first set forth in this country by Prof. Wm. Ferrel. It is believed that to him more than to any other individual the theory owes its origin and development. His discussion is a profound one, and constitutes a volume of itself; it is difficult of simple or disconnected treatment; however, his views are to a certain extent capable of condensation, and give satisfactory general ideas.

Assuming that the permanent difference of temperature between the equatorial and polar regions causes an interchange of air between them (and there can be little doubt that it does produce such an exchange), and assuming also that the initial condition of the air is one of relative rest when the interchanging motion begins, and that the air is without friction against the earth, Prof. Ferrel has shown that, under these circumstances, the different rotational velocities of the earth's surface, coupled with the interchanging motion of the air, will involve the entire mass of air between the parallels of 35° on both sides of the equator in a westward motion of considerable velocity, and that over the rest of the surface of the earth in an eastward motion which will be of much greater velocity in high latitudes.[*] He has shown that the deflections which the moving air will experience due to this motion, being to the right in the northern hemisphere and to the left in the southern, will cause the depth and pressure of the air to be greatly diminished at the poles, producing a virtual vacuum there, and considerably diminished at the equator, and increased at the parallels of 35°, where the velocity of the air changes sign, the velocity being westward between these parallels and eastward outside of them. Under these conditions a section of the earth and atmosphere would be as shown in Fig. 51.

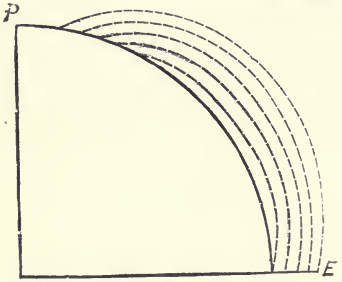

Fig. 51.—Earth with Frictionless Atmosphere.

Now, in the actual case of the earth and atmosphere, *with friction* against the surface and an interchanging motion, there would be a tendency toward the same state of affairs, but the deflecting forces are so modified by friction that the diminution of depth and pressure at the poles and at the equator are but slight, and there is but a small increase at about the parallel of 30°. That there must be a tendency to the same state of affairs as when there was no friction is evident because friction could not operate until the motions which produced the former condition had commenced. In this actual case, also, the *entire mass* of air between the belts of high pressure has not a westward velocity as in the first case, but at great altitudes this air has eastward velocity. The relative amounts of easterly and westerly motion at the earth's surface in this actual case will depend upon the condition that the sum of the moments of gyration arising from the action of the air by friction upon the earth over the entire surface must be equal to zero, or else the velocity of the earth's rotation would be affected.

In this explanation it will be observed that the accumulation of air at the limiting parallels and its diminution at the poles are due to the *deflections* caused by the earth's rotation, which press the

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[*] Many years after, though without a knowledge of Ferrel's work, Prof. Werner Siemens deduced the same limiting parallels as here given. *Sitzungsberichte,* March 4, 1886; *Phil. Mag.,* June, 1886.

moving air from both sides toward these parallels. The belts of high pressure near the tropics are therefore the unavoidable results of an interchanging motion on a rotating globe between the polar and the equatorial regions. The accumulation is more largely due to the greater deflection in the upper atmosphere, where the motion is greater and the resistance less ; hence this accumulation causes the air to flow out from beneath, where the tendency to heap it up is less, both toward the poles and toward the equator. It will be observed also that the deflections which cause the tropical high-pressure belts likewise produce a diminished pressure in the *polar* *regions,* but not a *belt* of *low* pressure about the *polar circles,* as has been supposed to exist.

FIG. 52.—GENERAL ATMOSPHERIC CIRCULATION. (AFTER FERREL.)

According to Ferrel's view, then, we summarize the most probable circulation of the air to be as indicated in the figure (Fig. 52). The upper strata move poleward, and the lower strata the reverse, except that in the middle latitudes there is a thin stratum at the earth's surface, deflected from beneath the parallels of high pressure, moving poleward. This surface current, however, does not extend all the way to the pole, but, being interfered with by a surface current from the pole, it gradually ascends, and returns toward the equator in a stratum higher up but below the poleward strata of the upper atmosphere. Ferrel's view of the planetary circulation and his explanation of the tropical belts of high pressure have, until recently, been very generally accepted.

The data of the U. S. weather bureau, collected in connection with the weather service and with international cloud observations, which data have been tabulated and very ably discussed by Prof. F. H. Bigelow, show that Ferrel's view of the general circulation needs to be modified in several respects. The modifications thus suggested, in the above outline, refer especially to the interchange of air between the equatorial and polar regions. According to Ferrel the equatorial warmer air flows poleward mostly at high altitudes, above five miles, and that below this, and above the surface winds, there is a sheet of cold air flowing from the northwest toward the equator.

The conclusions of Prof. Bigelow from observed cloud motions are that this interchange of air between warm and cold latitudes takes place over the United States almost entirely below the three-mile level, and is accomplished by counter-currents of warm and cold air advancing alternately from north and south ; that above the three-mile level there is but little interchanging motion between north and south, and that the circulation of the upper air is nearly east and but little affected by the interchanging north and south currents below. According to this view the tropical energy is expended in forcing the equatorial air northward in a succession of currents at low altitudes, rather than expanding it to great altitudes and sending it northward in a continuous sheet; the cold air also returns by currents, the currents from the opposite directions moving at about the same level instead of at different levels. These counter-currents result from the mechanical tendency of the air to maintain an equilibrium between the warm masses over the equator and the cooler masses to the north. The conclusions of Prof. Bigelow seem to be well founded so far as the United States is concerned.

SYSTEM OF WINDS.

The above view of the general circulation roughly outlines three zones in each hemisphere which approximately correspond with the adopted wind systems at the earth's surface.

The Equatorial System or Trade-Winds.—These winds prevail at the earth's surface approximately between the parallels of 30° north and 30° south latitude, and flow toward the equator. Their direction is *from* the northeast in the northern and *from* the southeast in the southern hemisphere, becoming more easterly as they approach the equator. Between the trades in the two hemispheres is a region of calms or variable winds, from three to ten degrees wide. This equatorial calm-belt constitutes the *doldrums.* The central line of the belt oscillates with the seasons, being one or two degrees north of the equator in the spring and nine or ten degrees north in the summer. The direction of the trades at the border of the calms is nearly westward, the northern trades blowing more to the westward than the southern.

These winds may be directly ascribed to two causes: first, the two belts of high barometer or great atmospheric pressure which encircle the earth at about the parallel of 32° in the northern and 25° in the southern hemisphere with a decrease of pressure toward the equator, these belts of high pressure resulting from the general circulation as described; second, the higher mean temperature of the air at and near the equator. Both these conditions cause the air within the limiting parallels to move toward the equator, the direction of motion being modified as stated by the earth's rotation.

Winds of the Temperate Regions.—Beyond the northern and southern borders of the trades in the two hemispheres, over a belt of from twenty-five to thirty-five degrees, the prevalent winds at the earth's surface are from the westward and blow toward the poles. In the northern hemisphere they blow from a point a little south of west, and in the southern hemisphere from a little north of west, being more nearly west at the centre of the belt. These winds are sometimes designated as *passage-winds.*

These winds are also directly attributable to the belts of high pressure mentioned. From beneath these belts the surface air flows toward the poles as well as toward the equator, so that the prevailing direction of the surface winds is from the southwest. In the temperate regions of the continents, and especially in North America, the interchanging currents already referred to, and the local conditions, greatly disturb the uniformity of the system.

Winds of the Polar Regions.—Beyond and to the north of the areas swept by the passage-winds in the northern hemisphere the atmospheric motions are very uncertain. Prof. Ferrel indicates this as a region of polar calms, though there are known to issue from these regions winds blowing to the southward at certain seasons.

Motions of the Upper Atmosphere.—It will be observed that the winds above referred to are those at the earth's surface. Now, the principle of continuity evidently requires that the mass of air moving in one direction over any parallel must just equal that moving in the opposite direction, otherwise the atmosphere would be gradually drawn from certain portions of the earth's surface and accumulated at others.

We should therefore expect to find the winds at certain heights in the areas embraced in the above systems blowing in directions in general opposite to those at the earth's surface, and such is the case. The ejected ashes from volcanoes situated in the tropical regions have been carried long distances by the upper currents in a direction opposite to that of the prevailing surface winds. Fine dust, supposed to be peculiar to certain regions, has been found at long distances from these regions, and is believed to have been lifted into the upper air and transported by the higher tropical currents whose directions are thus given. Lastly, on the peaks of several high mountains direct observations show that the winds of the upper regions are often blowing from the equator and come from the southwest, while the trades at the base of the mountains blow toward the equator and from the northeast.

By observations it is found that in the temperate regions, above the prevailing winds from the southwest, the wind frequently moves toward the equator. In the polar regions the meridianal interchange of air both at high and low altitudes takes place very gradually.

Directions of the Winds in the General Circulation.—The easterly and the westerly components of motion of the winds in all the general systems depend upon a principle, susceptible of demonstration, that, owing to the rotation of the earth on its axis, there arises a force which tends to deflect all motions in the northern hemisphere to the *right* and in the southern hemisphere to the *left*, supposing the observer to face in the direction of motion. This force varies with the latitude, being nothing at the equator and greatest at the poles, and is not limited in action to bodies moving north and south, as is frequently supposed, but extends to all motions, even to those along the parallels. The trade-winds moving toward the equator are thus swerved toward the west, the passage-winds moving from it are swerved to the east, the polar winds moving toward the equator would also tend to the west.

Local Winds.—The general circulation of the atmosphere which has been described is in many places materially and regularly modified by local conditions producing uniform results. Among the most important of these are the periodic winds.

1. Periodic Winds.—*Land and Sea Breezes.*—These are the well-known daily alternating breezes which prevail along the coasts of islands and continents. These winds are most marked in tropical countries, but also prevail far outside these limits. In the daytime they blow from the water to the land, and at night in the reverse direction. This is due to the fact that while the sun is shining the land becomes warm quicker than the water, and at night it also cools more quickly. The air, deriving its heat from the surface beneath, is consequently cooler and heavier over the water during the day, and warmer and lighter soon after sunset; consequently the directions of the breezes are as stated. It must be observed that these breezes depend primarily upon the diurnal variations of temperature, and secondarily upon the greater mobility of the water and the greater depth to which the heat-rays will penetrate it, its great latent heat, and the absorptive power of the water vapor which is more abundantly present over the water,—properties tending to prevent rapid changes of temperature. The simple difference of specific heats between land and water does not have the great effect usually assigned it.

Monsoons.—The annual variations of temperature accompanying the changing seasons also have their effect in modifying the prevailing winds. During one portion of the year the winds blow *toward* the continents, and during the remainder *from* them. Among the most remarkable of such winds are the monsoons, those winds which blow from the Indian Ocean over Southern Asia during the warmer half of the year and in the opposite direction during the other half. The difference of temperature between the continent and sea is the cause of them. The former of these winds, passing over the mountains of Hindostan, have their moisture condensed, giving a region of excessive rainfall.

Similar winds are produced in every part of the world near the coasts of extensive land areas. In the United States they are observed merely as modifying the direction of the prevailing winds. This is the case on both the eastern and the western coasts, and in Florida the winds are in opposite directions in summer and winter, and are by some deemed sufficiently constant to be classed as monsoons.

Mountain Breezes.—Very often in the ravines, gulches, and narrow valleys of mountain regions, distinct day and night breezes are felt. Those at night are due to the more rapid cooling by radiation of the peaks, spurs, and higher ridges, which in turn cool the air and cause it to flow down through the ravines into the valleys. In the morning the higher surfaces are first touched and warmed by the sun, and the tendency is for the air to flow up the ravines. The action here is the same as in the case of land and sea breezes, the plain at the base of the slope taking the place of the ocean. Generally the winds which pass over high mountains are deprived of their moisture and reduced in temperature, but reference is here had only to the local currents due to daily variations of temperature in small adjoining areas.

In addition to these regular winds there are other local disturbances which depend upon a fundamental principle that is to a greater or less degree concerned in many of the atmospheric motions ; to this principle we shall now allude.

Stable and Unstable Condition of the Atmosphere.—In the normal condition of the atmosphere we may consider it arranged in concentric spherical layers around the earth, the densest and warmest layers being below. The temperature of the air, as we have seen, decreases on an average about 1° F. for every 300 feet of ascent. If a volume of air from the lower strata be moved upward, it will expand, owing to the diminution of pressure at higher levels. This expansion will cool the air about 1° F. for every 186 feet of upward motion. In the normal condition of the atmosphere, then, the decrease of temperature due to the expansion that would occur in a volume of air moving upward is more rapid than the decrease of temperature in the surrounding air due to change of level. If, therefore, an unconfined volume of the dense, lower air could be forced upward through the higher strata, its temperature would decrease, due to expansion, at the rate of 1° F. for every 186 feet of its ascent, and it would be cooler at any level than the surrounding air at the same level and consequently heavier than an equal volume of that air. In the above-stated case the air is in a condition of *stable* equilibrium, and if disturbed would tend to return to the original condition.

But this normal state of the atmosphere does not always exist. On still, hot days in warm regions the lower layers of the air become very much warmer than those above, so much so that the rate of decrease of temperature upward is much greater than 1° F. for every 300 feet. Whenever this decrease of temperature upward becomes greater than that due to expansion, or greater than 1° F. for 186 feet of ascent, the condition of stable equilibrium is destroyed, and a volume of the lower air moving upward would be warmer than the surrounding air at the same level, and consequently lighter than an equal volume of it. In this case, then, if a volume of the lower air were to start upward, it would not tend to return to its original position, but would continue upward until its temperature became the same as that of the surrounding air.

Whirlwinds.—Under this head may be included the very sudden and local whirls produced by the meeting of rapid currents from different directions, as they pass along streets or other natural channels, such as gorges or ravines in irregular and mountainous regions. These are like eddies in the running stream. There is, however, a typical whirlwind peculiar to a quiet atmosphere which deserves attention. This is of frequent occurrence in still, hot, arid regions, and is a familiar sight to all who have had experience on the plateau and basin regions of our western territory, besides being of more rare occurrence in nearly all parts of the country. The perfect type of this wind is often seen on hot, still days in the dry, dusty valleys of the Utah and Nevada basins. In these arid valleys, during the hottest part of a quiet summer day, the observer may often see several tall, slender columns of dust, varying from one hundred to more than one thousand feet in height, travelling across the dusty flats.

Observations show that these disturbances begin in a whirling movement which extends spirally upward. The origin and continuance of these whirls in an apparently still atmosphere are due to the disturbance of the normal equilibrium of the air brought about by the greater heating which the lower strata receive from their contact with the earth. These strata become very warm, and press upward against the overlying strata ; finally an opening is made through them, and the hot air flows in from all sides toward this outlet to reach a region of less pressure.

The whirling motion is the result of a lack of absolute homogeneity of physical condition in the surrounding air and of equal smoothness of the earth's surface. These cause the inblowing air to depart from radial lines, and the direction of turning will be determined by the strongest current. The whirling once begun is continued by the centrifugal force developed by it. In these winds the direction of turning is not fixed, but depends upon local incidents. The volume perceptibly involved in the motion generally extends only a few feet, though, of course, these winds vary in strength and extent. The upward motion of the air will continue until the temperature of the ascending air is brought by expansion to that of the surrounding air of the same level, when it will spread itself among the strata above. The progressive motion of the spiral column is probably due to a slight general motion of the air in which the whirl occurs, especially of the upper layers. Theoretically these whirls would continue until the heated air below had escaped upward through the whirl, or as long as the difference of temperature between the lower air and the strata above was greater than 1° F. for every 186 feet of ascent, but ordinarily their progressive motion takes them beyond the limits of the areas fulfilling the conditions for their existence.

2. Storms.—Besides the general circulation and the more local winds which have been referred to, there are transient disturbances of widely varying extent and energy which are classed under the general head of *storms.* Many of these involve both local and general influences and in some cases may to a limited extent be considered as part of the general circulation. Certain of these storms will be briefly considered.

Cyclones.—This term is applied to those violent whirlwinds of great extent, involving large volumes of air in their action, sometimes extending over elliptical areas two thousand miles or more in axial direction, continuing for many days and travelling for great distances.

It has long been known that the depth of the mass of air involved in these cyclones is generally very small as compared to its horizontal extent, the relation being often as 1 to 500, and frequently even a greater difference. The difficulty which meteorologists have had to solve is to satisfactorily account for the energy which is unquestionably expended in cyclones, the energy necessary to keep in rapid rotation such an enormous mass of air as is generally involved in a cyclone.

The theory which, to within recent years, has been most generally accepted as offering the best explanation of the cyclone is known as the *convectional* or *condensation* theory. This theory supposes that the energy of the cyclone is mainly latent in the aqueous vapor of the air, and also to a small extent in the expanded strata of the unstable atmosphere in which the cyclone originates and is propagated. The theory assumes that if in an atmosphere moist and in unstable condition there is produced an ascending current at any point, the air rises, as in the case of the desert whirl, with this very marked difference : in the case under consideration the ascending air would be cooled by the expansion due to the diminished pressure, as in the whirlwind, but, as soon as a sufficient reduction of temperature takes place, condensation of the aqueous vapor would begin, with liberation of its latent heat. Therefore, the rapidity of cooling with ascension is diminished by continuous conversion of the latent heat of aqueous vapor into sensible heat. The condition of unstable equilibrium in such air is therefore reached with a much smaller decrement of temperature than in dry air. The difference of temperature between the ascending column and the surrounding air is accordingly greater than if the vapor were not present. Because of this greater difference of temperature at the same levels, the upward draught would be much more violent and would extend to a greater height. As the ascent is continued, the aqueous vapor is condensed into clouds or falls as rain, and the ascending air overflows in all directions from the upper end of the aerial chimney, and spreads over the adjoining area. The overflow diminishes the pressure beneath the up-draught and increases it in the annular area surrounding it, both of which causes tend to increase the draught.

In the case now under consideration the great amount of heat latent in the aqueous vapor existing in the lower air and which becomes sensible heat by condensation makes a difference in degree but not in principle between the action in the cyclone and whirlwind.

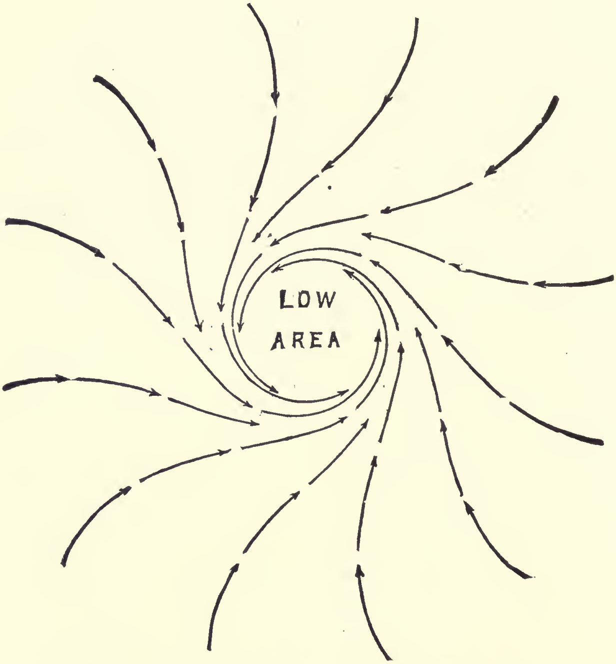

FIG. 53.—CYCLONIC MOTION, NORTHERN HEMISPHERE.

Under these conditions the air would flow from all directions toward the low-pressure centre, but by the rotation of the earth would be deflected around it as indicated in Fig. 53, the winds in the northern hemisphere always circulating in a counter-clockwise direction in the cyclone. The heat liberated by the condensation of the aqueous vapor of the atmosphere would keep up the vertical convection, and the discharge of the atmosphere from the upper end of the vortex tube would be largely instrumental in building up the areas of high pressure or anti-cyclonic areas, which are always found to be developed in connection with centres of low pressure. In the anticyclone the winds circulate in a clockwise direction.

The above is substantially the outline of the condensation theory of cyclones as given by Prof. Ferrel. There has been an increasing tendency in recent years among meteorologists to the belief that the theory was not sufficient to explain the observed phenomena. Some have thought it might apply to tropical, oceanic cyclones or others developed under certain conditions, but nearly all have agreed that there have been many other cyclonic storms which could not be explained by it.

There are two readily understood physical difficulties which limit the general application of the theory.

1st. The theory assumes that the source of energy of the cyclone is mainly in the heat from aqueous condensation. But there have been many well-developed cyclones, lasting several days, and travelling from one to two thousand miles with little or no condensation. Such often occur.

2d. The isotherms usually trend, in the United States, across the cyclones instead of running circularly about the centre as required by the condensation theory.

From a thorough study of cloud observations recently made in the United States a theory of cyclones has been proposed by Prof. Bigelow, of the U. S. weather service, which unquestionably seems to be more in accord with observed facts.

Under this idea the counter-currents from the north and south, whose circulation is established from cloud observations, and to which we have already referred as accomplishing the interchange of air between high and low latitudes, are the cause of the cyclonic circulation over the United States. These counter-currents, it will be remembered, flow in the strata below the three-mile level, their level of greatest activity being at about one and a half to two miles; they have different velocities at different altitudes, and depend for their motion upon pressure gradients extending far to the north and south. These thin streams from different directions pass alternately over the same areas, and by their interaction upon each other cause the phenomena of anticyclones and cyclones. It is attempted to convey an idea of the suggested interaction in Fig. 54.

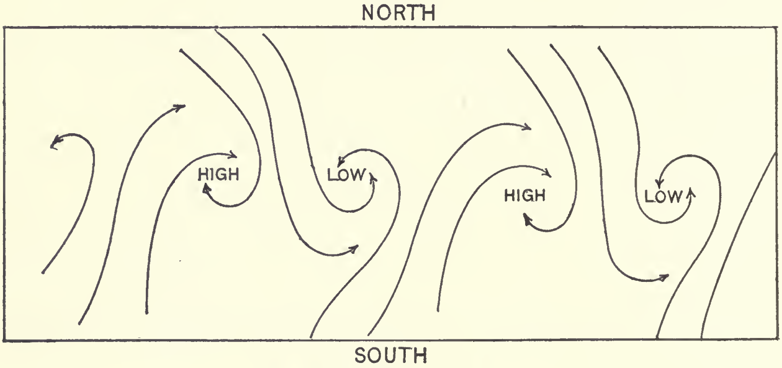

FIG. 54. (After BIGELOW.)

In the case under consideration, the currents coming from opposite directions, north and south, have the contiguous edges of adjacent streams deflected by the earth's rotation in opposite directions, thus tending to produce alternate areas of high and low pressure. In the *highs* the air is driven toward the ground, and in the *lows* it ascends by mechanical vortex motion.

The ascensional currents of the low areas are fed partly by the outflowing air from the high areas and partly from the outer branches of the currents which produce the highs.

The gyratory action produced is attributed to the meeting of currents at an angle, with the development of the couple effect which gives the circular adjustment common in fluid motions. A single current flowing obliquely over a mountain range or following a coast line of changing direction continually tends to run into this same motion.

The gyrations are most strongly developed at the height of about 1.5 miles in both cyclones and anticyclones, and the observations show that the effects of the anticyclonic motions of the high areas extend to a much greater altitude than the cyclonic motions of the low areas. We cannot, therefore, avoid the conclusion that the high areas are the dominant and the low areas the subordinate features in the circulation. The anticyclones draw from and the cyclones discharge into the upper atmosphere, both being produced by the interaction of currents from opposite directions, which themselves have their sources of energy at long distances from the gyrating mass. The motion of the air toward the axis of the cyclone under mechanical laws produces the ascensional flow, instead of this flow drawing in the air as the convectional theory requires.

It is true that the ascent and cooling of the air by contact with colder air causes condensation of the aqueous vapor, and the liberated heat thereof increases the upward motion. The mechanical causes would thus be assisted to varying extent by the heat from condensation, this agent being especially prominent in cyclones producing heavy rainfall. The heat, no doubt, in some cases, is a very important factor in producing the convectional current.

We therefore trace back the principal propelling energy of the cyclones and anticyclones to the general circulation. This energy is stored in horizontal convection currents flowing from north and south; these currents being driven by gradients produced by the general circulation and often extending long distances from the storm gyrations. Half the mass of the atmosphere is below the three-mile level, and it is in this mass that temperature changes mainly occur. In this mass the north and south currents flow, effecting an interchange between northern and southern regions, while the anticyclonic and cyclonic motions cause interchange in a vertical direction. Above the three-mile level there is little interchange in meridianal direction and the general drift of the air is eastward. This upward and downward interchange by gyrating columns connects the lower mass of air with the upper, and the general motion of the former is thus influenced by the eastward trend of the latter.

The planetary circulation as modified by the continental distribution of land and water, coupled with the relative temperature gradients which exist over these in summer and winter, establishes the interchanging currents which flow from north to south over our continent. The causes named tend to build up a permanent high area over the north and extreme northwest part of the continent in winter, from which currents of cold air flow to the south. The heat energy of the tropics expends itself in driving currents to the north. These currents by their interactions produce the high and low areas which sweep over the United States, the high areas being the dominant and the low areas the subordinate features ; the cyclones being mainly operated by the outflow from the anticyclones, and their motion being dependent upon the motion and location of the latter. Northern and southern currents, bearing the temperatures of the regions from which they come, produce, respectively, our cold and warm waves. Fig. 55 illustrates the relation of a high and a low in a storm covering the central valleys.

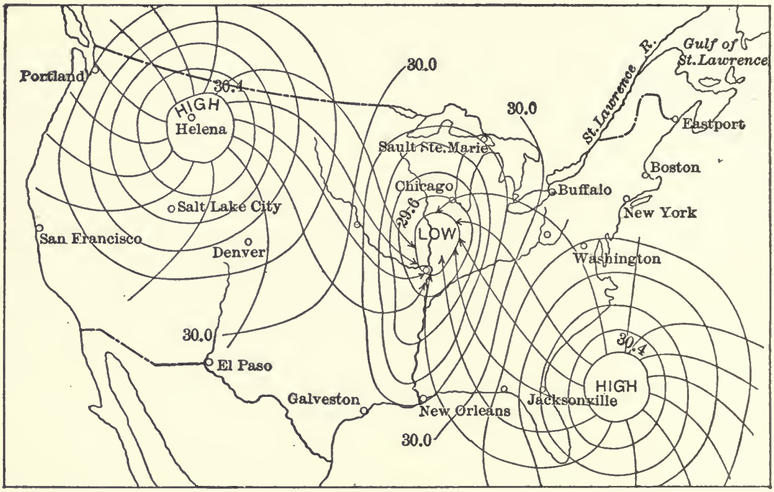

Fig. 55. (After Bigelow.)

Progressive Motion of Cyclones.—Besides the motion of the winds in the cyclone, the cyclone itself moves from one region to another, and with few exceptions the progression is eastward or northeastward. Several causes are thought to be active in producing this motion of translation.

1st. Probably the most important factor is the eastward motion of the higher air into which the gyrating columns of the cyclones extend ; they are thus drawn along by the upper air of the general circulation. The centrifugal force of the rotating winds is in the direction of the upper circulation on the east side of the cyclone and opposed to it on the west; this condition facilitates the ascent of the air, or prevents stagnation on that side and tends to transfer the centre in that direction.

2d. The winds which feed the cyclone are of unequal absolute humidity. Those most heavily laden with moisture produce the greater condensation when they enter the ascending column of the cyclone and thus produce a section of greater precipitation, and, more heat being produced in this section, the tendency is to transfer the storm centre to that side.

3d. The earth's rotation also is a factor in determining the progress. The deflective force due to this rotation increases with the latitude, and, since the cyclones are often of great extent, the difference of its action on the north and south sides of the cyclone has an influence. This force acts with the centrifugal force, due to the gyrations of the air, to transfer the centre of the cyclone toward the side of greatest deflection.

4th. The areas surrounding the cyclone will not all be at the same pressure. The strongest winds will blow from the area of greatest pressure. As these winds curve around the vortex of the cyclone they will resist being drawn inward more powerfully than the weaker winds, and consequently tend to draw the centre of the cyclone toward the swiftest part of the revolving disk.

In the progressive motion of the cyclone there is not a continuous transfer of the same gyrating mass of air to widely different places, but the progression takes place by the continual forming of a new cyclone in the line of advance, which line is determined by causes already given. New masses of air are thus continually brought into the movement, while the gyrations of that in the rear are destroyed by friction. Since the winds are travelling in nearly opposite directions on opposite sides of the cyclone, the progressive motion of the cyclone will evidently carry these opposite winds over any places properly situated; hence this progressive motion gives also an explanation of the *veering of winds* during the storm.

Paths of Cyclones.—The paths of cyclones are the lines travelled by their centres, and with few exceptions their directions are to the eastward. In the United States the average direction of motion, as given by Prof. Loomis, is nine degrees north of east, with an average of twenty-eight and four-tenths miles per hour. In the United States the valley of the St. Lawrence is the line most frequently swept by cyclones. The areas of low barometer are not circular but elliptical; the average ratio of the axes is about 1.5. The average direction of the longer axis of the storm is N. 36° E.

In Fig. 56 is shown by full barbed lines the approximate place of origin and the average line of travel of all the storms that passed over the United States from 1884 to 1893. The number travelling each route is indicated. It is seen that all leave the country by way of New England, and the greater number originate in Alberta.

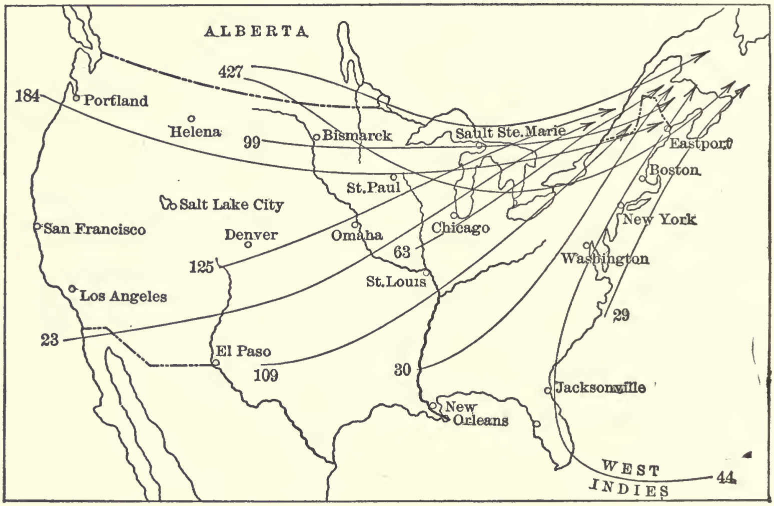

FIG. 56. (After BIGELOW.)

When a cyclone at sea reaches a low, level coast, the combined effect of the diminished pressure and the strong winds, especially if the tides also act in conjunction, may carry a destructive wave over the land. Such waves have wrought immense destruction over the lower delta of the Ganges and along our Texas coast.

Low-area Storms.—In the foregoing discussion the term *cyclone* has been used to include all large storms involving the cyclonic motion, and *low-area storms* are properly included. The custom of the United States Signal Office and the public press has, however, to a certain extent created a popular distinction between low-area storms and cyclones. By the limitations thus imposed, the term *cyclone* is generally restricted to certain tropical storms that usually have a parabolic path extending westward and northward from their point of origin off the west coast of Africa, near the doldrums, to about the 30th parallel and the 70th meridian. At this point the vertex of the parabola is reached, and the storm progresses to the northeastward parallel to the coast of the United States. These storms have a great power of continuance, and usually expand as they go. They sometimes extend their westward course to and beyond the United States coast, and then the northern branch of the path passes over the land, producing some of our most violent storms.

The *low-area storms*, under the above distinction, are those cyclonic storms that originate in the interior of our country and run their courses as modified by the causes already given.

The low-area storms are cyclonic, but the term cyclone, in popular use, is applied to those just mentioned or to the very violent of the low-area storms. Such real distinction as exists is based upon the path or intensity of the storm. It must be remembered that the term cyclone, as here used, applies to all cyclonic storms.

The progressive motion of the severe tropical cyclones just referred to is probably explained by the location of the high area in the North Atlantic, the cyclone being fed by and rotating along the edge of the high area. The motion of the trade winds and the great condensation which accompanies these storms are also probably important factors in their propagation.

Effects of the Cyclone and Anticyclone on Normal Temperature. —Since the gyratory motions of the winds in the cyclone in the northern hemisphere are always from right to left, as above defined, the colder air of the north is carried around to the west side, while the warmer air of the south is brought to the east side of the cyclone. The motions may materially affect the temperatures which would otherwise exist, especially on the east and west sides.

Wherever *high pressure* areas exist, the tendency is for the air to flow out beneath and to inaugurate more or less perfectly the conditions of a cyclone with a cold centre, or what is more generally designated an *anticyclone.*

It has been shown in such cases that there are descending instead of ascending currents, and under such conditions there could be no condensation; hence a high barometer usually brings or accompanies a clear and dry atmosphere. As radiation and evaporation take place much more readily under such conditions, the weather with high barometer is likely to be cooler also. These principles, coupled with the fact that the highs often draw air from great altitudes, are sufficient to explain the cooler and clearer weather which usually accompanies the high barometer.

Tornadoes.—Tornadoes are small violent cyclones. They extend over an area too small to be affected by the earth's rotation, yet they all in the northern hemisphere revolve from right to left (opposite to the hands of a watch with face up), and probably derive their gyrations from the motions of the air in which they originate. While the cyclone of considerable extent may be compared to a revolving disk of a diameter many times its depth, the tornado is a tall column of gyrating air whose height is many times its diameter. In the cyclone, therefore, the gyrations are much retarded by friction against the earth, and in the tornado the gyratory velocity, except in the lower strata, which are in contact with the earth, is very nearly in accordance with the law of central forces, varying inversely as the distance from the centre. On account of this rapid gyration, the effects produced in the cyclone are here intensified, and the gyrations a short distance above the surface are nearly circular, and the centrifugal force of the gyrations here tends to produce a vacuous column into which the air cannot enter from the sides. There is, therefore, a great diminution of pressure within, and especially at the centre of this column. The gyratory motion of the lower air only is much diminished by friction against the earth; it therefore flows toward the centre of low pressure and ascends with great velocity.

These indrawn currents are the most destructive ones, and are so strong that they sweep along and carry up heavy bodies and at times transport them long distances. The black funnel-shaped clouds which accompany the cyclone are due to the condensation of the moisture of the ascending air. The pressure of the air at and near the centre of the tornado is so greatly diminished that the stratum of condensation and cloud-formation is frequently there brought down (or nearly so) to the earth's surface. As we depart from the centre of the tornado the pressure is not so greatly diminished and the point of condensation is not so low, so that the base of the funnel-shaped cloud is above. The depending point is sometimes seen to withdraw into the cloud-mass above and to suddenly dart forth again. These effects are due simply to variations in the level at which condensation takes place, depending upon varying pressure, and this level may descend more rapidly than the air ascends, so that the vapor column shoots from above downward, while the air in which the condensation takes place is all the time moving upward. The diminution of pressure in violent tornadoes is very great, sometimes amounting to three inches of the barometric column. When such a tornado comes suddenly over a building, or other confined space, such as a cellar, from which the air at ordinary pressure cannot readily escape, there is exerted a great pressure from within outward. From this cause the explosions occur which unroof buildings and throw their walls outward, burst open cellar-doors against a strong direct wind, etc.

The average width of the path of destruction, as given by Finley from a large number observed, was about a thousand feet. Tornadoes generally accompany cyclones, and Finley has shown that they occupy pretty constant positions with reference to the centre of the cyclones. The greatest number of tornadoes occur, in this country, in the States of Kansas, Missouri, and Illinois, and they are most frequent in the month of June.

The phenomenon of a tornado is probably due to horizontal counter-currents, more local but similar to those which produce cyclones, flowing above an unstable atmosphere. These currents by their interactions develop gyrations which are doubtless greatly increased by the vertical convection of a moist unstable atmosphere, producing a vortex tube of great rotational velocity.

*Water-spouts.**—These are but special cases of tornadoes which pass over bodies of water, and in which the dependent portion of the accompanying cloud is reduced to a long slender stem extending down to the water. Owing to the diminished pressure at the centre of the tornado, the water beneath rises up into a mound, is lashed into foam, and large quantities of it are carried aloft by the

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* These phenomena might with equal propriety come in the next chapter where *results* are considered, but when causes are considered their explanation follows more naturally here.

ascending currents of air. From small lakes and ponds the inhabitants thereof may be carried aloft with the water and descend at considerable distances, giving showers of fish, frogs, etc.

*Cloud-bursts.**—By the ascending and gyrating currents of air in a tornado, a great quantity of rain or condensed moisture may be carried along until its weight becomes so great that it descends in streams, or until the tornado has its force broken by some material object, such as a crag or peak, when the accumulated rain descends almost in a mass, with terrific effect.

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* See foot-note on preceding page.

CHAPTER XI.

AQUEOUS METEORS.

Under this head are included all the visible phenomena which result from the condensation of the aqueous vapor in the atmosphere, and this condensation always occurs whenever the temperature of the air, from any cause, falls below the dew-point. The most commonly observed of such phenomena will be described.

Mists, Fogs, and Clouds.—These result whenever the aqueous vapor of the atmosphere is condensed and suspended in visible form. This condensed vapor is believed to exist as liquid particles or spheres, not hollow, differing from rain-drops only in size. Their suspension is due to the viscosity of the air and to the fact that the atmosphere is never absolutely quiescent, and the vapor particles are kept floating like dust and other solid particles which are often observed in the air and which are seen never to be at rest.

Fogs and Mists.—Fogs and mists differ from clouds merely in that they are formed at less elevation. They are due to local causes, and may be formed in several ways. At the first approach of winter, when the air of a region is often many degrees colder than the water, mists are seen to overspread the streams, the vapor arising from them being condensed by the cold air. The same phenomenon is often observed when the conditions are reversed,—when the water is colder than the air.

Fogs are often formed at night or late in the day, at the lowest lines of valleys and in depressed areas, while the sides of the valley and knolls, though of but slight elevation, especially if covered with vegetation, are exempt from them. This results from the presence of more moisture in the open valley and the more rapid radiation as compared to wooded areas, and also sometimes partly from the fact that the air which is cooled at the higher levels, if there are no winds, descends to the lower. Sheep and other animals learn to take advantage of these natural conditions, and are often seen, in the early morning, to have spent the night just above the damper atmosphere. In the elevated regions of our western country, among the narrow valleys of the Sierras and the Rocky Mountains, quite marked climatic effects result from these causes alone. In those regions flourishing gardens are often seen situated near the forest growth at the sides of the valley, while nearer the axis of the valley and not over five miles away, and two hundred feet lower, many of the same vegetables cannot be successfully grown. Again, orchards well up on the side slopes are productive, while lower down the valley they are comparative failures.

As a further illustration of these principles the following instance may be cited. In September, 1877, while engaged in survey work in the Sierras of Northern California, for the purpose of being early on the summit of a mountain the author spent the night far up the side, some two thousand feet above the camp of the party in the valley below, though within sight. Before sunrise the next morning the difference of temperature between the two stations at the same hour was 7° F., the upper being the warmer. The night was very clear and still. Recent investigations show that the air at higher altitudes is, at night, often warmer than that lower down —an inversion of the ordinary relations.

As low-lying fogs are usually accompanied by more or less dew, a knowledge of their origin is an important aid to the selection of the best camping sites where there are no other considerations. From the illustrations given, it will be seen that the most favorable sites, where it is desirable to avoid dampness and cold, are those protected from direct radiation, some distance above the lowest neighboring levels, and upon a ridge rather than a ravine leading to these levels. If not *within* the timber, it will be well to have the latter on the slope above rather than to camp upon an open hillside.

Clouds.—There are several kinds of clouds, and they shade into each other, so that there can be no precise classification. We shall refer only to the four principal classes.

Cumulus.—These are the rounded masses or convex heaps extending upward from flat horizontal bases. They are very common in summer, and are believed to be due to the condensation of ascending columns of vapor. The flat base marks the level where condensation begins, and the rounded masses are the tops of the ascending columns. If the cumulus is overhead, its typical form cannot be seen, and it will not be observed as such. These clouds are consequently noticed only on the horizon.

Stratus.—These consist of horizontal layers, and are generally at low levels. They are probably due to the cooling of a comparatively still atmosphere by radiation ; when the dew-point is reached at a certain level, the first layer is formed. These clouds may result from a fog lifted in a horizontal stratum. They frequently appear at sunset and disappear in the morning.

Prof. Bigelow has concluded from cloud observations that stratus clouds are often produced as sheets at the contact surface of the streams of air at different temperatures and altitudes flowing past each other, the upper having the greater velocity. The cumulus may be produced at different levels by vertical ascension of columns in strata having the same velocity throughout.

Cirrus.—These clouds are of great variety, but the most characteristic are the fibrous, feathery clouds which float in the higher atmosphere. It is to these clouds that halos are due, and such clouds are believed to be often composed of particles of ice.

Nimbus is any cloud from which rain is falling.

The classification of clouds is further differentiated into other types quite distinct, though grading into the classes given; as cirro-stratus, cirro-cumulus, alto-stratus, strato-cumulus, cumulo-nimbus.

Altitude and Thickness of Clouds.—Clouds are formed at various heights, from near the surface of the earth up to at least ten miles. Stratus and cumulus are the lowest, cirrus the highest, and composite clouds intermediate. Several cloud masses often overlie one another with clear space between. This arrangement has been observed in balloon ascents.

Cloud Shadows.—In a hazy atmosphere the shadows of clouds are frequently distinctly shown by dark lines proceeding from the sun. When these lines of light and shadow extend downward and toward rivers or other bodies of water, the sun is popularly said to be " drawing water." The same effect is frequently seen just before and after sunset and also at sunrise, being a conspicuous feature of morning and evening twilight.

Cloud Formation.—Clouds may result from reduction of temperature due to loss of heat by the air,—

(1) From direct radiation into the upper space.

(2) From proximity to colder masses, such as ice-fields or mountain-tops.

(3) From expansion due to diminished pressure, as when the air from any cause is made to ascend.

(4) From cooling by contact in the partial or complete mixture of two masses of air at different temperatures.

Rain.—When the condensation of the aqueous vapor takes place with such rapidity that the liquid particles enlarge and fall to the earth in drops, we have the phenomenon of rain. The causes which produce clouds *tend* also to produce rain, but only the third and fourth of the above causes are sufficient; the others are believed never to result in rain.

Any of the agencies, then, which cause a sufficient ascent of moist air will produce rain. The most evident illustration of this fact is seen wherever vapor-bearing winds blow over high mountains. The trade-winds deflected upward by the Andes give the heavy rainfalls at the head-waters of the Amazon. The coast ranges of Washington and Oregon, lifting up the prevailing winds from the Pacific, give the heavy rains of that region. The greatest average rainfall of the known world is at Chirra Poongee, in the Cassya Mountains, about three hundred miles north of the head of the Bay of Bengal. The rainfall at this place, according to General Greely, has averaged 493.2 inches per year since 1871; in 1861 there is said to have fallen there the enormous amount of 905.1 inches. The cause of this heavy fall is the passage of the winds of the Indian monsoon over the lofty ranges which are part of the Himalaya system.

It is not believed that currents of air ever mingle with sufficient rapidity to produce rain, but it is probable that a moisture-bearing stratum may be lifted upward by the intrusion of a colder, denser layer below, and thus produce rain. When such an atmospheric wedge protrudes from the north over the eastern part of the United States, especially in mild winter weather, we have, according to

Prof. Ferrel, an explanation of the drizzly weather with a north-northeast wind, sometimes lasting for several days. At other times such conditions give the *cold waves* already mentioned.

Cyclonic Rains.—These are the rains which accompany the great cyclonic or low-area storms already mentioned, and are the usual rains which prevail in this country east of the great plains. They are due to the ascent of the air in the cyclones as already described, and to the direct cooling of the moist warm air by contact with the cold air as the two winds are drawn into thin spiral filaments in their motion around the cyclonic centre.

In many of our cyclonic rain-storms the condensation produced by the ascension of the air in the cyclone is added to by the fact that the moisture-bearing winds from the sea move over a cold land at the same time that they are travelling northward. In other words, causes 2, 3, and 4 above given are united in the cyclonic storms.

The observations of these rain areas show them to be generally of an elliptical form, as is the case with isobars * of the cyclone, but the rain areas coincide only roughly and in a general way with the areas of barometric depression, for the condensed vapor is generally, in part at least, carried beyond the low area by the outflowing air before it can fall as rain. From Prof. Loomis's extended studies, these areas are seen to approximate to an ellipse, the major axis of which is about twice as long as the minor, the lesser axis frequently being more than five hundred miles long. North of 36° the average distance of the centre of the greatest rainfall from the centre of low pressure is about four hundred miles, and at times the distance is nearly twice as great. The direction of the longer axis of the rain area and the direction of the centre of greatest rainfall from the centre of low pressure are generally the same as the direction of the path of the cyclone.

Although rains *usually* accompany cyclonic storms, some, as already stated, have been observed without them. On the other hand, while rain areas are usually areas of low barometer, it is not always so. Rains may occur without sensible depression of the barometer. If the whole atmosphere of an extended region is nearly saturated and near to the unstable condition, local causes may give rise to ascending currents, with the production of clouds and rain without sensible depression of the barometer. Such an atmosphere in pass-

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* Isobars are lines drawn on a map through points at which the barometric pressure is the same.

ing over the land, especially during warm weather, is subjected to a variety of temperature conditions due to the varying nature of the earth's surface, and is likely to produce showery weather.

Measurement of Rainfall.—This measurement is made by determining the depth in inches to which the rain which falls on any area would cover that area. The time for which this record is kept determines the fall for that period. The instrument used for determining the fall is called a rain-gauge, and may consist of a plain cylindrical cup or any other vessel from which the depth of water which falls on any given area may be measured. The gauge should be so placed as to be entirely uninfluenced by other bodies, in a large open space with the upper surface a foot or two above the ground.

Rainfall of the United States.—The rainfall of the United States, as taken from the excellent chart of Prof. Loomis, may be summarized as follows:

Over the whole area east of the hundredth meridian there is less than 50 inches and more than 25, excepting South Carolina, Georgia, and the Gulf States, which have more than 50 and less than 75. Between the hundredth and hundred and twentieth meridian less than 25 and more than 10, except a strip about two hundred and seventy-five miles wide extending from Salt Lake to the Gulf of California, which has less than 10 inches. West of the hundred and twentieth meridian there is more than 25 and less than 50 inches, except in Northern Oregon and in Washington Territory, where there is more than 50 inches.

Dry Regions of the Globe.—There are large tracts of the earth's surface over which very little rain falls. This is due partly to the localization of the areas in the interior of continents or on the leeward sides of mountains, so that the air is deprived of all moisture before reaching them. Such are the Great Desert of Sahara, large portions of Arabia and Persia, the desert of Gobi in Asia, Central Australia, Western South America, and the southern portion of our own country between the Rocky Mountains and the Sierras. Besides their continental location some of these areas are materially influenced by their positions with reference to the general circulation of the air.

It has been seen that there are two belts of high barometer which encircle the earth near the tropics, and that the air settling down from them flows outward both toward the poles and toward the equator, the latter current helping to form the trade-winds. With descending motion and direction toward a warmer region, there would be no tendency to condensation, but the reverse. Where the regularity of the trade-winds is not interfered with, we should expect little rainfall, and such is found to be the case at sea. The same influences are felt to a certain extent over the land. By an inspection of a map it will be seen that the Desert of Sahara, the dry regions of Arabia, Persia, and our own country are between the fifteenth and fortieth parallels in the northern hemisphere, while the dry region of Southern Africa, of Australia, and a large part of that of South America are between the same parallels in the southern hemisphere.

Snow, Sleet, and Hail.—*Snow.*—The conditions which produce the rain-storms will precipitate snow when the level at which condensation takes place is at a sufficiently low temperature. Where the temperature does not sink below 32° F., snow cannot form. It is believed that snow is formed by the direct passage of vapor into the solid state, the minute crystals attaching themselves together into flakes. More than a thousand different forms of flakes have been observed, most of them being of great delicacy and beauty. From the loose texture of snow and because of the air imprisoned in the flakes, it is an extremely good non-conductor of heat, and protects the earth's surface from the cold due to its own radiation.

Sleet.—This term is often applied to small imperfect spheres of snowy ice, frequently mingled with rain, which sometimes fall to the earth. These are believed to be due to the partial melting of snow-flakes, during their passage through strata of higher temperature, and subsequent regelation.

Hail.—In the gyratory motions which constitute cyclones and tornadoes, we have seen that there is sufficient energy developed in the former to carry the rain up and outward beyond the region of ascending currents before it falls to the earth; in the tornadoes much heavier bodies are kept aloft. It is the developement of strong ascending currents in storms which explains the phenomenon of hail precipitation. If the hail be no larger than rain-drops, it is only necessary to conceive that the liquid drops were carried up into a freezing temperature, and then outward until the ascending currents no longer supported them, when they fell to the earth.

But frequently hailstones have fallen that were very large, some as much as five inches in diameter, and weighing nearly two pounds. These largest stones frequently have a bunch of snow at the centre, and are made up of alternate concentric layers of ice and snow. The most plausible explanation in these cases is probably that of Prof. Ferrel, which may be briefly outlined as follows: The strong ascending currents of the hail-storm carry the rain-drops up into the snow region, and before they freeze they moisten the snow-flakes; these adhere, forming an incipient snow-ball. This ball is then carried upward and out from the vortex of the storm and begins to descend, but before reaching the earth it is drawn by the inblowing currents below again into the ascending whirl and carried up to receive another coating of snow and perhaps subjected to a very low temperature. Descending again, as it passes outward from above it passes through a rain region, and, owing to its reduced temperature, it freezes the particles with which it comes in contact and thus receives a coating of ice. It may be again and several times drawn into the whirl, and repeat the circuit until it grows, by the alternate layers of ice and snow, too heavy to be kept up and falls to the earth. A hail-storm differs from a common tornado in that its ascending currents are sufficiently strong to carry the solid particles up to freezing regions. Hail usually occurs in summer, because the conditions for violent tornadoes are more frequent then, and because the freezing altitude in winter is so low that the necessary rain region does not exist below the snow, the passage through which gives the ice layer.

Dew.—The deposition of dew depends upon cooling caused by radiation. As soon as the sun passes below the horizon, the radiation of heat from the dark portion of the earth's surface is no longer compensated by solar rays, and it is steadily reduced in temperature. The air immediately above has its temperature reduced by contact with the cool surface, and, if this reduction reaches the dew-point of the air, the moisture is deposited, and gravity and the force of cohesion collect it into the pearly drops which sparkle in the morning sun. If there be clouds, foliage, or screens of any sort that partially or wholly intercept the radiant heat and return it to the earth, they will tend to and may prevent the formation of dew by preventing a sufficient reduction of temperature.

Those bodies, such as grass, leaves, etc., which radiate heat well but are not warmed by contact with the earth, collect the moisture more readily and abundantly than equally good radiators, such as stone and metal, when in contact with the earth. A gentle motion of the air by which a greater amount of it is brought into contact with the cool earth favors the deposition of dew, but stronger winds, which continually shift the air before any of it is reduced in temperature to the dew-point, prevent the deposition. The air itself does not radiate heat as readily as the bodies named, so that by its own radiation the air does not cool as rapidly as by contact with the earth and other better radiators. The deposition of moisture on the outside of a glass of ice-water or other cool surface when taken into a warm room is due to the cooling of the air to the dew-point, exactly as is done by the earth at night.

The result of this is that there is frequently a difference of several degrees in temperature between the earth's surface and the air a few feet above. Consideration of the principles here enunciated is of great practical importance in determining the best places for selecting camps in the field.

This explanation of the formation of dew is that first given in 1814 by Dr. Wells, an American residing at the time in London.

In 1879 certain observations were made at the Massachusetts Agricultural Station by Prof. Stockbridge which show that the earth, when dew is formed, is not always cooler than the air above it, and that in certain cases much of the vapor which is condensed into dew is exhaled from the warmer earth and condensed by the cooler air above instead of being condensed from the air by the cooler earth. Mr. Aitken of Falkirk, Scotland, in 1886 and subsequently, from apparently independent experiments of his own came to the same conclusion.

This idea of dew forming from aqueous vapor escaping from the ground into the colder space above must have occurred to all who have observed how abundantly dew often forms on the under side of an oil-cloth blanket or garment when placed upon the ground, when it would seem impossible for the moisture to have come from the air. Further observations on this interesting subject may materially modify Wells's general explanation.

Frost.—If the dew-point of the air be below the freezing point, the vapor will be condensed as ice and then constitutes hoar-frost. Deposited dew may also be frozen, and thus often forms part of the earth's mantle of frost

APPENDIX I.

PROBLEMS.

1. What temperature on the Fahrenheit scale corresponds to 12° C.? 3.9° C.? – 273° C.? 164° C.?

2. Convert the following into Centigrade and Réaumur readings: 98° F.; 60° F.; 212° F.; 0° F.; – 460° F.; – 40° F.

3. Convert the following into Fahrenheit and Réaumur readings: 36.67° C.; – 140° C.?

4. The difference of temperature between summer and winter at West Point is often 90° F. What would be the range by a centigrade thermometer?

5. What temperature is expressed by the same number on the two scales, Fahrenheit and Centigrade?

6. A thermometer has both scales (F. and C.) graduated upon it; the sum of the readings is 74. What is the temperature?

7. The three scales R., F., and C. are graduated upon the same thermometer tube; the sum of the readings is 52. What is the temperature?

8. An iron girder-bridge is ninety-two feet long at 0° C. What is the variation in its length when the winter temperature reaches 0° F., and the summer temperature 80° F.? The linear expansion of iron is given, page 15.

9. Taking the same extremes of temperature as above, what is the difference in length, in summer and winter, of the steel rails on the road between New York and Albany. The distance between the two cities is about 150 miles. Coefficient of expansion of the rails may be taken as .0000118 for each degree C.

10. Given 100 cu. ft. of air at 15.5° C., what will be its volume

if the temperature be raised to 19.5° C., external pressure remaining the same?

11. 170 cu. in. of oxygen are measured at 10° C. What will the volume be in case the temperature sink to 0° C., external pressure remaining constant?

12. A gas has its temperature raised from 15° C. to 50° C. under constant external pressure; at the latter temperature it measures 15 litres. What was the initial volume?

13. Given 300 cu. ft. of hydrogen at 150° C., what must be its temperature in order that its volume may be increased to 400 cu. ft.? At what temperature will its volume be 600 cu. ft.? External pressure constant.

14. Given 100 cu. ft. of nitrogen at 273° C., what will be its volume if the temperature be reduced to 0° C., the external pressure remaining constant? To −273° C.? What will be its volume if the temperature be raised to 546° C.?

15. Given 1000 cu. ft. of gas at 60° F., what will be its volume at 106° F., the external pressure remaining constant?

16. Given 400 cu. ft. of hydrogen at 100° F., required its volume at 200° C.

17. Having given two volumes of gas of 40 and 60 cu. ft., respectively, at 20° C.; what will be the volumes when the temperature falls to −10° C., external pressure remaining unchanged?

18. Prove that the coefficients of expansion $\frac{1}{273}$ on the centigrade scale and $\frac{1}{460}$ on the F. scale represent the same relative amounts.

19. If the bore of a thermometer tube be $\frac{1}{20}$ of an inch in diameter, and the distance between the freezing and boiling points on the scale be six inches, what is the capacity of the bulb and the tube below the freezing point?

20. The specific gravity of absolute alcohol at 0° C. is .793; what is it at 25° C.? The coefficient of expansion of alcohol is .001 for each degree C.

21. The coefficient of cubical expansion of mercury is .00018 and of water .0005 for each degree C. The specific gravity of mercury when compared with water at 20° C. is 13.568; what is it when compared with water at 0° C.?

22. A flask made to hold ten litres is filled with alcohol at 10° C.; when the temperature has risen to 30° C. how much alcohol

will overflow? The capacity of the flask is not supposed to change.

23. * 5 lbs. silver were heated to 160° C., and placed in 25 lbs. water at 69° C., the resulting temperature was 70° C. What is the specific heat of silver?

24. 30 lbs. sulphur were heated to 100° C. and placed in 150 lbs. water at 10° C.; the resulting temperature was 13.5° C. What is the specific heat of sulphur?

25. Required the number of thermal units necessary to raise the temperature of 10 lbs. of bismuth from 0° to 100° C. Sp. ht. of bismuth = 0.03.

26. Required the number of thermal units necessary to raise the temperature of 5 lbs. dry air (at constant pressure) from 0° to 50° C. Sp. ht. of dry air (at constant pressure) = 0.2375.

27. Given 10 lbs. ice at 0° C., and 100 lbs. water at 13.4° C. The two are mixed, and when all the ice is melted the temperature of the whole is 5° C. What is the latent heat of liquefaction of ice?

28. 10 lbs. of zinc were heated to 355° C. and placed in an ice calorimeter. At the end of a certain time the zinc had cooled to 0° C., and it was found that 4.27 lbs. ice had been melted. Required the specific heat of zinc.

29. Taking the annual rainfall at West Point as 43 inches, required the amount of heat set free among the clouds that give rain to one square mile of area in a year, by the simple condensation of the vapor. 1 cu. ft. water weighs 62.5 lbs. 1 mile = 5280 ft.

30. A ball of sulphur weighing 5 lbs. was heated to its fusing point, 111° C., and then dropped into 20 lbs. of turpentine heated to 150° C. The resulting temperature was 141.2° C. Required the latent heat of sulphur. Sp. ht. of turpentine = 0.467. Sp. ht. of sulphur = 0.234.

31. A ball of sulphur weighing 17.115 lbs. was heated to 100° C., and then dropped into 20 lbs. of turpentine at 150° C. The resulting temperature was 123.7° C. Required the latent heat of sulphur. Fusing point of sulphur = 111° C. Sp. ht. of sulphur liquid = 0.234; solid = 0.202. Sp. ht. of turpentine = 0.467.

32. Given 100 lbs. lead at 15° C. Required the number of

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* In all calorimetrical problems no heat is supposed to be lost.

thermal units necessary to melt it. Sp. ht. of lead = 0.03. Melting point = 320° C. Latent heat of fusion = 5.4° C.

33. Given 100 lbs. ice at 0° C. Required the temperature to which 150 lbs. of water must be heated in order to just melt the ice.

34. Given 5 lbs. ice at 0° C., and 50 lbs. water at 15° C. Required the first common temperature resulting from their mixture.

35. Given 10 lbs. ice at −10° C., and 40 lbs. water at 50° C. Required the first common temperature resulting from their mixture.

36. Given 10 lbs. steam at 100° C., and 30 lbs. ice at − 40° F. Required the temperature that results from condensing the steam in the ice?

37. Given 20 lbs. steam at 130° C., and 100 lbs. ice at − 30° C. Required the temperature that results from their action upon each other.

38. 2 lbs. of water were cooled 12° C. below the freezing point. Congelation then set in. Required the amount of ice formed.

39. The dew-point on a certain day is 10° C.; the temperature of the air 21.1° C. Required the relative humidity. At temperature 10° C., maximum pressure = 0.375. At temperature 211° C. maximum pressure = 0.721.

40. Given 10 cu. in. of water vapor (saturated) at 15.5° C. The volume remaining the same, the temperature is lowered to 10° C. Required the volume and weight of vapor liquefied. 100 cu. in. water vapor (saturated) at 10° C. weigh 0.247 grs. 100 cu. in. water vapor (saturated) at 15.5° C. weigh 0.338 grs.

41. Given 10 cu. in. of water vapor (saturated) at 10° C. The temperature remaining the same, the volume is diminished to 9 cu. in. Required the volume and weight of vapor liquefied. 100 cu. in. water vapor (saturated) at 10° C. weigh 0.247 grs.

42. Suppose the air over an area 10 miles square, to the height of $\frac{1}{4}$ of a mile, to be saturated at the temperature of 70° F. How much water would be produced, and how much heat liberated by the condensation of all the moisture in the space? A cubic foot of saturated vapor at 70° weighs 7.99 grs.

43. The absolute conductivities of wrought-iron and platinum are, respectively, 0.2 and 0.087. Required their diffusivities. Sp.

ht. wrought-iron=0.1138; sp. gr.=7.79. Sp. ht. platinum=0.0324; sp. gr. = 21.15.

44. In Joule's Experiment a weight of 25 lbs. was used; the distance through which it fell was 6 feet; the temperature of the water in the vessel was 10° C. before the experiment, and 11° C. after the weight had been allowed to fall 100 times. The water weighed 10.7914 lbs. Required the mechanical equivalent of a *unit of heat.*

45. Required the amount of heat, and its equivalent in units of work, necessary to convert 10 lbs. of ice at – 40° C. into steam at 120° C.

46. How much heat is given out by 10 lbs. of steam, at 130° C., in cooling and condensing to water at 15.5 C. What is the mechanical equivalent of this heat?

APPENDIX II.

TABLES.

Table I.

LOGARITHMS.

Proportional Parts.

Nat. No.	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0212	0294	0334	0374	4	8	12	17	21	25	29	33	37
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	8	11	12	13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8

Table I.—*Continued.*

LOGARITHMS.

Nat. No.	0	1	2	3	4	5	6	7	8	9	Proportional Parts.								
											1	2	3	4	5	6	7	8	9
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7704	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4

Table II.

SQUARE ROOTS.

n	$\sqrt{n}$	n	$\sqrt{n}$	n	$\sqrt{n}$	n	$\sqrt{n}$
1	1.0000	26	5.0990	51	7.1414	76	8.7178
2	1.4142	27	5.1962	52	7.2111	77	8.7750
3	1.7321	28	5.2915	53	7.2801	78	8.8318
4	2.0000	29	5.3852	54	7.3485	79	8.8882
5	2.2361	30	5.4772	55	7.4162	80	8.9443
6	2.4495	31	5.5678	56	7.4833	81	9.0000
7	2.6458	32	5.6569	57	7.5498	82	9.0554
8	2.8284	33	5.7446	58	7.6158	83	9.1104
9	3.0000	34	5.8310	59	7.6811	84	9 1652
10	3.1623	35	5.9161	60	7.7460	85	9.2195
11	3.3166	36	6.0000	61	7.8102	86	9.2736
12	3.4641	37	6.0828	62	7.8740	87	9.3274
13	3.6056	38	6.1644	63	7.9373	88	9.3808
14	3.7417	39	6.2450	64	8.0000	89	9.4340
15	3.8730	40	6.3246	65	8.0623	90	9.4868
16	4.0000	41	6.4031	66	8.1240	91	9.5394
17	4.1231	42	6.4807	67	8.1854	92	9.5917
18	4.2426	43	6.5574	68	8.2462	93	9.6437
19	4.3589	44	6.6332	69	8.3066	94	9.6954
20	4.4721	45	6.7082	70	8.3666	95	9.7468
21	4.5826	46	6.7823	71	8.4261	96	9.7980
22	4.6904	47	6.8557	72	8.4853	97	9.8489
23	4.7958	48	6.9282	73	8.5440	98	9.8995
24	4.8990	49	7.0000	74	8.6023	99	9.9499
25	5.0000	50	7.0711	75	8.6603	100	10.0000

Table III.

EQUIVALENT THERMOMETER READINGS.

F.	C.	R.	F.	C.	R.
0	$-17\frac{7}{9}$	$-14\frac{2}{9}$	284	140	112
− 4	− 20	− 16	293	145	116
+ 5	− 15	− 12	302	150	120
+ 14	− 10	− 8	311	155	124
+ 23	− 5	− 4	320	160	128
+ 32	0	0	329	165	132
41	+ 5	+ 4	338	170	136
50	10	8	347	175	140
59	15	12	356	180	144
68	20	16	365	185	148
77	25	20	374	190	152
86	30	24	383	195	156
95	35	28	392	200	160
104	40	32	401	205	164
113	45	36	410	210	168
122	50	40	419	215	172
131	55	44	428	220	176
140	60	48	437	225	180
149	65	52	446	230	184
158	70	56	455	235	188
167	75	60	464	240	192
176	80	64	473	245	196
185	85	68	482	250	200
194	90	72	491	255	204
203	95	76	500	260	208
212	100	80	509	265	212
221	105	84	518	270	216
230	110	88	527	275	220
239	115	92	536	280	224
248	120	96	545	285	228
257	125	100	554	290	232
266	130	104	563	295	236
275	135	108	572	300	240

Equal Differences of Temperature.

⊿ F	⊿ C	⊿ R
1	.56	.44
2	1.11	.89
3	1.67	1.33
4	2.22	1.78
5	2.78	2.22
6	3.33	2.67
7	3.89	3.11
8	4.44	3.56
9	5.00	4.00

⊿ C	⊿ F	⊿ R
1	1.8	.8
2	3 6	1.6
3	5.4	2.4
4	7 2	3.2
5	9.0	4.0

⊿ R	⊿ C	⊿ F
1	1.25	2.25
2	2.50	4.50
3	3 75	6·75
4	5.00	9.00

TABLE IV.

MELTING-POINTS.

	Melting-point. Degrees C.
Aluminum	625
Antimony	440
Bismuth	268
Cadmium	320
Cobalt	1500
Copper	1050
Gold	1050–1065
Iron, cast	1050–1200
" steel	1300–1400
" wrought	1400–1600
Lead	325
Magnesium	700–800
Mercury	— 40
Nickel	1600
Phosphorus	44
Potassium	62.5
Platinum	1770
Silver	945
Sodium	96
Sulphur	115
Tin	227
Zinc	415

TABLE V.

BAROMETRIC READINGS.

(To pass from Inches to Millimeters, and vice versa.)

Inches.	Mm.	Inches.	Mm.
28.0	711.19	30.5	774.69
28.1	713 73	30.6	777.23
28.2	716.27	30.7	779.77
28.3	718.81	30.8	782.31
28.4	721.35	30.9	784 85
28.5	723.89	31.0	787.39
28.6	726.43		
28.7	728.97		
28.8	731.51		
28.9	734.05		
29.0	736.59		
29.1	739.13		
29.2	741.67		
29.3	744.21		
29.4	746.75		
29.5	749.29		
29.6	751.83		
29.7	754.37		
29.8	756.91		
29.9	759.45		
30.0	761.99		
30.1	764.53		
30.2	767.07		
30.3	769.61		
30.4	772.15		

Equivalent Lengths.	
Inch.	Mm.
.01	.254
.02	.508
.03	.762
.04	1.016
.05	1.270
.06	1.524
.07	1.778
.08	2.032
.09	2.286

Equivalent Lengths.	
Mm.	Inch.
.1	.0039
.2	.0079
.3	.0118
.4	.0157
.5	.0197
.6	.0236
.7	.0276
.8	.0315
.9	.0354
1.0	.0394
1.1	.0433
1.2	.0472
1.3	.0512
1.4	.0551
1.5	.0591
1.6	.0630
1.7	.0669
1.8	.0709
1.9	.0748
2.0	.0787
2.1	.0827
2.2	.0866
2.3	.0906
2.4	.0945
2.5	.0984

TABLE VI.

DEW-POINT AND RELATIVE HUMIDITY.

Difference of Readings of Dry and Wet Bulbs.	Temperature of Air—Fahrenheit.											
	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	
1	−7	5	16	27	38	48	58	69	79	89	99	Dew-point
	71	80	86	90	92	93	94	95	96	96	97	Rel. humidity
2	−18	−1	12	24	35	46	57	67	77	87	98	D. P.
	42	60	72	79	84	87	89	90	92	92	93	R. H.
3	−39	−9	7	21	33	44	55	66	76	86	96	D. P.
	13	41	58	68	76	80	84	86	87	88	90	R. H.
4	....	−22	1	17	30	42	53	64	74	85	95	D. P.
	...	21	44	58	68	74	78	81	83	85	86	R. H.
6	....	....	−18	7	24	37	49	61	72	82	93	D. P.
	....	....	16	38	52	61	68	72	75	78	80	R. H.
8	....	....	....	−8	16	31	45	57	68	79	90	D. P.
	....	....	....	18	37	49	58	64	68	71	74	R. H.
10	....	....	....	....	4	25	40	53	65	77	87	D. P.
	....	....	....	....	22	37	48	55	61	65	68	R. H.
12	....	....	....	...	−16	17	35	49	62	74	85	D. P.
	....	....	....	....	8	26	39	48	54	59	62	R. H.
14	....	...	....	....	....	5	28	45	58	70	82	D. P.
	....	....	....	....	....	16	30	40	47	53	57	R. H.
16	....	...	....	....	....	−20	20	39	54	67	79	D. P.
	....	....	...	....	....	5	21	33	41	47	51	R. H.
18	....	....	....	....	....	....	8	33	50	63	76	D. P.
	..	...	....	....	....	....	13	26	35	41	47	R. H.
20	....	....	....	....	....	....	−13	25	45	60	73	D. P.
	....	...	....	....	....	....	5	19	29	36	42	R. H.
22	....	...	....	....	...	....	....	15	39	56	69	D. P.
	..	...	....	....	....	....	....	12	23	32	37	R. H.
24	...	...	....	....	....	....	....	0	32	51	66	D. P.
	.	...	....	....	....	...	..	6	18	26	33	R. H.

NOTE.—To obtain reliable results from the use of the psychrometer it is necessary to have a standard rate of air-movement past the instrument. This motion may be accomplished by attaching a string to the frame of the two thermometers, when they are properly mounted, and whirling them through the air for a couple of minutes at a velocity of twelve or fifteen feet per second. The above data are extracted from Hazen's table for use with the "sling" psychrometer.

TABLE VII.

MAXIMUM PRESSURE (TENSION) OF WATER-VAPOR BETWEEN − 20° AND 100° C. IN MILLIMETERS OF MERCURY.

Temperature, Deg. C.	Millimeters.	Temperature, Deg. C.	Millimeters.	Temperature, Deg. C.	Millimeters.
− 20	.907	21	18.4659	62	163.2889
− 19	1.0288	22	19.6297	63	170.9236
− 18	1.1202	23	20.8576	64	178.8585
− 17	1.2187	24	22.1524	65	187.1028
− 16	1.3248	25	23.5174	66	195.6663
− 15	1.4390	26	24.9556	67	204.5586
− 14	1.5618	27	26.4705	68	213.7895
− 13	1.6939	28	28.0654	69	223.3691
− 12	1.8357	29	29.7439	70	233.3079
− 11	1.9880	30	31.5096	71	243.6163
− 10	2.1514	31	33.3664	72	254.3048
− 9	2.3266	32	35.3181	73	265.3849
− 8	2.5143	33	37.3689	74	276.8675
− 7	2.7153	34	39.5228	75	288.7640
− 6	2.9304	35	41.7842	76	301.0860
− 5	3.1605	36	44.1577	77	313.8475
− 4	3.4065	37	46.6477	78	327.0549
− 3	3.6693	38	49.2950	79	340.7265
− 2	3.9499	39	51.9965	80	354.8730
− 1	4.2493	40	54.8651	81	369.5075
0	4.5687	41	57.8700	82	384.6432
+ 1	4.9091	42	61.0167	83	400.2933
2	5.2719	43	64.3104	84	416.4721
3	5.6582	44	67.7568	85	433.1938
4	6.0693	45	71.3619	86	450.4730
5	6.5067	46	75.1314	87	468.3240
6	6.9718	47	79.0714	88	486.7635
7	7.4660	48	83.1883	89	505.8059
8	7.9909	49	87.4882	90	525.4676
9	8.5484	50	91.9780	91	545.7650
10	9.1398	51	96.6644	92	566.7149
11	9.7671	52	101.5541	93	588.3349
12	10.4322	53	106.6546	94	610.6426
13	11.1370	54	111.9730	95	633.6567
14	11.8835	55	117.5162	96	657.3956
15	12.6739	56	123.2925	97	681.8791
16	13.5103	57	129.3095	98	707.1271
17	14.3950	58	135.5750	99	733.1602
18	15.3304	59	142.0973	100	760.0000
19	16.3189	60	148.8848		
20	17.3632	61	155.9456		

Table VIII.

PRESSURE OF SATURATED STEAM AT DIFFERENT TEMPERATURES IN POUNDS PER SQUARE INCH AT SEA-LEVEL.

Temperature, Deg. F.	Pressure per Square Inch, Pounds.	Temperature. Deg. F.	Pressure per Square Inch, Pounds.	Temperature. Deg. F.	Pressure per Square Inch, Pounds.	Temperature, Deg. F.	Pressure per Square Inch, Pounds.
100	.942	144	3.188	188	8.94	232	21.59
101	.971	145	3.270	189	9.13	233	21 99
102	1.001	146	3.354	190	9.33	234	22.40
103	1.031	147	3.440	191	9.53	235	22.82
104	1.062	148	3.527	192	9.74	236	23.25
105	1.094	149	3.616	193	9.95	237	23.67
106	1.127	150	3.707	194	10.16	238	24.11
107	1.160	151	3.800	195	10.38	239	24.55
108	1.195	152	3.895	196	10.60	240	25.00
109	1.230	153	3.992	197	10.82	241	25.46
110	1.267	154	4.091	198	11.05	242	25.92
111	1.304	155	4.192	199	11.29	243	26.39
112	1.342	156	4.295	200	11.52	244	26 87
113	1.381	157	4.401	201	11.76	245	27.35
114	1.421	158	4.508	202	12.01	246	27 84
115	1.462	159	4.618	203	12.26	247	28.34
116	1.504	160	4.730	204	12.51	248	28.85
117	1.547	161	4.844	205	12.77	249	29.36
118	1.591	162	4.961	206	13 03	250	29.88
119	1.637	163	5.080	207	13.30	251	30.41
120	1.683	164	5.20	208	13.57	252	30.94
121	1.731	165	5.32	209	13.84	253	31.48
122	1.779	166	5.45	210	14.12	254	32.03
123	1.829	167	5.58	211	14.41	255	32.59
124	1.880	168	5.71	212	14.70	256	33.15
125	1.932	169	5.85	213	14.99	257	33.73
126	1.985	170	5.98	214	15.29	258	34.31
127	2.040	171	6.12	215	15.60	259	34.90
128	2.096	172	6.26	216	15.91	260	35.50
129	2.154	173	6.40	217	16 22	261	36 11
130	2.212	174	6.55	218	16.54	262	36.72
131	2.273	175	6.70	219	16.87	263	37.35
132	2.334	176	6.85	220	17.20	264	37.98
133	2.397	177	7.01	221	17.53	265	38.62
134	2.461	178	7.17	222	17.87	266	39.27
135	2.526	179	7.34	223	18.22	267	39.93
136	2.594	180	7.50	224	18.57	268	40.60
137	2.663	181	7.67	225	18.93	269	41.27
138	2.733	182	7.84	226	19.29	270	41.96
139	2.805	183	8.01	227	19.66	271	42.65
140	2.878	184	8.19	228	20.03	272	43.35
141	2.953	185	8.37	229	20.41	273	44.07
142	3.030	186	8.56	230	20.80	274	44.79
143	3.108	187	8.75	231	21.19	275	45.53

Table VIII.—*Continued.*

PRESSURE OF SATURATED STEAM AT DIFFERENT TEMPERATURES IN POUNDS PER SQUARE INCH AT SEA-LEVEL.

Temperature, Deg. F.	Pressure per Square Inch, Pounds.	Temperature, Deg. F.	Pressure per Square Inch, Pounds.	Temperature, Deg. F.	Pressure per Square Inch, Pounds.	Temperature, Deg. F.	Pressure per Square Inch, Pounds.
276	46.27	308	75.69	340	118.43	372	178.23
277	47.02	309	76.81	341	120.02	373	180.42
278	47.78	310	77.94	342	121.63	374	182.63
279	48.55	311	79.08	343	123.26	375	184.86
280	49.33	312	80.23	344	124.89	376	187.11
281	50.13	313	81.40	345	126.55	377	189.38
282	50.93	314	82.59	346	128.23	378	191.67
283	51.74	315	83.78	347	129.93	379	193.98
284	52.56	316	84.99	348	131.64	380	196.32
285	53.39	317	86.21	349	133.37	381	198.68
286	54.24	318	87.45	350	135.11	382	201.06
287	55.09	319	88.70	351	136.87	383	203.46
288	55.96	320	89.97	352	138.65	384	205.88
289	56.83	321	91.25	353	140.45	385	208.33
290	57.72	322	92.54	354	142.27	386	210.79
291	58.62	323	93.85	355	144.10	387	213.28
292	59.53	324	95.17	356	145.95	388	215.79
293	60.45	325	96.51	357	147.82	389	218.32
294	61.38	326	97.86	358	149.72	390	220.88
295	62.33	327	99.23	359	151.63	391	223.46
296	63.29	328	100.62	360	153.56	392	226.07
297	64.25	329	102.02	361	155.51	393	228.70
298	65.23	330	103.43	362	157.48	394	231.35
299	66.22	331	104.86	363	159.46	395	234.02
300	67.22	332	106.31	364	161.47	396	236.72
301	68.24	333	107.77	365	163.49	397	239.44
302	69.27	334	109.25	366	165.53	398	242.19
303	70.31	335	110.74	367	167.60	399	244.96
304	71.36	336	112.24	368	169.69	400	247.75
305	72.42	337	113.76	369	171.79		
306	73.50	338	115.30	370	173.92		
307	74.59	339	116.86	371	176.07		

Table IX.

WEIGHTS AND MEASURES.

ENGLISH.

480.0 grains Troy = 1 oz. Troy.
437.5 " = 1 oz. Avoirdupois.
7000.0 " = 1 lb. Avoirdupois.
5760.0 " = 1 lb. Troy.

The imperial gallon contains of water at 60° (15°.5 C.)	70,000 grains.
The pint ($\frac{1}{8}$ of a gallon)	8,750 "
The fluid-ounce ($\frac{1}{20}$ of a pint)	437.5 "

The pint equals 34.66 cubic inches.

TABLE IX.—*Continued.*

EQUIVALENT FRENCH AND ENGLISH MEASURES.

Measures of Length.

	In English Inches.	In English Feet = 12 inches.	In English Yards = 3 feet.	In English Fathoms = 6 feet	In English Miles = 1760 yards.
Millimètre	0.03937	0.0032809	0.0010936	0.0005468	0.0000006
Centimètre	0.39371	0.0328090	0.0109363	0.0054682	0.0000062
Décimètre	3.93708	0.3280899	0.1093633	0.0546816	0.0000621
Mètre	39.37079	3.2808992	1.0936331	0.5468165	0.0006214
Décamètre	393.70790	32.8089920	10.9363310	5.4681655	0.0062138
Hectomètre	3937.07900	328.0899200	109.3633100	54.6816550	0.0621382
Kilomètre	39370.79000	3280.8992000	1093.6331000	546.8165500	0.6213824
Myriomètre	393707.90000	32808.9920000	10936.3310000	5468.1655000	6.2138244

1 inch = 2.539954 centimètres.
1 foot = 3.0479449 décimètres.

1 yard = 0.91438348 mètre.
1 mile = 1.6093149 kilomètres.

Measures of Weight.

	In English Grains.	In Troy Ounces = 480 grains.	In Avoirdupois Lbs. = 7000 grains.	In Cwts. = 112 lbs. = 784,000 grains.	In Tons = 20 cwts. = 15,680,000 grains.
Milligramme	0.015432	0.000032	0.0000022	0.00000002	0.000000001
Centigramme	0.154323	0.000322	0.0000220	0.00000020	0.000000010
Decigramme	1.543235	0.003215	0.0002205	0.00000197	0.000000098
Gramme	15.432349	0.032151	0.0022046	0.00001968	0.000000984
Decagramme	154.323488	0.321507	0.0220462	0.00019684	0.000009842
Hectogramme	1543.234880	3.215073	0.2204621	0.00196841	0.000098421
Kilogramme	15432.348800	32.150727	2.2046213	0.01968412	0.000984206
Myriogramme	154323.488000	321.507267	22.0462126	0.19684118	0.009842059

1 grain = 0.064798950 gramme.

1 Troy oz. = 31.103496 gram.

1 lb. avd. = 0.45359265 kilogr.

1 cwt. = 50.80237689 kilogr.

Table X.

HIGHEST AND LOWEST TEMPERATURES, WITH MONTH AND YEAR IN WHICH OBSERVED, AT SIGNAL-SERVICE STATIONS IN EACH STATE.*

State.	Place.	Highest.		Place.	Lowest.	
		Deg.	Date.		Degrees.	Date.
Alabama	Montgomery	106.9	July, 1881	Montgomery	54	January, 1886.
Arizona	Fort McDowell [1]	119	June, 1887	Prescott	— 18	December, 1879.
Arkansas	Fort Smith	104.5	August, 1886 July, 1884	Fort Smith	— 6.9	January, 1886.
California	Red Bluff	111.5	July, 1887	Fort Bidwell	— 25.5	January, 1888.
Colorado	Las Animas	105.2	July, 1885	Denver	— 29	January, 1875.
Connecticut	New Haven	100	September, 1881	New Haven	— 14	January, 1873.
Dakota	Fort Sully	111	June, 1874 1876	Ford Buford	— 49.2	January, 1888.
Delaware	Del. Breakwater	98.1	August, 1885	Del. Breakwater	1	December, 1880.
District of Columbia	Washington	104.3	September, 1881	Washington	— 14	January, 1881.
Florida	Jacksonville	104	July, 1879	Pensacola	14.9	January, 1886.
Georgia	Augusta [2]	105	July, August, 1878	Atlanta	— 24	January, 1886.
Idaho	Fort Lapwai	115	August, 1882	Eagle Rock	— 38	January, 1883.
Illinois	Cairo	103	August, 1881	Chicago	— 23	December, 1872.
Indiana	Indianapolis	101	July, August, 1881	Indianapolis	— 25	January, 1884.
Indian Territory	Fort Gibson	109	July, 1879	Fort Reno	— 20	January, 1886.
Iowa	Des Moines	104.4	July, 1886	Dubuque	— 31.5	January, 1887.
Kansas	Dodge City	108	July, 1876	Leavenworth	— 29	January, 1873.
Kentucky	Louisville	104.6	August, 1881	Louisville	— 19.5	January, 1884.
Louisiana	Shreveport	107	July, [3] 1875	Shreveport	1.3	January, 1886.

Maine	Portland	97	July,	1876	Eastport	— 21	December,	1884.
Maryland	Baltimore	101.8	July,	1887	Baltimore	— 6	January,	1881.
Massachusetts	Boston	101.5	September,	1881	Boston	— 13	January,	1882.
Michigan	Detroit	101	July,	1887	Mackinaw City	— 33.4	February,	1885.
Minnesota	St. Vincent	103.2	August,	1886	St. Vincent	— 53.5	January,	1888.
Mississippi	Vicksburg	101	June,	1881	Vicksburg	3.1	January,	1886.
Missouri	St. Louis	106.4	August,	1881	St. Louis	— 21.5	January,	1884.
Montana	Fort Benton	110.8	July,	1886	Poplar River	— 63.1	January,	1885.
Nebraska	North Platte	107	July,	1877	North Platte	— 34.6	January,	1888.
Nevada	Winnemucca	104	July,	1877	Winnemucca	— 28	January,	1888.
New Hampshire	Manchester	93.3	July,	1887	Manchester	— 11	February,	1888.
New Jersey	Sandy Hook	101	September,	1881	Barnegat	— 10	January,	1875.
New Mexico	Fort Bayard	115	July,	1882	Fort Stanton	— 18.2	December,	1887.
New York	New York City	100.2	September,	1881	Oswego	— 22.9	January,	1885.
North Carolina	Kitty Hawk	107.1	July,	1887	Charlotte	— 5	December,	1880.
Ohio	Cincinnati	103.5	July,	1881	Sandusky	— 28	February,	1884.
Oregon	Umatilla	110	August,	1882	Fort Klamath	— 39	January,	1888.
Pennsylvania	Pittsburg	102.7	July,	1881	Erie	— 16	January,	1875.
Rhode Island	Narragansett Pier	92	July,	1885	Narragansett Pier	— 9	December,	1884.
South Carolina	Charleston	104	July,	1875	Charleston	10.5	January,	1886.
Tennessee	Nashville	104	August,	1874	Knoxville	— 16	January,	1884.
Texas	El Paso	113	June,	1883	Fort Elliott	— 14.2	January,	1888.
Utah	Fort Thornburgh	103.5	July,	1884	Salt Lake City	— 20	January,	1883.
Vermont	Burlington	97	August,	1876	Burlington	— 24.8	January,	1882.
Virginia	Cape Henry	103	August,	1881	Lynchburg	— 5	December,	1880.
Washington	Walla Walla	104	July,	1886	Spokane Falls	— 30.5	January,	1888.
West Virginia	Morgantown	97	July,	1874	Morgantown	— 10	February,	1875.
Wisconsin	La Crosse	101	July,	1874	La Crosse	— 42.0	January,	1888.
Wyoming	Cheyenne	100.5	July,	1881	Fort Washakie	— 53.5	February,	1883.

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[1] Also Phœnix, 119°, June, 1883.

[2] Also Savannah, 105°, July, 1879.

[3] Also August, 1881.

* From Gen. Greely's "American Weather."

TABLE XI.

HEAVIEST MONTHLY RAINFALLS EVER RECORDED IN THE VARIOUS STATES.*

State.	Station.	Month.	Year.	Rainfall in Inches.
Alabama	Opelika	July	1887	20.13
Arizona	Camp Goodwin	August	1880	14.45
Arkansas	Lead Hill	October	1883	18.11
California	Upper Matole	January	1888	41.60
Colorado	Trinidad	June	1878	12.83
Connecticut	Canton	May	1868	18.00
Dakota	Webster	July	1884	14.65
Delaware	Fort Delaware	September	1868	19.85
District of Columbia	Washington	July	1886	10.63
Florida	Ft. Barrancas	August	1878	30.73
Georgia	Raburn Gap	October	1877	19.40
Idaho	Lewiston	June	1884	5.63
Illinois	Cairo	January	1876	15.05
Indiana	Indianapolis	July	1875	13.12
Indian Territory	Fort Gibson	July	1875	11.89
Iowa	Rockford	June	1885	18.70
Kansas	Elk Falls	April	1885	19.00
Kentucky	Louisville	July	1875	16.46
Louisiana	Alexandria	June	1886	36.91
Maine	Eastport	May	1881	13.22
Maryland	St. John's Church	May	1881	12.30
Massachusetts	Amherst	July	1874	12.61
Michigan	Northport	May	1884	19.85
Minnesota	Sylvan Park	July	1872	21.86
Mississippi	Jackson	April	1874	23.80
Missouri	St. Louis	June	1848	17.07
Montana	Fort Ellis	June	1885	12.26
Nebraska	Table Rock	June	1883	17.07
Nevada	Fort McDermit	April	1883	13.00
New Hampshire	Mt. Washington	July	1884	23.90
New Jersey	Newark	August	1843	22.50
New Mexico	Fort Union	August	1886	8.04
New York	Troy	October	1869	13.80
North Carolina	Asheville	August	1887	28.65
Ohio	Carthagena	June	1877	17.33
Oregon	Astoria	January	1880	29.80
Pennsylvania	Wellsboro	August	1885	15.25
Rhode Island	Block Island	June	1881	12.93
South Carolina	Charleston	August	1885	19.18
Tennessee	White	July	1883	28.11
Texas	Brownsville	September	1886	30.57
Utah	Mt. Carmel	March	1877	10.00
Vermont	Craftsburg	October	1869	10.72
Virginia	Cape Henry	August	1887	16.82
Washington	Neah Bay	December	1886	30.70
West Virginia	Helvetia	August	1882	12.60
Wisconsin	Neillsville	September	1881	14.01
Wyoming	Hat Creek	April	1879	6.93

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* From Gen. Greely's "American Weather."

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