AERONAUTIC INSTRUMENTS.

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ABSTRACT.

The purpose of this paper is to describe briefly the various types of aircraft instruments which have reached a state of development such that they have found extensive use in service. These are grouped in accordance with the outline given immediately below. A general description of representative instruments of the various types is given, which will be useful to a person who wishes to familiarize himself with the different instruments used on aircraft but is not interested in the mechanical details of their construction.

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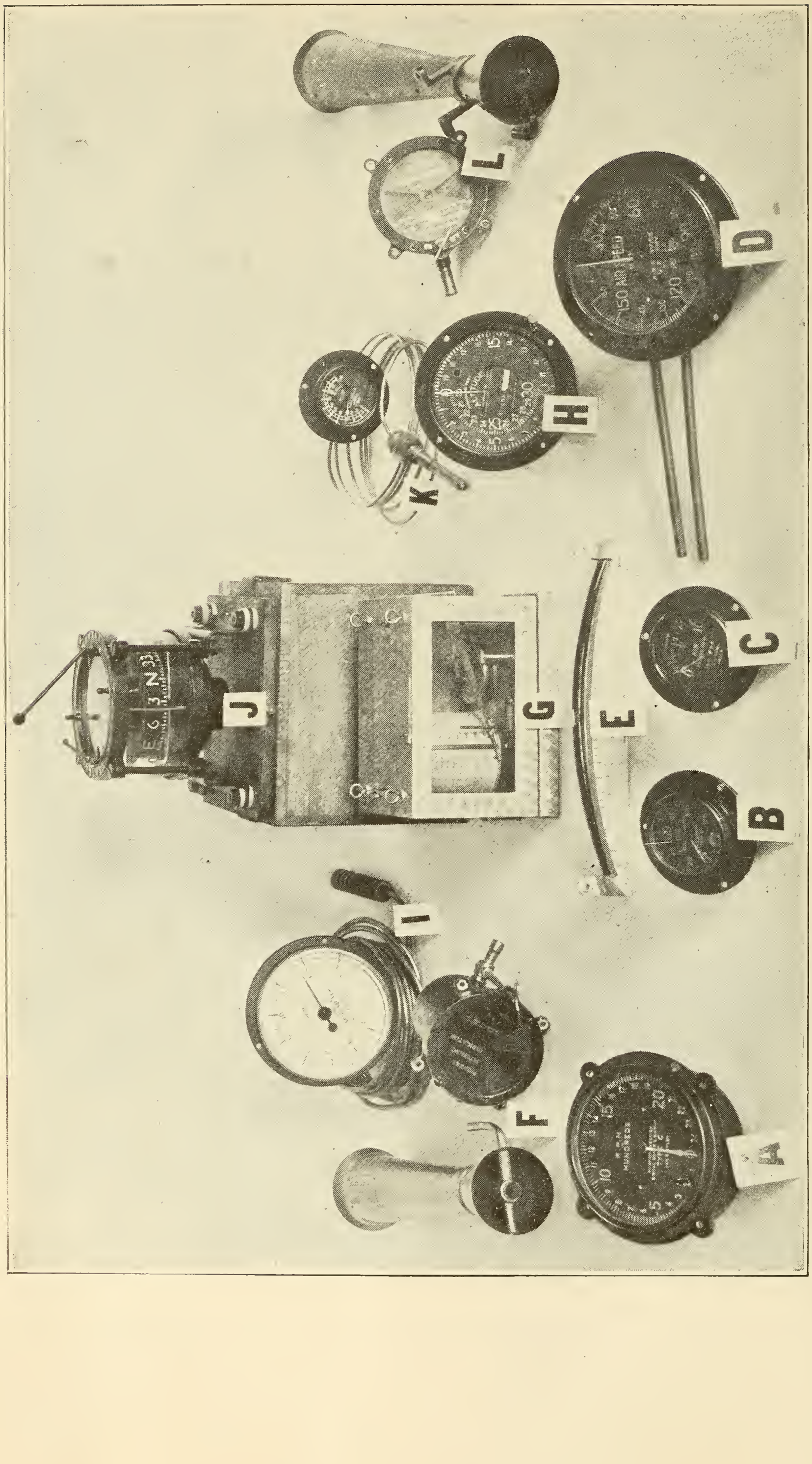

Fig. 1.—*Aeronautic instruments.*

A, tachometer; *B*, oil-pressure gauge; *C*, air-pressure gauge; *D*, air-speed indicator; *E*, bubble inclinometer; *F*, gyroscopic pitch indicator; *G*, barograph; *H*, altimeter; *I*, strut thermometer; *J*, compass; *K*, radiator thermometer; *L*, gyroscopic turn indicator.

I. INTRODUCTION.

The instrument equipment of modern aircraft ordinarily consists of a group of 10 or more instruments which are located on an instrument board in front of the pilot. They serve to assist him in the control of the altitude, speed, and orientation of the aircraft and the behavior of the engine. In addition to the regular equipment special instruments are frequently installed, such as navigating instruments, where long-distance flights are to be made; experimental instruments for airplane performance tests; or instruments for military use. The purpose of this paper is to describe briefly the various types of aircraft instruments which have reached a state of practical development such that they have found extensive use in service.[1] These may be conveniently considered in the order mentioned above. A group of typical airplane instruments is shown in Figure 1.

II. ALTITUDE INSTRUMENTS.

1. ALTIMETERS.

Altimeters are used to indicate the altitude of aircraft. They are the same in principle as aneroid barometers and have as the essential working element a corrugated metal capsule from which the air is exhausted and which is maintained distended by an external or an internal spring. With decreasing atmospheric pressure, such as is experienced when an aircraft climbs, the evacuated capsule expands under the action of the spring. This motion, which is very small, amounting to only a few thousandths of an inch, is multiplied by a suitable transfer mechanism and used to operate a pointer moving over a circular dial. The dial is graduated either in feet or in meters in accordance with some empirical mathematical relation between the atmospheric pressure and the altitude. The dial is rotatable, so that the zero of the instrument can be adjusted for fluctuations in ground-level barometric pressure. The pressure-altitude relation used in calibrating American altimeters is based on the assumption of a uniform air column temperature of 10° C. and the corresponding mean humidity. It is calculated from the constants used in Smithsonian Meteorological Tables 51 and 54, fourth revised edition, and consequently neglects the small effect due to the

[1] For a more detailed discussion see Reports No. 125–132, inclusive, of the National Advisory Committee for Aeronautics, 1922.

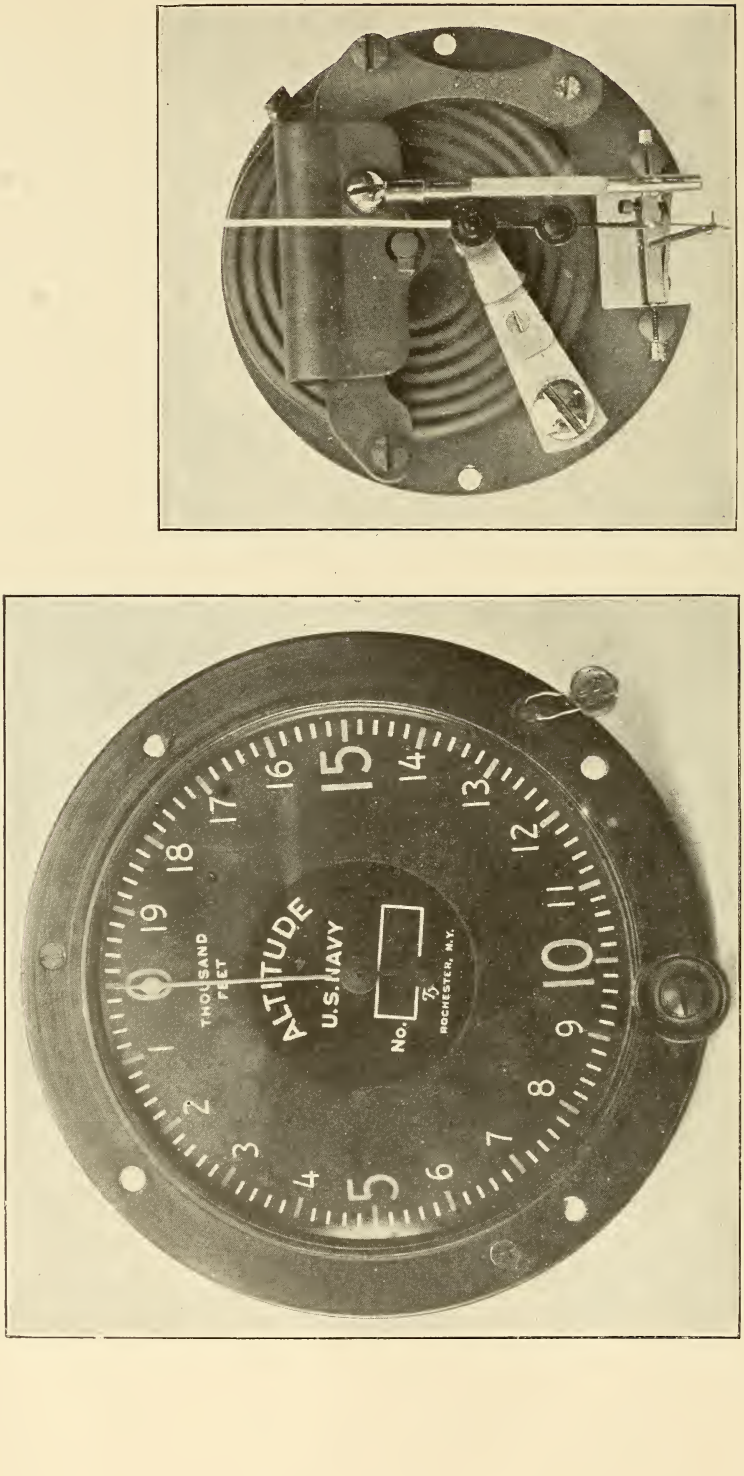

FIG. 2.—*Tycos altimeter and mechanism.*

variation of gravity. This relation may be expressed by the formula

$$H = 62900 \log_{10} \frac{759.6}{P}$$

where H is the altitude in feet and P the barometric pressure in millimeters of mercury. Practically the same formula is used in Great Britain. A typical altimeter is shown in Figure 2.

2. BAROGRAPHS.

Barographs are the same in principle as altimeters but are provided with a recording mechanism which gives a continuous

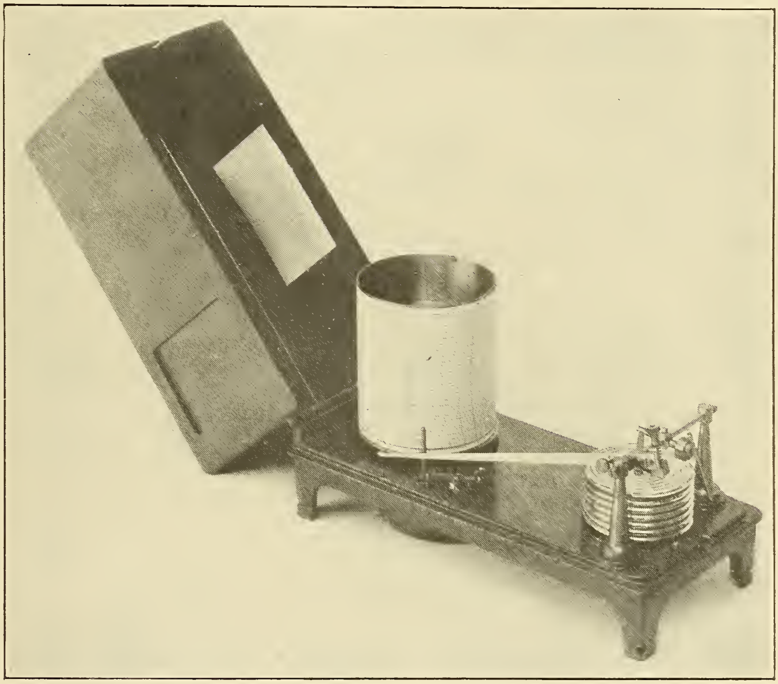

FIG. 3.—*Friez barograph.*

and permanent record of the altitude throughout flight. A battery of corrugated evacuated capsules is ordinarily used instead of a single capsule as in the altimeter, and interior springs are more frequently used than exterior ones. The expansion of the battery of capsules with decrease of external pressure operates a pointer, which carries a pen and makes a record on a chart attached to a drum which is rotated by clockwork. The chart is graduated in feet or meters in accordance with some mathematical pressure-altitude relation, usually the same as that used for altimeters. Figure 3 shows a typical aviation barograph.

3. STATOSCOPES.

Statoscopes are used more frequently in lighter-than-air craft than on airplanes. They provide a sensitive means of indicating qualitatively whether an aircraft is rising or falling and help the aviator to maintain horizontal flight. The ordinary type consists of a closed air chamber, which is connected to the exterior air through a glass U-tube containing a small quantity of colored liquid, thus forming a trap which seals the air in the container. Heat insulation is used to prevent the expansion and contraction of the confined air with changes of external temperature. When the aircraft rises or falls the pressure of the air inside the container becomes greater or less than that of the external air, according as the aircraft is ascending or descending, and as a result the liquid in the trap, which is visible to the aviator, is forced in one direction or the other, indicating a change of level. When the difference in pressure becomes sufficiently great, equilibrium is reestablished by air being forced past the liquid in the trap, after which the liquid again collects in the trap as previously. The frequency with which the air is forced past the liquid or, as it is ordinarily expressed, the rate at which the bubble breaks is a rough measure of the rate of ascent or descent. Statoscopes can be made to detect changes in level of from 5 to 10 feet. A typical instrument is shown in Figure 4.

III. SPEED INSTRUMENTS.

1. AIR-SPEED INDICATORS.

Air-speed indicators show the speed of aircraft relative to the air. They give the speed with reference to the ground only in the absence of wind. The most commonly used types depend for their action on the pressure developed in suitably constructed nozzles by the impact of the air stream caused by the motion of the airplane or on the speed of rotation of small cup anemometers or air propellers. The indications of the pressure type are proportional to the density of the air, so that the readings depend on the altitude. The anemometer type, on the other hand, shows practically no altitude effect. In the most usual form of the pressure type the pressures developed by a Pitot or Venturi nozzle located on one of the struts of the airplane is indicated by a sensitive gauge which is located on the instrument board. It is also necessary to determine the static pressure at the point where the Pitot or Venturi nozzle is located. This is effected by

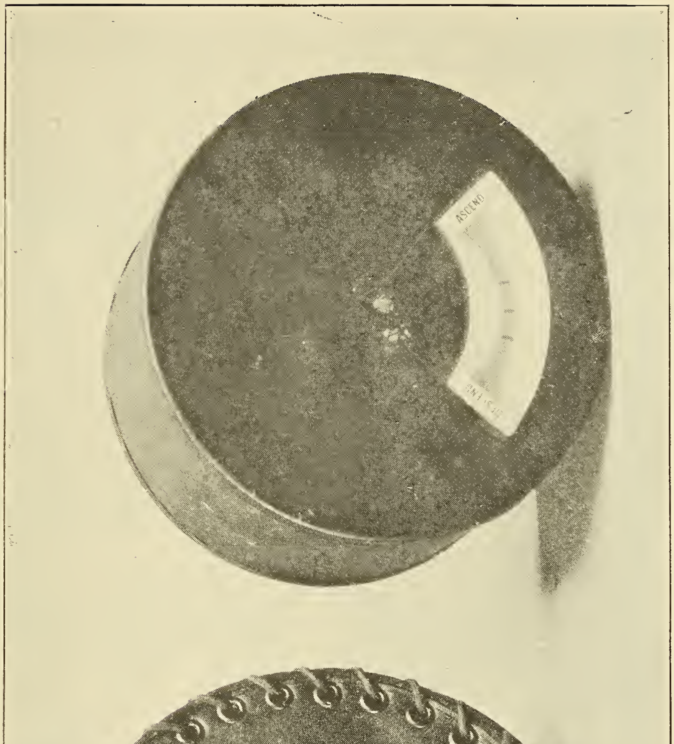

FIG. 4.—*Custer bubble statoscope.*

using what is known as a static head, which consists of a straight tube closed at the end with a concentric ring of small holes or narrow slots at the sides. This tube is pointed in the direction of motion, so that the pressure within is maintained equal to that

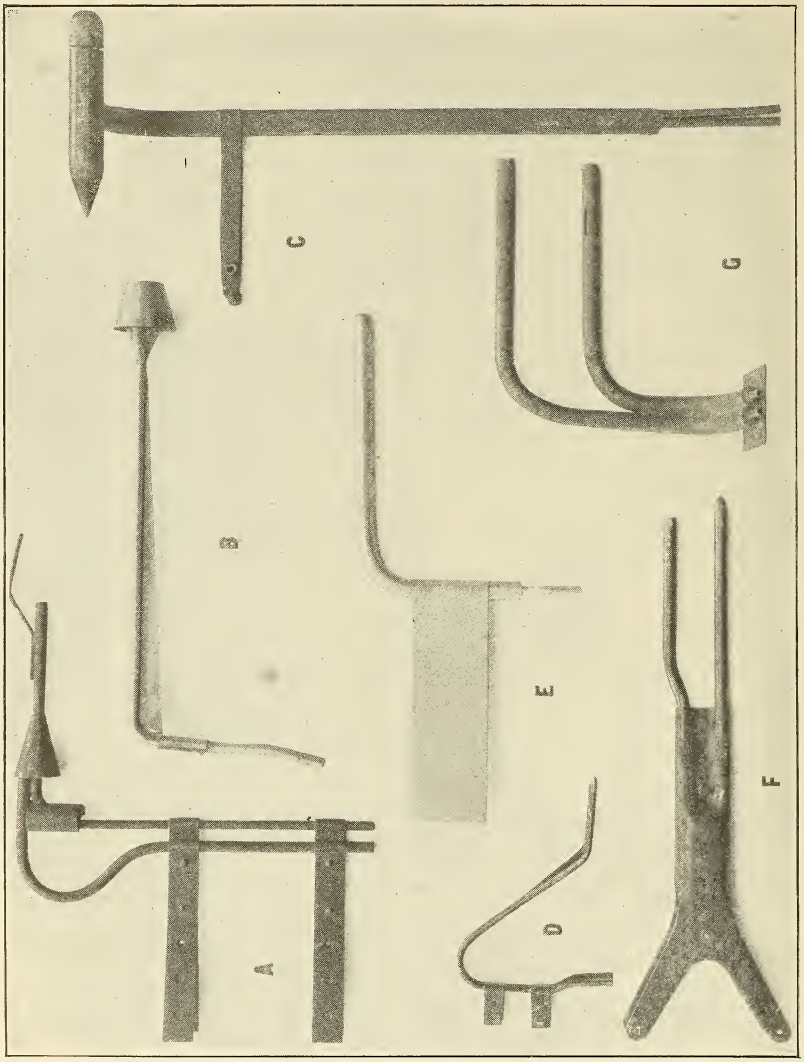

Fig. 5.—*Pitot nozzles.*

A and *B*, nozzles with static hoods; *C* and *E*, nozzles with concentric static heads; *D*, *F*, and *G*, nozzles with separate static heads.

of the undisturbed air without, since the rush of air past the openings at the side of the tube is at right angles to these openings. Typical Pitot and Venturi nozzles are shown in Figures 5 and 6.

The indicator, which is, in effect, a sensitive pressure gauge, ordinarily consists of one or more corrugated metal capsules inclosed in an air-tight case or of an air-tight case separated by a membrane of rubber or doped fabric into two air-tight chambers. The dynamic head of the pressure nozzle is connected to the diaphragm capsule and the static head to the air-tight case or in the doped fabric diaphragm type one head is connected to each of the air-tight chambers. In some cases a combination of Pitot

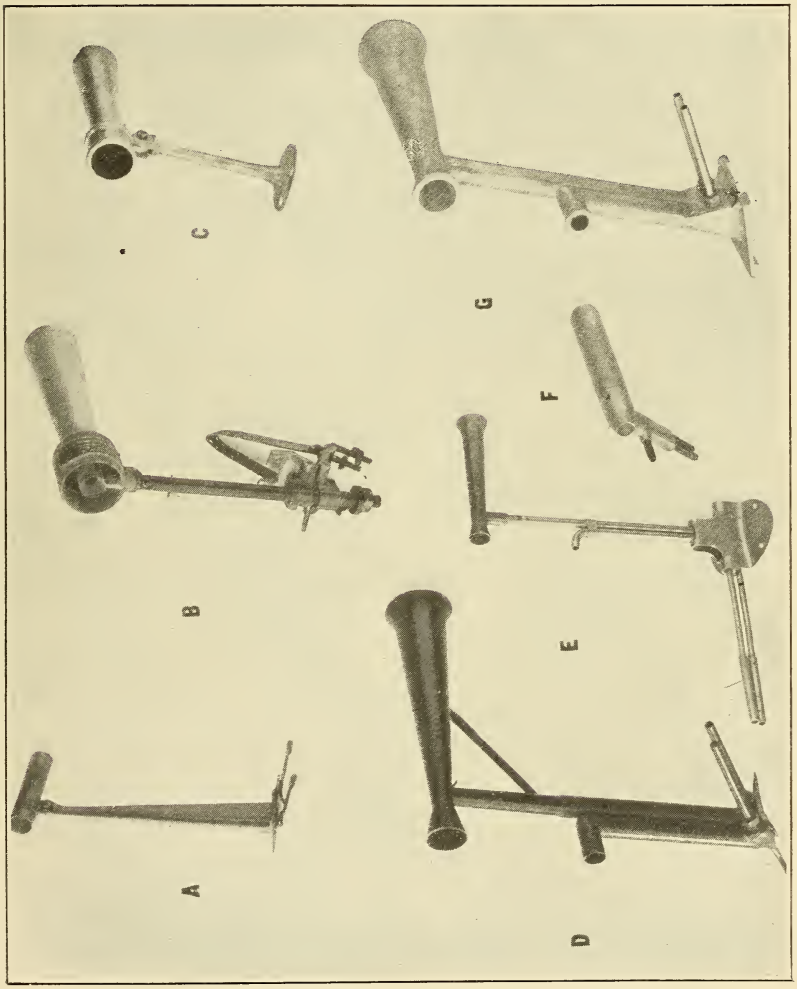

Fig. 6.—*Venturi nozzles.*

A, single Venturi nozzle with concentric static head; *B* and *C*, double Venturi nozzles; *D*, *E*, *F*, and *G*, Pitot-Venturi nozzles.

and Venturi nozzles is used to take advantage both of the pressure developed by the former and the suction by the latter. Under these circumstances no static head is used, the Pitot nozzle being connected to one of the air-tight chambers and the Venturi to the other. The differential pressure developed by the nozzle causes the diaphragm to expand or contract according to the magnitude and direction of the excess pressure. This motion is carried by a suitable transfer mechanism to the pointer, indicating corresponding speeds on a dial which is graduated in miles per hour or kilometers per hour in accordance with the pressure-speed relation of the nozzle used. Most nozzles of the Pitot and Venturi type obey the so-called ρv^2 law; that is, the pressure developed is

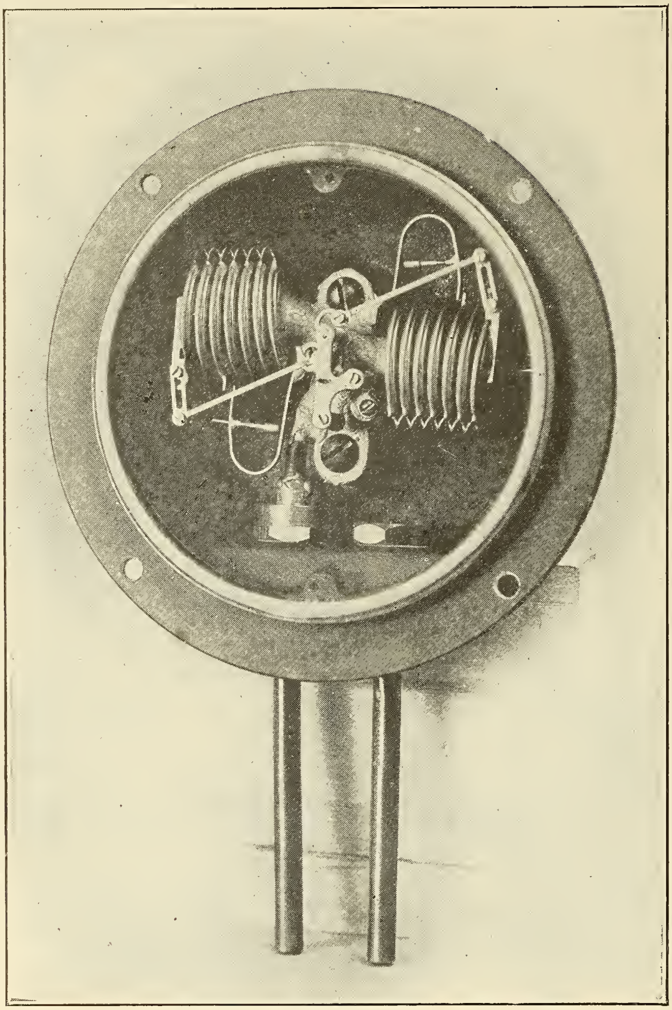

FIG. 7.—*Foxboro bellows diaphragm air-speed indicator.*

proportional to the density of the air and the square of the velocity of motion. Typical air-speed indicators of the Pitot and Venturi type are shown in Figures 7 to 12.

Instruments in which a flat plate held perpendicular to the direction of motion is used to measure the air pressure have also

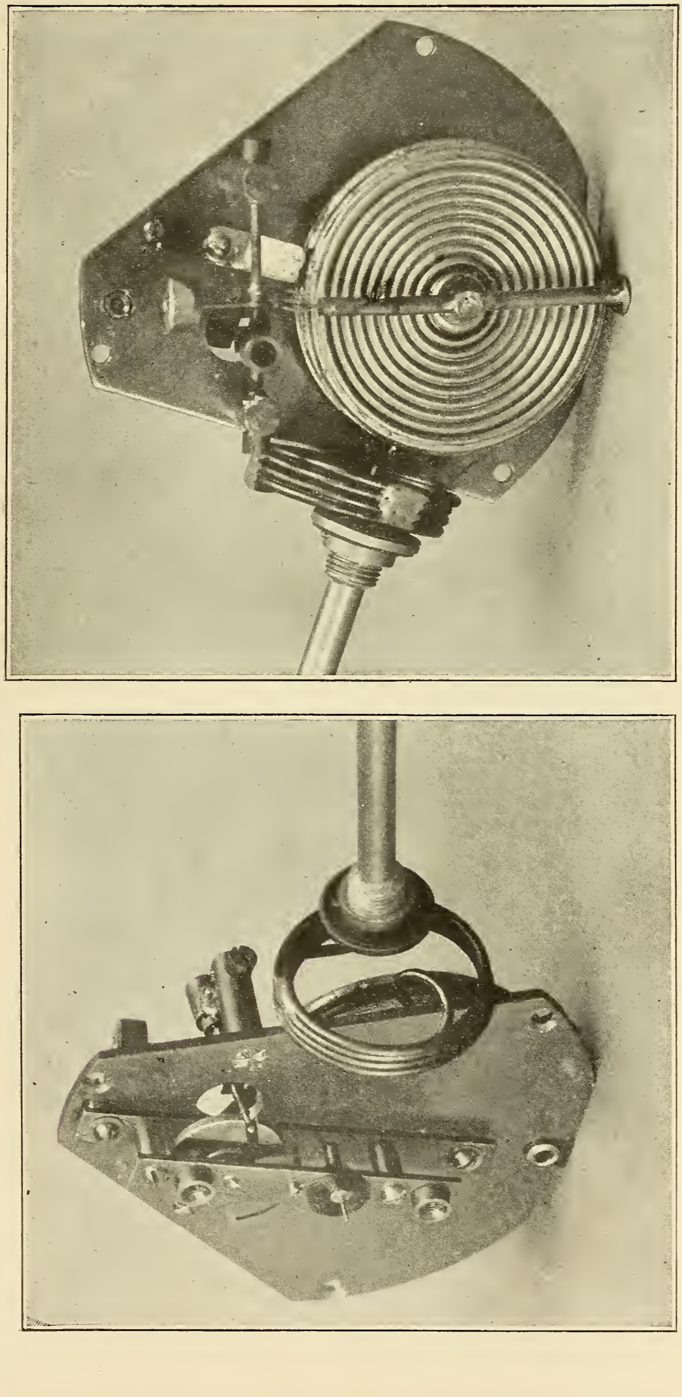

FIG. 8.—*Bristol double diaphragm air-speed indicator.*

been constructed. In these the plate is attached to a lever whose motion is resisted by a spring. The displacement of the lever which depends upon the air speed is used to indicate the air speed directly or it may be attached to a sector and pinion and a dial and pointer added. An instrument of this type is shown in Figure 13. The pressure developed by these instruments also obeys the ρv^2 law. In instruments of the anemometer type the air speed is determined by the rate of revolution by a cup anemometer or air propeller. In most cases the rate of revolution is

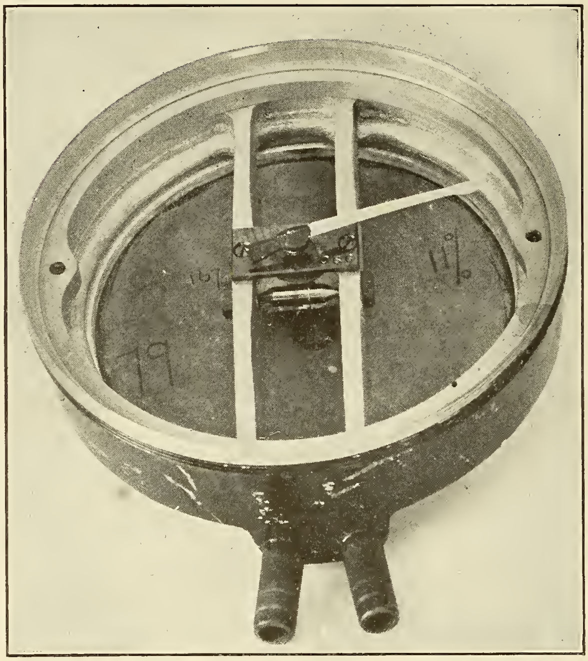

FIG. 9.—*Ogilvie rubber diaphragm air-speed indicator.*

determined by attaching the rotating element to a centrifugal tachometer similar to that used in indicating the rate of revolution of the engine. (See below.) Anemometer instruments are ordinarily located on one of the struts of the airplane and are read from this position by the pilot. Instruments of the anemometer type with distant control have recently been developed in which the anemometer element alone is located on the strut. Wires lead from a specially designed commutator operated by the anemometer to the indicator which is on the instrument board. Typical anemometer air-speed indicators are shown in Figures 14 and 15. Hot-wire anemometers in which the cooling effect of the air stream on an electrically heated wire grid is measured have also been used to a limited extent, but the device is complicated and not suited for ordinary use in determining the speed of aircraft.

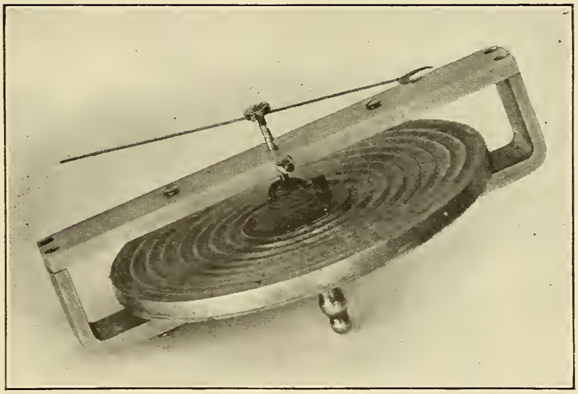

Fig. 10.—*Sperry single diaphragm air-speed indicator.*

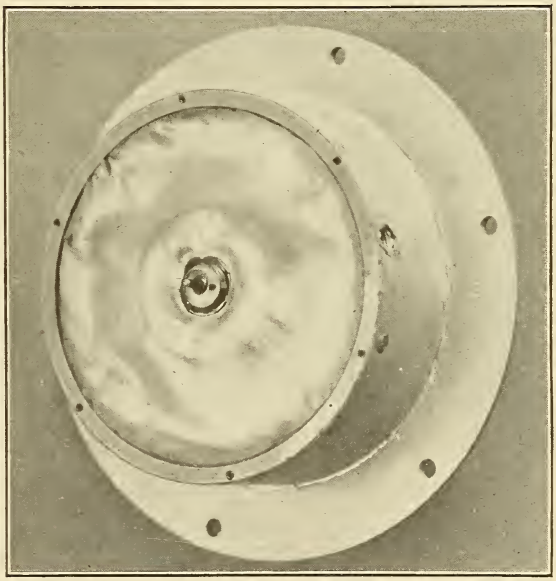

Fig. 11.—*Clift doped fabric diaphragm air-speed indicator.*

2. GROUND-SPEED INDICATORS.

The measurement of the speed of aircraft relative to the ground is of importance in connection with long-distance flying, aircraft performance tests, and military operations such as bombing. In the case of aircraft performance tests, the ground speed attained is ordinarily determined by flying the aircraft over measured courses or by sighting upon the aircraft from the ground with theodolites. These methods will not be considered in detail here, since we are primarily interested in the instruments carried by the aircraft itself. The methods of determining ground speed from the aircraft such as are used in long-distance flying and in bombing are fundamentally either optical, dynamical,

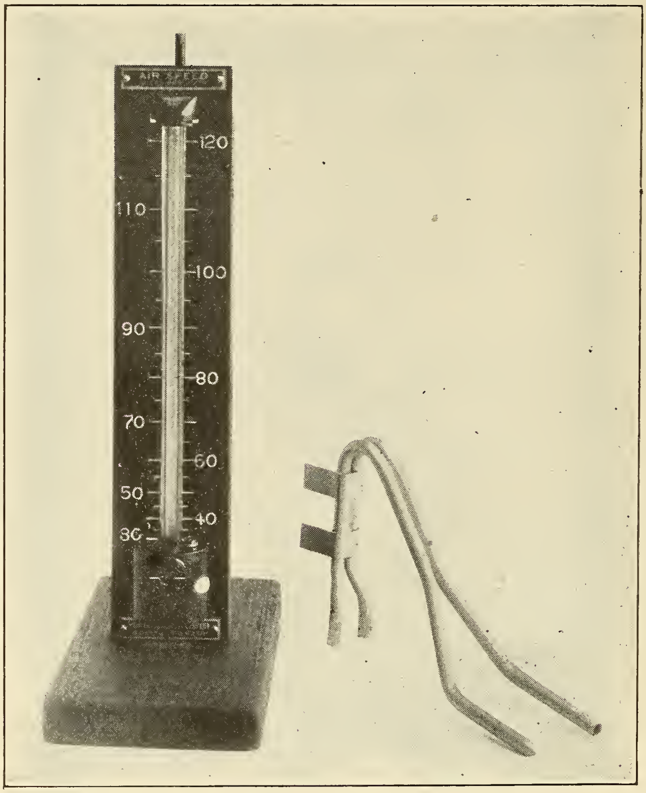

FIG. 12.—*Pioneer liquid manometer air-speed indicator and Pitot nozzle.*

or electrical in principle. The actual instruments are still for the most part in an experimental state, so only the methods of their operation will be considered here.

The simplest type of optical ground-speed indicator depends upon determining with a stop watch the time for some object on the ground to pass between two sighting points in a horizontal line on the instrument. The ground speed can then be calculated from the separation of the two sighting points, the distance from the horizontal line defined by them to a third sighting

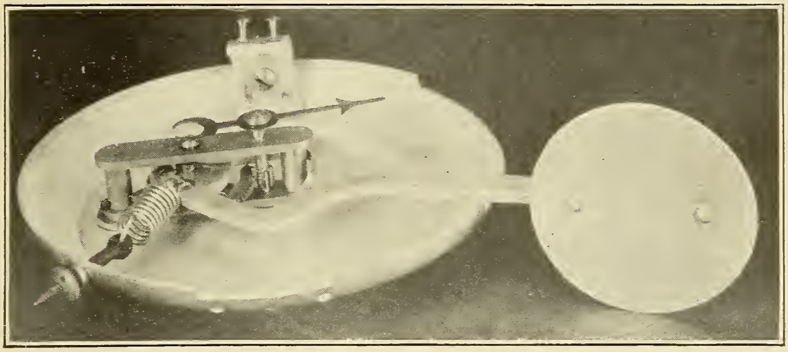

Fig. 13.—*Pensuti pressure plate air-speed indicator.*

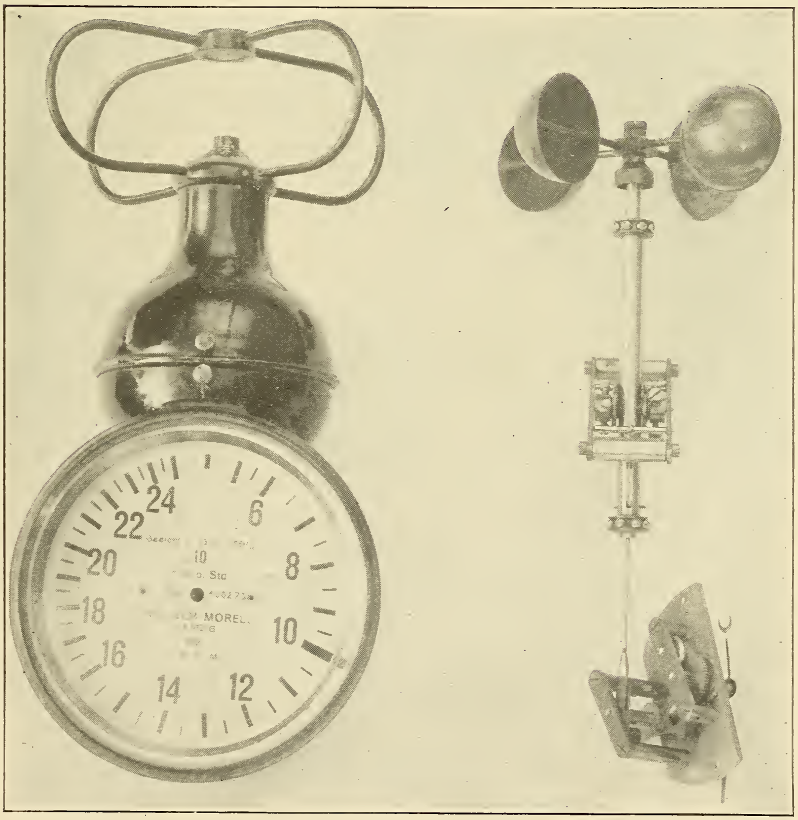

Fig. 14.—*Morell cup anemometer air-speed indicator.*

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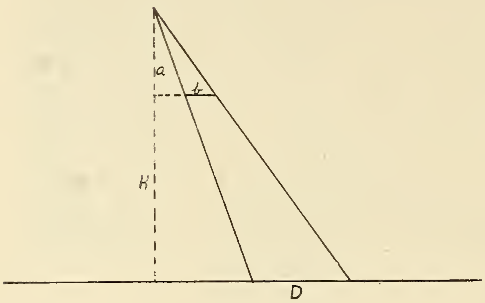
point at the observer's eye, and the altitude of the aircraft. The principle may be demonstrated as follows:



Let a = distance from line b to the eyepiece.
H = the altitude.
b = distance between the two sighting points.
D = the distance traversed by the aircraft while the object on the ground appears to move between the two sighting points.
t = time in seconds required.
S = Speed of the aircraft.

Then

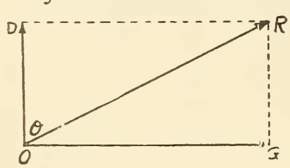
$$\frac{a}{H} = \frac{b}{D}$$

$$\therefore S = \frac{H}{a}\frac{b}{t}$$

$$= \text{Const.}\ \frac{H}{t}$$

Another method is to use a rotating or reciprocating optical arrangement to neutralize the apparent motion of objects on the ground as seen through a telescope or to cause a reference line in the telescopic field to move at the same rate as the image of the object on the ground. If then the rate at which the telescope or the image in the telescopic field is moving is determined and the altitude of the aircraft is known, the ground speed may be found. Several devices of this kind have been tried.

A modification of the last method is to introduce by means of a rotating telescope or similar device an artificial drift at right angles to the actual drift of the aircraft relative to the ground. From the direction of the resultant apparent drift and the magnitude of the artificial drift the ground speed can be computed. The principle may be illustrated as follows:



Let OG represent the ground speed of the aircraft, the magnitude of which is to be found and the direction of which is shown by the use of a drift indicator, and OD the known artificial drift introduced at right angles to the ground speed OG by the rotating telescope or other device. Then OR will represent the resultant apparent drift as seen through the rotating telescope, and if the angle θ between the artificial drift and the resultant apparent drift is measured, the magnitude of the ground speed can be calculated by the relation

$$OG = OD \tan \theta.$$

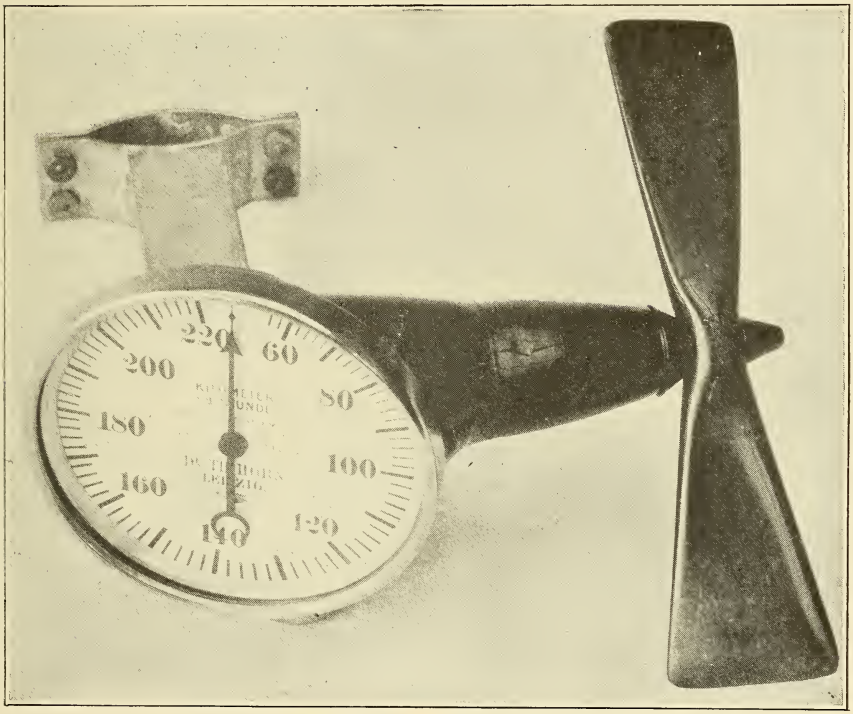


FIG. 15.—*Horn propeller air-speed indicator.*

Theoretically, it would be possible to find the ground speed of an aircraft by determining the time integral of the accelerations to which it is subjected from the beginning of the flight. It has been proposed to do this by supporting a mass between springs so that it is free to move in a horizontal plane in a fore-and-aft direction. The displacement of the mass under these circumstances will be proportional to the acceleration of the aircraft. If then the time integral of this displacement can be obtained mechanically and shown on a direct-reading dial, the ground speed at any given instant will be known. Actually the inherent friction of the integrating mechanism and the inevitable accumulation of errors in integration make the device impractical. It is also necessary

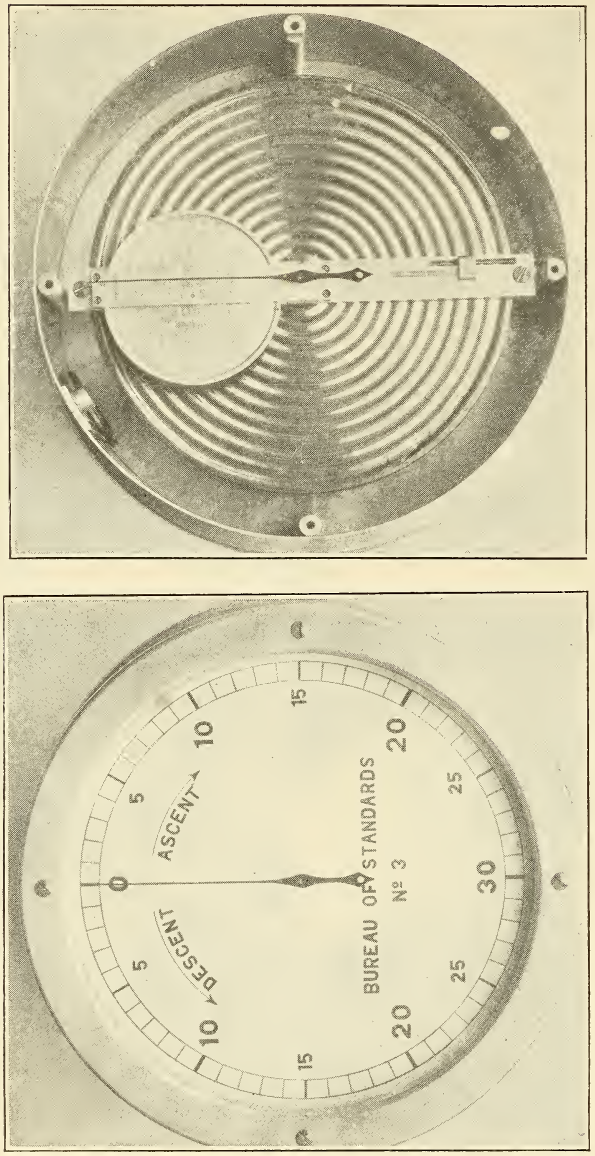


Fig. 16.—*Bureau of Standards single diaphragm rate-of-climb indicator.*

that the mass move only in a horizontal plane to prevent accelerations of the mass due to gravity. This can be brought about apparently only by gyroscopic stabilization which means much added weight and complication. No practical instrument of this type has been made.

Directional radio telegraphy has recently presented another possibility for ground-speed measurement. With a directional receiving apparatus, the position of the aircraft with reference to two sending stations of known distance apart may be determined at successive times and from these observations the ground speed computed. This is at present the only practical method of determining the ground speed of aircraft when the ground can not be seen.

3. RATE-OF-CLIMB INDICATORS.

Rate-of-climb indicators are used to determine the component in a vertical direction of the velocity of aircraft. Like statoscopes they usually depend for their operation on the expansion or contraction of a volume of air confined in a heat insulated container. This container is connected to the external air through a fine capillary tube. When the aircraft rises, the pressure of the air in the container becomes greater than that of the surrounding atmosphere owing to the lag in the pressure equalization caused by the fine capillary tube. The magnitude of the excess pressure is a function of the rate of climb. If then means are provided for measuring the excess pressure, this can be used to indicate the rate of climb. The method ordinarily adopted is to make one side of the container a flexible metal diaphragm connected to an indicating mechanism or to connect to it a U tube filled with colored liquid. An instrument of the former type is shown in Figure 16. The motion of the flexible diaphragm is multiplied by a system of aluminum pulleys and phosphor-bronze strips, and operates a pointer which moves over a dial graduated to indicate the rate of ascent or descent in feet per minute. An instrument of liquid manometer type is shown in Figure 17. In this case the height of the liquid column is used as a measure of the vertical velocity.

IV. ORIENTATION INSTRUMENTS.

1. COMPASSES.

The adaptation of the magnetic compass to use in aircraft presents serious difficulties because of the violent accelerations to which the instrument is subjected and also the unavoidable proximity of large moving masses of magnetic material. Liquid-

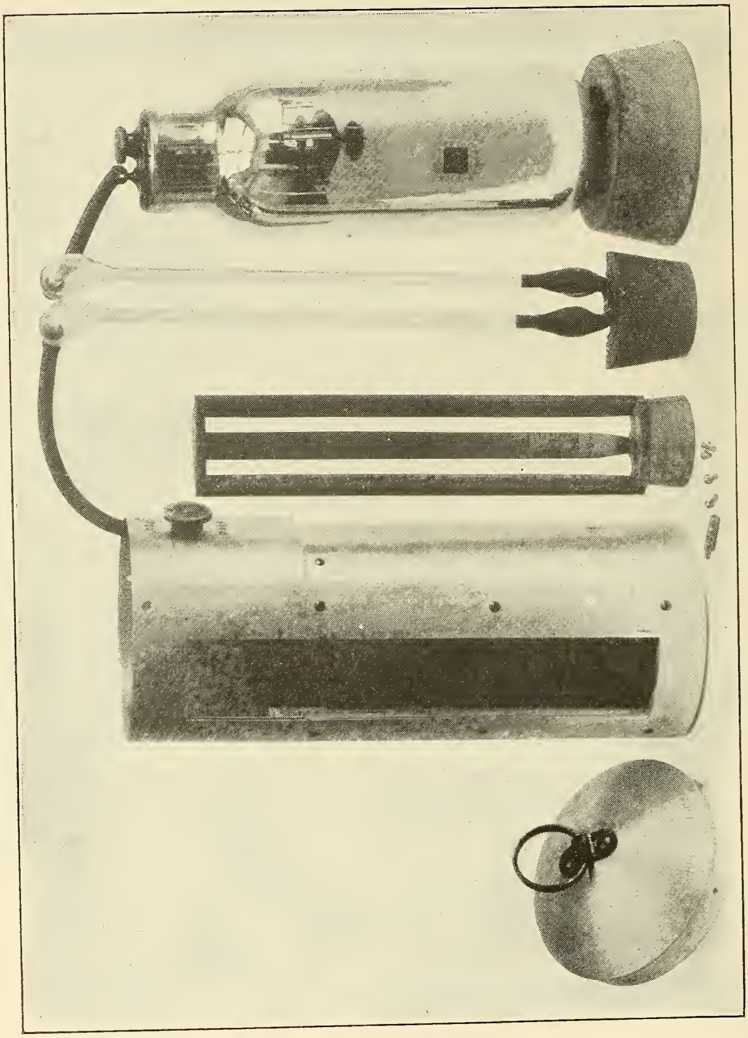


FIG. 17.—*Wright liquid manometer rate-of-climb indicator.*

filled compasses are used almost exclusively because heavy damping is required. Aircraft compasses are, in general, quick-acting instruments with periods varying from 10 to 20 seconds. Compasses with longer periods are less disturbed by small transient accelerations, but those with periods between these limits are usually preferred, especially when used in connection with turn indicators (see below), which have recently reached a practical

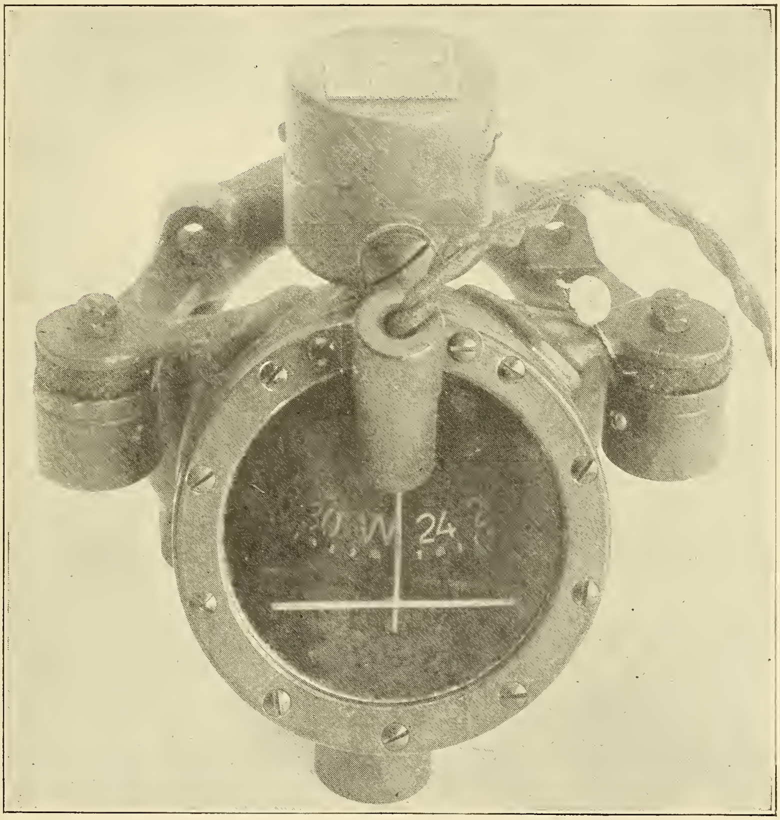


Fig. 18.—*General Electric inclined card compass.*

state of development. Efforts have been made to overcome the unsteadiness and swirling of the liquid of airplane compasses by mounting the magnet and card in the center of a spherical bowl. Another method recently developed is to make the compass aperiodic by eliminating the ordinary card and mounting the needles on a light spider made of small straight wires projecting radially from the point of support in the damping liquid. Standard compasses of the ordinary type are shown in Figures 18 and 19 and one of the aperiodic type in Figure 20. Some compasses are provided with both horizontal and vertical cards, others with inclined cards. The aperiodic compass dispenses with the card entirely and uses parallel wires on a rotatable bearing plate over the flat cover glass to sight on the needle.

The disturbing effect of masses of iron in the vicinity of the instrument board have led to an effort to develop distant-reading

FIG. 19.—*Sperry combined horizontal and vertical card compass.*

compasses in which the compass proper can be located far away from the motor, for instance, in the fuselage, near the tail of the airplane, while the indicator is located on the instrument board. One method which has been tried is to use the current developed by a coil of wire rotating in the earth's magnetic field, the magnitude of the current thus induced being a function of the orientation of the coil with respect to the earth. This device is known as an earth inductor compass. Another method takes advantage of the change of resistance of selenium when exposed to light by providing two selenium cells located at diametrically opposite points above the compass card. Below each cell is an incandescent lamp. The card shields the selenium cells to a greater or lesser extent according to the position of the compass card, thereby changing the resistance of the selenium cells which constitute two arms of a Wheatstone bridge. This unbalances the bridge and indicates by means of a galvanometer on the instrument board the amount of displacement of the compass card. This device

FIG. 20.—*Campbell-Bennett aperiodic compass.*

(shown in Fig. 21) is complicated and with its auxiliary attachments much heavier than an ordinary aircraft compass.

2. TURN INDICATORS.

Turn indicators are used to inform the aviator when he is deviating from a straight-line course. The essential working element is a gyroscopic rotor, which in accordance with the principle of gyroscopic action tends to maintain its direction in space when the airplane deviates. The resultant relative motion is made evident to the pilot by the motion of a pointer connected to the rotor by a lever system. The rotor is ordinarily driven

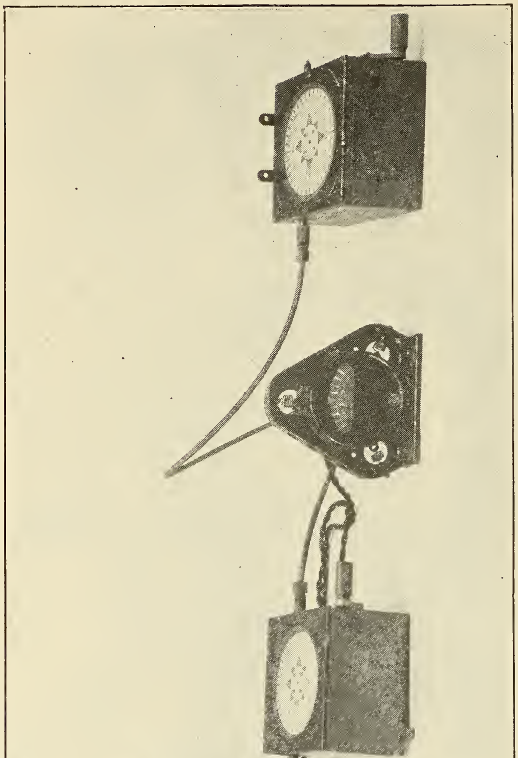


FIG. 21.—*Bamberg distant-reading compass, with indicator and course controls.*

either by the impact of an air stream on the serrated edge of the rotor itself or by making the rotor the rotating element of an induction motor. In the air-driven type the air stream is maintained by a Venturi tube, which exhausts the air from the case in which the rotor is inclosed. Small orifices are provided in the case opposite the serrated edge of the rotor. Through these the air streams in from outside the case impinging on the wheel and causing it to rotate. The electrical type can be connected to the storage battery which is a part of the standard equipment of modern aircraft, or it may be operated by a small auxiliary generator driven by a wind propeller. Instruments of both types have reached a practical stage of development and are an invaluable adjunct to the compass, particularly for use in cloud flying, since they can be made more sensitive to slight deviations than the compass and moreover function when the turn commences, at which time the compass is ordinarily temporarily useless because it is oscillating. Turn indicators of both types are shown in Figures 22 and 23.

3. INCLINOMETERS.

Inclinometers which indicate the rolling and pitching motions of aircraft are of two general types: (1) Those involving the principle of the liquid-bubble level which show the aspect of the airplane with respect to the resultant of gravity and forces of acceleration acting on the aircraft, and (2) gyroscopic instruments which indicate the position of the airplane with reference to the true vertical. The former is much the simpler and more frequently used type. Representative inclinometers of liquid type are shown in Figures 24 and 25. These are designated by the name lateral and fore-and-aft inclinometers according as they refer to the condition of the airplane with reference to rolling or pitching. The liquid lateral inclinometer is essentially a curved glass tube filled with colored liquid in which a bubble forms. The displacement of the bubble indicates the inclination. The fore-and-aft inclinometer is the same in principle, except that in this case it consists of a triangular-shaped closed circuit of glass tubing partially filled with liquid. The liquid changes its level in the front arm of the circuit when the airplane pitches. (See Fig. 25.) Liquid inclinometers of sector type are shown in Figure 26. In these a disk-shaped receptacle with a circular glass face is half filled with colored liquid. The position of the surface of the liquid with reference to the normally horizontal diameter of the dial indicates

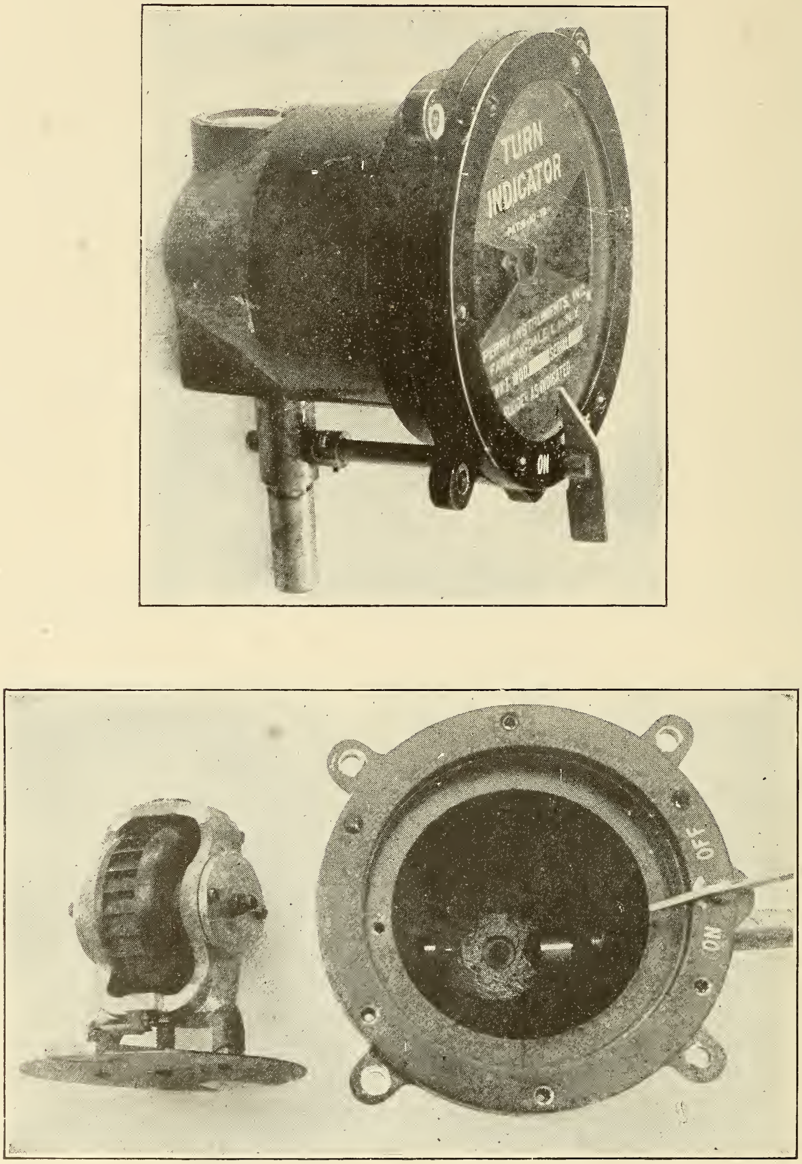


FIG. 22.—*Sperry air-driven gyroscopic turn indicator.*

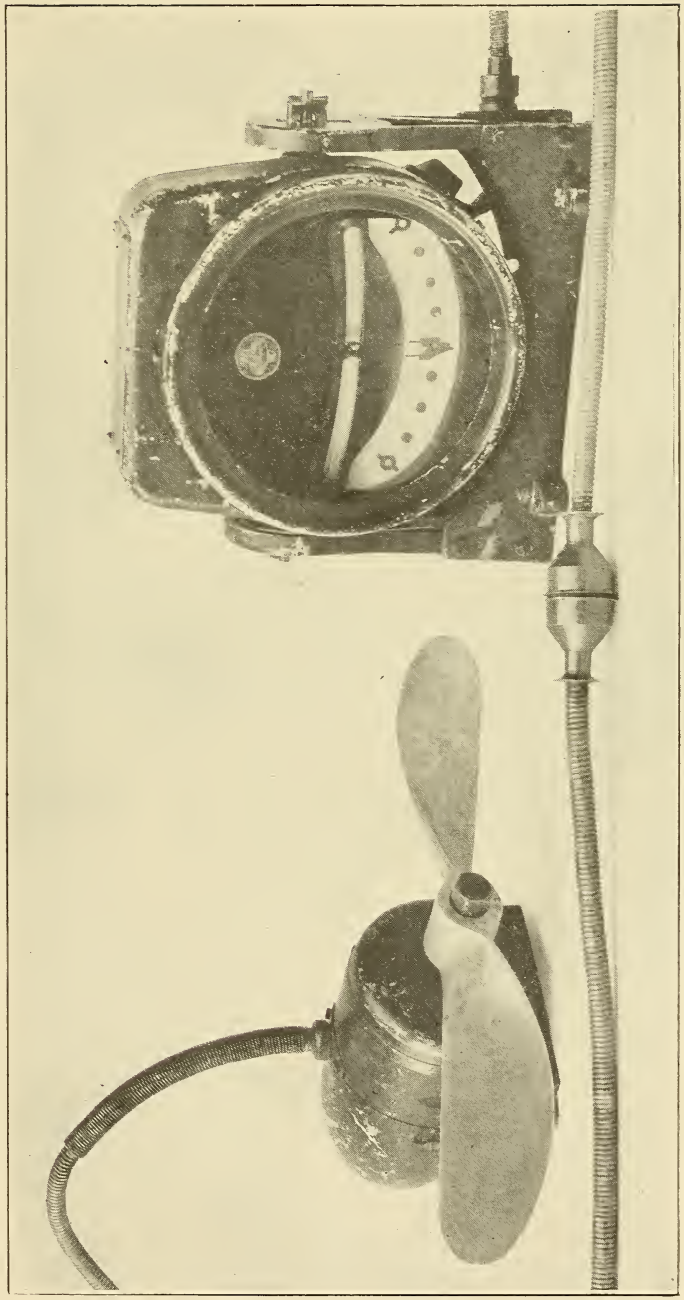


Fig. 23.—*Drexler electric gyroscopic turn indicator.*

the inclination of the aircraft. Liquid and air damped pendulum devices have also been used instead of instruments of the bubble type. These are shown in Figures 27 and 28.

An instrument of gyroscopic type is shown in Figure 29. It is essentially a spinning top mounted on a pivot near its center of gravity. It is rotated rapidly by an air stream impinging upon the serrated edge of the top. The gyroscopic action of the top tends to maintain its position vertical when the airplane pitches or rolls. The amount of displacement either laterally or longitudinally is indicated by the position of the pin of the top relative to the hemispherical glass cover of the instrument which is graduated in degrees. The power to drive the top is supplied by a Venturi tube which exhausts the air from the case and rotates the top as in the air-driven turn indicator described above.

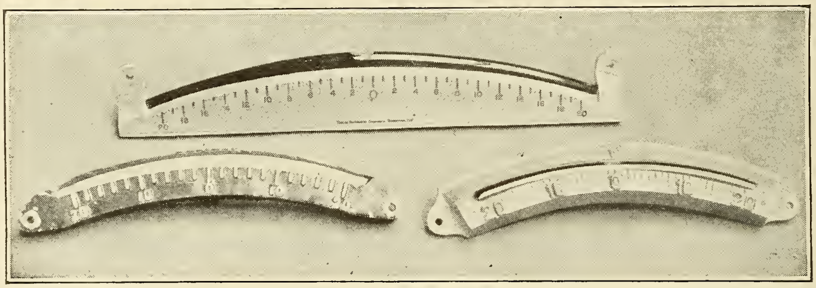


FIG. 24.—*Lateral liquid-bubble inclinometers.*

V. ENGINE INSTRUMENTS.

1. TACHOMETERS.

Tachometers are used to indicate the rate of revolution of the crank or propeller shaft of aircraft engines. They are usually driven by a flexible shaft which runs from the engine to the instrument board where the tachometer itself is located. The two types most commonly used are the centrifugal and the chronometric.

The centrifugal tachometer is the same in principle as the familiar ball governor, and depends upon the tendency of a mass to move away from the axis of rotation under the action of centrifugal force. This tendency is resisted by a spring. The amount of motion, which is a measure of the rate of rotation, is applied through a transfer mechanism to the pointer which moves over a dial graduated in revolutions per minute. A centrifugal

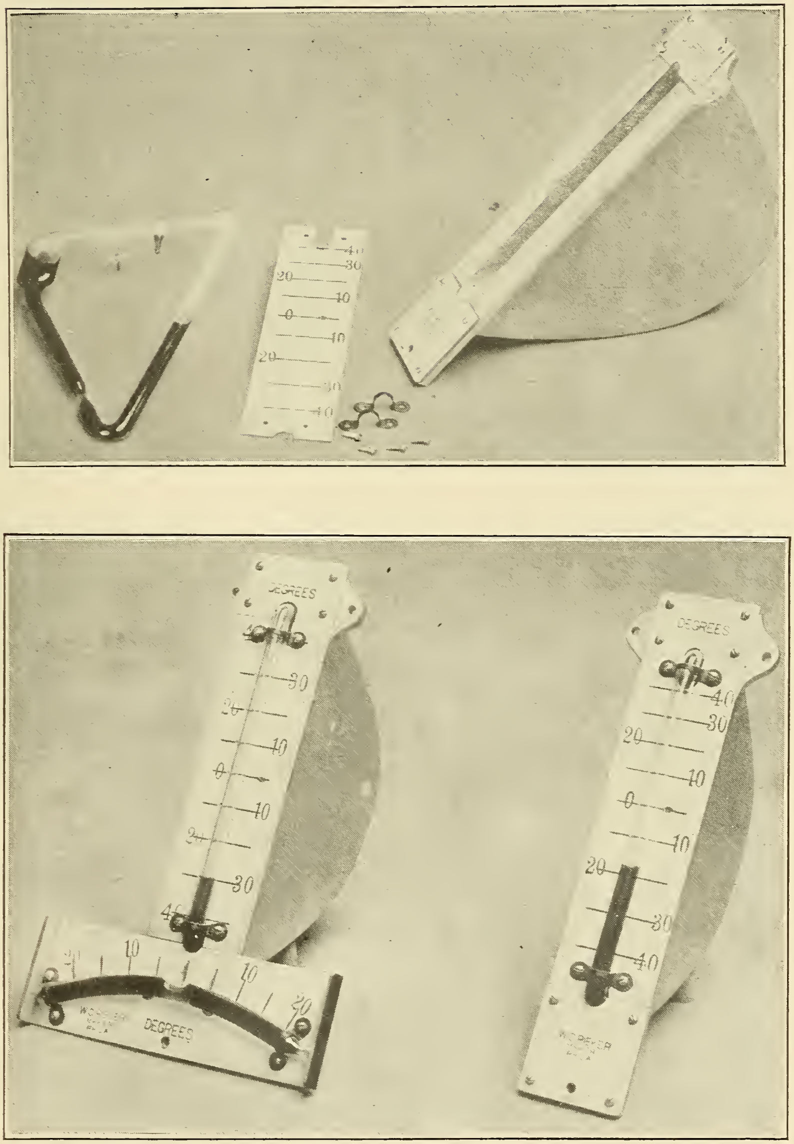


FIG. 25.—*Ricker fore-and-aft liquid inclinometer and combined fore-and-aft and lateral liquid inclinometer.*

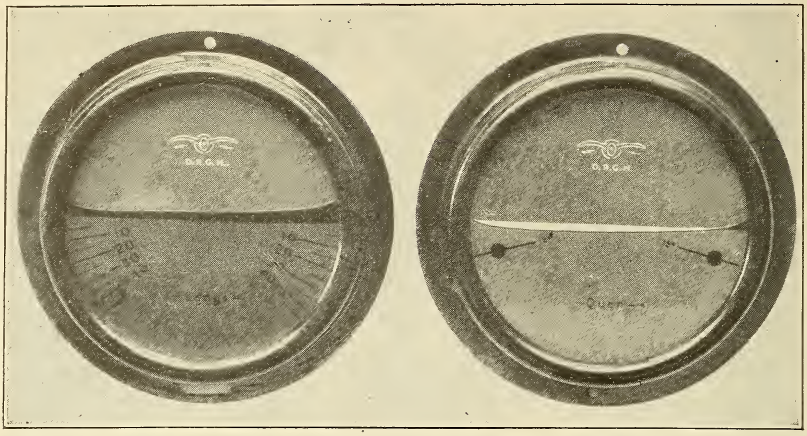


FIG. 26.—*D. R. G. M. sector type liquid inclinometers.*

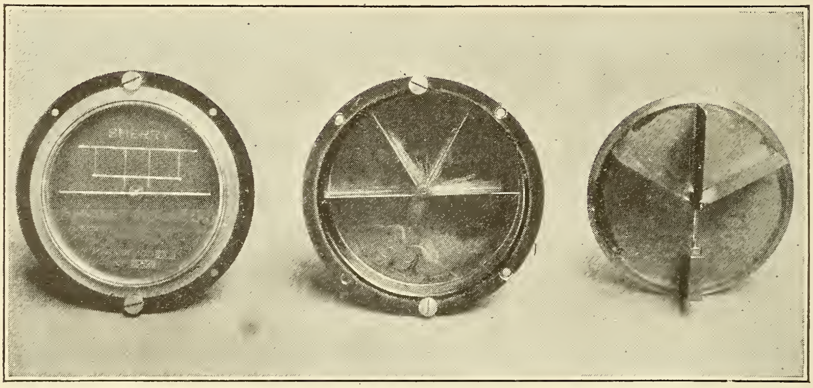


FIG. 27.—*Sperry air-damped pendulum lateral inclinometer.*

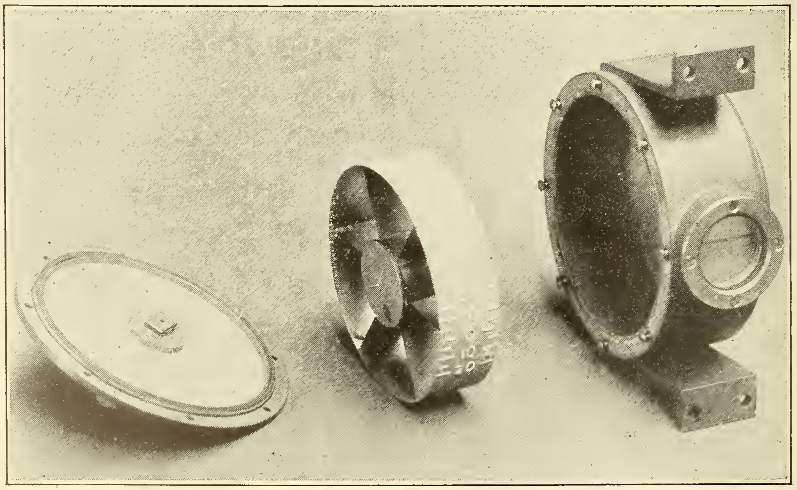


FIG. 28.—*Sperry liquid-damped pendulum fore-and-aft inclinometer.*

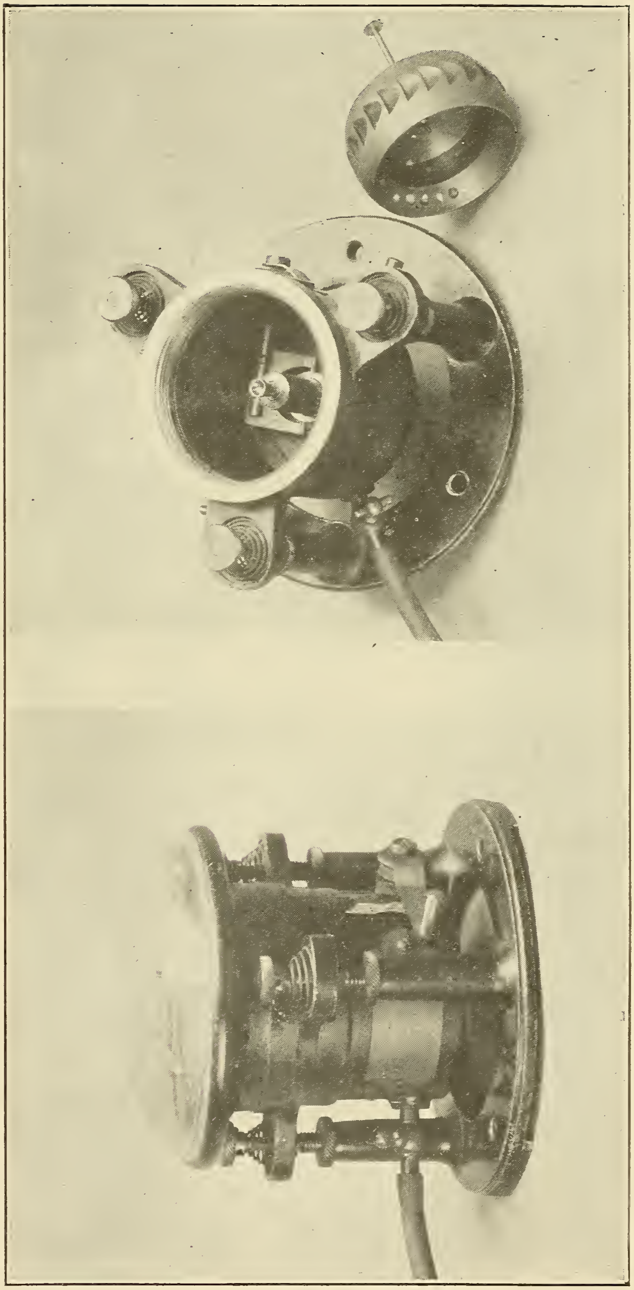


FIG. 29.—*Garnier gyroscopic top inclinometer.*

30145°—23——3

instrument of standard design is shown in Figure 30. In some the centrifugal element consists of two or more small weights connected to the shaft by links as shown in the illustration and in others of a single inclined weight which tends to assume a horizontal position under the action of centrifugal force. Centrifugal instruments are much simpler in construction and more durable than the chronometric type, but are not so accurate as the latter.

In chronometric tachometers the speed is determined by the amount of motion, in a definitely measured interval of time, of a toothed rack or gear system operated by the driving shaft of the engine. The time interval, which is usually one or two seconds, is controlled by a clockwork escapement. The motion of the rack or gear system is communicated to the pointer of the instrument, which is deflected in the given time interval an amount depending upon the speed of rotation of the driving shaft. The mechanism is so designed that the pointer is locked in position during each succeeding time interval while the toothed rack or gears are in action. At the end of each time interval the pointer is released and suddenly jumps to its new position, which is determined by the rate of rotation of the engine shaft during the time interval just ending. The result is that the pointer of the instrument moves by discontinuous jumps instead of continuously, as in instruments of the centrifugal type. A representative tachometer of the chronometric type is shown in Figure 31. As stated above, they are more accurate than centrifugal tachometers, but they involve a complicated clockwork mechanism which easily gets out of order and is difficult to repair. Nevertheless, a number of satisfactory instruments of this type have been made.

Several other types of tachometers have been used to a limited extent. Among these may be mentioned magnetic and electromagnetic tachometers, air-viscosity and air-pump tachometers. In the magnetic tachometer a permanent magnet is rotated near a conducting disk, thereby dragging the disk, by virtue of the induced eddy currents, in opposition to a resisting spring an amount depending upon the rate of rotation of the magnet. A pointer attached to the disk moves over a scale graduated in miles per hour. An instrument of this type is shown in Figure 32.

In the electromagnetic type a small magneto is attached to the engine shaft and connected to a galvanometer on the instrument

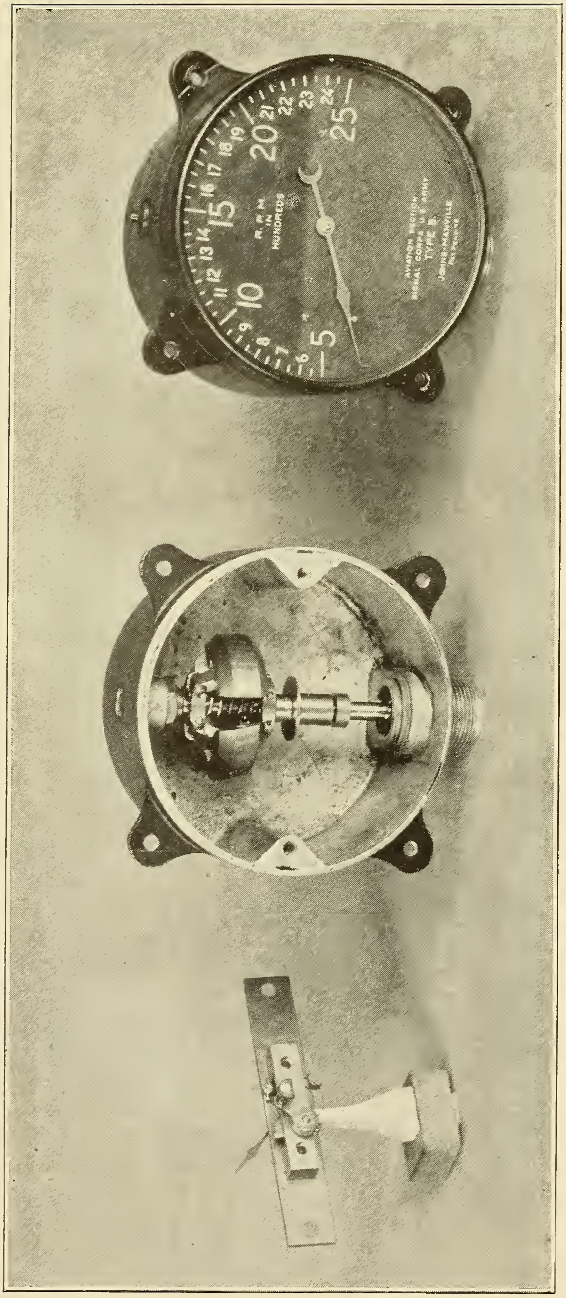


Fig. 30.—*Johns Manville centrifugal tachometer.*

board. The voltage developed by the magneto and hence the deflection of the galvanometer is proportional to the rate of revolution of the engine. The galvanometer is graduated to read in revolutions per minute. Magnetic and electromagnetic tachometers show larger errors than the centrifugal and chronometric type instruments and do not maintain their calibration as long.

The air-drag or viscosity tachometer consists, essentially, of two concentric cylinders separated by a thin film of air. One cylinder

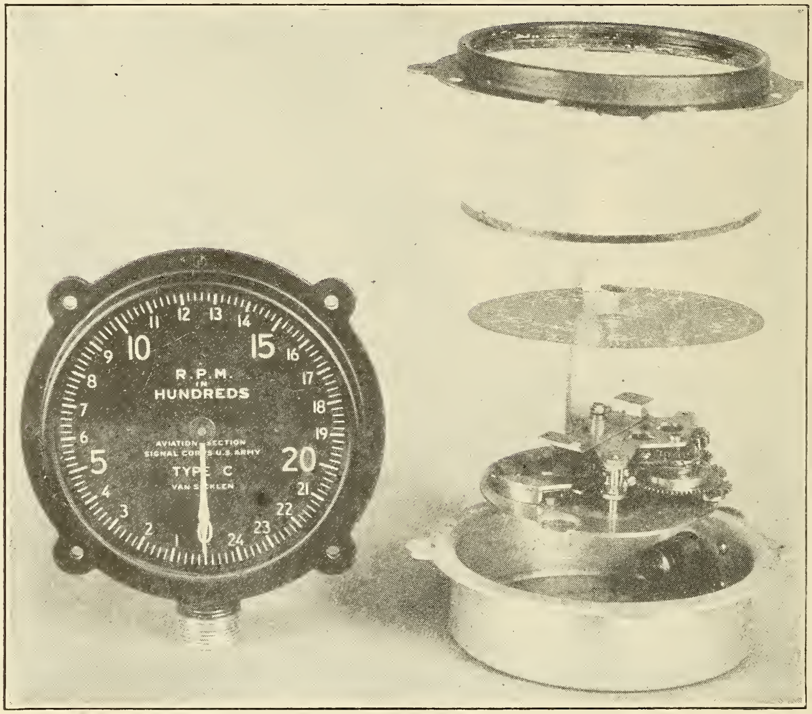


Fig. 31.—*Van Sicklen chronometric tachometer.*

which is attached to the engine shaft tends to rotate the other by virtue of the viscous action of the air film between them. This tendency to rotation is opposed by a spring. A pointer is attached to the second cylinder, and the amount of deflection is a measure of the rate of revolution of the first cylinder. The deflection in this case, however, is not proportional to the speed.

The air-pump type has a pump which forces air into a chamber provided with a leak orifice. The pressure developed in the chamber depends upon the rate at which the pump, which is connected to the driving shaft, rotates. In escaping from the chamber the air deflects a vane and pointer whose motion is opposed by a restraining spring. The amount of the deflection of the vane is thus a measure of the speed of revolution of the driving shaft. The air-viscosity and air-pump instruments are subject to altitude errors caused by the change in air density.

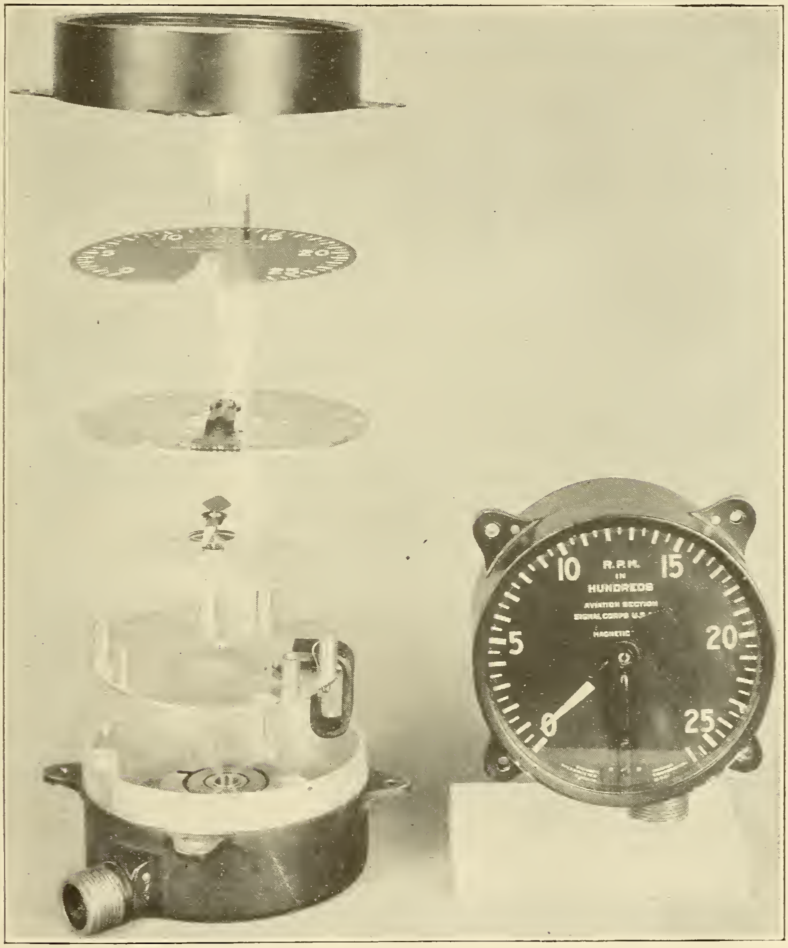


FIG. 32.—*Stewart-Warner magnetic tachometer.*

2. PRESSURE GAUGES.

Air and oil pressure gauges are used in aircraft to indicate the air pressure in the gasoline tank and the oil pressure of the engine lubricating system. Both types of gauges are ordinarily of the Bourdon type but of different range, air-pressure gauges having a range of approximately 0 to 5 lbs/in.^{2} and oil-pressure gauges from 0 to 100 lbs./in.[2] A group of representative air and oil pressure gauges is shown in Figure 33. The essential working element is a Bourdon tube, one end of which is rigidly attached to the instrument case and the other to the indicating system, which is either a sector and pinion or a system of levers. With increase in internal pressure the Bourdon tube expands, thereby causing the pointer to move across the scale. In some of the

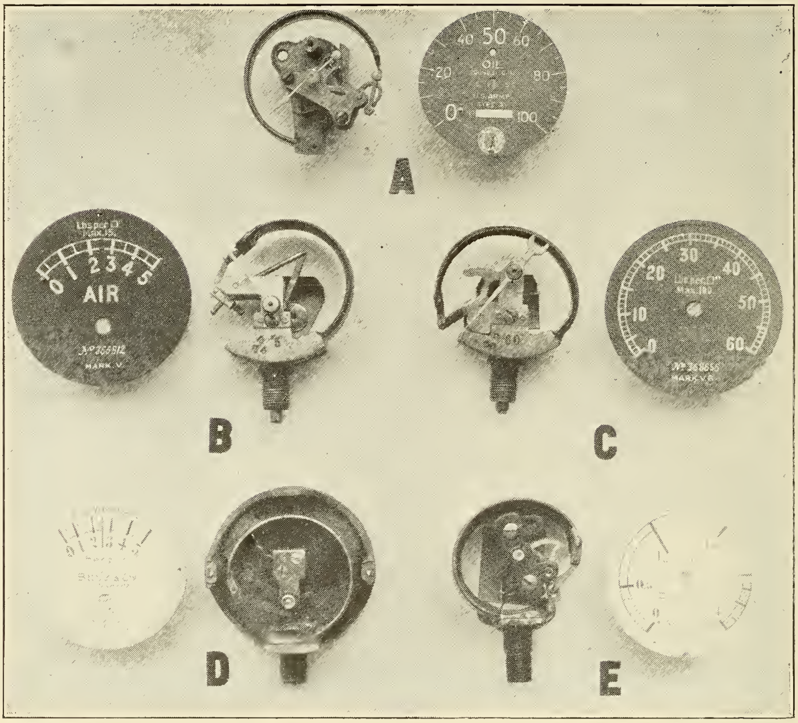


FIG. 33.—*Air and oil pressure gauges, Bourdon tube type.*

A, *C*, and *E*, sector and pinion transmission; *B* and *D*, linkage transmission.

instruments the pointer is concentric and in others eccentric, the advantage of the former being that it gives a much more open scale.

3. GASOLINE GAUGES.

Gasoline gauges are used to indicate the depth of gasoline in the gasoline supply tank. The most common type consists of a float of cork, wood, or hollow metal which rests on the surface of the gasoline and which is connected to the indicating mechanism by a metal rod or a flexible cord. Where it is possible to mount the indicator on the tank, the float is allowed to travel up and down between two vertical fixed rods. (See Fig. 34*B*.) A stiff twisted metal ribbon or inclined rod is caused to rotate by the float as it changes its position, thereby operating the indicator which is mounted above the float and attached to the moving rod through a system of gears. A disadvantage of this type of gauge is that the float is likely to stick between the guide rods if they get out of alignment. Another method is that shown in Figure 34*C*, in which the indicator is mounted at the center of the side of the tank facing the aviator. In this case the float is attached to a long metal rod and rotates about the indicator. At the end of the float rod is a small magnet which drags the iron pointer about as the float follows the level of the gasoline. Between the magnet and the pointer there is a thin metal disk which protects the cover glass from the hydrostatic pressure of the gasoline.

Float gauges, in which the float is connected to the indicator by a light-weight silk cord, are shown in Figure 34*D*,*E*. The float consists of an air-tight, hollow, brass cylinder which moves up and down in a metal tube which reached from the top to the bottom of the tank and whose diameter is slightly greater than that of the float. When the indicator is located at a distance from the float, the connecting cord passes through a metal tube with rollers at the bends. The gauge itself consists, essentially, of a drum on which the cord winds and unwinds and a system of gears which connects the drum to the indicating pointer. The cord is always maintained taut by a coiled spring which is attached to the drum. The indicator shown in Figure 34*D* has a magnetically controlled pointer similar to that described above. The one shown in Figure 34*E* is provided with a spiral scale, and by means of a rack and pinion mechanism the tip of the pointer is made to follow the convolutions of the spiral as it rotates. This makes it possible to allow the pointer to make several complete revolutions without confusing the indications.

Another type of gasoline gauge which has been used to a limited extent depends upon measuring the hydrostatic pressure of the head of the gasoline in the tank. This pressure is indicated by a gauge with corrugated flexible metal diaphragm capsules similar to those of an air-speed indicator. This type of gauge operates by connecting the case of the pressure indicator to the air space above the gasoline tank and the diaphragm capsules to a tube extending to the bottom of the tank. Air is caused to bubble

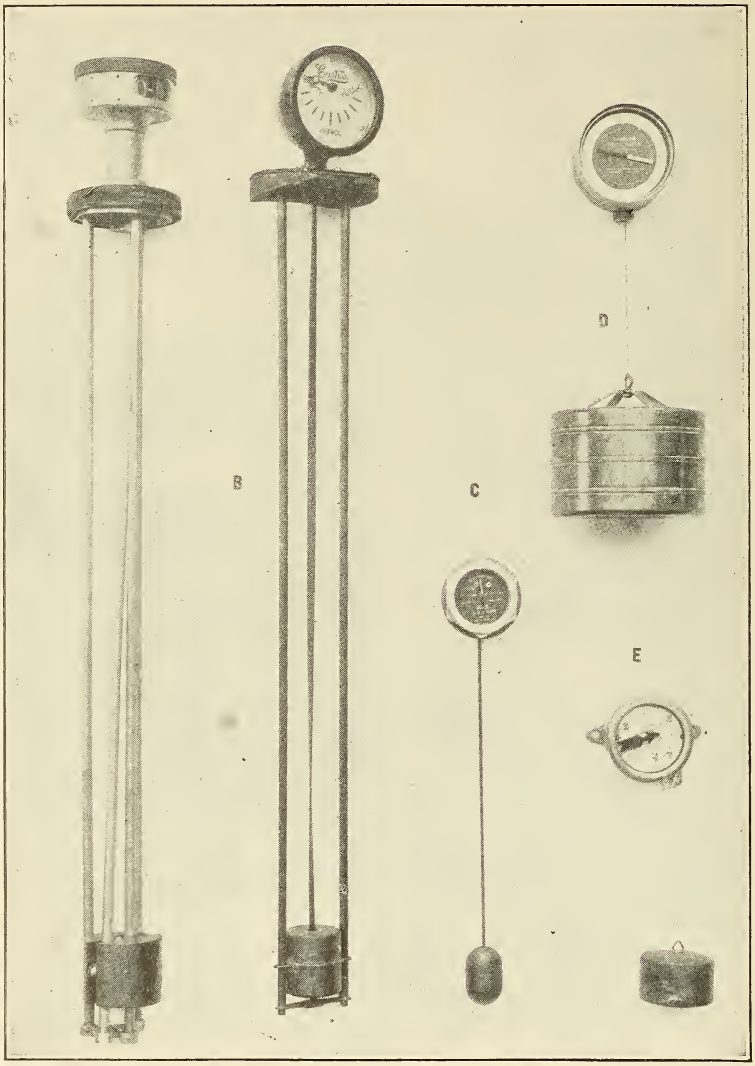


Fig. 34.—*Float type gasoline gauges.*

B, twisted strip transmission; *C*, lever transmission; *D* and *E*, cord transmission.

through the tube either by the use of a hand pump or automatically by the use of a power pump, thereby impressing on the indicator a differential pressure equal to the head of gasoline. With this type of gauge it is possible to have the indicator on the instrument board and connected to the gasoline tank by metal tubing. A disadvantage, particularly from the military point of view, is that a rupture in the connecting tube is likely to cut off the fuel supply from the engine. A group of gauges of this type is shown in Figure 35.

4. GASOLINE-FLOW METERS.

The rate of gasoline consumption in aircraft engines is found by the use of flow meters. Typical instruments are shown in Figure 36. In the one at the left of the figure a metal vane restrained by a coiled spring is deflected by the gasoline as it flows through the instrument. The gasoline flows past the vane in the space between the vane and the case. The case is provided with a cam surface which varies the space between the vane and the case as the vane rotates, so that the deflection of the vane is made proportional to the rate of flow of gasoline. A pointer attached to the vane indicates the rate of flow in gallons per minute. In the meter at the right the gasoline is forced out through a slit in a vertical metal tube surrounded by a concentric glass tube. A small rider shown at the left floats on the gasoline. The height reached by the gasoline as it flows through the slit and consequently the reading indicated by the rider is proportional to the rate of gasoline consumption.

5. THERMOMETERS.

Thermometers are used on aircraft to indicate the temperature of the radiator water and oil supply of the engine, the temperature of the atmosphere, and on lighter-than-air craft the temperature of the gas in the balloon bags. The last two mentioned types are described below under special instruments. Thermometers for measuring the temperature of water and oil ordinarily consist of a metal bulb partially or completely filled with liquid, which is located at the point whose temperature is to be determined and which is connected by means of a capillary tube to some form of pressure gauge, usually of the Bourdon type, located on the instrument board. Two types of pressure thermometers are used. These are known as the vapor-pressure and liquid-filled type, according as they depend upon measuring the variation of the

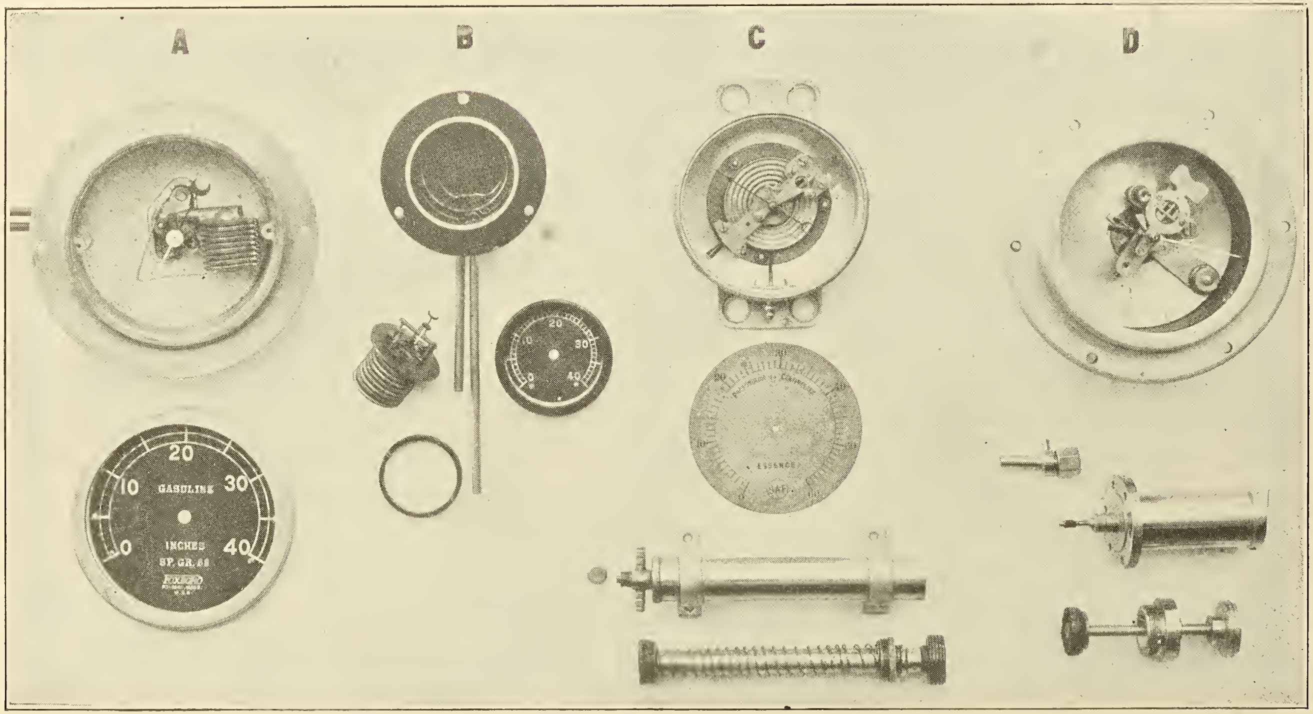


Fig. 35.—*Differential pressure type gasoline gauges.*

A and *B*, multiple diaphragm type; *C* and *D*, single diaphragm type with hand-operated pressure pumps.

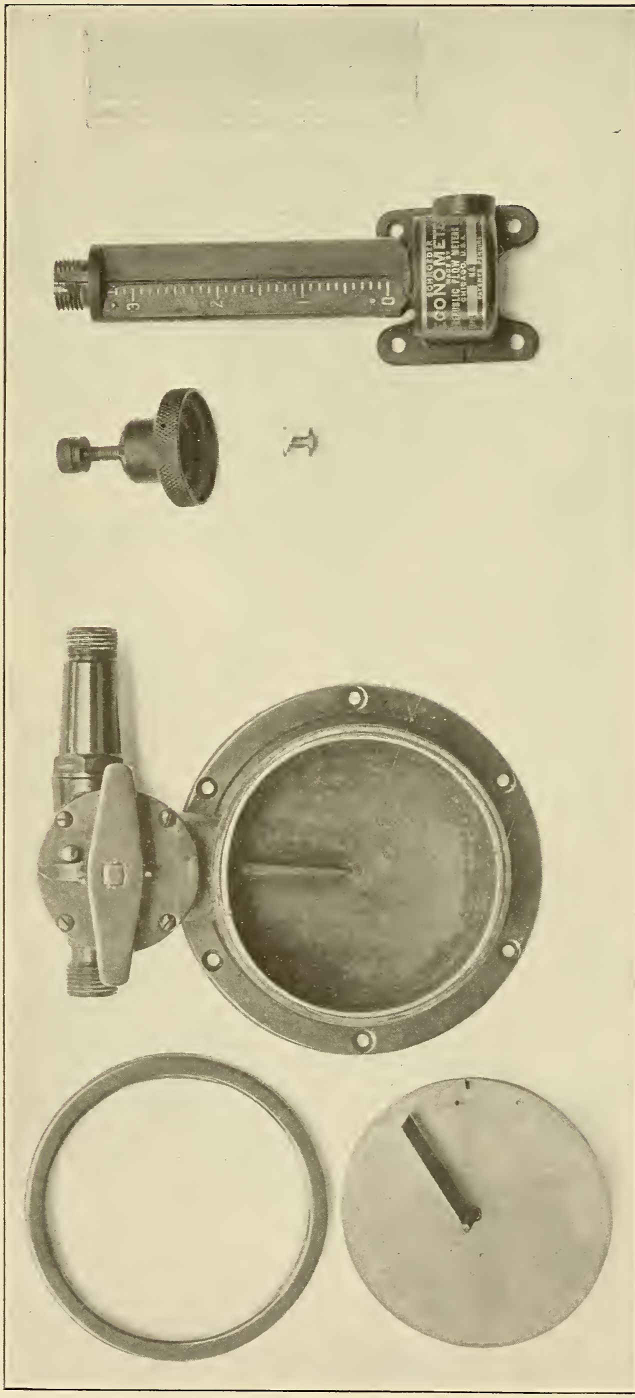


Fig. 36.—*Gasoline flow meters.*

pressure of the vapor of a volatile liquid or the expansion or contraction of a liquid with change of temperature. In the former case the bulb is only partially filled with liquid and the connecting capillary tube and gauge is filled with vapor, while in the latter case the entire system, including the bulb, capillary tube, and gauge, is completely filled with liquid under pressure. Ethyl ether and methyl chloride are most frequently used as the volatile liquid. Ethyl alcohol is the liquid usually used in the liquid-filled type. The vapor-pressure type is affected by changes of altitude. The liquid-filled type, on the other hand, gives erroneous readings if the temperature of the gauge and the capillary tube differs from that at which the instrument was calibrated. Typical thermometers of both types are shown in Figure 37. The vapor-pressure instruments (Fig. 37*B*, *C*) have an ordinary Bourdon tube, which is connected to the indicating mechanism by a sector and pinion, such as that used in pressure gauges previously described. The liquid-filled thermometer (Fig. 37*A*) has a helical Bourdon tube with several convolutions. It is also provided with a bimetallic temperature compensator which is connected between the Bourdon tube and the indicating mechanism.

VI. NAVIGATING INSTRUMENTS.

The use of aircraft for long-distance flights over both land and water and for night flying has required the development of aerial navigating instruments. The methods are fundamentally the same as those used in the navigation of ships at sea, the most important difference being the necessity of adapting the instruments to the relatively swift and unstable aircraft and also the uncertainty introduced by swift air currents which change rapidly in magnitude and direction, not only with time but also with altitude. It is thus impracticable to chart air currents as is done in the case of ocean currents.

The simplest method of air navigation is that in which maps of the territory traversed are used and the course is guided by following landmarks known to the pilot. More general methods, which involve calculating the course of the aircraft, are (1) dead reckoning in which the course at a given time is calculated from a previous known position by determining the direction of flight and speed with reference to the earth, and (2) astronomical observations in which the altitude or azimuth of the sun or stars is measured and the position computed from the Greenwich siderial time, the equation of time, and the position of the sun

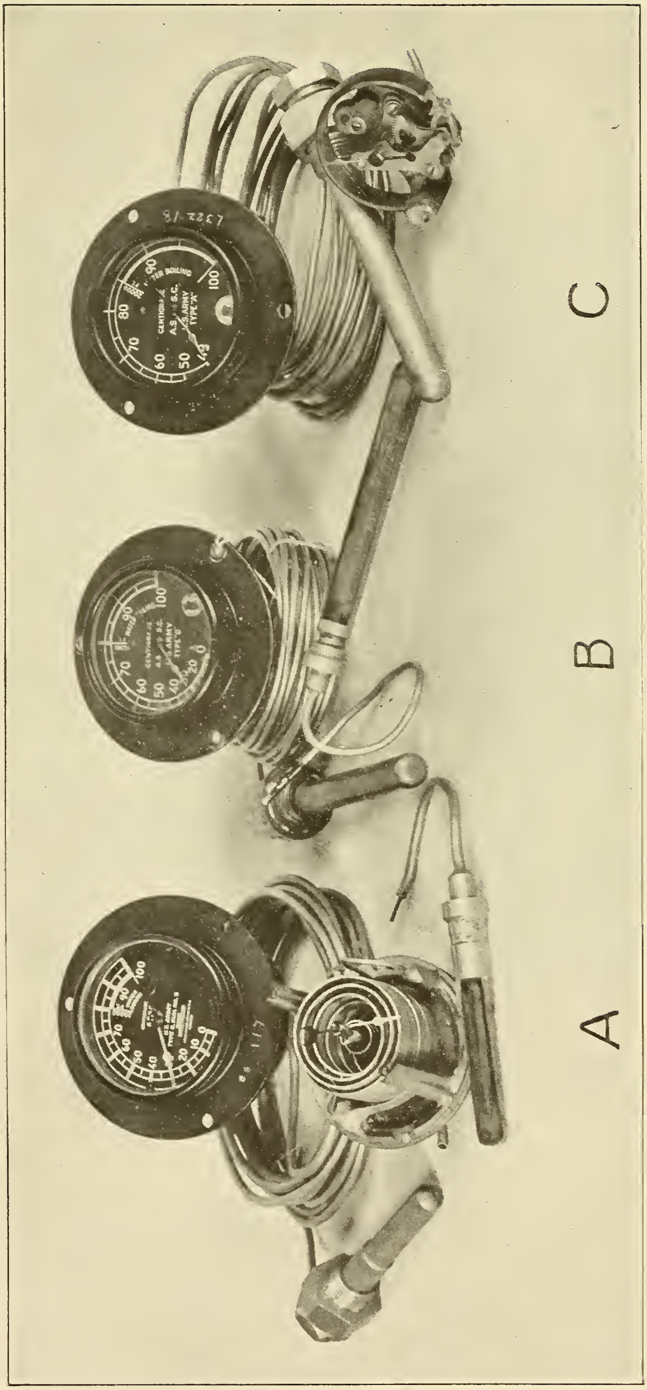


Fig. 37.—*Liquid-filled (A) and vapor-pressure (B, C) thermometers.*

or stars. Still another method recently developed is the use of the radio direction finder with which the position is determined with reference to radio stations by the use of a radio direction finder on the aircraft.

1. MAPS AND CHARTS.

Where maps are used, they are frequently mounted on rolls in a map case (see Fig. 38), so that a number of maps can readily be made accessible. Sometimes the map is mounted on a board

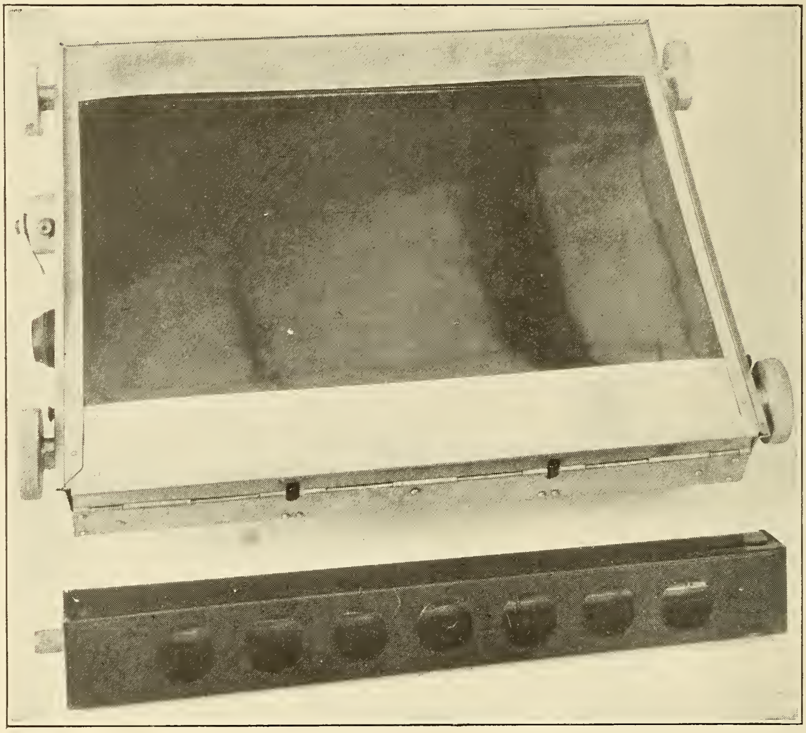


Fig. 38.—*Map case.*

and protractors and parallels provided for convenience in locating directions and measuring distances. Such a device is shown in Figure 39.

2. DEAD-RECKONING INSTRUMENTS.

The factors involved in the method of dead reckoning are the direction of the aircraft as determined by a compass, the air speed, the ground speed, and the drift with reference to the earth. Instruments used in making the first three measurements have already been discussed in this paper. Drift indicators usually depend upon determining by sighting wires or parallel lines in the instrument or in the focal plane of a telescope the apparent direction of motion of objects on the ground or on the water or even of the waves of the sea whose motion is so slow compared with that of the aircraft that it can be neglected. Instruments of this type known as drift-bearing plates are shown in Figure 40. These consist of a rotatable graduated circle with diametral sighting wires which are turned parallel to the direction of drift.

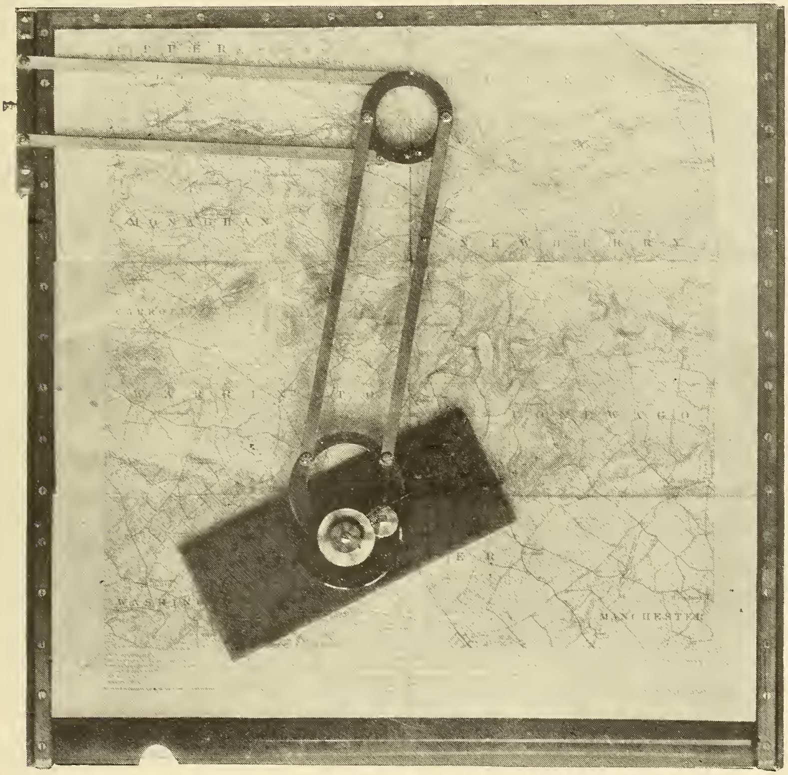


FIG. 39.—*Bigsworth chart board.*

The vertical attachment is used in determining the ground speed and carries an eyepiece which is adjusted for altitude by the graduated scale on the attachment. The ground speed is determined by finding with a stop watch the time required for an object on the ground to pass between two ball sights on the instrument. A more complicated device with attachment for adjustment of the lubber line of the compass is shown in Figure 41. In this case the direction of drift is determined by adjusting to the direction of drift a system of parallel lines in the focal plane of the telescope shown at the left of the figure. This automatically changes the position of the lubber line of the compass.

The drift indicator shown in Figure 42, in addition to determining the direction of drift and the ground speed, has adjustments which, when the instrument is also set for the air speed, automatically determines the magnitude and direction of the prevailing wind, or, as it is ordinarily expressed, solves the velocity triangle. The ground speed is determined as in the drift-bearing plate just described by placing the eye at the eyepiece and noting the time required for an object on the ground to pass between two points on the sighting arm.

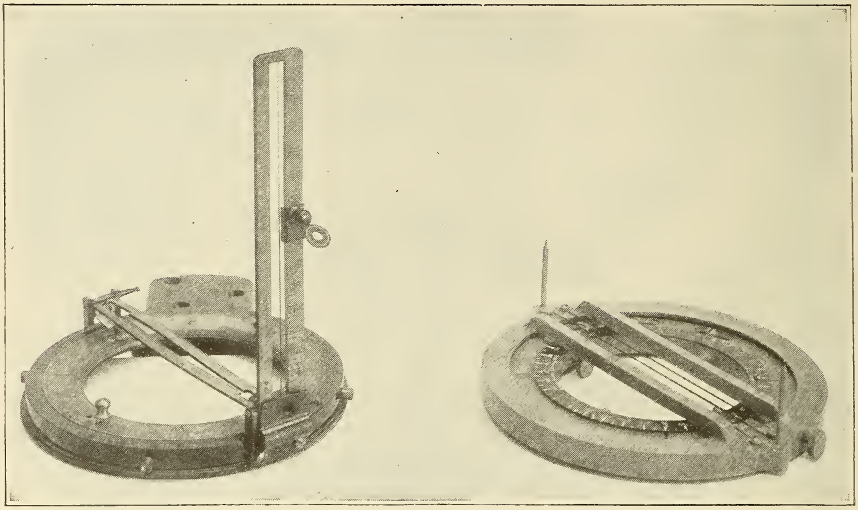


Fig. 40.—*Drift bearing plates.*

The navigraph shown in Figure 43 is a synchronized drift sight which determines the wind vector from the direction and magnitude of the drift and the air speed. The repeater, which is attached to the main instrument, indicates the result to the pilot. The unique feature of this device is the method used to determine the drift. An object on the ground is followed by means of the telescope at the right of the figure and at the same time a series of points is plotted on the paper by depressing the pencil which is maintained parallel to the telescope by a lever system. A series of points showing the direction of drift is thus obtained, defining a line in which the irregularities of the individual observations due to the oscillations of the aircraft are eliminated.

A number of simple devices have been invented to aid in solving the velocity triangle. Three of these are shown in Figure 44. They are used by setting the adjustable arms in the direction of the two known velocities of the velocity triangle, setting the adjustable sliders for the magnitude of these velocities and rotating the disk until the arrow on it is parallel to the line through the two sliders. The direction of the arrow is the direction of the third velocity component. Its magnitude is determined from the scale on the disk by the distance between the two adjustable sliders.

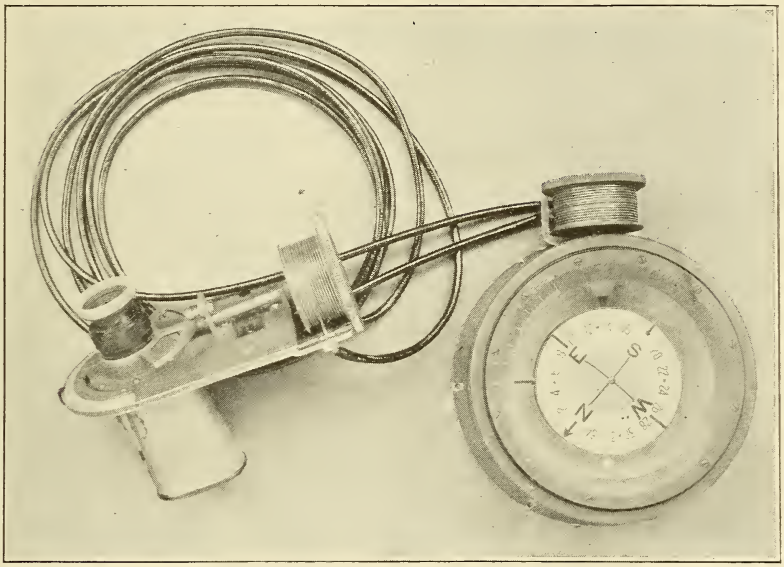


FIG. 41.—*Sperry synchronized drift set.*

3. ASTRONOMICAL INSTRUMENTS.

When astronomical methods are employed, the requisite observations are almost always made with sextants (see Figs. 45 to 48) which the observer uses to determine the altitude of the sun or some star. From such altitude measurements, together with the Greenwich time which is read from a chronometer, and the time equation and declination, as determined from the Nautical Almanac, the position can be determined. The sextants used differ from marine sextants principally in that an artificial horizon is used. In most cases this consists of a liquid-bubble level which is so arranged that it can be seen in the optical field simultaneously with the sun or star

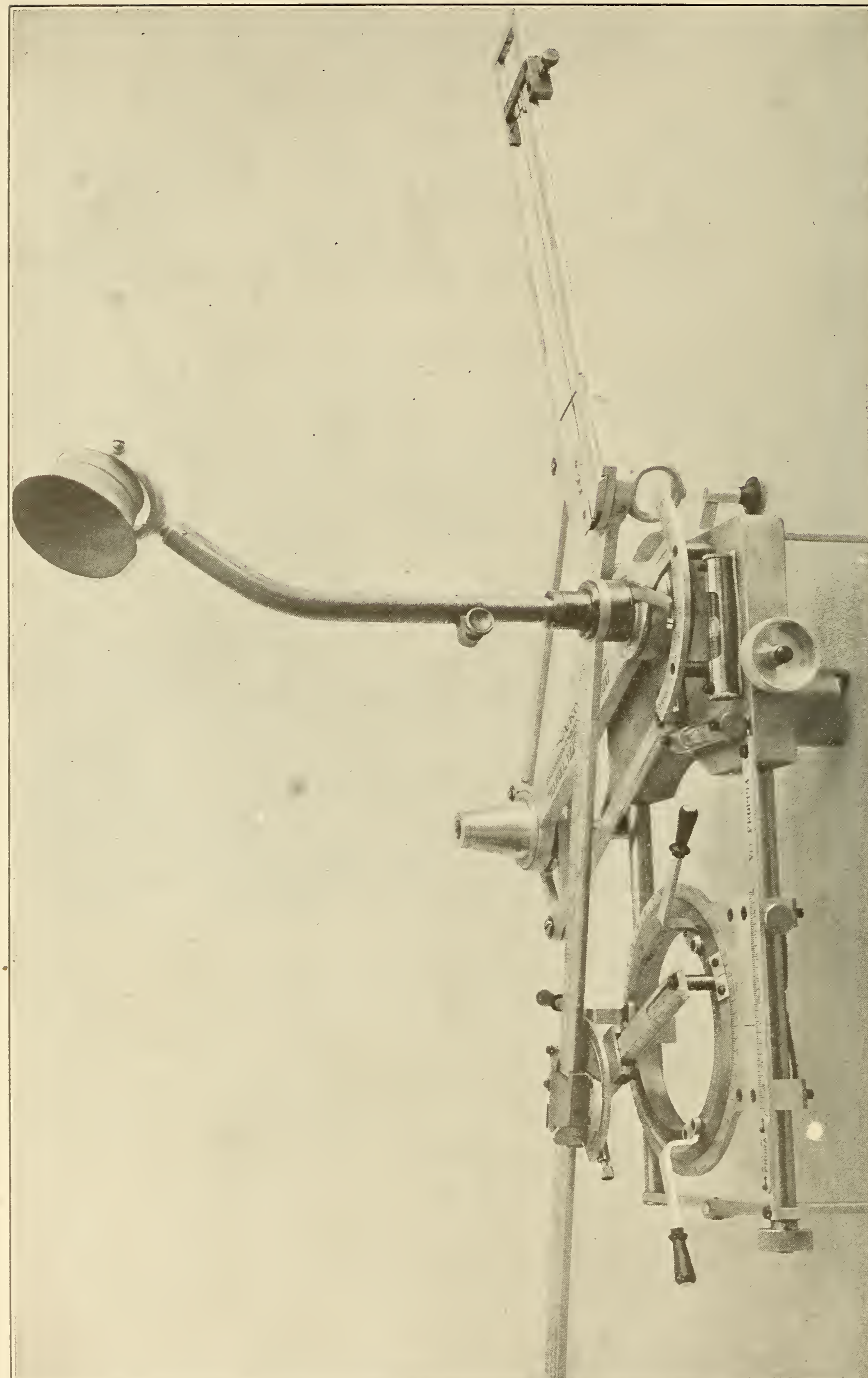


FIG. 42.—*Crocco drift indicator.*

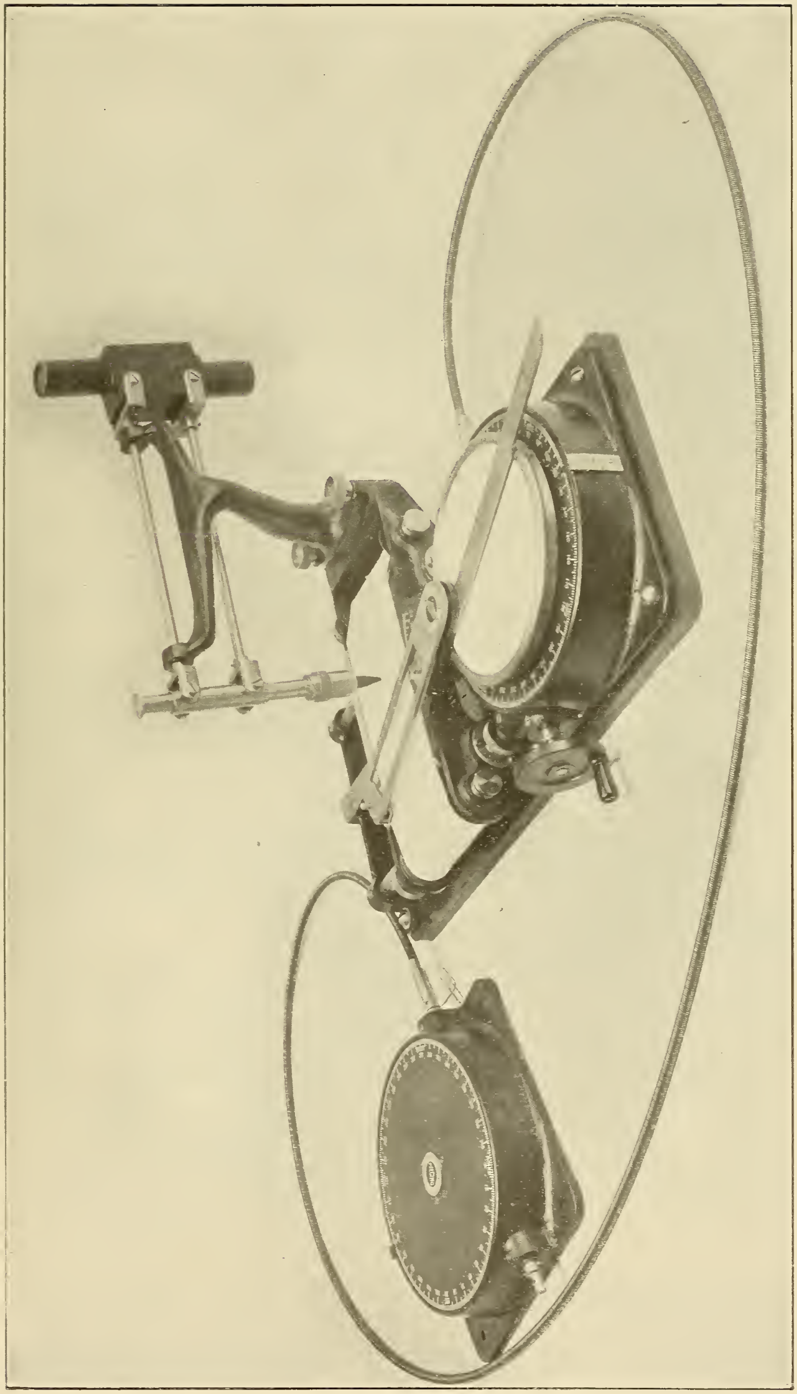


FIG. 43.—*Le Prieur navigraph.*

on which the instrument is set. Sextants have also been constructed in which pendulums have been used instead of bubble levels. Another method which has been tried is to construct an

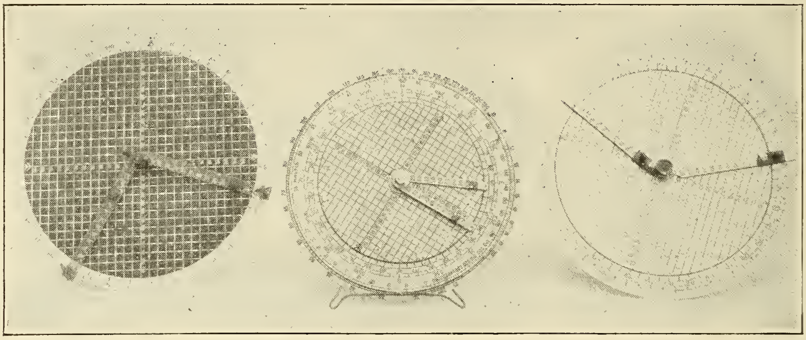


FIG. 44.—*Course and distance calculators.*

artificial horizon by mounting a mirror on the upper surface of a gyroscopic top and arranging the optical system so that the image of the sun or star reflected from the mirror and viewed

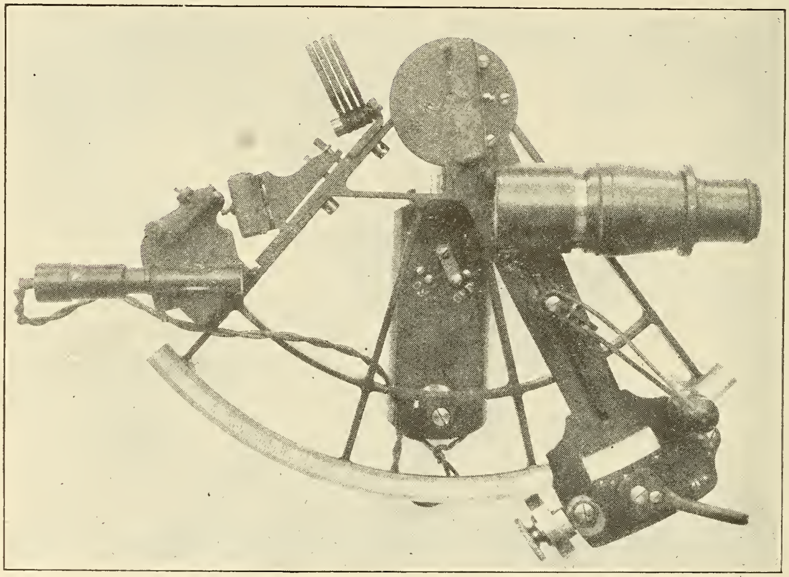


FIG. 45.—*Byrd bubble sextant.*

directly are simultaneously seen by the observer. An auxiliary apparatus is required to drive the gyroscope. Usually the gyroscope is air driven, in which case the auxiliary apparatus is a pump. An instrument of this type is shown in Figure 48.

With good piloting and a skillful observer the error of bubble sextant observations ordinarily does not exceed from 10 to 20 minutes of arc.

4. RADIO DIRECTION FINDER.

The use of radio direction finders in aerial navigation is of recent origin and still in the experimental stage. These devices consist, essentially, of a radio receiving apparatus with a coil antenna which the pilot orients to determine the direction of the radio sending stations whose identity and location are made known to him by the character of the signals sent. One important advantage of this method is that it can be used when both the earth and sky are obscured.

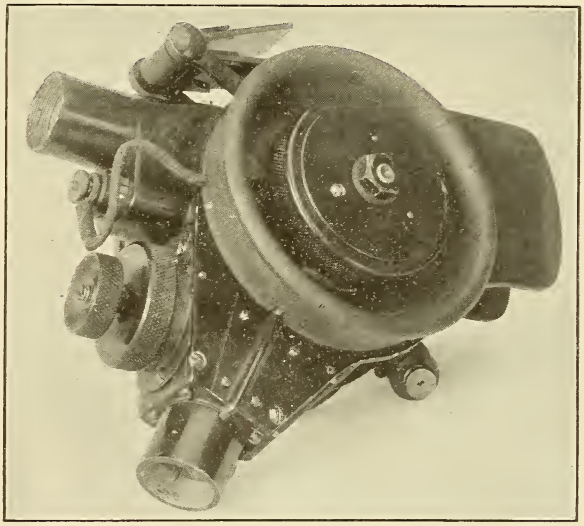


FIG. 46.—*Booth bubble sextant with rotating drum scale.*

VII. SPECIAL INSTRUMENTS AND ACCESSORIES.

In this category may be included apparatus to supply oxygen to aviators at high altitudes, instruments used in airplane performance tests which, in general, are of the recording type, timepieces and instruments pertaining particularly to the navigation of lighter-than-air craft, such as manometers, ballast gauges, and hydrogen leak detectors.

1. OXYGEN INSTRUMENTS.

The physical condition of aviators is seriously affected from lack of oxygen when altitudes above 15,000 feet are maintained for extended periods of time. This difficulty can be almost entirely

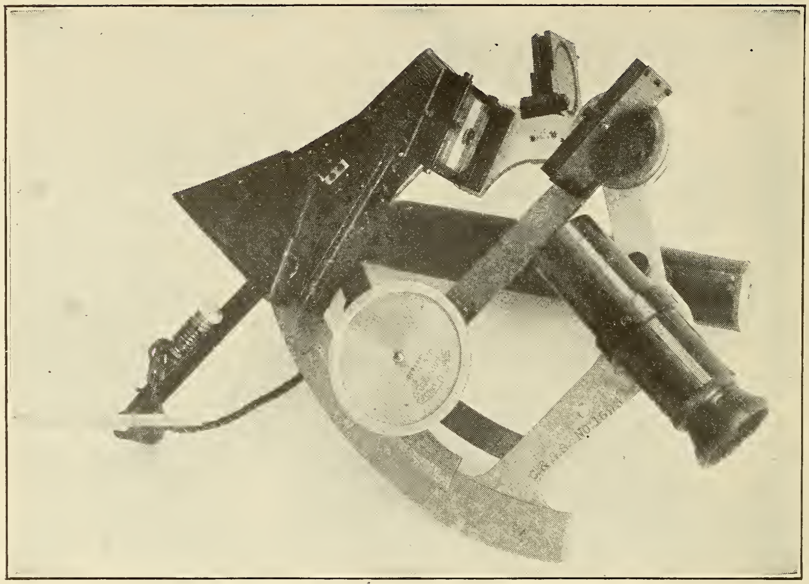


FIG. 47.—*Schwarzschild bubble sextant.*

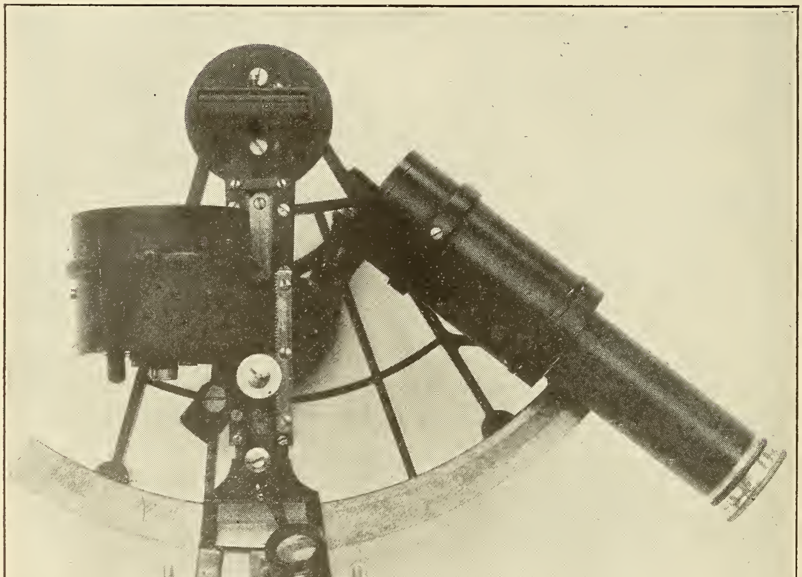


FIG. 48.—*Derrien gyroscopic sextant.*

overcome by supplying the aviator artificially with oxygen during flight. The oxygen is carried either in the form of compressed gas in steel cylinders or in liquid form in vacuum jacketed receptacles. A supply sufficient for a flight of two or more hours is usually provided. It has been found that 4 liters of oxygen per minute is ordinarily required by the aviator in view of his physical activity in flight. The expression for the amount to be supplied artificially at any altitude then becomes

$$V=4\left(1-\frac{P}{760}\right)$$

where V is the volume delivered in liters and P is the pressure of the atmosphere in millimeters of mercury.

An essential feature of the oxygen equipment is a device for controlling the amount of oxygen delivered to the aviator. In the earliest types this was simply a hand-controlled valve attached to the oxygen supply tank which the aviator operated to deliver the gas according to his needs. In later forms a barometric control is provided for regulating automatically the amount of oxygen supplied to the aviator according to his altitude. The instrument also has a pressure gauge to indicate the pressure of the oxygen in the supply tank and a flow indicator to show when oxygen is being delivered by the apparatus. An automatic regulator of American design is shown in Figure 49. It is provided with two pressure chambers—a high-pressure chamber into which the oxygen flows from the supply tank to reduce the pressure from 100 atmospheres to approximately atmospheric pressure and a low-pressure chamber to control the delivery to the masks. The pressure in each of these chambers is controlled by the action of valves operated by corrugated diaphragms, one of which forms the end of each chamber. The valve of the low-pressure chamber is also acted upon by an aneroid capsule which expands with increasing altitude, and thereby allows more oxygen to flow through the apparatus, the amount increasing in accordance with the above altitude-delivery formula. The helical-coil gauge shown in the figure is used to indicate the pressure in the supply tank. The rate of flow is shown through the action of the pressure of the outgoing gas on another corrugated diaphragm capsule connected between the low-pressure chamber and the masks.

Another instrument of the compressed oxygen type is shown in Figure 50. It was originally of British design, but was made in this country also during the recent war. In this instrument the pres-

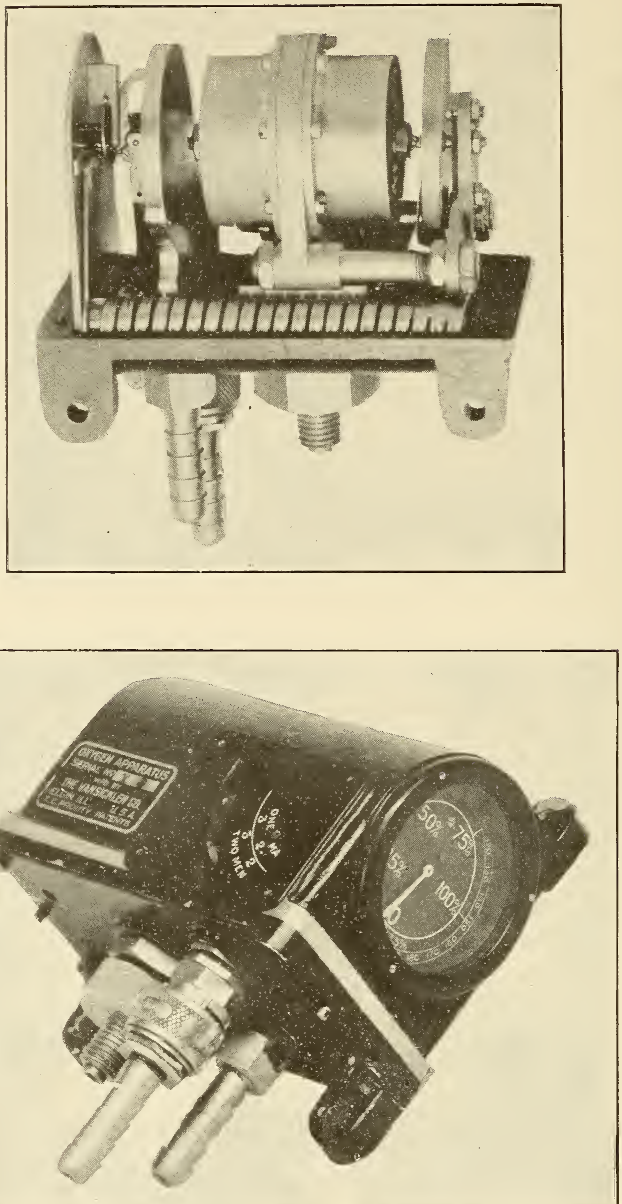


Fig. 49.—*Van Sicklen-Prouty oxygen regulator.*

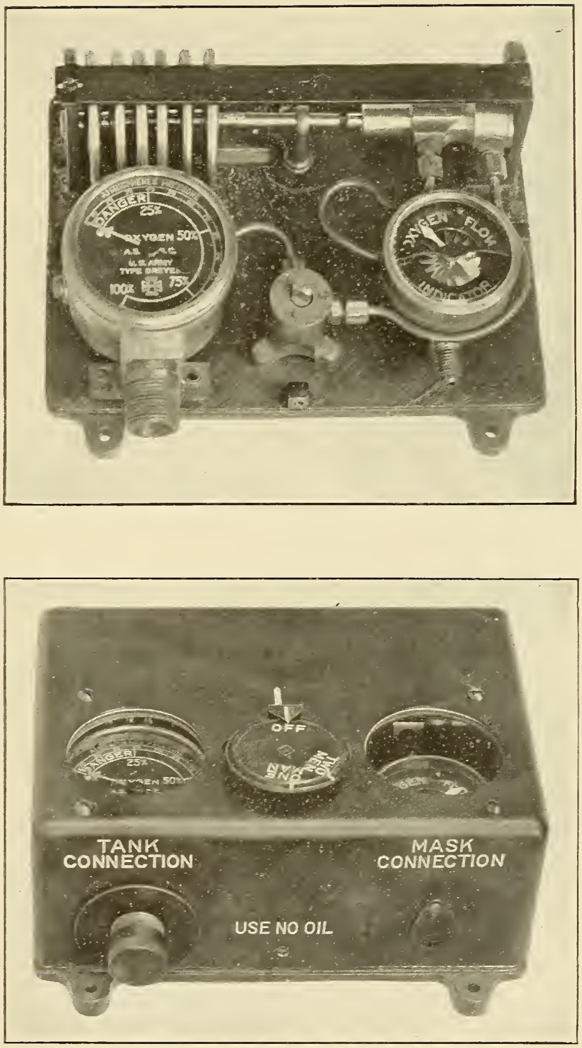


Fig. 50.—*Dreyer oxygen regulator.*

sure of the gas as supplied by the tank is reduced by passing into a chamber in which the pressure is controlled, as in the device described above, through the action of a valve connected to a corrugated diaphragm. This reduces the gas from a pressure of 150 atmospheres to a pressure of approximately one atmosphere above atmospheric pressure. From the reduced-pressure chamber the gas passes to a piston valve controlled by a battery of aneroid capsules. With increase of altitude this battery of capsules expands under the action of internal springs, thereby increasing the delivery of oxygen through the piston valve. The amount delivered is determined by the size of the port in the piston valve, which varies so as to deliver oxygen in accordance with the above-mentioned altitude-delivery formula. From the piston valve the oxygen passes through a flow indicator, which is a sensitive anemometer on which the gas impinges as it passes to the masks. A pressure regulator to indicate the pressure of oxygen in the supply tank is also provided. The essential difference between this instrument and the one previously described is that in this case the supply of oxygen is increased by enlarging the port of the control valve, while in the previous instrument the same result is effected by increasing the pressure under which the oxygen is forced from the reduced-pressure chamber through an outlet of constant size to the masks.

Where liquid oxygen is used the supply is ordinarily carried in double-walled spherical copper vessels with an evacuated space between the inner and the outer walls and polished surfaces facing the evacuated space to minimize loss through heat radiation. A typical instrument of this type is shown in Figure 51. It has a capacity of from 3 to 4 liters of oxygen, which corresponds to approximately 2,000 to 3,000 liters of gas. The neck of the bottle is a long metal tube closed at the top and connected to a pressure gauge and safety valve (shown on the instrument board), which are used to control the pressure of the gas which evaporates. This pressure forces the liquid oxygen out through evaporating coils which surround the neck of the bottle. From these coils the gas passes through flow indicators on the control board and thence to the masks. Liquid-oxygen apparatus has the advantage of being considerably lighter and more compact than the complete equipment necessary when compressed oxygen is used. On the other hand, there is an inevitable loss of gas due to evaporation when the supply is not actually being used. On this account it is

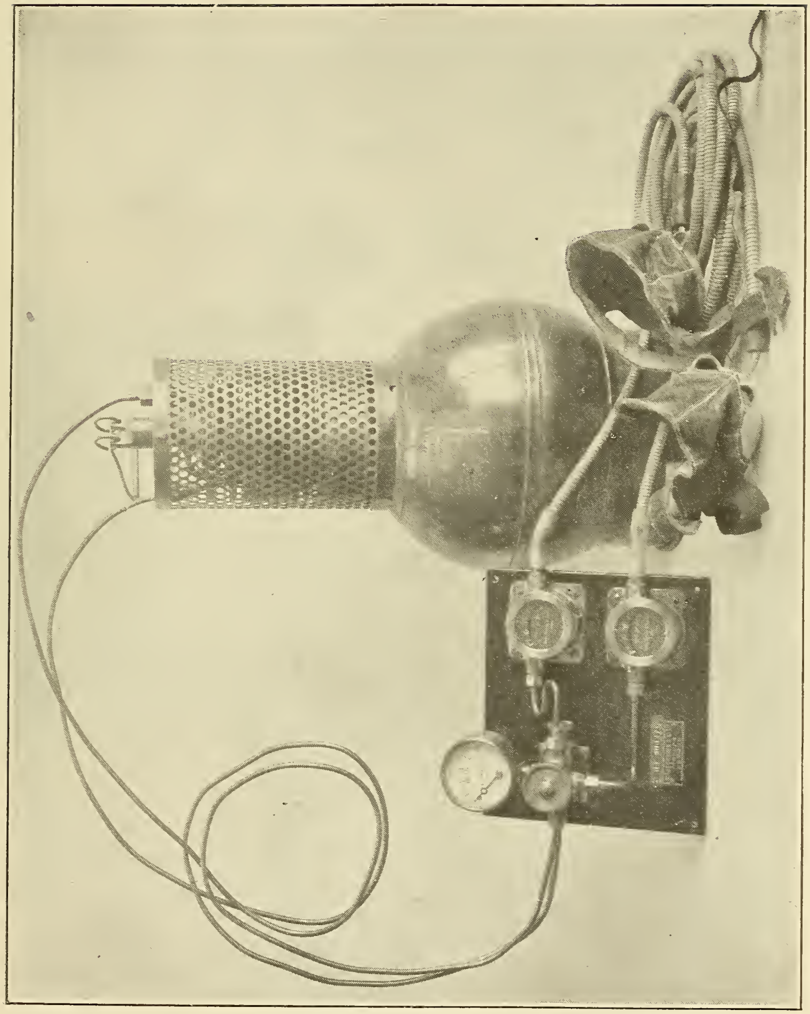


FIG. 51.—*Siebe-Gorman liquid-oxygen apparatus.*

necessary that the apparatus be filled within a relatively short time before using and that a liquefying plant be available in the vicinity.

2. RECORDING INSTRUMENTS.

For experimental work and airplane performance tests, permanent records of altitude, air speed, rate of revolution of the engine, rate of ascent or descent, temperature, and humidity are sometimes required. To this end special instruments have been designed which are the same in principle as indicating instruments of the corresponding type previously described, but which are provided with recording attachments. Typical instruments of this class are described below.

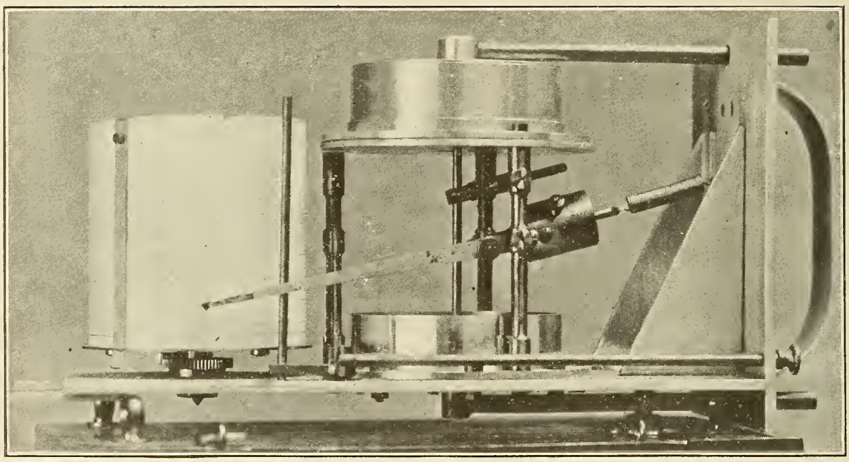
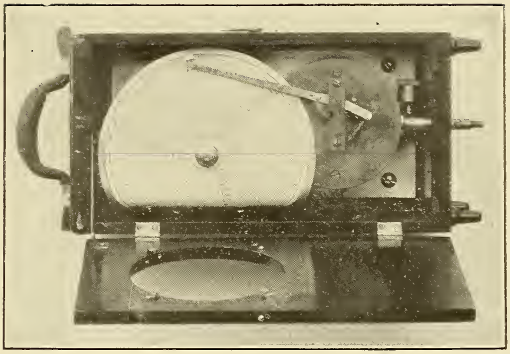


FIG. 52.—*Toussaint-Lepère air-speed recorder.*

The air-speed recorder, shown in Figure 52, is of the Pitot-Venturi type. It was designed for use with the nozzle shown in Figure 6 *F* and is provided with two pressure chambers, one of which is connected to the Pitot head and the other to the Venturi head of the nozzle. Rubberized silk diaphragms constructed like bellows are used. Under the action of the differential pressure these operate the lever system which controls the recording pen. The excursion of the diaphrams is resisted by a coiled spring.

A recording tachometer is shown in Figure 53. In this instrument a long pointer with attached pen is substituted for the indicating element of a chronometric tachometer. The pen rests on a circular chart, graduated in revolutions per minute, which is rotated uniformly by the clockwork mechanism shown in the lower figure.



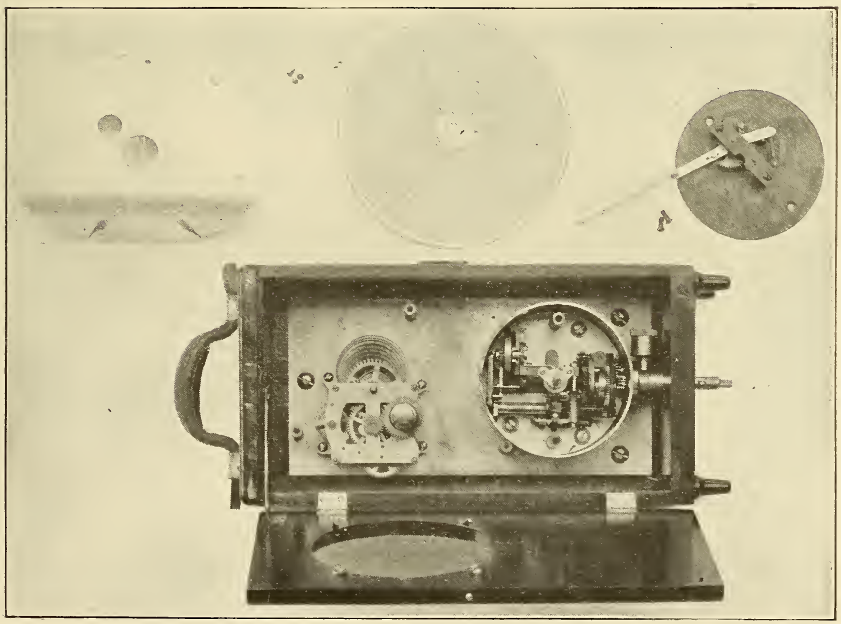


FIG. 53.—*Bristol recording tachometer.*

Rate-of-climb recorders have been made which are the same in principle as the rate-of-climb indicators previously described, except that the excursion of the diaphragm is made to deflect a small mirror from which a beam of light is reflected onto a photographic film moved by clockwork. In this way a permanent record of the rate of ascent and descent of the airplane is obtained. A photographic record is used instead of a pen and ink recording device, because the force available for operating the recording mechanism is too small to give satisfactory results with a pen and ink recorder of the ordinary type.

An instrument which gives records of temperature and humidity in addition to barometric pressure is shown in Figure 54. The lowest pen is operated by the aneroid capsules of an ordinary barograph and gives a record of the atmospheric pressure. The middle pen is controlled by the bundle of human hair fibers shown at the right of the figure and gives a record of the relative humidity in consequence of the expansion and construction of the fibers with changes of the moisture content of the atmosphere. The top pen is connected by a lever system to a bimetallic strip shown beneath the instrument and gives a record of the temperature throughout the flight.

3. STRUT AND GAS TEMPERATURE THERMOMETERS.

In performance tests on airplanes it is necessary to determine the temperature of the surrounding air at intervals during flight. This is effected by strapping a pentane or other liquid type thermometer, which can be read at a distance, to one of the struts of the airplane or by fastening the bulb of a liquid filled or vapor pressure type thermometer to the strut, the indicator being located on the instrument board. Instruments of both types are shown in Figure 55. They are called strut thermometers.

Electrical-resistance thermometers are also used in aircraft, more commonly on lighter-than-air craft to determine the temperature of the gas and the atmosphere. These consist of resistance coils of fine wire, located at the point whose temperature is to be determined, which are connected to an ohm meter graduated directly in degrees which serves as an indicating element. Several resistance elements may be located at different points on the aircraft and the temperature of each point determined in succession by making suitable connections at the indicator.

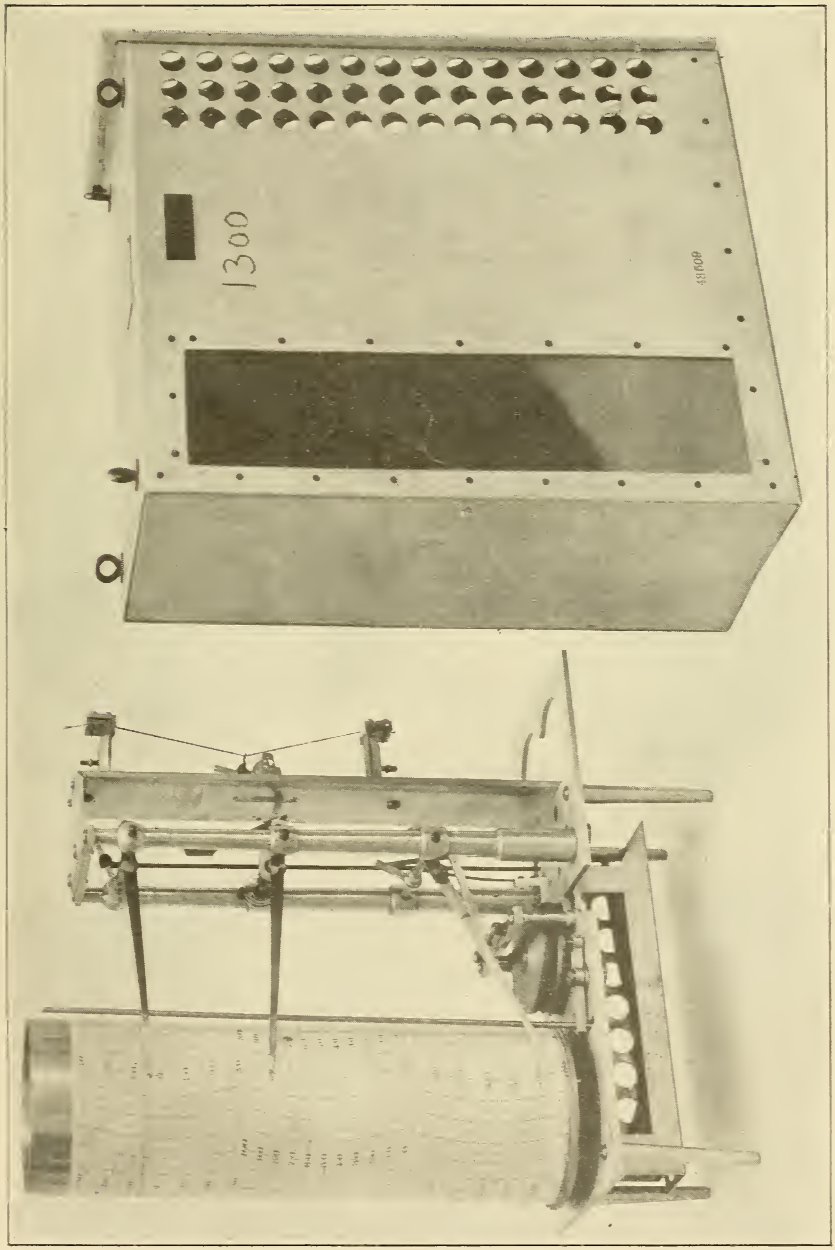


Fig. 51.—*Richard baro-thermo-hygrograph.*

4. TIMEPIECES.

A clock or watch is part of the standard equipment of most aircraft. Any reliable make of clock mechanism can be used for the purpose provided it is sufficiently rugged to withstand the shocks of landing and the inevitable vibration experienced in

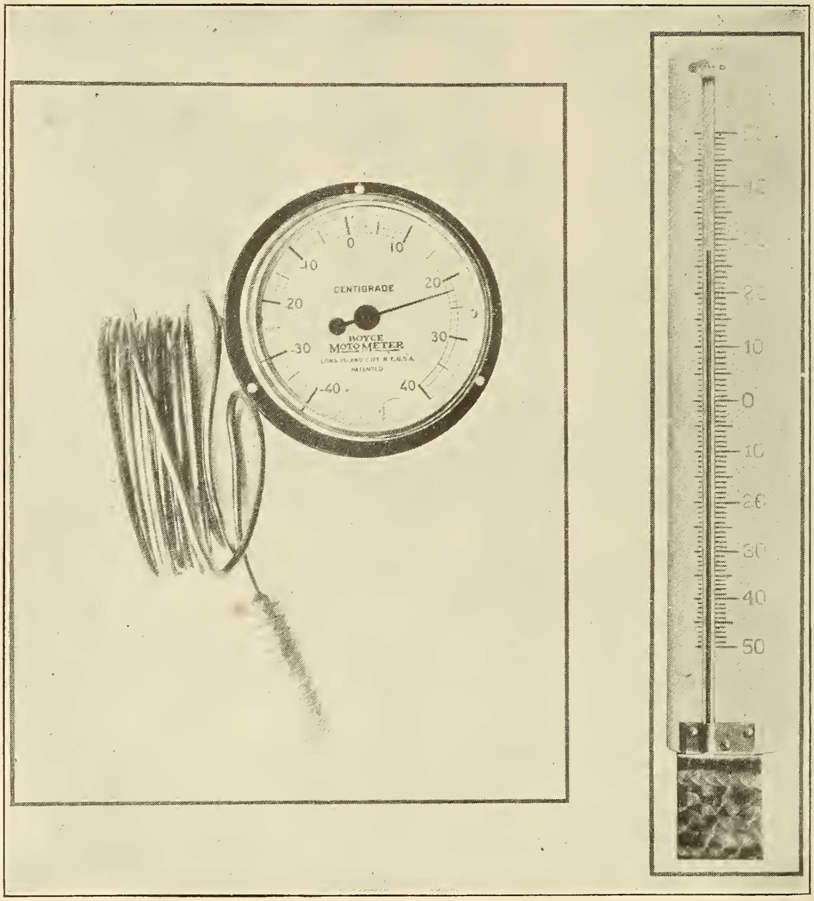


FIG. 55.—*Strut thermometers.*

aircraft. Chronometers of precision are ordinarily not required. The only clocks peculiar to aircraft are reversing stop watches used in bombing. These are so constructed that when the stem is pressed for the second time the pointer starts to move back to zero instead of stopping as in a stop watch of the usual type.

5. MANOMETERS AND HYDROGEN LEAK DETECTORS.

Among the special instruments pertaining particularly to the control of lighter-than-air craft may be mentioned water ballast gauges, manometers, and hydrogen leak detectors.

A typical water ballast gauge is shown on Figure 56. It consists of a corrugated metal diaphragm capsule inclosed in an airtight case and is used to indicate the pressure of the head of ballast water in a manner similar to that of the gasoline gauges previously described. The dial is graduated to indicate the head in inches of water.

A manometer to indicate the pressure of the gas in the bags of lighter-than-air craft is shown in Figure 57. It is provided with

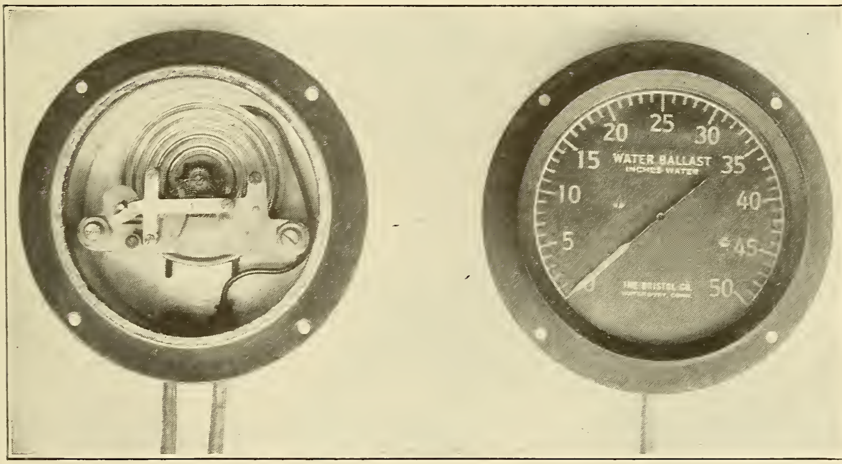


FIG. 56.—*Bristol water-ballast gauge.*

a thin colon leather diaphragm, which indicates the difference in pressure between the gas in the bags and the external air through the intermediary action of a lever system which operates a pointer which sweeps over a vertical linear scale. The distinctive characteristic of this type of pressure gauge is the extreme sensitiveness required. In the one shown 3 inches of water gives full-scale deflection.

A hydrogen leak detector is shown in Figure 58. This instrument is used to indicate when gas is escaping from the gas bags of lighter-than-air craft. It is provided with a disk-shaped air chamber, the back face of which is made of semipermeable porcelain. The front face is provided with a flexible corrugated metal diaphragm. Owing to the difference in the rate of diffusion of

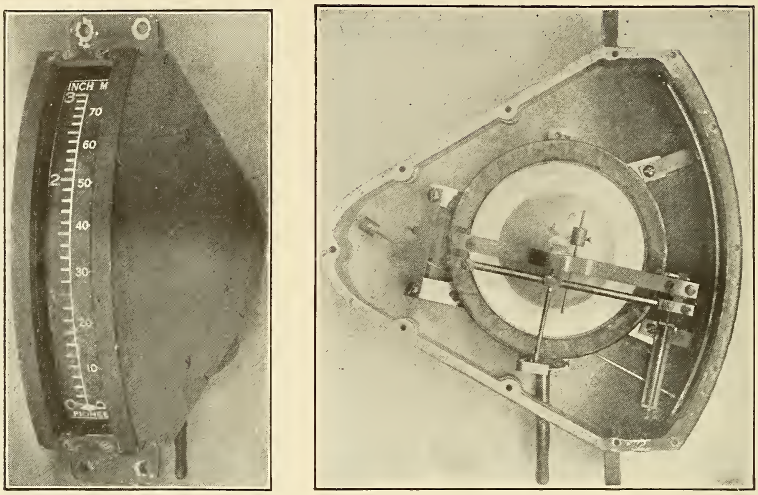


FIG. 57.—*Pioneer gas-pressure manometer.*

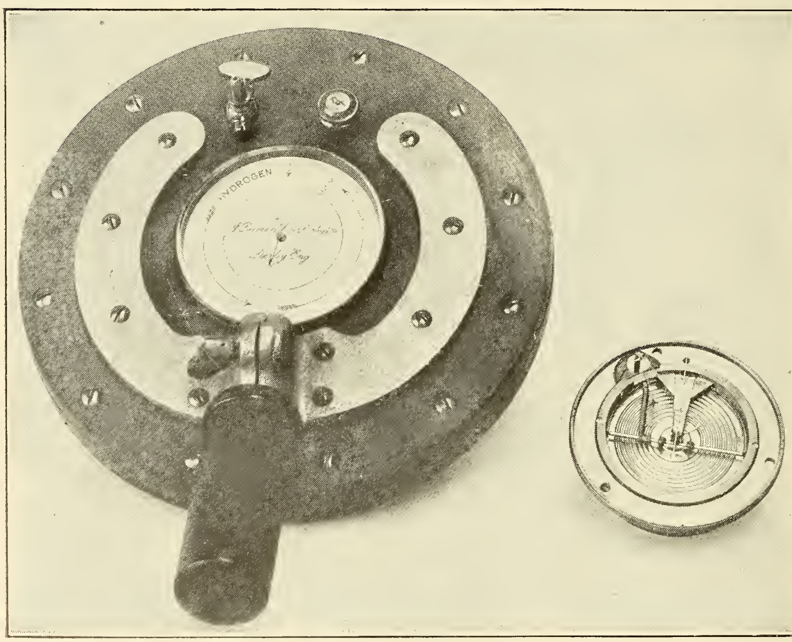


FIG. 58.—*Davis hydrogen leak detector.*

hydrogen and air when the porcelain face is placed near a leak the hydrogen diffuses through the porcelain into the closed chamber more rapidly than the air diffuses out, thereby increasing the pressure in the chamber, which causes the diaphragm to expand. This motion is used to operate the indicating mechanism.

VIII. CONCLUSION.

The recent origin of the aeronautic instrument art is emphasized by the fact that practically all of the instruments described in this paper have been invented or adapted to the special needs of aircraft within the past decade. The equipment of early airplanes was extremely meager and in many cases entirely lacking, the pilot depending on his individual skill and experience in the maneuvering of his craft, but with the increase in size and complexity of aircraft the need of instruments became apparent and has stimulated a rapid development. Improvements in existing instruments and the development of new types are continually being made as the rapid growth of aviation creates new needs.

WASHINGTON, October 27, 1922.