REPORT No. 371

PRESENT STATUS OF AIRCRAFT INSTRUMENTS

Report prepared by Subcommittee on Instruments

INTRODUCTION

This report includes the following sections:

1. Speed instruments.
2. Altitude instruments.
3. Navigation instruments.
4. Power plant instruments.
5. Oxygen instruments.
6. Instruments for aerial photography.
7. Fog-flying instruments.
8. General problems.
9. Summary of instrument and research problems.

A brief description is given of the present state of development and of the performance characteristics of the instruments included in each group. The items considered under performance include sensitivity (associated with aircraft needs), scale errors, effects of temperature and pressure, effects of acceleration and vibration, time lag, damping, leaks, elastic defects, and friction. The viewpoint will be that of the maximum demand which may be made on the instruments. Where possible the trend of present development work will be given.

In 1928 the Bureau of Aeronautics, Navy Department, initiated changes in the dimensions of instrument cases, so as to standardize on two sizes. Altimeters, air-speed indicators, and tachometers are now provided with 2¾-inch dials and can be mounted interchangeably with but minor modifications of the instrument panel. Engine thermometers, fuel and oil pressure gauges are provided with 1⅞-inch dials and can also be mounted interchangeably. These sizes were adopted after consideration of the design of the mechanism and of the accuracy with which various scales could be read. The new sizes are more economical of space, take up an area which is roughly equivalent to the corresponding vertical-scale instrument and simplify the layout and construction of instrument boards. Instruments such as turn indicators, fuel quantity gauges, fuel flow meters, rate-of-climb indicators, air logs, and clocks can also be mounted interchangeably with the first group of instruments named above.

The discussion of the dial sizes would not be complete without mentioning the great stimulus given to their adoption by the instrument section of the Army and Navy Standardization Conference, held in February, 1929, at the Naval Aircraft Factory. At this conference of manufacturers and interested Government representatives an agreement was reached which practically insures the universal adoption of the new small-dial instruments. The new sizes were adopted as standard by the Society of Automotive Engineers in August, 1929.

Vertical-scale instruments are not used to any great extent commercially. Several vertical-scale instruments have been adopted as standard equipment in the United States Army Air Corps, notably power plant instruments and air-speed indicators. The Bureau of Aeronautics of the Navy no longer specifies vertical-scale instruments for use in new aircraft. Such instruments conserve space on the instrument board, particularly when compared with the old large size dials. The type is generally more expensive and the performance is usually inferior to the round dial instrument. The latter point is not of importance in many cases in which the performance adequately meets requirements.

Flight test instruments are receiving wider attention. (Reference 45.) The data usually required in measuring the performance of aircraft in flight are as follows:

(1) Free-air pressure.
(2) Free-air temperature.
(3) Engine speed.
(4) Air speed.
(5) Fuel consumption.

The technique employed in securing these data varies greatly, and may be classified as follows:

(*a*) The use of photographically recording instruments, as exemplified by the flight research work at the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics.

(*b*) The dummy-observer method in which a set of indicating instruments is periodically photographed.

(*c*) The observation of indicating instruments by the pilot.

(*d*) The use of a combination of recording and indicating instruments.

Method (*d*) is in general use by the military services. Methods (*a*) and (*b*) are technically fully as satisfactory and in addition eliminate the personal element. In flight testing, consideration must also be given to the cost of the instruments, the ease of installing and testing, and the inherent accuracy of the instruments commercially available.

1. SPEED INSTRUMENTS

Speed instruments include those for measuring the speed of the aircraft relative to the air, known as air-speed instruments, and those for measuring ground speed. Air-speed instruments divide into two classes, the differential-pressure type and the true air-speed meters.

Differential-pressure air-speed meters.—These instruments operate on the differential pressure developed either by Pitot-static, Venturi or Pitot-Venturi tubes. The Pitot static instrument is now almost exclusively manufactured in this country, superseding the Pitot-Venturi type which was formerly preferred. The instrument has a twofold function, to measure air speed and to indicate the stalling speed. The indicator is calibrated in terms of air speed at a standard density of the air. In order to obtain the actual air speed at other densities a correction must be applied to the readings. The reading of the indicator, corrected for instrumental errors, but uncorrected for deviations in air density from the standard value, is called the "indicated" air speed. Stalling at all altitudes occurs at the same value of the indicated speed.

The performance of the indicators as now made by several manufacturers meets all ordinary requirements. The size of dial and the length of scale are such that the instruments can be easily read to about 1 knot or 1 mile per hour, these units being one-fifth of a scale division. Errors arising from elastic defects such as drift, hysteresis, etc., are ordinarily not greater than 1 to 2 miles per hour. The drift in five hours amounts to, roughly, one-half per cent of the reading. The effects of seasoning and of overpressure 50 per cent beyond the range of the instrument have been reduced by the manufacturers so as to be well below an average of 1 mile per hour. Changes in temperature from +45° to −30° C. cause a change in reading varying from 1 to 1½ per cent in individual instruments. Greater changes due to temperature have been found in some instruments but the values given are for instruments of the best quality, made in quantity production.

The performance of the Pitot-static tube is, under present conditions of installation, far from being as satisfactory as that of the indicators, due to the difficulty in finding a location for the Pitot-static openings in a position free from structural interference effects. The Pitot tube is now usually mounted either on a strut or on the leading edge of the wing of monoplanes. On strut mountings the openings are usually but a few inches from the place of support; when mounted on the leading edge of the wing the openings are usually carried forward or upward from 2½ to 4 feet. As a result, the readings are often in error, especially at low speeds, the error depending upon the particular installation. The indications at low speeds are usually below the true values. The best position for the tube remains to be determined. The effect of structural interference is even more of a problem on monoplanes where the Pitot-static nozzle must be attached to the wing. One way of meeting the difficulty is to calibrate the installed instrument over a speed course. The corrections at essential points, such as stalling speed, can then be permanently marked on the indicator.

In flight testing of aircraft, the air speed is held constant during a given maneuver. The use of an indicating instrument does not therefore add measurably to the amount of recording done by the pilot. In the flight tests conducted by the military organizations, the air-speed indicator on the airplane is used. It is calibrated over a speed course by observing the time required to fly the airplane up and down the course at a constant indicated air speed. The airplane is flown low, so that the air density is substantially that at the field meteorological station.

Air-speed recorders of the Pitot-static type are available commercially and are of value in flight testing in providing a check on the piloting, thus aiding in forming an estimate of the trustworthiness of the flight data. If the recorder is to be used to measure speeds accurately, it must also be calibrated over a speed course or its equivalent.

An auxiliary calibrating instrument is useful in measuring air speed during flight tests. In its usual form the measuring head of the instrument is suspended by a cable some distance below the airplane and is provided with vanes to keep the head oriented correctly. Two types of head have been used for this purpose: (*a*) Static (with Pitot tube mounted on the airplane) or Pitot-static tube, (*b*) propeller with commutator. The suspended static head is in general use for experimental purposes abroad. The suspended Pitot-static tube is used by the Langley Memorial Aeronautical Laboratory for flight testing, and by the Pioneer Instrument Co. to calibrate air-speed indicators at low speeds. Some experimental work has been done on the propeller type of instru-

ment at the Bureau of Standards, using the commutator-condenser principle of the suspended-head air-speed meters now in use on lighter-than-air craft. (References 1 and 2.)

True air-speed meters.—Air-speed instruments with rotating surfaces, such as Robinson cups or a propeller, give readings independent of the density of the air, and are known as true air-speed meters. Instruments of this type are preferred on airships because they are especially suited for the measurement of air speeds in the lower speed ranges.

An instrument used by the United States Navy on airships is that known as the commutator-condenser type, in which a condenser is alternately charged and discharged, in the latter case through an ammeter, the rate being governed by the propeller trailing in the air. The number of discharges per second determines the reading of the ammeter, which can thus be calibrated in terms of air speed. (Reference 1.)

When a knowledge of true air speed is required in addition to the indicated air speed, attention should be directed to the possibility of obtaining this data with one instrument. The true and indicated air speed differ by a factor depending on the air density. The latter may be assumed with sufficient accuracy in most cases to be that of the standard atmosphere at the indicated altitude. The Pitot-static tube instrument may consequently be provided with a manually-operated adjustment in the mechanism so that either true or indicated air speed can be indicated at will. The adjustment serves to control the multiplication of the mechanism of the indicator. An experimental model of an instrument of this kind has been developed for the Bureau of Aeronautics of the Navy by the Bureau of Standards, which shows the idea to be practicable.

Ground speed.—In ground-speed measurements, as carried out at present, it is necessary that the ground shall be visible. The methods used (in the few cases where ground speed is measured) follow:

(*a*) The wind-star method.
(*b*) Traverse method.
(*c*) Optical method.

(*a*) The wind-star method of measuring ground speed has been adopted as standard by the Bureau of Aeronautics of the Navy. This method does not require a knowledge of the tapeline altitude, but it necessitates flying widely off course for a short time, or in the modified form, flying at two speeds. This method is part of the procedure for the determination of the heading of the aircraft and is therefore described under Navigation Instruments. It requires a minimum of apparatus and a relatively small amount of computation, provided the course heading is determined at the same time.

(*b*) The traverse method is very often used in measuring ground speed. The traverse instrument consists of two parallel wires attached to the aircraft, together with a rotatable sighting telescope or eyepiece. The correction for altitude is made by a linear motion of either the eyepiece (or telescope) or one of the wires. An object is sighted under one of the wires and the time required for it to come under the second wire is measured. The time interval, the constants of the apparatus, and the altitude are sufficient to determine the ground speed. The method is dependent on a knowledge of the tapeline altitude above the ground, which constitutes a serious limitation in its usefulness.

(*c*) The optical method depends on neutralizing the apparent speed of some object on the ground by means of a rotating reflector or refractor. The rate of rotation of the reflector or refractor is proportional to the ratio of the ground speed to the altitude of the airplane above the observed object. An instrument of the refractor type suggested by Anderson was built for the United States Army Air Corps by the Bureau of Standards about six years ago. From this experience it appears that an instrument either of the reflector or the refractor type can be made mechanically satisfactory and at the same time can be so designed as to require no computation by the pilot. This method is also dependent on the tapeline altitude. An error of 5 per cent in the altitude measurement introduces an equal error in the ground-speed determination.

Ground-speed instruments which do not depend on the visability of the ground have been proposed. (See Reference 5.) There has been no recent progress in their development.

2. ALTITUDE INSTRUMENTS

This class of instruments includes the following:
Aneroid altimeter.
Barograph.
Absolute altimeter.
Rate-of-climb meter.
Free-air thermometers.

The latter instrument is included here for want of a better classification.

Altimeter, aneroid type.—The performance of this type of altimeter has been improved remarkably in the last few years. The accuracy of the best commercial instruments (quantity production) is now superior to that of any instrument on the market in 1926. The usefulness of altimeters now appears to be limited by the inherent defects of the barometric method of measuring altitude rather than by instrumental difficulties. As recently as six or seven years ago, reports were common that an altimeter set to zero

before a flight would indicate an altitude of 200 or 300 feet on landing. This after effect, as determined by the customary laboratory test, is now of the order of 20 to 40 feet for good instruments and approximately zero for the best instruments. The maximum elastic hysteresis has been found to be as low as 0.1 per cent of the range (20,000 or 35,000 feet) with values not exceeding 0.3 per cent for a fair proportion of the instruments tested.

Altimeters are usually compensated for temperature at one pressure (760 millimeters of mercury). The compensation can be made as complete as desired but the cost may be increased.

The change in scale value of the instrument with temperature, as determined by calibration or scale error tests made at two temperatures, appears to depend on the design of the pressure element as well as on the effect of temperature on the elastic moduli of the pressure-element materials. Ten years ago the tolerance for the change in scale value was 5 per cent for a 50° C. change in temperature, compared with about 3 per cent now. Most of the instruments ranging up to 35,000 feet which have a low elastic hysteresis have changes in scale value which do not exceed 1.5 per cent, which is entirely accounted for by the changes in the elastic moduli with temperature.

There are two errors which are important in using the aneroid altimeter for landing purposes. These are drift (creep) and secular error.

The secular error is the change in reading with time when the instrument is subjected to a constant pressure of approximately 760 millimeters of mercury. In instruments of good quality the secular error is attributable mainly to the gradual release of internal stresses in the pressure element and in the bimetallic strip. Secular errors may be eliminated or minimized by suitable artificial seasoning. In instruments of poor quality, drift may also be an important factor.

It is well known that both the drift and secular error of instruments made 10 years ago were rather large. An instrument of that period was considered "good" if the drift did not exceed 200 feet in 5 hours at an altitude of 20,000 feet. The Bureau of Standards is now studying the drift and secular error of selected instruments supplied by several manufacturers. It has been found that the drift has been reduced in some cases to about 50 feet in 5 hours at 15,000 feet and the change in correction (secular error) at room temperature is less than 100 feet in 15 months.

Sensitive altimeters are useful in indicating small changes in altitude when attempting to fly level or in landing during poor visibility. Instruments with a pointer motion of one revolution per 1,000 feet and a range of 20,000 feet are being made by several manufacturers. The first instrument of this type was developed by the matériel division of the Army Air Corps. One manufacturer has recently reduced the size of the sensitive altimeter so as to use a 2¾-inch dial, at the same time securing a performance about equal to that of the best service altimeter. At present these altimeters have an over-all accuracy of 50 feet in level flight and readily indicate changes of 10 feet in altitude. When used for landing, the best of these instruments will indicate altitudes near zero with an accuracy of the order of 20 feet under most conditions of use, providing that all known instrumental corrections are applied and proper adjustment is made for the effect of changes in ground-level air pressure. This estimate is the result of a laboratory investigation and of course requires verification by means of flight tests.

In many airplanes, particularly those having inclosed cabins, it is necessary to make the case of the altimeter air-tight and to connect it to a static tube mounted in the free air stream in order to eliminate the effect of pressure differences between the cabin and the free air.

A desirable feature in altimeters used to indicate level flight is to have the pointer horizontal at the required altitude, so that deviations in altitude are shown by an up-and-down motion of the pointer. Two instruments with this feature are now available. One has a pointer called the tendency pointer which moves vertically upward or downward from the level flight position for an increase or decrease in the altitude at which level flight is desired. This instrument also indicates the altitude on an altitude dial, the reading of which is controlled by a setting knob. As designed the adjustment of the setting knob controls the force exerted by a spring on the diaphragm capsules. The tendency pointer is connected to the diaphragm capsules through a mechanism so that the indication of level flight is associated with one definite deflection of the diaphragm. In practice the altitude dial is adjusted when at a desired flying altitude so that the tendency pointer indicates a balance of the air pressure and the spring tension acting on the diaphragm capsules. The altitude is then given on the altitude dial and deviations therefrom indicated by the tendency pointer. The instrument is bulky and has the defect that the altitude indicator is about four times as sensitive as the tendency pointer. The tendency pointer has a motion of about 1 inch for a total altitude range of 800 feet, while the pointer of the 2¾-inch dial sensitive altimeter described above moves 6 inches for the same change in altitude.

The other level flight altimeter is an adaptation of the round dial sensitive altimeter to indicate in a similar way. This is done by arranging the mechanism (including the pointer) so that it may be rotated with reference to the case. When the desired

flying level is reached the mechanism is rotated so that the pointer is horizontal.

Barographs.—In the flight testing of aircraft the air pressure is recorded against time by use of a barograph. One manufacturer in this country makes an instrument in which the pen traverses a 5-inch chart twice for the pressure range, thus giving an equivalent chart length of 10 inches. The performance of the instrument is in general satisfactory if reasonable care is taken in its use. Laboratory tests show that elastic defects such as hysteresis and after effect are about as low as for high-quality indicating instruments and that the change in scale value usually amounts to less than 2 per cent of the change in reading for a temperature change of 50° C. A slight discontinuity (which can be allowed for) exists in the time-pressure record at the reversing point of the pen. Present practice is to have the record made on a smoked-paper chart by a metal stylus. The record may be "fixed" by a mixture of collodion and pyroxylin lacquer solvent without changing the dimensions of the chart.

It may be advantageous in some cases to make the case of the barograph air-tight and connect it to a static tube mounted in the free air stream. This would eliminate the effect of any difference between the pressure in the cockpit and that in the free air.

Other methods of recording the air pressure include (1) the photographic recording of the deflection of a pressure capsule, as is done at the Langley Memorial Aeronautical Laboratory, and (2) the use of a "dummy observer," by means of which periodic photographs are secured of the indications of an aneroid barometer and other instruments.

Absolute altimeter.—Instruments which indicate the altitude of the aircraft with respect to the ground over which it is flying at the time, are usually called absolute altimeters. Three types of instruments are under development; (*a*) the capacity altimeter, (*b*) the radio altimeter and (*c*) the sonic altimeter.

(*a*) The capacity altimeter has been developed in this country mainly by the Bureau of Standards, the Army Air Corps, and the Bureau of Aeronautics of the Navy Department. See reference 6 for the present status. Two insulated conductors, usually flat metal plates, are mounted beneath the airplane. The electrical capacity between these plates varies with the distance of the airplane from the ground. Above 100 feet the variation with altitude is not perceptible. From 100 feet down the altitude may be read directly on an indicating instrument. A zero adjustment must be made at an altitude above 100 feet each time the instrument is put into operation. The indication is then continuous and for a reasonable length of time the apparatus needs no further attention. On account of the limitation of its range to the small height of 100 feet, the device has not proved useful in practice.

(b) Absolute alimeters of the radio type are under development. (References 7, 34, and 41.) One of these (Reference 7) depends on the interference between radio waves emitted from the airplane with waves reflected from the ground. The apparatus is understood to measure altitude up to 1,500 feet. In addition to giving scale indications, the instrument can be designed to warn the aviator of his approach within 200 feet of the ground by successively flashing green, amber, and red lights, the latter appearing at 50 feet above the ground. More development work appears necessary. The devices described in the section below on Fog Flying Instruments also have some application as altimeters.

(*c*) Sonic altimeters depend for their indication upon the measurement of the time required for a sound emitted at the aircraft to be reflected from the ground and to return to the aircraft. The only instrument which thus far has reached the test stage is that of Behm. (References 8 and 46.) An instrument of his design forms part of the equipment of the *Graf Zeppelin.* In airplanes the noise of the engine may be expected to interfere with its operation. The Daniel Guggenheim Fund for the Promotion of Aeronautics is supporting research in the development of a sonic altimeter, and allotments have been made to the University of California and to the University of Delft, Holland. (Reference 34.)

Rate-of-climb indicators.—An accurate instrument of this type could be used advantageously in the flight testing of airplanes to measure the rate of climb. The present indirect procedure is to use a barograph or an aneroid barometer and a timepiece. The instrument would also be useful in the ordinary operation of aircraft in many cases. Recent experience with rate-of-climb indicators of the capillary-tube type has shown that they can not be used for accurate measurement in airplanes. Temperature effects and excessive time lag are the chief difficulties.

The rate-of-climb indicator is now being used by many pilots as a null instrument to give an indication of deviation from level flight. It is superior to the usual liquid type fore-and-aft inclinometer because its indications are independent of accelerations and angle of attack. On the other hand, errors arising from a rate of climb below the sensitivity of the instrument are cumulative as regards altitude changes and can only be detected by use of the altimeter. The instrument is inherently delicate since it operates on very small differential pressures, the maximum pointer deflection in sensitive instruments being produced by differential pressures of the order of 1 inch of water.

The climb indicator is often equipped with a valve for closing the capillary tube, thereby converting the instrument into an exteremely sensitive aneroid statoscope for use as an aid in flying at a constant pressure level. Changes in the temperature of the entrapped air are minimized by the use of a vacuum-jacketed container. A change of 1° C. is equivalent to a change in altitude of 100 feet. Measurements by the Pioneer Instrument Co. indicate that when a vacuum-jacketed container is used, a change in the external temperature of 12° C. does not produce an error of more than 16 feet in altitude during a time interval of 30 minutes. See section on Instruments for Aerial Photography.

A rate-of-descent meter of the hot-wire type has been developed for flight research work abroad (Reference 10), but because of its bulk appears to be useful only for research purposes.

Sensitive rate-of-climb indicators of the capillary-leak type have been found useful in the navigation of airships. The design of the instrument differs from that for airplanes in that a U-tube manometer containing a liquid of low density is used to measure the differential pressure. A vacuum-jacketed bottle is used as the air chamber.

Free-air temperature.—Free-air temperatures are measured in the flight testing of aircraft and in special investigations, such as meteorological studies and the formation of ice on aircraft. In flight testing free-air temperatures are now usually observed on a strut thermometer, owing to the lack of a satisfactory recorder. The thermometers are of the liquid-in-glass type with a very open scale and are being supplied by several manufacturers. Except in one respect the instruments are meeting requirements. The unsatisfactory aspect is the thermal lag of the thermometers. The thermal lag for well-designed instruments with small bulbs, when exposed in an air stream of 100 miles per hour at normal density, is given for various rates of climb in the following table:

Rate of climb ft./min.	Air density per cent of standard	Lag in thermometer °C
0	100	0
1,000	100	0.5
2,000	100	1.0
3,000	100	1.5
0	50	0
1,000	50	1.0
2,000	50	2.0

To meet the flight-testing requirements of the Langley Memorial Aeronautical Laboratory and the Bureau of Aeronautics, an electric resistance thermometer with low thermal lag has recently been developed by the Bureau of Standards. The instrument is based upon the principle of the unbalanced Wheatstone bridge. The indicating instrument and battery (thermally insulated) are located in the cockpit; and the resistance coil forming the temperature element is mounted on a strut. (Reference 45.)

The ideal method of measurement from the flight-test viewpoint would be to record the air pressure and temperature on the same chart. Practical considerations limit the design to an instrument with the recorder in the cockpit and the temperature element suitably exposed on a wing or strut. At present the only practical temperature element seems to be a liquid-filled system similar to an aircraft engine thermometer. Such an element has excessive lag and is troublesome to install. The present strut thermometers are preferable. A distant element thermograph with electrical transmission offers greater possibilities in the way of small thermal lag, recording at a distance, and ease of installation, but no electric recorder suitable for routine use in aircraft is now available.

A thermometer for general service use now seems desirable to many pilots as an aid in avoiding conditions favorable for the formation of ice. An instrument which indicates in the cockpit is essential since poor visibility would otherwise prevent observations being made. A distant-indicating liquid-filled instrument is offered by one manufacturer for this purpose. The instrument as designed has an excessive line error. An electric resistance thermometer of the type mentioned above may be suitable, but it requires an occasional adjustment of the voltage.

In considering the instrumental indication of conditions favorable to the formation of ice, it should be borne in mind that humidity is a factor of equal importance with free-air temperature. A satisfactory method of distant indication of relative humidity for use on airplanes is not available at the present time.

3. NAVIGATION INSTRUMENTS

These instruments are used for maintaining the proper direction of flight, the normal flying attitude, and for determining the position of the aircraft. A list of such instruments includes—

Magnetic compasses.
Induction compasses.
Directive radiobeacon.
Radio marker beacons.
Radio direction finders.
Turn indicators.
Gyroscopic instruments (other than turn indicators).
Inclinometers.
Drift sights.
Sextants.
Chronometers.
Course and position computing devices.
Air logs.
Clocks.

When the airway is charted and the ground is visible, air navigation is reduced to its simplest elements. The normal attitude of the airplane can be maintained without instruments. The direction of flight is held true by using instruments but is checked by landmarks. The landmarks at the same time give the position. As an auxiliary, dead reckoning is frequently used to determine the position between landmarks, but it is less accurate in air than in marine navigation, largely owing to the great effect of the wind. The present program of marking on the roofs of buildings the town name, the meridian, and the distance and direction to the nearest airport is evidence of the importance of the visual method of direction and position finding. Visual beacons on airways enable a course to be followed at night and the position to be determined.

In transoceanic flights the position of the aircraft has been determined by the astronomical method used in marine navigation. The method of computation has been simplified in order to adapt it to aeronautics; but it is necessary to provide an artificial horizon. The precision of the measurements is less than on ships at sea, owing to the greater instability and speed of the aircraft.

When the ground is not visible the difficulties of navigation increase enormously. Without guidance from the ground, the normal flying attitude must be maintained solely by instruments, the course is uncertain owing to the drift which can not be measured, and the position is unknown. Obstacles must be cleared by flying at what appears to be a safe altitude. This picture of the difficulty of navigation is modified when the directive radiobeacon is available to fix the course and the radio marker beacon to determine the position. The possibilities of radio aids in making landings during poor visibility are discussed in the section on Fog Flying Instruments.

Magnetic compasses.—The present American practice restricts the function of the magnetic compass to that of indicating direction when flying a straight course. No reliance is placed on it while making turns or while its card is in motion. The turn indicator is used to indicate deviations from straight flight and is thus associated with the compass in maintaining straight flight or in resuming it after a turn.

In the past, much effort has been expended upon magnetic compasses in an effort to have them operate so that a course may be maintained in blind flying, but without complete success. The indication can not be relied upon during turns. However, the effort has led to the development of a number of types of compasses, the extremes of which are represented by the original Campbell-Bennett aperiodic instrument and the present short-period compasses. The latter type is favored.

The damping liquid now in use is varnolene or mineral spirits which freezes at a temperature below −40° C. and has a viscosity which increases not more than five times when the temperature is decreased from +30 to −30° C. (See Reference 12 for further data on this and other damping liquids.) It is comparatively low in price and easily obtained. Provision must be made for the expansion of the liquid and also for preventing leakage when the compass is subjected to either low atmospheric pressures or high temperatures (+45° C.). This problem must be met in the design of each type of instrument and presents no unsolved difficulties.

Most of the troubles with the magnetic compass arise from the conditions connected with its use in aircraft. (See Reference 29.) The effect of vibration is serious in many installations. Practically all compasses are provided with antivibration mountings but these are often insufficient when the compass is installed in a convenient reading position. At the present time the satisfactory installation of the compass from the standpoint of vibration is an individual problem for each type of airplane.

All electric circuits and electrical instruments installed in the aircraft are a source of possible magnetic disturbance. Every effort should be made to keep these circuits as far from the compass as possible, and the two wires forming the circuit should be laid together in a single cable or twisted together throughout their length. Electrical instruments should be mounted in iron or steel cases so as to be magnetically shielded. Another source of magnetic disturbance is the engine and the structural steel parts of the airplane itself. There is some evidence that the magnetization of the steel and iron parts changes in a manner depending on the preceding orientation of the airplane with respect to the magnetic meridian. This condition when present makes the compass unreliable because it is impossible to compensate for it. Attention is called to the need of investigating the changes in the magnetic conditions on airplanes in so far as they affect the accuracy of compasses. Experience indicates that if the deviations of the compass are large, changes during flight are likely to occur.

Induction compasses.—The induction compass has three primary advantages over the magnetic compass.

(*a*) The inductor element can be placed in a position which is relatively free from the magnetic effects due to the engine and its related parts.

(*b*) It is a null-reading instrument and shows a deflection only when the airplane is off the course.

(*c*) An inductor element may have more than one indicator. This permits a navigator to set a new course which is promptly indicated to the pilot by the off-course position of his indicator.

It shares with the magnetic compass the following disadvantages:

(*a*) In all cases the inductor element must be compensated similarly to the magnetic compass.

(*b*) If the fuselage is of steel, complete protection from magnetic disturbances is not secured.

The disadvantages of the induction compass as compared with the magnetic compass are its greater weight and greater mechanical complication. Faulty operation may occur owing to trouble with the brushes and the course-setting device, and from the effect of vibration on the relatively fragile indicator now used. A recent advance has been the adoption of a constant-speed wind-driven propeller for turning the inductor element. The cost of the induction compass is about eight to ten times that of the magnetic compass.

The induction compass manufactured by the Pioneer Instrument Co. is based on setting the brushes by means of a mechanical connection extending from the course setter in front of the navigator to the inductor element. In the Heyl-Briggs instrument, the inductor element is connected with the course setter and indicator by an electric circuit. The null reading is secured by means of a bridge.

The General Electric laboratories have recently developed a new induction compass (References 14, 35, and 41) utilizing special alloys of high permeability in the magnetic circuit. The armature, which is spherical and which has the comparatively small weight of 4 ounces, is connected directly to a small wind-driven impeller. The magnetically sensitive element is stabilized instead of the armature as in other types, which is achieved by means of a damped short-period pendulum. Carbon brushes are used. A course setter is used in same way as in the Pioneer type except that the magnetic element is rotated instead of the brushes. The total weight of the installation is 12 pounds.

A distant-indicating magnetic compass known as the telecompass has been developed by the German instrument firm Askania-Werke A. G. As in the induction compass, a course setter and an indicator are located on the instrument board and the compass may be installed in the rear part of the fuselage. The indicator consists of a differential pressure gauge which is operated by a Venturi tube and controlled by the magnetic element of the compass, so that when the correct course is flown the differential pressure is zero. (For details see Reference 28.) No results of either laboratory or flight tests in this country are at present available.

Directive radiobeacon.—The directive radiobeacon (radio range) provides a means for keeping an aircraft on its proper course during poor visibility. This can not be done with the magnetic compass, owing to the uncertainty of the drift which can not be measured. When used to mark a fixed course, the directive radiobeacon is called a radio range, by analogy with the range lights used to mark a marine channel. The radio receiving equipment on the aircraft used to receive the beacon signals may be equipped with either an aural or visual indicator, the latter being preferable. The visual type consists of two tuned reeds which vibrate with equal amplitude when on the course and unequal amplitude when off. (References 9, 15, 16, 32, 36, and 44.) The airways equipped with the directive radiobeacons in 1929 require the use of the aural type indicator. (References 31 and 37.) When aural reception is used, a dot-dash and a dash-dot are transmitted so as to be received as a long dash when on the course; and when off the course as a signal in which either the dot-dash or dash-dot predominates. At present the range of the directive radiobeacon is from 125 to 200 miles, and its directional beam has a width of about 2°.

Radio marker beacons.—It may also be desirable to know the position on the course marked by a radio directive beacon. This is determined by means of the radio marker beacon, which is a low-power radio transmitter. These are placed at intervals along the airway, each transmitter emitting a characteristic signal which when picked up by the aircraft indicates its position on the airway.

Radio direction finders.—The position and the course of an aircraft may be also determined by means of radio direction finders. This system is used quite extensively in Europe and to a limited extent in the United States where it is being replaced by the directive radio beacon. In operation, each of two or more radio stations when requested obtain a bearing, by means of a directional receiver, on the aircraft transmitting the radio signals. These bearings fix the position which is transmitted to the navigator of the aircraft. Knowledge of the course is obtained if the position is determined at intervals.

Turn indicator.—This instrument contains a small gyroscope so mounted that its spin axis is horizontal and at right angles to the longitudinal axis of the airplane. The gyroscope is free to precess about an axis parallel to the longitudinal axis of the airplane, but this motion is constrained by a spring. The direction of precession and the angular motion against the restoring torque of the spring are shown by the motion of a pointer. The gyroscope is usually wind driven, although an electrically driven instrument is available. The indication of the wind-driven instru-

ment is qualitative because the speed of the gyroscope depends on the air speed. In the lower speed ranges of airships, the wind-driven instrument lacks sensitivity. In airplane navigation the instrument is used principally to indicate a departure from straight flight. The rate of turn appears to be of secondary importance. (See Reference 18 for description of instruments of the latest type.)

The specifications of the Army and Navy require a given sensitivity when the gyroscope is driven by air at a stated pressure. A uniform sensitivity is probably not desirable in all cases inasmuch as the maneuverability and speed of airplanes vary widely. To provide a basis for determining the proper sensitivity, flight tests have recently been carried out using instruments of different sensitivity and damping.

Current military specifications do not require tests of turn indicators at low temperatures. A recent series of tests at the Bureau of Standards on a few instruments showed a wide variation in the operating characteristics of the instruments when subjected to a temperature of about −30° C. The cause was traced by the manufacturer to the freezing of the lubricant in some of the instruments. At present a lubricant with a pour point of −40° C. is being used.

Turn meters (as distinguished from turn indicators) are used in free-flight investigations and also on airships. The electrically driven instrument permits close speed regulation and consequently may be calibrated to show rate of turn.

Gyroscopic instruments (other than turn indicators).—The problem of maintaining the normal flying attitude and direction of an airplane during poor visibility has led to studies of the suitability of gyroscopic instruments for such purposes. The outstanding problem is that of securing an indication of the horizon. The Sperry Gyroscope Company has recently developed an instrument for this purpose which shows deviations from the horizontal plane in both roll and pitch. Two instruments of German make are also available which indicate the deviation of the aircraft from the horizontal in roll but not in pitch. These are known as the Anschütz Horizont and the Gyrorector.

The Anschütz Horizont depends for its indication upon an electrically-driven gyroscope mounted with its spin axis vertical and with two degrees of freedom The gyroscope is slightly pendulous and therefore is affected by accelerations. The gimbal to which the pointer is attached is restrained from deflecting more than about 55° from the horizontal. The instrument is equipped with a bank indicator consisting of a ring-shaped glass tube, half filled with liquid, and weighs 15 pounds together with its generator. It has been little used in this country.

The Gyrorector consists of a gyro element, a separate bank indicator and a fore-and-aft inclinometer. The gyro element indicates the lateral horizon in straight flight and during turns. For a good discussion of the instrument see Reference 22. Its weight complete is about 35 pounds.

A free gyro has recently been constructed by the Sperry Gyroscope Co. for the Guggenheim Fund which indicates the angle of turn of an airplane. The instrument is for use in making turns incident to landing during poor visibility, and replaces the present compass and turn indicator for this particular purpose. A period of straight flight of the order of 30 seconds is needed after making a turn before the indication of the magnetic compass can be relied upon. In changing the direction of a course in order to make a landing this period of uncertainty was found to be troublesome, leading to the desire for an instrument with less time lag. The new angle-of-turn meter is in effect an inertia instrument, holding its orientation in space while the airplane is turning. It is operated for a short time only and at other times the gyroscope is kept locked to prevent the precession which would otherwise occur. It may be mentioned here that the gyroscopic compass is not suitable for airplanes, but that one recently developed in Germany for use on airships is installed on the *Graf Zeppelin*.

The precession of a gyroscope due to rotation of the aircraft can be used as an indication of the rotation of aircraft. The turn indicator, already described, and a pitch indicator are examples. This pitch indicator consists of a gyroscopic element rotating about an axis parallel to the fore-and-aft axis of the airplane and free to precess about the vertical axis, and of a pendulum free to swing in the fore-and-aft direction. The pendulum and gyroscope are mechanically coupled so that motion of the pendulum also involves precession of the gyro and vice versa. The design is such that the indication is controlled by the precession of the gyroscope when the angle of inclination is changing, and by the pendulum when the inclination is constant. The effect of fore-and-aft accelerations are minimized by this design as contrasted with that of a simple pendulum of equal sensitivity.

Lateral inclinometers.—The lateral inclinometer or banking indicator now in favor consists of a steel ball in a curved glass tube which is filled with a damping liquid. Experiments on the use of balls of glass and noncorrosive metals are now being conducted. The instrument is ordinarily attached to the turn indicator to form a combined turn-and-bank indicator. Its function is to indicate the proper angle of bank in a turn and to indicate wing up or wing down in straight flight.

The Bureau of Aeronautics specifies the performance of inclinometers and not the damping liquid or the ball and tube clearance. Until quite recently a 1/4-inch ball has been used, but in the opinion of pilots this is too small and a 7/16-inch ball with a tolerance of minus 1/16-inch is now specified.

Difficulty was experienced in finding a satisfactory damping liquid. The requirements are that (1) when the inclinometer is vibrated the damping must be sufficient at all temperatures (−35° C. to +45° C.) to prevent the ball from climbing up the tube and (2) the damping must not be excessive at −35° C. If the damping is satisfactory at about +25° C, it will in all probability be satisfactory at temperatures up to +45° C. Laboratory tests show that when the underdamped inclinometer is vibrated the ball bounces and spins, which often causes the ball to climb up the tube and give a false indication.

Tests have shown that the inclinometers with relatively large clearance between the ball and the tube behave best under vibration. When the ball diameter was reduced to three-eighths inch, maintaining the other dimensions unchanged, it was found that in addition to better performance under vibration, a liquid could be used which had a kinematic viscosity at −35° C. ten to fifteen times that at +30° C. This has largely eliminated the difficulties in securing a satisfactory inclinometer.

Fore-and-aft inclinometers.—Two instruments are available for the measurement of fore-and-aft inclination with reference to a horizontal plane, one a liquid manometer and the other a combined gyroscope and pendulum instrument. The latter is discussed in the section on Gyroscopic Instruments.

The liquid-type instrument consists of a closed-circuit tube manometer with its long dimension placed fore-and-aft. The instrument also indicates fore-and-aft accelerations which are indistinguishable from inclination, so that this type of instrument is of little value. It is reliable only if the flight path is linear and the speed is constant, and these conditions must be established independently.

The chief value of a pitch indicator or fore-and-aft inclinometer is to assist in maintaining level flight, for which sensitivity is essential. Instruments other than inclinometers are usually employed for this purpose, such as (*a*) the rate-of-climb indicator, (*b*) the combinated air-speed meter and tachometer, (*c*) the gyroscopic artificial horizon, or (*d*) a sensitive altimeter.

Methods of determining the course.—The proper heading of the airplane in most of the flying on established airways is determined by the landmarks familiar to the pilot, without the need of measuring the drift. With the advent of the directive radiobeacon and the constantly improving meteorological service in furnishing data on winds at flying levels, the need for drift measurement in order to determine the course is becoming less. This relieves the navigator or pilot of a computation or a graphical construction which in its simplest form is a burden.

In flying over strange country, without the aid of a serviced airway, and especially over bodies of water, the course may be determined by one of three general methods. (See Reference 3.)

A. By means of separate instruments the drift and ground speed are measured and the indicated air speed noted, all while on a definite course. By reference to suitable charts the true air speed is evaluated. The wind velocity can be graphically determined from the drift, ground speed, and true air speed. By another graphical construction in which the known elements are the air speed, wind speed, and the angle between the desired course and the wind direction, the drift angle when on the desired course is determined. A simple addition or subtraction then gives the proper compass heading.

B. *Wind star method.*—The drift angle is measured for two different compass headings, the air speed remaining constant, or in a modified form, for one compass heading and two air speeds. These two drift angles, together with the air speeds and compass headings are sufficient to determine the wind velocity. If a graphical method is used to measure the drift, in which the drift lines are drawn directly on a chart, following the wind star method as described by Wimperis (Reference 3 or 4), or the modified form discussed by Lonnquest (Reference 43), one additional line gives the wind velocity. This is a neat solution and reduces the necessary graphs to a minimum, but other considerations may not permit its use. If this graphical method is not used, the computation may be made by a course and distance computer or other suitable apparatus. The proper compass course heading can now be determined graphically in the manner outlined in method A. The graph which determines the drift while on the proper heading gives the ground speed, which can be read off directly by use of a suitable scale.

C. This method involves no computation or graphical consideration. Neither the wind speed nor the ground speed is determined. It merely affords a rough-and-ready method for determining the proper compass-course heading. The pilot flies on a course which is believed to be correct. The drift is measured. The course is adjusted in accordance with the result of the drift measurement. The drift angle is again determined and the course again adjusted if necessary.

It will be seen that methods A and B are correct in principle and that there is little to choose between them as to the amount of computation. Method A involves the use of an independent ground-speed indi-

cator. At the present time such an instrument must be of the type in which the true altitude of the plane above the sighted object enters as a factor in the computation of the ground speed. The result is therefore subject to an error proportional to the uncertainty in the altitude measurement. Since the latter is large, method B is at present preferable.

Method C has the merit of requiring only a drift meter and no computations. This feature has appealed to many transoceanic navigators. The course thus determined is not in error, but if ground speed is also desired, method B is preferable.

Drift sights.—All drift indicators consist essentially of a reference line fixed to the aircraft, a movable sighting line (wires, cross hairs, etc.) and a suitably graduated circle for measuring the angle between them. Objects are sighted on the ground, in some cases through an optical system, with the movable line also in the field of view. The movable line is adjusted until the sighted objects have no apparent motion at right angles to it.

Instruments have also been developed which combine the measurement of the drift together with the facilities for computing the course. Outstanding examples are the Wimperis instruments, the Crocco drift and ground-speed meter, the Bureau of Aeronautics Mark IV drift computer, and the Le Prieur Navigraphe. The latter instrument records the drift. A drift recorder has been constructed at the Bureau of Standards along lines suggested by the Bureau of Aeronautics.

Drift measurements over water present difficulties in the selection of an object to be sighted on. Navigators have usually been able to pick out some peculiarity of the water surface or in the absence of such markings have dropped smoke bombs or flares.

The tendency in long-distance flights has been to use simpler methods of measuring the drift. Thus, in the Army around-the-world flight, the MacMillan-Byrd Arctic expedition of 1925 and in the Maitland-Hegenberger flight to Hawaii, all outstanding examples of careful preparation, the drift meter consisted of lines painted on the horizontal tail surface, which radiated from a point in the navigator's cockpit.

Sextants.—The chief use of sextants is in flying over unserviced airways and over oceans. The air lines which offer regular service between two terminals along a definite airway rely on lights, the radio-beacon, and other ground aids for position finding.

In contrast with marine sextants, aircraft sextants must be provided with artificial horizons. Modern instruments in the United States use either the tube or the circular bubble level. Pendulum horizons have been discarded since they are of necessity more complicated and delicate than bubble levels and offer no corresponding advantages. The gyro form has been investigated in the past but no instrument suitable for aircraft has yet been devised and little development work is in progress.

Three aircraft sextants are being manufactured in the United States: (1) An instrument of the single mirror type with a counter for indicating the altitude instead of a graduated arc; (2) an adapted marine sextant with a Willson telescope containing the bubble; and (3) an instrument of radically new design known as the Darad sextant. All three types are being gradually improved as a result of use in aircraft. The weight is being reduced where possible.

In order to obtain a satisfactory position line from sextant observations in an airplane, the average of a number of readings must be taken. These observations require considerable time because the images of the heavenly body and bubble must be brought into coincidence, a manipulation which requires skill and patience when on a moving airplane. The time required for observations can be shortened by the use of a recording instrument which permits a correction to be made for lack of coincidence of sun and bubble. An instrument of this kind has been constructed at the Bureau of Standards for the Bureau of Aeronautics of the Navy, in which the images of the sun and bubble are both recorded photographically. The instrument has been further developed and improved through the efforts of Pierce, who initiated the project. This recording instrument can not be used for star sights, as the star images are not bright enough to record during very short exposures. It should, however, be practicable to record the position of the bubble during star sights, the exposure in each instance being made when the star is on the cross wire. This method would presumably be less precise than recording both images, owing to the uncertainty of the star being exactly on the cross wire at the instant of exposure.

Chronometers.—A knowledge of Greenwich time is required in order to obtain a "fix" with a sextant. An error of four seconds in time is equivalent to an error in position of one minute of arc or approximately 1 mile. In marine navigation it is customary to use high-grade rated chronometers, but in aircraft navigation it has been the practice to use a high-grade watch.

The uncertainty of sextant observations made from airplanes is at best of the order of five minutes of arc, which is equivalent to 20 seconds in time, but the precision in time demanded on board ship is not required for aircraft. Moreover, ship chronometers do not perform well on aircraft, owing probably to the variable temperature and consequent variation in lubrication due to types of oil usually employed.

If radio communication is maintained during future long-distance flights, the watch may be rated at intervals from time signals. Weems has suggested that the second hand of the watch be made adjustable in the same manner as the hour and minute hands. A navigation watch is now available the second hand of which may be stopped and started at will, permitting synchronization with time signals.

Course and position computing devices.—These include such apparatus as course and distance computers, astronomical computers, and map cases. Course and distance computers are instruments which facilitate the determination of the proper course, allowing for drift, and of the ground speed. These data, together with the time, are required for finding the position by dead reckoning. The computers have been developed in great variety based on the various methods of determining the drift, wind speed, and ground speed. The nomenclature of these instruments needs clarification.

A great deal of attention has been given to methods for computing the astronomical triangle. The solution may be found by the aid of convenient tables, by nomograms and diagrams or by mechanical devices such as slide rules. (See Reference 11 for descriptions.) The tables of Weems (Reference 19) and especially of Dreisonstok (Reference 33) are arranged very conveniently for obtaining the position from astronomical observations. Tables, supplemented by simple charts, are favored for aerial navigation.

Airlog.—At least two types of instruments are available commercially which indicate distance based on relative air speed. (Reference 1.) Both types have a rotating surface element. The air distance so indicated requires a knowledge of the drift angle and wind speed in order to obtain the actual distance over the ground. The instrument is useful in long-distance flights whenever the dead reckoning method of position finding must be used, and for indicating the air mileage of particular flights and the total air mileage of the aircraft.

Clock.—Clock mechanisms are used on aircraft (1) to indicate the time of day, (2) to indicate elapsed time in flight tests, and (3) to record time in recorders such as barographs. The performance at low temperatures has been very unsatisfactory. The trouble has heretofore been attributed to the congealing of the oil in the bearings and gear trains, but Cordero has shown that the congealing of the oil in the main spring box was the chief source of the trouble. Substitution of a graphite suspended in a low-freezing oil or kerosene for the oil commonly used in the main spring box resulted in satisfactory operation of the clocks experimented with, even when the oil in the remainder of the mechanism was left unchanged.

4. POWER-PLANT INSTRUMENTS

Instruments used in connection with the power plant are as follows:

Tachometer, recording tachometer, thermometer, oil-pressure gauge, fuel-pressure gauge, fuel-quantity gage, fuel-flow meter, and supercharger pressure gauge. These are considered in detail.

Tachometers.—Although the tachometer was one of the earliest instruments to be installed regularly in airplanes, its development is still in progress. The centrifugal and the chronometric types are driven directly by the engine through a flexible drive shaft, and are commonly used in most single-engined airplanes where only a short drive shaft is required. With a long drive shaft the operation is not satisfactory. Different instruments are therefore required in the two cases. The status of chronometric and centrifugal instruments will be first considered.

Two chronometric tachometers are being manufactured in this country. This type of instrument has a fine performance as regards accuracy and effect of temperature, but its endurance was until recently comparatively low. Although conditions of use vary from aircraft to aircraft and the individual instruments also vary in their durability, the running life of commercial instruments has in the past not been over 200 hours on the average. Instruments now supplied to the Army Air Corps have a running life of over 1,000 hours on a laboratory test stand. In operation the pointer of the instrument does not move evenly, its indication varying only at the end of each time interval of integration. This feature is objected to by some pilots when trying to maintain a given engine speed.

The centrifugal tachometer has a satisfactory performance in most respects except that a change in calibration slowly takes place with use, mainly owing to wear at the point where the motion of the rotating element is transferred to the multiplying mechanism. The rate of change varies considerably from instrument to instrument but on the average is of the order of 2 per cent in 300 hours of running. The problem is well understood, but the added requirements of small size, low weight, accuracy, and low cost have proved troublesome. The instruments are now available in the 2¾-inch-dial size as well as in the old 3¾-inch-dial size. The centrifugal tachometer is widely used in commercial aircraft.

The magnetic-drag tachometer, such as is used for automobile speedometers, has not been widely used in aircraft, largely because of the difficulty in maintaining permanency of magnets and accuracy of air gap. Several manufacturers of automobile accessories offer an instrument of this type for use in aircraft.

In flight testing the engine speed is usually obtained from the tachometer installed on the aircraft, and is recorded by the pilot. It is essential that the scale errors of the instrument should be determined before the flight tests are made. With increasing refinements in flight testing, greater accuracy is desirable in engine-speed measurement. An over-all accuracy of about 5 or 10 revolutions per minute in the measurement of engine speed during flight appears to meet present needs. This requires increasing the sensitivity either by an increase in the dial diameter or in the angular motion of the pointer. It is preferable to keep the dial size the same as in the service instrument so that the special flight test instrument and the service instrument could be interchanged.

In multi-engined airplanes and in certain single-engined airplanes in which the engine is mounted back of the pilot, direct-drive instruments are not satisfactory, owing to the long length of flexible drive shaft or to the necessity of having a number of sharp bends in it. It has consequently been the practice to mount the direct-driven tachometer for an outboard engine on a near-by strut, which forces the pilot to look out of the cabin in order to obtain the engine speed.

One instrument which has been developed to meet the need for a distant-indicating tachometer consists of a commutator attached to and operated by the engine, and an indicator on the instrument board. The latter contains an electromagnet which is intermittently energized by the current from a 12-volt battery at a rate depending on the speed of the engine. This magnet operates a pawl which in turn operates a chronometric tachometer. The instrument is of the vertical scale type and has been given thorough laboratory tests by the matériel division of the Air Corps. Satisfactory operation at —20° C. is reported, which was the test point in the low temperature test under the old specifications (prior to 1930). Current specifications require satisfactory operation in the temperature interval −35° to +45° C. and also during a time interval of 300 hours. Both requirements are very severe for any lubricant which may be selected.

A very promising development in the field of distant-indicating tachometers is the direct-current magneto type. One manufacturer has produced an experimental model of a magneto which generates 3 volts at 1,000 revolutions per minute and weighs only 1 pound. The chief defect of the indicator is that the pointer has a total motion of only 120°, which requires a large dial to give the sensitivity required in aircraft operation. (Reference 20.) Another manufacturer is now producing a tachometer of the magneto type with an indicator having a dial 2¾ inches in diameter and a pointer motion of approximately 270°. Both British and German manufacturers have had an instrument with this pointer movement on the market for some years. In the British instrument the moving coil is attached to the pointer shaft, while in the German instrument the required angular motion is secured by multiplying the motion of the moving coil by means of a sector and pinion.

The improvement of flexible drive shafts for tachometers should receive attention. An improvement in the quality of the drive shaft would permit the installation of a tachometer on the instrument board in many instances in which it is now impossible. Another consideration is the reduction of the pointer vibration in direct-drive instruments, resulting from excessive whipping of the shaft.

Recording tachometer.—The Bureau of Standards has recently modified a Van Sicklen chronometric tachometer to include a recorder. It may be installed on the instrument board in place of the standard 3¾-inch round-dial instrument. From the front of the board the appearance is the same as an indicating instrument. The recording attachment is built on the rear, increasing the dimension of the case in depth only. The record is accessible from the rear of the instrument without disturbing the indicating mechanism. Flight tests showed satisfactory operation and gave records which could be easily read to 10 revolutions per minute.

A combined indicating and recording instrument of foreign manufacture, now sold in this country, gives excellent performance, but the weight and bulk are excessive for aircraft use. It weighs about 10½ pounds and its over-all dimensions are 4 by 3¾ by 11½ inches.

The electrical recorders now available are not suitable for use on aircraft. To obtain records from distant-indicating tachometers of the electrical type, it will be necessary to develop a special recorder, which should be rugged, compact, and light.

Thermometers.—The thermometers used to measure the temperature of the oil or water of the engine are of two types, vapor-pressure and liquid-filled.

The liquid-filled instruments thus far produced in this country for aircraft use seem to be subject to two defects. The first is the error arising from a variation in temperature of the indicator and line. This can be compensated within the necessary tolerances, which are large compared with those usually specified in temperature measurements, but difficulty arises in making this compensation without testing and adjusting each individual instrument. The second defect relates to the excessive drift, or change in reading with time, while the temperature is held constant. The overcoming of this error offers no fundamental difficulties. An advantage of the liquid-filled instrument is that it has the same sensitivity throughout its temperature range.

In the vapor-pressure thermometer the following features are essential: (1) The volume of the bulb must exceed the volume of the remainder of the closed system; (2) the volume of liquid must be so chosen that the free surface of the liquid is always within the bulb under all conditions of use. This type of thermometer is subject to a change of indication with altitude due to the action of the external pressure on the Bourdon tube. This may be controlled, within limits, by the proper selection of filling liquid, the one with the higher vapor pressure at a given temperature being preferable. The vapor pressure-temperature curve of liquids is nonlinear, and the deflection of the Bourdon tube per degree increases markedly as the temperature rises. In the latest instruments an effort has been made to secure an evenly divided temperature scale, the difficulty of which may be appreciated when attention is called to the vapor pressures of liquids commonly used.

	Vapor pressure in atmospheres				
	Temperature, °C.			Pressure change per degree at	
	0°	50°	100°	0°	100°
Sulphur dioxide (SO_2)	1.53	8.18	27.7	0.073	0.55
Methyl ether (C_2H_6O)	2.54	11.25	32.6	.10	.57
Methyl chloride (CH_3Cl)	2.50	10.7	31.4	.10	.55

Considerable trouble has been experienced by aircraft operators by the breaking of the thermometer tubing. More attention to the installation of the thermometer should prevent much of the breakage, which is due almost entirely to vibration of the tube in such a manner as to impose excessive stresses at certain points, usually near the bulb or indicator. This can be avoided by supporting the tube so as to prevent vibration. (See Reference 21.)

Thermocouple thermometers are being used to measure the temperature of the various parts of air-cooled engines. If the temperature is measured in flight the cold junction can not be easily maintained at constant temperature, so that a method of compensation must be used. One manufacturer has developed a thermometer for aircraft use in which compensation is provided by the change in the permeability of a selected material in the magnetic circuit of the indicator (in which the cold junction is located). (See References 40 and 41.) The use of a bimetallic strip in the indicator for compensation has proven satisfactory in other types of thermocouple thermometers and is an alternative method.

Oil and fuel pressure gauges.—Satisfactory service is being obtained from the fuel-pressure gauge.

The oil-pressure gauge is also satisfactory except under low-temperature conditions. The oil pressure is transmitted by means of the lubricating oil itself through a copper tube to the indicator placed in the cockpit. At low temperatures the oil congeals, making the operation of the oil-pressure gauge uncertain. In a recent French development the oil-pressure gauge is a self-contained unit filled with a nonfreezing liquid. The bulb fitting into the engine contains a sylphon through which the oil pressure is transmitted to the liquid in the gauge. A gauge similar in principle but with certain additional safety features is under development in this country.

The precautions urged in the installation of thermometers to prevent breakage of the copper tubing connecting the element to the indicator apply with equal force to the oil and fuel pressure gauge lines.

Fuel-quantity gage.—Many designs of fuel-quantity gages have been developed in an effort to meet the requirements of maximum safety from fire hazard, distant indication, simplicity of design, and low cost. None of the instruments now available seems to be generally accepted as meeting all of the above requirements.

A common type in successful use consists of a differential pressure gauge, with an air-tight line leading from each side of the gauge to the fuel tank. One tube passes through the top of the tank and ends in the fuel very near the bottom, while the second is connected to the air space above the fuel. Air is forced into the first line by means of a pump until the tube is free from fuel. The pressure is then the hydrostatic head of the fuel. Variations in density of the fuel from that for which the instrument is calibrated is an inherent error. When used in wing tanks with a maximum depth of about 6 inches the indicator must be very sensitive.

Another type of gage consists of a pressure indicator connected by air lines to the bottom and top of the tank. The line to the bottom of the tank connects with a nonmetallic capsule, which is air-tight but contains air at normal pressure. The gasoline surrounds this capsule. If this capsule is without appreciable stiffness and the volume of the system is correctly proportioned, it transmits to the indicator the pressure produced by the head of the fuel and at the same time allows the air in the closed system to expand or contract with temperature without causing any change of pressure in the system. This instrument is still in the experimental stage and depends for its success upon finding a suitable material for the capsule. Cellophane meets requirements except for the effect of water upon it.

An electric type of gage now used on some automobiles appears to have possibilities in aircraft. This instrument consists of a resistance unit operated by a float located at the fuel tank, and an ohmmeter

on the instrument board as the indicator. Tests show that the indication of the instrument is substantially independent of temperature and of the voltage within reasonable limits. Although severe laboratory tests indicate the absence of fire hazard, an electrical circuit in a gasoline tank is not impressive from the standpoint of safety. It is understood that in the commercial airplanes in which the instrument is now installed, the current is switched off except when a reading is desired.

In some airplanes the indicator can be located at the fuel tank. In such cases a float mechanically connected to an indicator can be used, although this necessitates leaving a small opening from the fuel tank to the indicator, which may require making the case of the indicator liquid-tight. One manufacturer has eliminated the mechanical connection between the float and the indicator, transferring the position of the float to the indicator by means of magnets.

One electrical manufacturer has recently announced the development of a distant-indicating fuel quantity gage. The pressure head of the liquid acts primarily on a carbon pile through an intervening diaphragm. The carbon pile is connected in series with a solenoid, which carries about 95 per cent of the load applied through the diaphragm. The variation of the current in the circuit serves to measure the changes in pressure and thus the quantity of fuel. The arrangement minimizes the effect of zero shifts in the carbon pile. (See References 38 and 41.)

Attention should be called to the two foreign types of quantity gages which, according to Stewart, have met with favor. (See Reference 22.) Both are of the float type. In the "Televel" instrument the position of the float is adjustable from the instrument board until it strikes the liquid, whereupon the buoyant force causes a pawl to engage a rack, preventing further motion. In the "Spirobloc" instrument the float is rotated until it engages a spiral stop. The indication in each case is governed by the position at which the mechanical stop is encountered. The power which is needed to operate the indicator by means of a mechanical coupling is furnished by the observer, thus eliminating friction effects.

Fuel-flow meter.—The fuel-flow meters now available in this country are based on the use of a Venturi tube in the fuel line. The differential pressure is measured by an indicator very similar in design to that of air-speed indicators. Two gasoline lines from the Venturi tube to the indicator on the instrument board are required, one of which connects with the pressure capsule and the other with the case of the instrument. The case must therefore be made leak-tight against a maximum pressure of about 5 pounds per square inch. To eliminate the hazard of having the case filled with gasoline, it may be possible to modify the design of the indicator so that two pressure elements are used, the differential motion of which controls the indication. The chief difficulty involved in the change would be the development of pressure elements which would give sufficient deflection for the small differential pressures and yet withstand the comparatively large pressure of 5 pounds per square inch.

This type of instrument is subject to a density error. If the indication is in gallons per hour, it is proportional to the reciprocal of the square root of the density; if in pounds per hour to the square root of the density.

The fuel consumption during a flight test is at present determined by weighing the fuel in the tanks before and after a flight, from which the rate of fuel consumption is calculated. A reliable flow meter would be preferable. The Venturi type of flow meter now manufactured in this country has not been tested sufficiently to determine its value in flight testing. In any event it is probable that a calibration would be necessary at the time flight tests are made, which would require some special equipment.

An alternative method depends upon the use of the Bowser fuel-consumed meter; an instrument which has recently become available. In this instrument all of the fuel passes through one or more of its five cylinders. The displacement of the pistons of these cylinders operates a wobble plate which in turn operates a commutator shaft. The commutator, which is immersed in oil to reduce fire hazard, controls the action of an electromagnet in the indicator, which through a pawl operates a train of gears ending with a pointer shaft. In order to measure rate of flow, the measurement of time is necessary. The instrument is bulky and heavy, weighing 12.75 pounds complete without the battery.

The sink-and-tube flow meter has recently been perfected by the R. A. E. (References 22 and 39) and is reported to be giving a satisfactory performance. The sink operates vertically up and down in a tapered brass tube. The fuel before reaching the carburetor flows into the lower end of the tube and through the annular orifice formed between the sink and tube. The sink rises in the tapered tube until equilibrium is reached, and its position, as seen through a slot in the brass tube, indicates the flow. To minimize the effect of variation of the fuel density, the density of the sink is twice the average value of that of the fuel.

Supercharger pressure gauge.—It is necessary to measure the pressure of the air in the carburetor when a supercharger is used. Instruments which measure absolute pressure are used for this purpose and are graduated to indicate standard altitude with a range from −4,000 to +20,000 feet. The accuracy required

is relatively low. An aneroid altimeter can be used for this measurement by making the case tight and providing a connection to the carburetor.

5. OXYGEN INSTRUMENTS

Oxygen instruments are used to supply oxygen to personnel when flying at altitudes above 15,000 to 20,000 feet. Oxygen is now supplied either as a liquid (at atmospheric pressure), or as a gas at a pressure of about 1,800 pounds per square inch. When supplied as a gas, a reduction valve, either manually operated or automatic, must be used. When supplied as a liquid, control of the rate of evaporation is needed so that an adequate amount is always available.

Nipple and mask.—There has been considerable discussion regarding the relative merits of a nipple and a mask for taking oxygen at high altitudes. The Bureau of Aeronautics uses a nipple (with a face mask) for compressed oxygen. The Air Corps when using liquid oxygen prefers a mask which completely incloses the pilot's head. Less oxygen is wasted with the nipple, but the mask is more comfortable during long flights at high altitudes. The incoming oxygen is moistened somewhat by the water vapor present in the mask, which alleviates to some extent the excessive drying of the mouth and throat and makes it possible for a pilot to breathe partly through his nose.

Compressed oxygen.—The last traces of moisture must be removed from compressed oxygen for use in altitude flights. The expansion of the gas through the needle valve of the regulator is accompanied by a marked drop in temperature. If water vapor is present, it may condense and freeze in the narrow passages through the regulator. The importance of drying compressed oxygen thoroughly can not be too strongly emphasized.

The military services require an automatic pressure regulator for use with compressed oxygen. The rate of flow is difficult to specify, because (1) some men require more oxygen than others, (2) either a nipple or mask may be used, and (3) there is always some leakage past the mask. A number of the instruments have been modified so as to include a manual adjustment, by means of which any one of three rates of flow may be obtained. The type of regulator now commonly used was designed by Prouty in 1918 and has beeen improved in design in recent years.

In experimental flights a manually operated pressure regulator is often used. This type requires adjustment in flight, because the flow required depends on the altitude and flow delivered at a given setting depends upon the temperature of the regulator. The pilot has greater control over his supply, but the need for dry oxygen is just as great as with the automatic type of instrument.

Liquid oxygen.—The use of liquid oxygen saves weight. The ratio of weight of oxygen to weight of container is many times greater for liquid oxygen than for compressed oxygen. The Army Air Corps has developed to a high degree the technique of using liquid oxygen. Containers for storing the liquid on the ground have been greatly improved. Containers holding 60 pounds of liquid oxygen lose oxygen at the rate of only 2½ to 3 pounds in 24 hours, and consequently oxygen may be kept for a week without the loss being excessive. It is now possible to procure larger containers holding approximately 125 and 250 pounds, respectively, of liquid oxygen with an evaporation loss or not more than 3 pounds in 24 hours.

The container used to carry liquid oxygen on aircraft has a vacuum-walled jacket. The tube which carries the liquid to the vaporizer extends nearly to the bottom of the flask, which prevents water (in the form of ice floating on top of the liquid oxygen) from entering the tube. The small amount of heat which reaches the oxygen through the double-walled container vaporizes some of the oxygen and develops a pressure in the closed container. The differential pressure increases with the altitude of the airplane and reaches 15 pounds per square inch in the neighborhood of 35,000 feet. A safety valve prevents higher pressures. To avoid freezing the faces of the users, the oxygen after vaporization is passed through an electric heater or through a coil wound around one of the exhaust pipes of the engine.

With two or more men in the aircraft it is believed to be the best practice to carry two liquid oxygen containers, with the two vaporizers feeding into the same supply line. The advantage of this system is that failure of either one of the oxygen supply units will not cause a complete stoppage of oxygen.

6. INSTRUMENTS FOR AERIAL PHOTOGRAPHY

No special performance is demanded from aircraft instruments in aerial photography except in the measurement of altitude and in maintaining the direction of flight. There are a number of problems associated with the proper functioning of the camera but a consideration of these is out of place here.

Altitude.—Within comparatively wide limits the absolute value of the altitude is at present of less importance in aerial photography than changes in altitude during a given flight. The technique requires that the flight be made at a constant altitude above sea level. The current practice is to fly at a constant pressure level. The only inherent error in the latter method, assuming perfect instruments, is the change

in altitude introduced by the change in barometric pressure and air temperature with time. This error can be reduced to reasonable tolerances with the aid of a barograph at the landing field.

There are three instruments which may be used as aids in flying at a constant pressure: (a) Statoscope; (b) rate-of-climb indicator; (3) sensitive altimeter. Recent work indicates that the sensitive altimeter is the most promising of these three types.

The aneroid statoscope is an instrument containing a sensitive pressure element which is open to the air until the flying level is reached. The connection to the outer air is then closed, after which the instrument indicates small deviations in the differential pressure between the outer air and the air inside the pressure element. One objection to the use of the statoscope is that changes in the temperature of the air in the pressure element give rise to pressure changes which are equivalent to 0.35 per cent of the pressure per degree of centigrade. For example, when flying at 15,000 feet, a change of 1° C. in the temperature of the statoscope will give rise to an indicated change of 90 feet in altitude. Compensation for this error is particularly difficult. Aside from introducing compensation into the mechanism of the aneroid instrument, two alternatives have been suggested: (1) Insulating the instrument against temperature changes, or (2) bringing it in equilibrium with the temperature of the free air. Neither of these methods is entirely practical.

The bubble statoscope has a thermally-insulated chamber connected to the outer atmosphere through a shallow U tube. The tube contains a short column of liquid which breaks when the pressure difference exceeds about 1 millimeter of mercury. The instrument is subject to the same temperature error as the aneroid instrument. See the section on Altitude Instruments for a discussion of the value of the rate-of-climb indicator for indicating level flight.

The value of a sensitive altimeter for flying level has long been realized, but until recently the instrument makers have had difficulty in producing satisfactory instruments. The present state of development is discussed in the section on Altitude Instruments.

Direction.—In aerial photographic mapping it is necessary to fly straight parallel courses for relatively short distances, which in general requires closer navigation than is possible with a compass and turn indicator. A visual indicator is needed for this purpose in order to correct for the drift. The Topographical Survey of Canada has developed a navigating sight by means of which straight parallel courses may be flown. The specifications for the sights vary with the particular method of mapping used.

7. FOG-FLYING INSTRUMENTS

When flying through fog or under conditions such that the ground is not visible, it is necessary to depend upon instruments (*a*) to maintain the normal flying attitude, (*b*) to maintain the course to the destination, (*c*) to locate the landing field, and (*d*) to make a landing. Although improvements are desirable, the instruments essential for (*a*), (*b*), and (*c*) are now available and have been successfully used by many pilots. The major problem at present unsolved is that associated with landing in fog.

(*a*) In maintaining the normal flying attitude in both straight flight and turns during low visibility the turn-and-bank indicator and the rate-of-climb indicator are now primarily relied upon. The combination is known as a flight indicator. The use of a sensitive altimeter to replace the rate-of-climb indicator is a possibility. All of these instruments have already been discussed. The addition of an artificial horizon, preferably with complete indication from a single instrument, has been found desirable. Gyroscopic artificial horizons, largely in the experimental stage, are available. For descriptions, see the section on Gyroscopic Instruments.

Ground obstacles are now avoided by flying at a safe indicated altitude. While flying on the airways or on a known course, an aneroid altimeter can be used to indicate a safe altitude, but when the position of the aircraft can not be determined an absolute altimeter would contribute to greater safety. It would give information on both the altitude of the aircraft and the character of the land below comparable with that derived from a sounding apparatus in marine navigation. It would not prevent all accidents arising from abrupt changes in the height of the terrain. The status of the development has been discussed under Altitude Instruments.

(*b*) The compass and turn indicator are not sufficient to determine the course during poor visibility owing to the drift of the aircraft. No way of measuring the drift in poor visibility is known at present. The directive radiobeacon eliminates the need for drift measurement and by its aid a straight course may be flown to the beacon. All of these instruments are discussed in the section on Navigation Instruments.

(*c*) The location of the landing field may be accomplished by adaptations of the radiobeacons, or by induction effects of wires on or near the ground carrying alternating current. One of the simplest methods is furnished by the directive radiobeacon which gives a marked decrease in signal strength when the aircraft, equipped with a vertical rod antenna, is above the radiobeacon transmitter. The decreased signal strength locates the beacon with a horizontal radius of about 100 feet.

(*d*) The problem of landing during poor visibility is complicated but progress is being made toward its solution, relying largely on radio. The experimental work is directed toward the development of methods for indicating the direction of flight in which a landing should be made, taking into account the wind direction and available runways, and for indicating continuously a proper flight path to be followed as the airplane approaches a landing. A low power directive radio beacon serves to indicate the runway to be used in making the landing. Marker beacons can be used to indicate the position of the aircraft along this path. The principle of these two instruments is discussed under Navigation Instruments. A directed radio beam is now under development by the Bureau of Standards for the Aeronautics Branch of the Department of Commerce, for use in marking out a flight path of suitably varying height for the airplane to follow in landing. A very simple receiving arrangement with a visual indicator is used on the airplane. When the airplane is maneuvered so as to keep the deflection of this indicator always at a fixed point, a gliding path is followed down to the ground.

Other instruments which may be of use in landing require further development. The sensitive aneroid type altimeters, absolute altimeters and artificial horizons have been discussed. An important point brought out in the fog flying experiments of the Guggenheim Fund (Reference 34) is the need of an instrument which will indicate the angle of turn with less lag than the present magnetic compass and turn-indicator combination. This has resulted in the development of the angle-of-turn meter described in the section on Gyroscopic Instruments under Navigation Instruments.

In conclusion, aircraft and instruments are now available which enable flight to be maintained over a desired course to the destination during poor visibility. Instruments for landing during fog are still in the experimental stage.

8. GENERAL PROBLEMS

There are a number of projects associated with instruments, looking to their improvement or to their more effective operation, which require consideration. Some of these can be studied advantageously in the laboratory; others require a combination of laboratory and flight tests. A number are listed:

(A) Elastic defects of diaphragm and spring materials.
(B) Effect of temperature on elastic moduli.
(C) Vibration.
(D) Lubrication.
(E) Damping liquids.
(F) Friction of pivots and bearings.
(G) Artificial horizons.
(H) Pressure in aircraft cabins.
(K) Instrument-board arrangements.
(M) Technical information circulars.

(A) *Elastic defects of diaphragm and spring materials.*—The so-called elastic defects when applied to instrument performance are known by various names and often include other instrumental defects such as friction and backlash. In the design of instruments which involve the use of an elastic system it is essential to know the relative magnitude of the elastic defects of various metals and alloys, especially in relation to such factors as the stress and time. The defects which affect instrument performance may be classified roughly as drift, hereditary hysteresis, and cyclic hysteresis. The Bureau of Standards has been giving attention to these elastic phenomena with particular reference to instrument needs. (See References 24, 25, 26, and 30.) A brief statement regarding the status of this work follows:

Drift or creep, as it is often called, is the increase in the deflection of an elastic body with time when kept under a constant load. From the aircraft instrument viewpoint, drift is most serious in altimeters, because as a consequence of drift the instrument fails to return to zero. The departure is roughly the same as the drift and should be small to make the instrument serviceable for landing purposes. Data on the value of drift for various spring and diaphragm materials and its relation to such factors as stress and time are incomplete. The efforts of individual manufacturers have been directed toward using the best of the materials now available and they have in large measure restricted their tests to securing enough information to meet a given problem. In practically no instance have their findings been published. Experimental work should be continued in order to determine more completely the drift phenomena of metals and alloys which might prove useful in the elastic systems of instruments. The chief need is for dependable experimental data. As an illustration, elinvar might prove useful as a diaphragm metal owing to its low temperature coefficient of elasticity if experiment showed that the drift and other elastic defects were within permissible limits.

Hereditary hysteresis.—This term (Reference 25) is applied to the hysteresis occurring in a load cycle, owing to the drift of the elastic body. It is therefore dependent upon the time taken in making the load cycle. It is obvious that the values of hereditary hysteresis are dependent upon the values of the drift.

Statical hysteresis.—This is the hysteresis in a given load cycle which is independent of the time. It is measured when the material under test is in a "cyclic" state, which is secured by first subjecting

it to a number of load cycles. This type of hysteresis has received considerable study in both Europe and this country, but largely from the viewpoint of its relation to endurance, which is not ordinarily a factor of importance in instrument work. It is still necessary to develop a satisfactory method for determining the hysteresis modulus. This constant for metals and alloys would be useful in the selection of metals for elastic systems for instruments.

The small value to which the elastic hysteresis can be reduced in instruments is surprising. Again taking the altimeter as an example, the tolerance a few years ago for the ratio of the maximum hysteresis in a cycle to the altitude range was one per cent. Instruments having a hysteresis of 0.5 per cent were considered exceptionally good. At the present time a number of manufacturers have produced instruments which have a maximum hysteresis ratio of 0.1 per cent. This is all the more remarkable when it is noted that the conditions of test are such that the instrument is not in the cyclic state, so that the measurements include the sum of the hereditary and statical hysteresis. Putting the instrument in a cyclic state would further reduce this value.

(B) *Effect of temperature on elastic moduli.*—The change in scale value due to temperature changes is troublesome in aircraft instruments, owing to the range in temperatures encountered in flight. The effect is complicated by the diaphragm design in some instances, but the larger part is due to the change in the elastic modulus. Metallurgists have made many determinations at temperatures ranging from +20° C. to 800° C. For aircraft instrument purposes data are required in the temperature interval roughly from +50° to −50° C. The subject is now under investigation at the Bureau of Standards in cooperation with the National Advisory Committee for Aeronautics. Data are being obtained on the temperature coefficient of both moduli, for diaphragm and spring materials.

(C) *Vibration.*—Excessive vibration of the instrument board imposes additional stresses on aircraft instruments and their connections, interferes with their satisfactory performance, and shortens their life. The vibration of the board appears to be much more severe in some types of airplanes than in others, depending on the mounting of the board and on the lack of balance of engine and propeller. While it is not possible to eliminate all vibration, it would appear to be sound engineering practice from the standpoint of instrument design, to restrict the vibration to limits which experience has shown can be realized in the better types of installation. Ability to withstand vibration below the specified limits could then be made a requisite of instrument performance, while the failure of instruments in installations showing vibration in excess of the prescribed limits would be properly chargeable to the installation and not to the instruments.

The study of the effect of vibration on aircraft instruments has been undertaken by the Bureau of Standards in cooperation with the Bureau of Aeronautics. A vibration rack has been constructed which permits the independent control of frequency and amplitude. This apparatus is now being used to study aircraft instruments which are submitted for type tests by the Bureau of Aeronautics. The instruments are subjected to vibration for three hours, followed usually by a scale error test. The data will be used to determine the effect of vibration frequency and amplitude on the performance of various types of aircraft instruments. Consideration should be given also to life tests of instruments on the vibration rack.

Apparatus is also being developed for the measurement of the frequency and amplitude of the vibration of instrument boards during flight.

(D) *Lubrication.*—Laboratory tests are now made on aircraft instruments at three temperatures, −35° C., +20° C., and +45° C. The lubrication must be satisfactory throughout this temperature range in order to meet specifications. Special precautions are necessary for lower temperatures. The instruments which require lubrication are tachometers, turn indicators, gyro-pitch indicators, induction compasses, clocks, and watches. At the present time mineral oil with a pour point of −40° C. is being used by instrument manufacturers. It is open to question, however, whether this oil is adequate for instruments like the tachometer, without making provision for oiling while in service. A grease or its equivalent which will function at low temperatures would also be useful. A deflocculated graphite suspended in an oil with a pour point of −40° C. is now on the market and may fill this need in some cases.

A vegetable or animal oil is the usual lubricant for clocks and watches. The stopping of clocks by the congealing of the oil on the mainspring has already been mentioned. The substitution of a graphite suspended in a low-freezing oil gave satisfactory operation at −30° C. with the usual oil in the bearings.

(E) *Damping liquids.*—Damping liquids are used in magnetic compasses, banking indicators, artificial horizons, and certain research instruments. Liquids or mixtures of liquids, with various viscosities are needed which freeze at temperatures below −35° C. These liquids should be stable and colorless, and the rate of change of viscosity with temperature should be small.

Experimental results for a number of liquids are given in Reference 12. Further work is being carried

on at temperatures below −20° C. A striking conclusion from the data now in hand is that a small rate of change of viscosity with temperature is associated with a small absolute value of the viscosity. An effort is being made to find liquids or mixtures which are exceptions to this rule.

(F) *Friction of pivots and bearings.*—Investigations of the friction of pivots and bearings have been carried out at the Langley Memorial Aeronautical Laboratory (Reference 27) and at the Bureau of Standards, the latter being covered in a report to the Army Air Corps, dated March 3, 1926. The National Physical Laboratory of England is studying the friction of jewel bearings. The progress and scope of this work is described in recent annual reports of this laboratory.

Further work on the friction of pivots and bearings is warranted in view of the lack of quantitative information regarding the performance which may be expected from various types of bearings. If the engineering information which manufacturers of small ball bearings have secured were available, it would be of value not only to the aircraft instrument manufacturer but to the entire instrument industry.

(G) *Artificial horizons.*—Artificial horizons are used in sextants, bomb sights and in blind flying. These instruments are of two types, the bubble level and the gyroscopic pendulum. Such studies as have been made of the bubble level show that a liquid of low viscosity and small rate of change of viscosity with temperature is desirable, and that the time lag is diminished by increasing the size of the bubble. The bubble can not be increased in size indefinitely because it breaks up under vibration. In recent years levels with an adjustable bubble have received considerable attention. The problem is largely mechanical in nature and is made difficult by the necessity of keeping the parts very small. The reduction in the apparent inertia of the bubble in the level is very desirable and would greatly facilitate the use of sextants in aircraft.

The gyroscopic type of artificial horizon has been built into a few aircraft sextants, mostly of French design. It is understood that an experimental model of a sextant with a gyro horizon is under construction in this country. Developments up to the present time have not been as satisfactory for sextants as the simpler bubble level.

(H) *Pressure in aircraft cabins.*—It is now well recognized that the pressure within a cabin of an airplane may vary measurably from the pressure of the free air. This affects instruments such as altimeters, barographs, and climb indicators, the indication of which depends upon the true static pressure. At the present time air-speed indicators are connected to a static head. Sensitive landing altimeters, barographs and climb indicators should be similarly connected. An alternative procedure for altimeters and barographs would be to measure the differential pressure between the cabin and the free air for various types of airplanes, to determine the error through the flying speed range.

(K) *Instrument board arrangements.*—Considerable attention has been given to finding an arrangement of instruments which would be most convenient and least tiring to the pilot. Arrangements have been suggested in which certain instruments are grouped together. In one proposed arrangement the pointers of selected instruments point to a common center in horizontal flight at cruising speed and at the customary altitude. An arrangement which is being used by a number of transport companies provides a group of six instruments in two rows of three each, the upper row from left to right comprising the airspeed indicator, turn and bank indicator, and climb indicator; the lower row, the tachometer, compass, and altimeter. In its most acceptable form, the air speed indicator and tachometer dials are graduated specially so that at the normal cruising speeds the hands point horizontally to the right; while the altimeter is so constructed that the hand may be set to point horizontally to the left for any desired altitude.

A further point in connection with the instrument board is the nature of the illumination. The indirect electric lighting of the dials and pointers of instruments is meeting with favor. In the interest of safety it does not appear wise at present to do away entirely with the use of radium paint on the dials and pointers of instruments.

(M) *Technical information circulars.*—In 1920 the aeronautic instruments section of the Bureau of Standards prepared for the National Advisory Committee for Aeronautics eight reports covering the field of aircraft instruments, which were published in 1921 as Technical Reports Nos. 125 to 132, inclusive. It is desirable that they should be supplemented by reports giving the present state of the art, and the preparation of new reports on air-speed measurement, altitude measurement, and engine instruments has accordingly been undertaken. An additional report on flight-test instruments would also be advisable in view of the great development of commercial aircraft.

9. SUMMARY OF PROBLEMS

The problems outlined in this report are given below by title.

(*a*) Investigation of proper installation of Pitot static tubes.

(*b*) Solution of the installation and operation problems of compasses, particularly as regards vibration and changing magnetism of aircraft.

(*c*) Investigation of the proper sensitivity of turn indicators for various types of aircraft.

(*d*) Further development of possible methods of locating the landing field and of landing during fog.

(*e*) Preventing failure of tubing of pressure gauges and thermometers.

(*f*) Development of a combined true and relative air-speed meter.

(*g*) Further development of gyroscopic instruments for providing an artificial horizon.

(*h*) Development work on recording tachometers.

(*i*) Development of more satisfactory fuel quantity gauge.

(*j*) Development and improvement of fuel flowmeters.

(*k*) Development of absolute altimeter.

(*l*) Improvement of the induction compass.

(*m*) Improvement in the design of drift indicators.

(*n*) Improvement of the design of electric transmission type of distant-indicating tachometers.

(*o*) Improvement of oil pressure gauge with respect to low-temperature operation.

(*p*) Improvement of oxygen supply instruments.

(*q*) Improvement of thermometers for measurement of free air temperature.

(*r*) Refinement of methods of measuring ground speed.

(*s*) Improvement in the method of measuring rate of climb.

(*t*) Improvement of technique and instruments associated with astronomical methods of position finding.

(*u*) Development of distant indicator of relative humidity.

(*v*) Research work relating to the selection of suitable damping liquids for bank indicators. Part of the general problem.

General problems are summarized by title in the opening paragraph of the section on General Problems.

Respectfully submitted.

SUBCOMMITTEE ON INSTRUMENTS,
L. J. BRIGGS, *Chairman.*

WASHINGTON, D. C., *October 9, 1930.*

REFERENCES

1. Eaton, H. N., and others: Aircraft Instruments. Ronald Press, 1926.
2. Hunt, F. L.: New Types of Aircraft Instruments. Journ. Opt. Soc. Am. and R. S. I., pp. 227–269, V 12, 1926.
3. Eaton, H. N.: Aerial Navigation Instruments. N. A. C. A. Technical Report No. 131, 1921.
4. Wimperis, H. E.: Air Navigation. Constable & Co., 1920.
5. Hunt, F. L., and Stearns, H. O.: Aircraft Speed Instruments. N. A. C. A. Technical Report No. 127, 1922.
6. Hyland, Dick: True Altitude Meters. Aviation, Oct., 1928.
7. Alexanderson, E. F. W.: Height of Airplane Above Ground by Radio Echo. Int. Civil Aero. Conference, p. 613, Dec., 1928.
8. Behm, A.: Das Behmlot und seine Entwicklung als akustisher Höhenmesser für Luftfahrzeuge. J. & W. G. L. (Z. F. M. heft 13, May, 1926) pp. 56–76, 1925.
9. Dellinger, J. H., Diamond, H., and Dunmore, F. W.: Development of the Visual Type Airway Radio Beacon System. Bureau of Standards Journ. of Research, pp. 425–459, V 4, 1930, RP 159.
10. Gardner, G. W. H., and Meredith, F. W.: Report on the Development of a Hot Wire Rate of Descent Meter. British A. R. C. Reports and Memoranda No. 1144, 1927.
11. Belj, K. H.: Astronomical Methods in Aerial Navigation. N. A. C. A. Technical Report No. 198, 1924.
12. Keulegan, G. H.: Investigation of Damping Liquids for Aircraft Instruments. N. A. C. A. Technical Report No. 299, 1929.
13. Heyl, P. R., and Briggs, L. J.: The Earth Inductor Compass. Proc. Am. Phil. Soc., p. 15, V. 61, 1922.
14. Tear, J. D.: Electromagnetic Compass Systems for Aircraft. Int. Civil Aero. Conference, p. 469, Dec., 1928.
15. Dellinger, J. H., and Pratt, H.: Development of Radio Aids to Air Navigation. Proc. IRE, pp. 890–920, V. 16, 1928.
16. Dunmore, F. W.: Design of Tuned Reed Course Indicators for Aircraft Radio Beacon. Bureau of Standards Journ. of Research, pp. 751–769, VI, 1928.
17. Bureau of Standards: Direction Instruments. N. A. C. A. Technical Report No. 128, 1922.
18. Lonnquest, T. C.: Use and Maintenance of Turn Indicators. Bureau of Aeronautics Technical Note No. 184, 1928.
19. Weems, P. V. H.: Line of Position Book. 2nd edition, U. S. Naval Institute, 1928.
20. Whitman, V. E.: Electrical Instruments for Aircraft, Elec. Mfg., pp. 32–34, August, 1929.
21. Kelly, R. D.: Means for Reduction of Breakage of Thermometer Capillaries as Experienced on Service Types of Airplanes. Air Corps Technical Report No. 2904, 1928.
22. Stewart, C. J.: Modern Developments in Aircraft Instruments. Journ. Roy. Aero. Soc., pp. 425–481, V. 32, 1928.
23. Cooch, H.: Landing Aeroplanes in Fog. Journ. Roy. Aero. Soc., June, 1926.
24. Hersey, M. D.: Diaphragms for Aeronautic Instruments. N. A. C. A. Technical Report No. 165, 1923.
25. Keulegan, G. H.: Statical Hysteresis in the Flexure of Bars. Bu. of Stand. Technical Paper No. 332, 1926.
26. Keulegan, G. H.: Stastical Hysteresis in Cycles of Equal Load Range. Bu. of Stand. Paper No. 365, 1928.
27. Norton, F. H.: The Effic'ency of Small Bearings in Instruments of Type Used in Aircraft. N. A. C. A. Technical Report No. 94, 1920.
28. Askania Telecompass. Inst. World, pp. 121–122, Aug., 1928.
29. Schoeffel, M. F.: The Installation and Correction of Compasses in Airplanes. N. A. C. A. Technical Note No. 262, 1927.
30. Henrickson, H. B.: Tension Experiments on Diaphragm Metals. N. A. C. A. Technical Note. No. 261, 1927.
31. Kear, F. G., and Jackson, W. E.: Applying the Radio Range to the Airways. Proc. Inst. Rad. Eng., pp. 2268–2282, V. 17, 1929. B. S. Journ. of Research, p. 371, V. 4, 1930.
32. Dellinger, J. H., and Diamond, H.: Radio Developments Applied to Aircraft. Mech. Eng., V. 51, p. 509, July, 1929.
33. Dreisonstok, J. A.: Navigation Tables for Mariners and Aviators. U. S. Navy Hydrographic Office Publication No. 208, 1928.

34. Solving the Problem of Fog Flying (52 pages). The Daniel Guggenheim Fund for the Promotion of Aeronautics, 1929.

35. New Magneto Compass. Instruments, pp. 478–480, V 2, 1929.

36. Diamond, H. Applying the Visual Double-Modulation Type Radio Range to the Airways. Bu. of Stand. Jour. of Res., pp. 265–287, V 4, 1930.

37. Walls, H. J. The Civil Airways and Their Radio Facilities. Proc. Inst. Rad. Eng., pp. 2141–2157, V 17, 1929.

38. New Airplane Gasoline Gauge. Instruments, pp. 467–468, V 2, 1929.

39. Kerr, P. S. Fuel Flow Meters Designed to Measure Mass Flow. British A. R. C. Reports and Memoranda No. 1245, 1929.

40. Engine Temperature Indicator for Aircraft. Instruments, pp. 476–477, V 2, 1929.

41. Developments in the Electrical Industry During 1929. Gen. Elect. Rev., pp. 14–17, V 33, 1930.

42. Aeronautic Radio Research, Fog-Landing Developments. Air Commerce Bull., p. 14, VI, Feb. 15, 1930.

43. Lonnquest, T. C. The Drift Factor in Air Navigation. Bureau of Aeronautics Technical Note No. 66, 1930.

44. Dunmore, F. W. A Tuned-reed Course Indicator for the 4 and 12 course Aircraft Radio Range. B. S. Journ. of Research, p. 461, V 4, 1930.

45. Peterson, J. B., and Rounds, E. W. Flight Test Instruments. SAE Journ. pp. 313–317, V 26, 1930.

46. Ernest Schreiber, Das Behmlot fur Flugzeuge und die mit ihm erzielte Genauigkeit. Jahrbuch 1930 der Deutschen Versuchsanstalt für Luftfahrt, pp. 483–490. Trans. N. A. C. A. Technical Memorandum No. 588, 1930.