FURTHER IMPROVEMENTS IN THE ELECTRONIC DEW-POINT HYGROMETER

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ABSTRACT

The electronic dew-point hygrometer described by Barrett and Herndon in 1951 has been improved in three distinct areas: the servo-amplifier system, the optical system in the sensing head, and the operating-adjustment system. The improvements are described, and the operational use of the improved hygrometer is discussed briefly.

1. Introduction

A previous article (Barrett and Herndon, 1951) described an electronic dew-point hygrometer designed and built in the instrument laboratories of the Department of Meteorology of the University of Chicago. Extensive operational experience with a number of these instruments demonstrated the practicality of their design; it also suggested, however, certain improvements in the circuitry and mechanical arrangement which would increase the stability of operation and the ruggedness of the apparatus. When the need arose for several hygrometers to be installed in airplanes for use in the Cloud Physics Project investigations, it was decided to incorporate these improvements into a redesigned model of the instrument.

Improvements in the 1951 model have been effected in three distinct areas. By certain circuitry changes, it has been possible to improve the long-term stability of the servo-amplifier system and to make it less susceptible to fluctuations in the filament voltage. The mechanical features of the optical system in the sensing head have been completely redesigned. In the 1951 model the entire optical system, including the lamp, phototubes, shutter and condensation mirror (dew-sensing surface), lacked the rigidity necessary for operation under field conditions. This condition has been improved considerably in the new model. A third weakness of the 1951 model became obvious when it was realized that the new instrument would be operated by relatively unskilled personnel, working under the rigors of research flying (turbulence, oxygen masks, bulky clothing, *etc.*). The operating adjust-

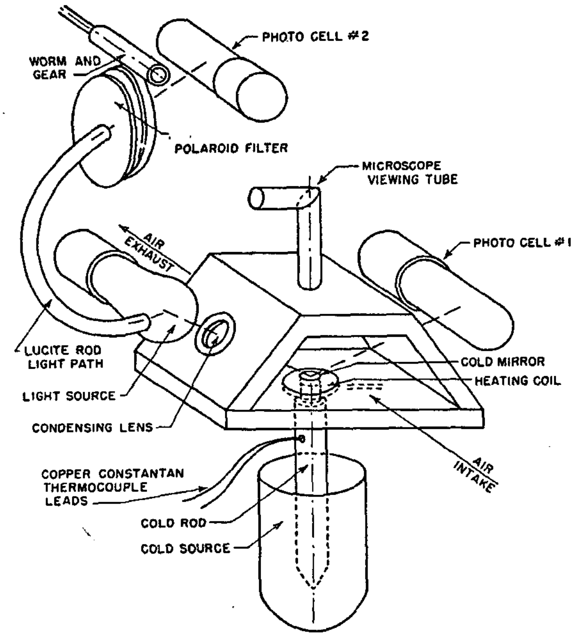

FIG. 1. Schematic of sensing head.

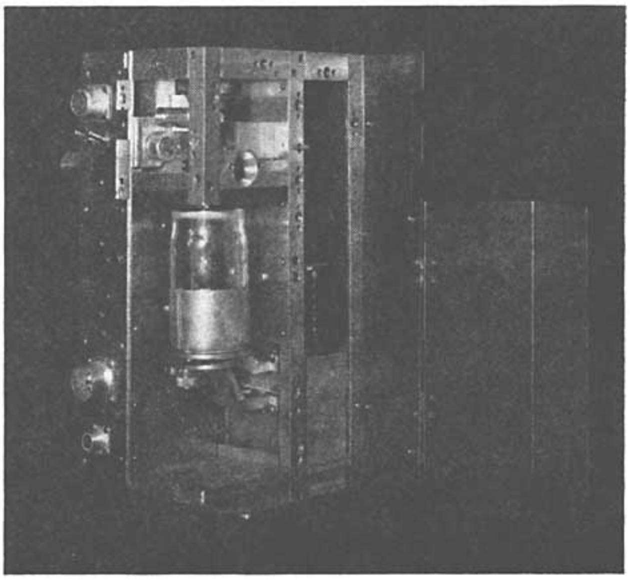

FIG. 2. Photograph of sensing head, showing air inlet, light source, viewing tube, and coolant container. Lucite rod not in place.

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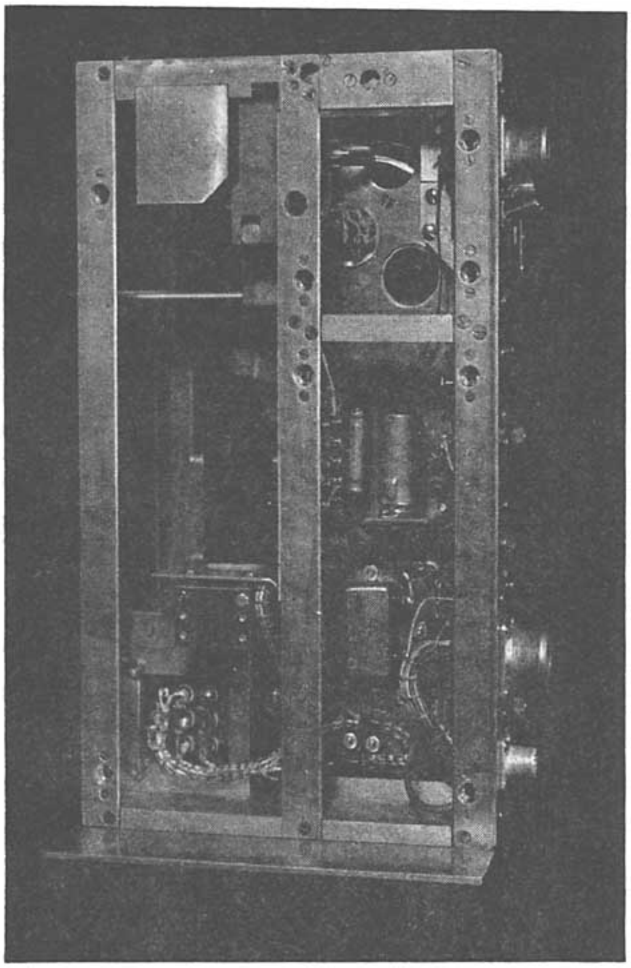

FIG. 3. Photograph of sensing head, showing electronic components, exhaust port, and lucite rod.

ments of the first instrument involved considerable skill on the part of the operator. To alleviate this difficulty, an indicator was incorporated in the new instrument to show unambiguously the proper operating adjustments. In the new design, the proper indicator reading for an instrument is established initially by an experienced operator; subsequently, less skilled operators have only to adjust the shutter during inflight checks to give the predetermined indicator reading, thus insuring proper operation of the hygrometer.

The specific changes in circuit and mechanical layout required to achieve these desired improvements are presented in detail in the following sections. Fig. 1 is a schematic representation of the new sensing head. Figs. 2 through 4 are photographs of various parts of the new instrument. The revised circuit diagrams are shown in figs. 5 and 6.

2. Revision of the electronic circuit

The principal change in circuitry in the new instrument is elimination of the balanced detector and direct-coupled modulator, to improve long-time amplifier stability. In the new instrument, the heating oscillator also functions as a phase-sensitive detector; modulation, or power-output control, is provided directly by the alternating voltage from the error-signal amplifier. The only change in the oscillator circuit is the change of the plate supply from filtered DC to pure AC, accomplished by connecting the

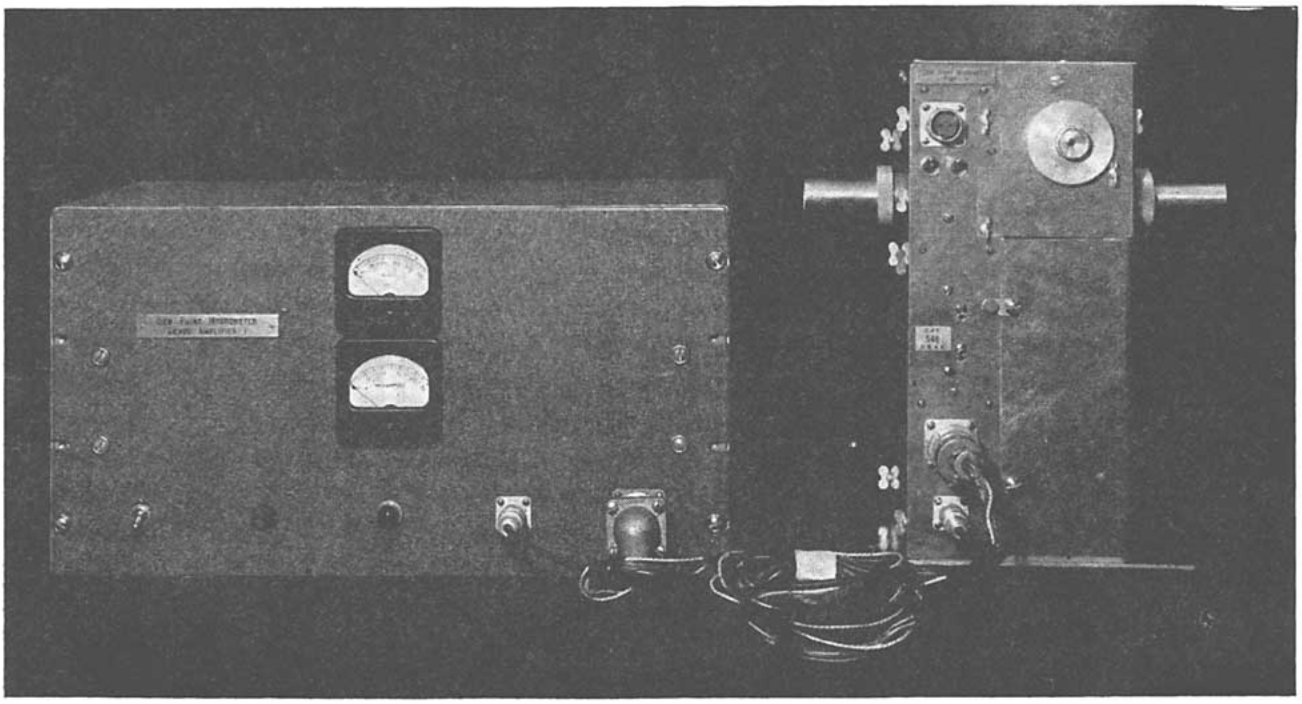

FIG. 4. Photograph of assembled instrument.

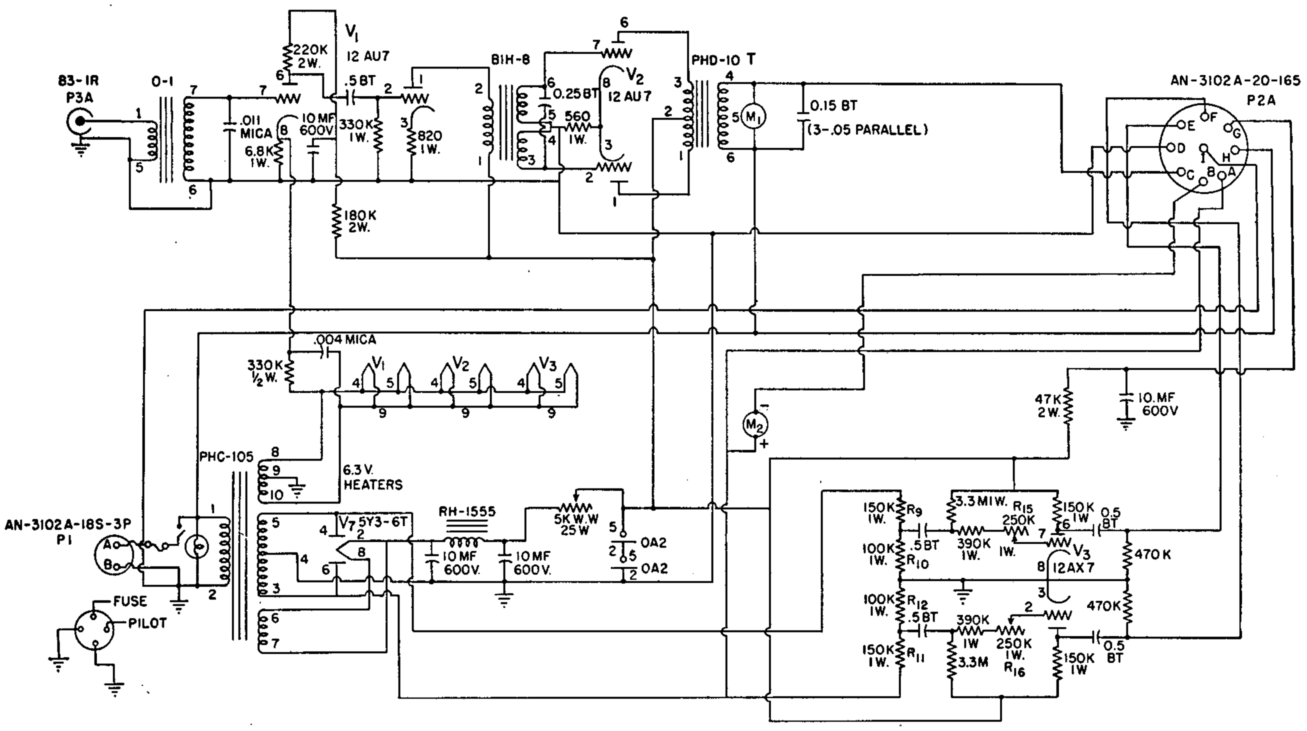

FIG. 5. Circuit diagram of amplifier chassis.

plate-supply lead to one end of the high-voltage winding of the power transformer.

Operation of the oscillator as a half-wave phase-sensitive detector can best be understood by references to figs. 5 and 6. The control, or error signal, which is an alternating voltage of the same frequency as the plate supply and either in phase or 180 deg out of phase with the plate supply, is applied to the screen of the oscillator in series with a fixed alternating voltage which is in phase with the plate supply. This fixed reference voltage is chosen so that, when the control voltage is zero, the oscillator output is just sufficient to maintain the hygrometer in proper balance at a dew point in the middle of the atmospheric range (near 0C). Since the reference voltage is in phase with the plate supply, the plate and screen go positive together during alternate half-cycles of the supply voltage. Thus, radio-frequency power is developed on alternate half-cycles, and the oscillator is inactive on the other half of each cycle.

The power output is determined by the amplitude of the voltage at the screen. When the error signal is in phase with the plate supply, it adds directly to the steady screen voltage and so increases the oscillator power-output. On the other hand, an out-of-phase error signal will subtract from the reference voltage at the screen and reduce the oscillator power. An out-of-phase error signal which is just equal in amplitude to the reference voltage will just cancel the latter and reduce the oscillator output to zero. Further increases in the amplitude of the out-of-phase control voltage simply drive the screen negative during the positive half-cycle at the plate, and the output remains at zero. (The positive excursion of the screen during the negative part of the plate cycle produced no measurable output from the oscillator.) For proper operation of the hygrometer, the various transformers must be properly phased so that an increase in the density of dew or frost produces an increase in amplitude of an in-phase control signal (or a decrease in amplitude of an already existing out-of-phase control signal) so as to increase the heating power available at the condensation mirror.

A second circuitry change has resulted in improved short-time stability. In the earlier instrument, the exciting voltage for the anodes of the phototubes was

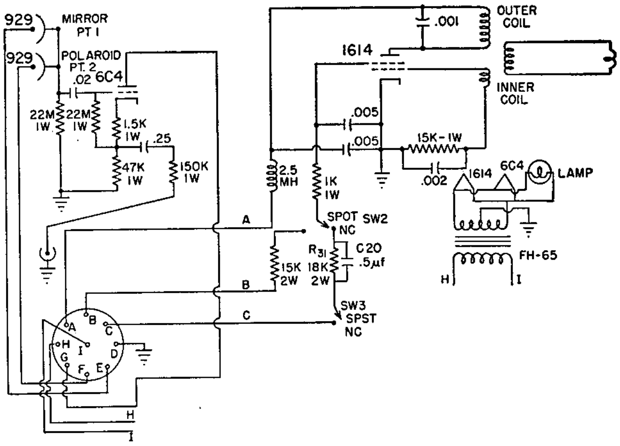

FIG. 6. Circuit diagram of sensing head.

sinusoidal alternating voltage derived from the plate-supply winding on the power transformer, with additional positive direct bias to provide a slight overlap in the conduction cycles of the two phototubes. Experience with this arrangement showed that the waveform of the control signal was excessively rich in harmonics, the amplitudes of which varied markedly with line-voltage changes and changes in oscillator-plate current. This was found to be caused by small changes in the amplitude of the alternating exciting voltage with line and load changes; the relation between those changes and the change in the direct bias was such as to change the overlap in the conduction cycles and therefore to change the waveform of the control signal.

In the new design, the phototubes are supplied with square-wave excitation so that the duty cycle of each phototube is sharply defined and unaffected by line and load variation. Two out-of-phase sinusoidal voltages are derived from the high-voltage center-tapped winding on the power transformer through identical voltage dividers, R_9-R_{10} and R_{11}-R_{12} (fig. 5). These voltages (about 150-volt peak amplitude) are fed to the grids of the two halves of the 12AX7 tubes, V_d. The latter functions as a pair of heavily over-driven clipping amplifiers; the grids are driven rapidly from saturation to cutoff. A square wave of voltage, the amplitude of which is fixed by the (regulated) plate voltage, appears across the load resistor in the plate of each half of the tube. The alternating component of one of these square waves is applied to each of the phototubes, providing out-of-phase square-wave excitation. Rheostats R_{15} and R_{16} set the duty ratios of the two channels; when the instrument is set in operation, these ratios are set so that no "spike" or overlap pedestal appears in the phototube-output waveform as viewed on an oscilloscope, and so that the duty ratio is very nearly 50 per cent for each phototube.

Since the output waveform of the phototubes as seen at the common load resistance is approximately square, it was necessary to filter the harmonics so that proper modulation of the oscillator could be effected. To accomplish this, all interstage, input, and output transformers in the control amplifier are resonated at the power frequency by means of capacitors. These capacitors are selected to insure that the phase of the output voltage from the control amplifier is either zero or 180 deg with respect to the plate voltage. This phasing, rather than maximum amplitude, is the criterion for resonance; if the phase error exceeds more than a few degrees, the control sensitivity is reduced and it becomes impossible to cut the oscillator off completely.

3. Adjustment indicator

Although it involved only minor modifications of the amplifier circuitry, the addition of an indicator to assist the operator in properly adjusting the operating condition for the condensation mirror has resulted in a substantial increase in the utility of the dew-point hygrometer. It is readily appreciated that proper operation requires a delicate adjustment of the density of the dew deposit on a dew-sensing mirror. The difficulty of establishing this adjustment has led many individuals to abandon the electronic dew-point hygrometer as a tool for humidity measurements. In the new instrument, it has been possible to reduce this problem to one of setting the control voltage to a predetermined value as measured on a voltmeter on the instrument face.

The indicator, an AC voltmeter M_1 (fig. 5), is connected across the secondary of the control amplifier-output transformer T, to measure the root-mean-square amplitude of the control voltage. In practice, the mirror is cleared of dew or frost deposit by closing a switch, SW_2, which transfers the screen to the plate supply through a dropping resistor chosen to provide maximum power output from the oscillator without overloading the oscillator tube. While the mirror is thus held at the temperature far above the dew point, the light shutter is adjusted until meter M_1 reads the proper value for the control voltage (approximately 175 volts for instruments built with the specified components). Since the meter does not indicate the phase of the control signal, there are two possible shutter settings which will give this voltage, and an additional check for signal phase must be made. After the clearing switch is released, the behavior of the oscillator plate-current meter, M_2, is observed. If this meter, which has been indicating a value of about 25 milliamperes during the clearing period, drops to zero, or to a very low value upon release of switch SW_2, the phase is correct. If the plate current remains high, the phasing is incorrect and the shutter must be repositioned until M_1 indicates the desired value but where the indication on M_2 will drop when the switch is released. As dew or frost forms on the mirror, the readings of both meters will change and reach quasi-steady values which depend upon the dew point and temperature of the air being sampled.

4. Revisions of mechanical and optical components of sensing head

The early model of the hygrometer was limited in performance by shortcomings in the mechanical design of the sensing head. Principal among these was a tendency for mechanical vibration of the optical components and a lack of provision for fine adjustment in the optical system. In addition, a redesign was indicated to make possible a more easy access to the coolant receptacle and to other optical and electronic components which might require in-flight cleaning, adjustment or replacement. To correct these difficulties of the earlier model, the mechanical arrangement of the components of the sensing head have been completely altered.

Fig. 1 shows a schematic arrangement of the mechanical and optical components in the sensing head. A beam of light from a steady light source passes through a condensing lens and impinges on a small rhodium-plated copper mirror of (1/8)-in diameter and 0.002 in thick. The mirror is mounted on the top of a hollow soft iron rod, 11/16 in long. A copper-constantan thermocouple is held to the back of the copper mirror by means of an extremely fine solder joint (Barrett and Herndon, 1951). The rhodium plating prevents corrosion of the mirror, yet provides a satisfactory thermal contact and optical surface. The whole mirror assembly is imbedded in an aluminum cold rod, except for a $\frac{1}{4}$-in section which projects above the cold rod and through the heating coil. The aluminum cold rod has openings through which the thermocouple leads are brought out. The focused beam of light impinging on the mirror surface is reflected into the sensitive element of a phototube, Pt_1 in fig. 6. The heating coil is formed of No. 18-gauge wire coupled to the plate coil of the radio-frequency oscillator through a link and pickup coil consisting of three turns of (1/8)-in heavy-walled copper tubing. The heating coil is cast into a disc of thermosetting plastic. The latter is pierced by a hole concentric with the coil and having a diameter of such size as to allow a snug fit with the mirror support. The thickness of the disc is such that the mirror surface is flush with the upper surface of the disc when the instrument is assembled. In this way, the coil is held securely against vibration and accidental electrical shorting to the mirror support. In addition, enclosure of the mirror support prevents accumulation of frost on the sides of the support and on the top of the cold rod. Such an accumulation might cause serious scattering of light into the phototube and thus interfere with normal operation of the instrument.

A special microscope viewing-tube has been installed in the side of the heavy-walled air chamber, to permit the operator to view the condensation mirror during the adjustment of the instrument.

The heavy-walled air chamber has been machined from solid aluminum-alloy blocks and serves as a mounting base upon which to assemble the mirror and cold rod, the condensing lenses, the microscope viewing-tube, and the intake and exhaust air-nozzles. A small static-pressure tube is imbedded in one interior wall of the air chamber, to permit measurement of the air pressure a few millimeters from the cold-mirror surface.

A second beam of light from the light source is conducted to an adjustable shutter and caused to impinge on the photo-sensitive element of a phototube, Pt_2 in fig. 6. It was found convenient, for reasons of compactness and balance, to conduct the light beam through a lucite rod to the rear of the instrument, thence through the shutter and into the reference photocell. The shutter consists of two polaroid glass filters, one mounted in a fixed position, the other mounted in the interior of a tooth gear of root diameter only slightly larger than the filter. The gear is held in place by a small groove machined just inside its root diameter, which engages a series of lugs or guides in the cover of the shutter case. The filter is rotated by means of a small worm gear, mounted on a shaft extending through the side of the case. To prevent backlash or vibration of this polaroid filter, the worm-gear shaft is spring loaded and turns against the gear with sufficient friction to hold it rigidly in position.

To minimize the difficulty of slightly different filament positions in different bulbs which might be used in the instrument, the light source was mounted in a separate detachable bracket provided with fine adjustment screws in two directions. Subsequent to each installation of a new light bulb, adjustment of the light position is required for best performance. The bulb socket is molded in a thermo-plastic potting compound which, in turn, is machined to the contour and size required to fit the mounting bracket.

It was found necessary to construct rigid housings for the phototubes, to shield them from light and stray radio-frequency radiation from other components, as well as to hold them rigidly positioned with respect to the other optical components. The phototube housings are mounted to a machined aluminum-alloy frame, upon which most of the other optical components and sub-assemblies are fastened to create one compact structure. The compactness of the whole instrument aids in reducing the consequences of any degree of freedom of angular vibration which the optical parts retained after attachment in their respective places.

Figs. 2 and 3 show the sensing head with exterior panels removed. The aluminum angle-members shown in the foreground of fig. 3 serve primarily as panel supports. The main support for the mechanical sub-assemblies is obtained from two interior panels, which also serve as a chassis for the electronic components. The exterior paneling is secured to the frame by Dzus fasteners, which provide ready accessability for service without sacrifice of a sturdy protective shroud about the inner parts of the instrument.

5. Operational use of improved hygrometer

Several instruments incorporating the above modifications have been in operation on airplanes involved in cumulus-cloud studies for a period of several months. No mechanical or electrical failures, other than normal tube replacement, have been encountered. This indicates that the reliability required in such an instrument has been achieved. Inexpert personnel encountered no difficulty in operating the equipment even under turbulent flight conditions, thanks to the excellent shutter design and the reliability of the operating-adjustment indicators.

The electronic circuits exhibit great stability. When operated in the laboratory, the instrument is subject to a slow drift caused by contamination of the mirror by atmospheric particulates. This drift is readily detected with the operating-adjustment indicators and may be compensated for by daily cleaning of the mirror and frequent adjustment of the shutter to reestablish the proper operating conditions. The exact nature of these particulates has not been determined, but they must be of ground origin since they were much less troublesome in the airplane operations than in the laboratory. In a large majority of the flights, the instrument, once adjusted, required no attention other than periodic replacement of the coolant.

The instrument requires control of the power-supply frequency. A deviation of ±1 cy/sec results in a marked deterioration of the response time, and a 3-cycle deviation renders the instrument inoperative. Although this characteristic is not important when the unit is operated where power is derived from commercial power-company mains, it must be considered in airplane operation where close regulation of the power frequency may be difficult.

The qualitative analysis of the instrument's operation, although not complete, has demonstrated its accuracy and speed of response. In laboratory tests, there was excellent correlation between data taken with this instrument and sling-psychrometer measurements. Flight measurements have agreed, well within the limits of the parameters, with weather-station radiosonde data. Results of measurements with this instrument during the cumulus-cloud studies will be published with other flight data.

REFERENCE

Barrett, E. W., and L. R. Herndon, 1951: An improved electronic dew-point hygrometer. *J. Meteor.*, **8**, 40–51.