The AEROVOX Research Worker

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INDUSTRIAL APPLICATIONS OF ELECTRONIC DEVICES

PART 1

By the Engineering Department

AEROVOX Corporation

A paper by the Engineering staff of Aerovox Corporation. In order to preserve the unity of the text, this material which is too lengthy to be included in the usual four page edition of the Research Worker, is being published in three eight page editions. The second part of the paper will appear in the October-November issue of the Research Worker.

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Industrial Applications of Electronic Devices

PART I

THE vacuum tube in any of its applications is inherently a sensitive relay with no moving parts. This fact accounts for the term *valve* which was first used to name the device and still is to be found in British technical literature. The relay action of the tube makes it useful in industry.

Applied scientists quickly recognized the early radio tube's industrial potentialities. But the exceeding delicacy and eccentricity of those first models necessarily deferred the actual adaptation of the tube to uses outside of radio communication to a date when greater stability, longer operating life, and lower cost could be achieved by tube design and manufacture.

The leading advantage of the tube over the mechanical relay lies in the former's extreme power sensitivity. Moreover, the tube's dependence upon electronic action rather than mechanical motion makes it less liable to the common vagaries of mechanical devices. Tubes have no contacts to stick, moving parts to become noisy and be retarded by inertia, nor pivoted members to be disturbed by external vibrations. Consequently, they are often more reliable in operation and more rugged than electromechanical devices in spite of their reputation for delicacy.

But the diversified electronic relay is not the sole industrial adaptation of the vacuum tube. Various tube circuits designed originally for radio communication, and a few developed specifically for industrial purposes, form the basis of measuring instruments and control devices in industries far beyond the speculation of their inventors. The tube, condenser, and resistor are faithful workers in many factories.

Today, the layman has first-hand familiarity with numerous applications of the vacuum tube outside of radio. The tube frequently joins company with the photoelectric cell, another electronic device, to perform commonplace tasks in modern everyday life. The cell-amplifier combination forms the brain of automatic speed traps on our highways. At this writing, a huge speed-warning billboard at a trunk highway junction outside Minneapolis flashes on automatically when approached by a vehicle exceeding the local speed limit. Vacuum tube oscillators spot metal objects in the pockets of employees passing through the exit doors of factories; and, in the service of the police, betray concealed weapons on suspicious persons. Photoelectric burglar alarms have been commonplace for more than ten years, and so have photoelectric devices that protect the operators of maiming factory machinery. The photocell opens doors for traffic through public places, and sound-actuated relays and amplifiers open garage doors when waiting motorists sound their horns. The hard-of-hearing are aided by miniature pocket amplifiers, and medical science finds increasing worth in diathermy and short-wave therapy.

However, it is the application of the vacuum tube specifically to industrial operations other than the manufacture and testing of radio equipment that is not so commonplace, although of increasing instance. The demands imposed upon electronic devices by various industries have been justifiably stern and it is gratifying at this time to observe that the tube, condenser, and resistor have made good in a number of industries too numerous to list completely on these pages.

In this series of articles, we will enumerate some of the outstanding industrial applications of electronic devices and explain the basic principles underlying their operation, insofar as space permits.

DETERMINATION OF WEIGHT AND THICKNESS

Weight and thickness are being determined very precisely by instruments which make use of tubes and associated radio circuit components.

Figure 1 illustrates the principle of one system for determining the thickness of non-conducting materials.

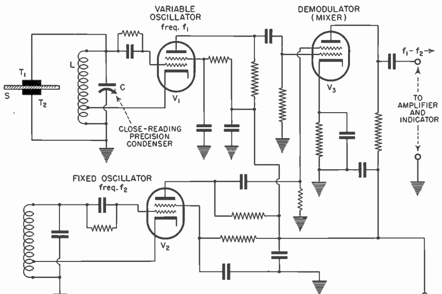

FIG. 1

AEROVOX BUILT BETTER CONDENSERS AND RESISTORS

as shown in Figure 11. The output of this oscillator is presented to a demodulator and beat-indicator circuit together with the output of a standard-frequency fixed oscillator. The variable oscillator tuning condenser is a precision instrument which may be read very closely.

The variable oscillator is set to zero beat with the fixed oscillator (with the empty test cell connected). The reading of the tuning condenser is noted. When the sample oil is introduced into the cell, the latter's capacitance will be increased in proportion to the dielectric constant of the oil and the frequency of the variable oscillator will be shifted accordingly. The variable oscillator is then reset for zero beat and the reading of the tuning condenser noted at this point. The ratio of the "oil capacitance" to the "air capacitance" is the dielectric constant of the sample.

CONTROL OF PACKAGING MACHINERY

An increasing number of food products is delivered sealed in printed wrappers of paper or other transparent or translucent material. The wrapper material is supplied in large rolls with a repetitive design and is wrapped around packages, cut, and sealed by machines.

In these machines, the gears which control the rate of paper feed are operated by the same mechanism which propels the rotary knife, and it is endeavored to synchronize the cutting action with the rate of feed in order that the design may not be sliced. Nevertheless, slipping and creeping of the paper often causes the predetermined cutting point to reach the knife out of time, with the result that the design is clipped or displaced on the package.

In modern packaging machines, this difficulty has been overcome by means of electronic apparatus which controls the paper speed closely to allow a predetermined length to pass through the rollers during each revolution of the knife. The control index is a small spot printed on the paper in proper relation to the design.

As the paper progresses from its roll through the machine, it passes between a light source and a photo-cell; and the printed index spot casts a shadow on the cell as it arrives in position, varying the latter's output current.

The photocell current variations are built up by an amplifier to operate "speed up" or "slow-down" relays which advance, retard, or "neutral" a variable-speed paper-feed motor, depending upon whether the index spots arrive over the photocell early, tardy, or on time.

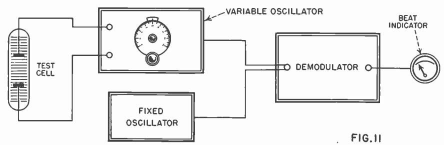

FIG. 11

APPLICATION TO WIRE DRAWING

It is essential in wire making that the wire be drawn through the last die at constant speed and tension. Before the advent of automatic devices for the purpose, it was imperative that this final operation be skilfully attended.

The basic elements of an electronic circuit now employed to control speed and tension in the last stage of wire drawing is shown in Figure 12. A Thyratron tube arrangement controls the speed of the motor that winds the wire on its reel.

Variations in speed and tension cause the movable pulley to be displaced vertically and to move a plunger within a solenoid coil. The latter is connected to the Thyratron grids.

Movement of the plunger effectively alters the inductance of the tube grid circuit and the tube output voltage is in turn altered accordingly. This variable voltage is then impressed upon the armature of the reel-turning motor. The speed of this motor is varied from zero to maximum by a plunger movement of only a few inches.

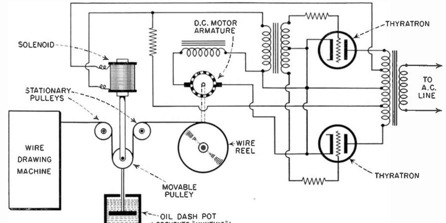

FIG. 12

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Ghirardi Enlarges, Revises Handbook

The second edition of Alfred A. Ghirardi's Radio Troubleshooter's Handbook has just been released, (Radio & Technical Publ. Co., $3.50). Over 50% of its 710 pages are devoted to 4600 receiver and automatic record-changer "case histories", in itself the largest compilation of its kind ever published. The Handbook also contains a 50-page tabulation of IF peaks and alignment data; 60 pages of data for the auto-radio specialist; 20 pages of tube charts giving complete information on characteristics, classification, interchangeability, and socket connections of every type of American receiving tube ever made. Much additional, clearly-compiled information, applicable to the serviceman's daily work, completes this all-inclusive Handbook.

resistor. The d.c. microammeter, M, is connected in a bridge circuit of which the tube plate resistance is one leg. By adjustment of another leg, R_2, the steady plate current of the tube is initially balanced out to set the meter circuit to zero.

The limitations of such an instrument are severe, since the simple photovoltmeter is incapable for the most part of distinguishing between color changes and density changes. Nor, when it is operated by reflected light from solid samples, can it be easily isolated from sample-surface effects, directional light effects, and variations in illumination. Moreover, color waveforms are generally complex and the simple instrument cannot show the relative amplitudes of each light-frequency component. The restrictions of the instrument are comparable to those of the a.f. harmonic totalizer against the advantages of the complete wave analyzer.

Complete analysis of colors and precise color matching are made possible by the ingenious *color comparator*. These instruments are analagous to the audio-frequency wave analyzer in that they make it possible to explore a complex visual waveform, measuring the amplitude of each component. The necessarily high order of selectivity is obtained with optical filters; and when the separate readings for two samples are identical, the two match perfectly in hue, saturation, and brilliance.

The commercially available color comparator operates in the following manner: Three light-frequency bands corresponding to the red, blue, and green regions, are selected for measurement from the complex color waveform by means of optical filters, and a measurement is made separately in each band of light reflected from the sample. The three readings give a complete account of the color.

OIL ANALYSIS

The petroleum industry has borrowed some of the apparatus and methods long employed in dielectric measurements in the condenser industry to study oil characteristics more closely. At the same time, certain electronic equipment has been designed primarily for use by oil refiners in their research work.

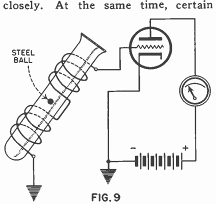

FIG. 9

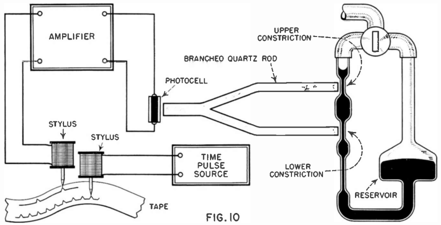

FIG. 10

Measurements are now being made electronically of several oil characteristics including viscosity, dielectric constant, power factor, lubricating quality, electrical resistance, gasoline "knock" properties, and hydrogen ion concentration (pH).

Viscosity has been measured by several methods, one of the first of which is illustrated in Figure 9. In this instance, the viscous liquid is retained by an inclined glass tube, the lower end of which is closed, and around the outside of which are wound two solenoids. The ends of the series-connected coils are connected to grid and ground terminals of a vacuum-tube circuit, and a d.c. milliammeter is included in the tube plate circuit.

With the circuit in operation, if a steel ball is dropped into the liquid, it will pass from the surface to the bottom at a rate of speed dependent upon the viscosity of the liquid.

As the ball passes through the two coils, there will be two corresponding deflections of the plate milliammeter and the ensuing time interval may be measured. The viscosity is determined from the time taken by the ball to travel a given distance through the liquid. For accuracy, the angle of inclination of the test tube must be adjusted with reference to the temperature.

A set-up for the chronographic study of viscosity is diagrammed in Figure 10. Jones and Talley described such a system in the June 1933 issue of the *Journal of Chemical Education*.*

The sample liquid is drawn up from a reservoir into a glass capillary tube with two narrow constrictions near its top. Solid quartz rods are arranged between these constrictions and a photocell, as shown, for the purpose of communicating impulses to the cell from light beams directed through the constrictions. The tube and reservoir are immersed in a constant-temperature bath.

As the liquid slowly falls in the tube, its meniscus interrupts the light beam as it passes successively through each constriction and the resulting electrical pulses are delivered by the photocell to an amplifier.

An electromagnetically - operated stylus in the amplifier output circuit records each pulse on a chronograph tape opposite pulses similarly recorded by a second stylus operated by a standard time source, such as a seconds pulser.

It is thus possible with the arrangement of Figure 10 to determine very precisely the length of time taken for the meniscus to fall from one constriction to the other and to determine the viscosity of the liquid from this data.

The dielectric constant and power factor of oils are determined by means of a *standard cell* which is in essence usually a refined two-plate fixed air condenser with suitable, self-contained guard circuit. Accurate measurements are made of the capacitance and/or the power factor of the cell (condenser) before and after the sample oil has been introduced between its plates; i.e., successively with air and oil dielectric.

The ratio of the "oil capacitance" to the "air capacitance" is the dielectric constant of the sample.

The all-metal test cell utilizes its outer metal shell as one condenser electrode and a central metal rod as the other, the oil being poured into the intervening space. Another refined type of cell consists of a glass sample-oil container into which a cylindrical, concentric-plate air condenser assembly with appropriate guard ring is immersed. Either type may be immersed into a constant-temperature bath during measurements.

For dielectric constant measurements, the test cell may be connected, instead of to a capacitance bridge, to the extremities of the tuned circuit of a highly-stable tunable r.f. oscillator,

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Operation of this circuit is based upon the variation of condenser capacitance directly with the dielectric constant of the material between the plates and inversely with the thickness of the material. The apparatus employed for this measurement is essentially a beat-frequency audio oscillator. It consists of two r.f. oscillators (one fixed; the other tunable) and a mixer circuit which delivers an audio-frequency voltage of frequency (corresponding to the difference between the two oscillator frequencies) to an indicator. The latter is at zero when the two radio frequencies are identical.

The sample-testing "head" consists of two condenser plates, T_1 and T_2. Both are rigidly mounted, but T_2 is stationary and T_1 movable in order that the spacing may be altered for various samples when desired. The sample material, S, is placed between the plates.

The head is connected directly across the tank circuit, L-C, of a highly stable tunable oscillator, and the r.f. voltage delivered by this variable oscillator is mixed in the demodulator (mixer) stage with r.f. output voltage from the fixed oscillator. The fixed oscillator is often a standard-frequency crystal stage.

Any difference in frequency between the two oscillators will show up as an a.f. beat-note voltage which is delivered by the demodulator to the indicator. The latter may conveniently be an a.c. voltmeter, electric eye, or indicating audio frequency meter.

Before testing a sample, the instrument is "balanced" with no material between the test plates by setting the variable oscillator to zero beat with the fixed oscillator fundamental frequency or one of its harmonics, as shown by zero beat at the indicator.

When the sample is introduced between the plates of the measuring head, the capacitance of the condenser, T_1-T_2, will be altered in proportion to the thickness of the sample, and the amount of retuning of the oscillator condenser, C, necessary to restore zero beat is an indication of this thickness. The dial of the tuning condenser may therefore be graduated in fractions of an inch or fractions of a centimeter.

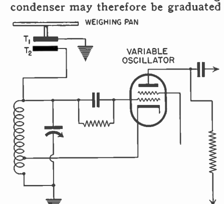

FIG. 2

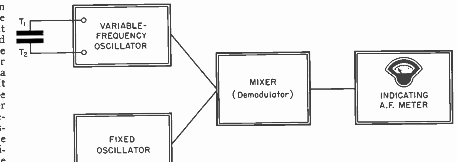

FIG. 3

Since the capacitance of T_1-T_2, when the sample is inserted, will depend upon the dielectric constant of the material as well as its thickness, measurements which will involve no computation can be made only on samples for which the dielectric constant is known, is consistent for all samples of the material, and for which the circuit has been compensated. This is particularly important to remember when, as in the case of paper, long lengths of the sample may be kept passing continuously between the measuring plates during production.

A similar basic arrangement for the determination of weight is shown in Figure 2. The same electrical circuit as Figure 1, embodying fixed and variable oscillators, is used here, the main difference being that the head is arranged in a slightly different manner. The bottom plate, T_2, is rigidly secured, while the top plate, T_1, is movable vertically and may carry a weighing pan.

The oscillators are set to zero beat with the pan empty. When subsequently a sample is placed in the pan, its weight will reduce the plate spacing proportionately and shift the variable oscillator frequency. As in the preceding applications, the amount of retuning necessary to restore zero beat is an indication of the weight of the sample. The dial of the tuning condenser, C, may therefore be graduated in weight units. Weights of exceedingly small magnitude are determined very precisely by this heterodyne method.

A circuit arrangement which eliminates the painstaking retuning operation and will show an increase or decrease in weight or thickness around a predetermined value is shown in Figure 3. Here the demodulator drives an indicating audio frequency meter. The circuit is balanced initially first by setting T_1 and T_2 to a separation corresponding to the predetermined weight or thickness and then setting the variable oscillator for a beat-note frequency at mid-scale on the indicating meter. The variable oscillator must operate on the high-frequency side of the fixed oscillator frequency.

Assuming a steady value of dielectric constant, a positive deflection of the meter will then indicate greater than desired thickness or less than desired weight. A negative deflection will indicate less than desired thickness or greater than desired weight.

The indicating meter may be replaced with a suitable recorder to obtain a continuous record of variations in thickness of a sample.

With either of the systems just described, it is clear that an error may be occasioned by temperature changes which act to change the initial plate separation. For this reason, the temperature-capacitance coefficient of the measuring head must be known very accurately and used to correct all figures obtained by the measuring process.

THE STROBOSCOPE

The unaided eye cannot follow the gyrations of a rapidly-moving machine. Because of this physiological limitation, accurate diagnoses of mechanical troubles have hitherto been hampered by the inability to make observations under actual operating conditions. But again the electron art has come forward with a useful tool—the *stroboscope*. Under stroboscopic lighting, a rushing machine may be made apparently to stand still or to go through the antics of a slow-motion movie while the movement of any of its parts is studied under dynamic conditions.

The stroboscope operates by intermittently illuminating the moving object at the rate of the latter's movement. The object is accordingly viewed under rather strong illumination at regular timed intervals. Each flash brings the moving part into view in the same position as when illuminated by the preceding flash.

When the flashing speed lags behind that of the moving object, motion will apparently be slowly in the direction of actual movement. When the flashing speed is higher than that of the machine, a slow movement apparently takes place in the opposite direction. When the flashing rate coincides with the actual speed of movement, the object appears to stand still.

The early stroboscopes used a mechanically-operated shutter to produce the flashes. The shutter was motor driven at controllable speed. The modern stroboscope is a flashing lamp instrument developed by Edgerton and Germeshausen.

The electronic stroboscope, like its mechanical predecessor, depends upon persistence of vision. By the optical illusion of arresting motion, it makes possible the study of moving machinery, determination of speed without attaching instruments to the moving parts, and similar observations. It may be used to study any recurrent motion visually. Any non-repetitive motion may be studied photographically by means of single-flash pictures.

Stroboscope flashes are very brilliant and of a few microseconds duration. They must be very short in order that the eye will discern no motion of the object. They are produced by a lamp filled with rare gases (principally neon) or mercury which possesses the ability to be ignited and extinguished at high rates of speed. The discharge of a capacitor flashes the lamp.

The flashing speed frequently is controlled by a multivibrator type of tube oscillator. (Multivibrators were discussed in the November 1940 issue of the *Research Worker*). One stroboscope in wide present use provides flashing speeds up to 14,000 per minute for visual observations and up to 120,000 per minute for high-speed photography.

Because of the stroboscope's ability apparently to arrest motion when the flashing speed coincides with the speed of the moving object, it finds ready application as a very efficient tachometer which takes no power from the machine for its own operation. For this application, the instrument dial which controls the flashing speed is graduated in revolutions per minute, and speed measurements may be made with an accuracy between 0.1% and 1.0%.

The stroboscope is used in studying rotations, vibrations, contact action, torsion in shafts, whipping, slipping, chattering, bending, hunting, etc. It is employed in textile mills to check the speed of spindles, in automobile factories to study crankshaft whip and engine vibration, and in watch and clock factories in the adjustment of the swinging balance wheels of timepieces. Since it will reveal the condition of whirling samples subjected to centrifugal force, structural engineers have found the stroboscope invaluable for testing and viewing stresses in reduced-scale building models, using controlled centrifugal force in lieu of gravity. The stroboscope "slows down" paper rushing through a high-speed printing press in order that pressmen may correct the register in color printing without stopping the press and before a large number of prints are spoiled.

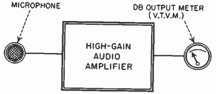

FIG. 4

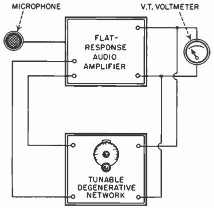

FIG. 5

The superiority of the stroboscope in its numerous applications rests in the ability it affords to study the action of machine components while they are actually in their normal motion.

SOUND AND NOISE MEASUREMENT

Sounds and noises are of concern in industry for the reasons that they may indicate mechanical troubles or inefficiencies and they exert a pronounced influence upon the nervous health and efficiency of workers. Likewise, the manufacturers of motor-driven appliances are eager to have their products run as quietly as possible and to this end devote considerable time to noise reduction programs.

The *sound-level meter* and the *sound analyzer* are employed in the study and control of industrial sounds and noises. Determinations of loudness and pitch not only enable engineering and maintenance crews to localize machine troubles at their outset but also lead the acoustical engineer to the source of each sound tending to impair concentration of the attention, worker efficiency, and nervous stability.

The sound-level meter aids materially in the reduction of unavoidable factory noises (such as those occasioned by the operation of presses, slapping of belts, rolling of trucks, and vibration of heavy machinery) by evaluating in quantitative terms each step in noise-reducing operations. This instrument reveals the actual noise level in decibels in accordance with standards adopted by sound engineers.

The sound-level meter is employed by various factories, builders, and acoustical engineers in the investigation of sound transmission and absorption in a number of materials.

A functional block diagram of a sound-level meter is shown in Figure 4. It is seen that this instrument consists of a high-gain audio amplifier with sensitive microphone input and vacuum-tube output voltmeter. The microphone has uniform frequency response and the meter is graduated in acoustical levels.

Operation of the sound-level meter is notably simple. After easily-made preliminary adjustments, it is placed in the neighborhood of the noise to be studied and the noise level is read directly on the meter scale.

A functional block diagram of the sound analyzer is shown in Figure 5. This instrument consists of a flat-response amplifier with a sensitive microphone of uniform frequency response connected to its input and a vacuum-tube voltmeter to its output circuit. Between the output and input is connected a highly-selective tunable R-C circuit (degenerative network) which permits the amplifier to be tuned sharply to admit only one frequency at a time. The tuning covers the entire a.f. spectrum and is continuously variable.

The selectivity of the sound analyzer permits it to be adjusted successively to the fundamental frequency of a sound or noise and to each harmonic of the fundamental. It is essentially an audio-frequency wave analyzer and shows the relative amplitude of each component of a complex sound wave.

The sound analyzer and noise-level meter have been used extensively in the automotive industry to measure car noise and in developmental work directed toward quieter car interiors and quieter mechanisms. The airplane industry employs both instruments in vibration measurements on engines and propellers. Railways study the internal and external noise characteristics of their rolling stock with these two instruments, and pure scientists have used the sound analyzer for study of supersonic sounds in nature.

In some industrial noise measurements, it has been desirable to employ the audio-frequency test oscillator, another electronic laboratory instrument, in combination with an amplifier and loudspeaker, to induce vibrations in machines and parts to identify disturbing resonant frequencies.

MOISTURE CONTROL

In various industries, the moisture content of the product must be controlled with great care and precision.

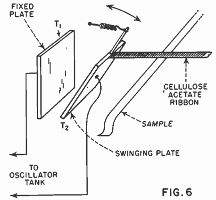

FIG. 6

An outstanding example is in the last stage in paper manufacture. Moisture studies are carried on electronically by means of the *precision hygrometer*. The basic principle of operation of this instrument is illustrated by Figure 6.

The chief electrical component consists of a special condenser comprising the highly stationary plate, T_1, and a movable plate, T_2, so arranged that a spring tends to pull the movable plate toward the stationary one against the action of a ribbon of cellulose acetate. Cellulose acetate ribbon is unusually sensitive to variations in the moisture content of samples brought close to it. As the ribbon quickly absorbs or loses moisture in accordance with the moisture content of a nearby sample, its length is quickly altered proportionately. The sample does not come in contact with the ribbon.

In the arrangement of Figure 6, the changes in length of the acetate ribbon produce corresponding changes in separation between T_1 and T_2. If the plates are connected across the tuned circuit of the variable oscillator in any of the circuits shown in Figures 1 to 3, the oscillator frequency will be varied in accordance with the changes in ribbon length (moisture content).

In practice, a long strip of manufactured material, such as paper or cellophane, passes near the acetate ribbon as it progresses from one stage to another of the fabricating machines. Baffles are strategically placed to protect the sensitive ribbon from moisture other than that in the sample. The oscillator circuits are connected to an indicating meter, such as shown in Figures 1 to 3, or their output voltages may be amplified to regulate steam jets or air streams for correcting the moisture content of the sample. If desired, a suitable recorder may be connected in lieu of an indicating meter to obtain a continuous running record of moisture content. This recorder may be actuated simultaneously with the jet-controlling mechanisms.

SMOKE CONTROL

Many of the larger cities have enacted ordinances prohibiting heavy industrial stack smoking except for intervals of stated duration during any single hour. Automatic photoelectric systems are in use to keep the boiler room informed constantly of the density and time of smoking by suitable signal lights, bells, or indicating gauges.

A further refinement consists in arranging the system to check dampers and stokers automatically after excess smoke has issued from the stack for the prescribed period of time.

Apparatus for translating changes in smoke density into electrical impulses of suitable voltage for practical purposes is shown in Figure 7. A light source, such as a protected incandescent lamp, is mounted in a housing on one side of the stack and directs a beam of light through the ascending smoke to a photocell mounted in a similar housing on the opposite side of the stack. The photocell is connected to the input circuit of an amplifier which delivers voltage across a load circuit proportional to variations of the light beam. These variations are in turn proportional to those in smoke density. The output voltage is made sufficiently high to actuate the alarms or draft-control mechanisms by appropriate choice of amplifier constants or by the use of Thyratron or grid glow tubes after the amplifier.

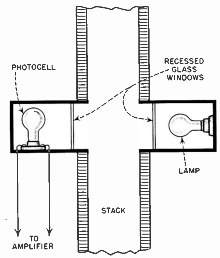

FIG. 7

CHECKING OF TURBIDITY OF SOLUTIONS

With a similar electronic circuit, chemical laboratories may investigate the turbidity of solutions quantitatively with greater precision than is possible with the eye.

As in the preceding application, a light source (preferably followed by an appropriate optical filter) is placed on one side of a transparent sample container; a photocell on the opposite side. The cell is connected to a resistor of several megohms and the voltage drop across the latter due to cell current is measured with a sensitive vacuum-tube voltmeter. The meter scale may be graduated in suitable units of turbidity to give a direct-reading instrument, since voltage variations will be directly proportional to variations in solution turbidity.

If a self-generating cell, such as the Photronic cell, is employed, a sensitive d.c. microammeter may be used directly without vacuum tubes to indicate the cell-current variations. This arrangement will be recognized at once as identical with that of the well-known photographic exposure meter.

The simple turbidity meter is useful also for studying acidity and alkalinity of solutions by measuring the relative coloration of sample solutions to which have been added an indicator such as litmus or phenolphthalein. However, efficient colorimeters may assume more complex configurations, as will be shown.

COLOR COMPARATOR

It has been stated that a relatively simple photoelectrically-operated voltmeter, intended for turbidity measurements in chemical analysis, might be used as a rudimentary *colorimeter*.

Figure 8 shows the circuit of an instrument which is applied to the simple measurement of colors. The resistance, R_1, is very high in value, generally of the order of 50 megohms. The photocell is actuated by a light beam passing through a test film on which is smeared the sample color and produces a voltage drop across R_1 proportional to the amount of light reaching it. The tube circuit is that of a simple vacuum-tube voltmeter which measures the voltage drop across the

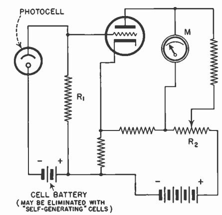

FIG. 8