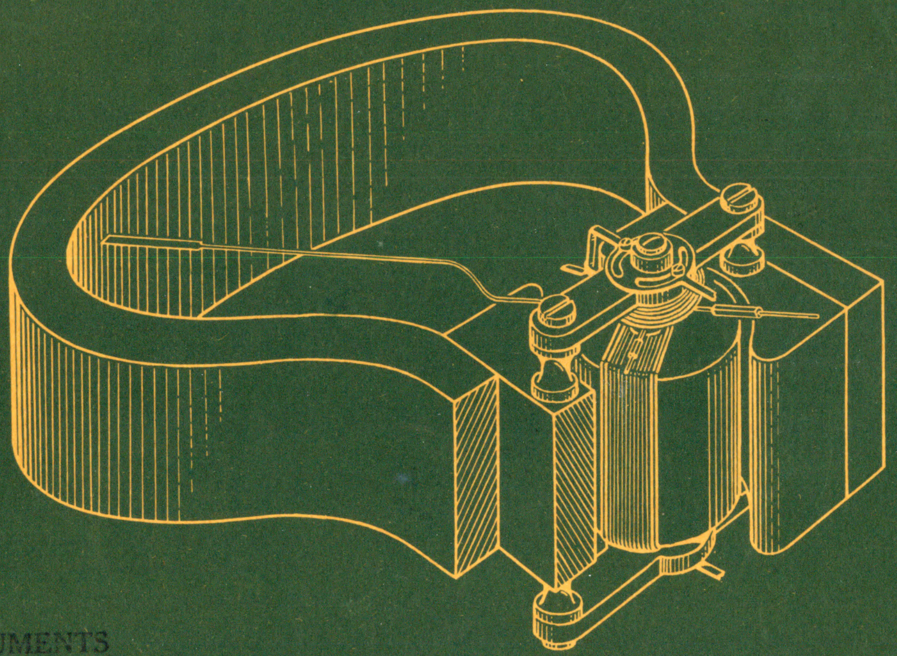
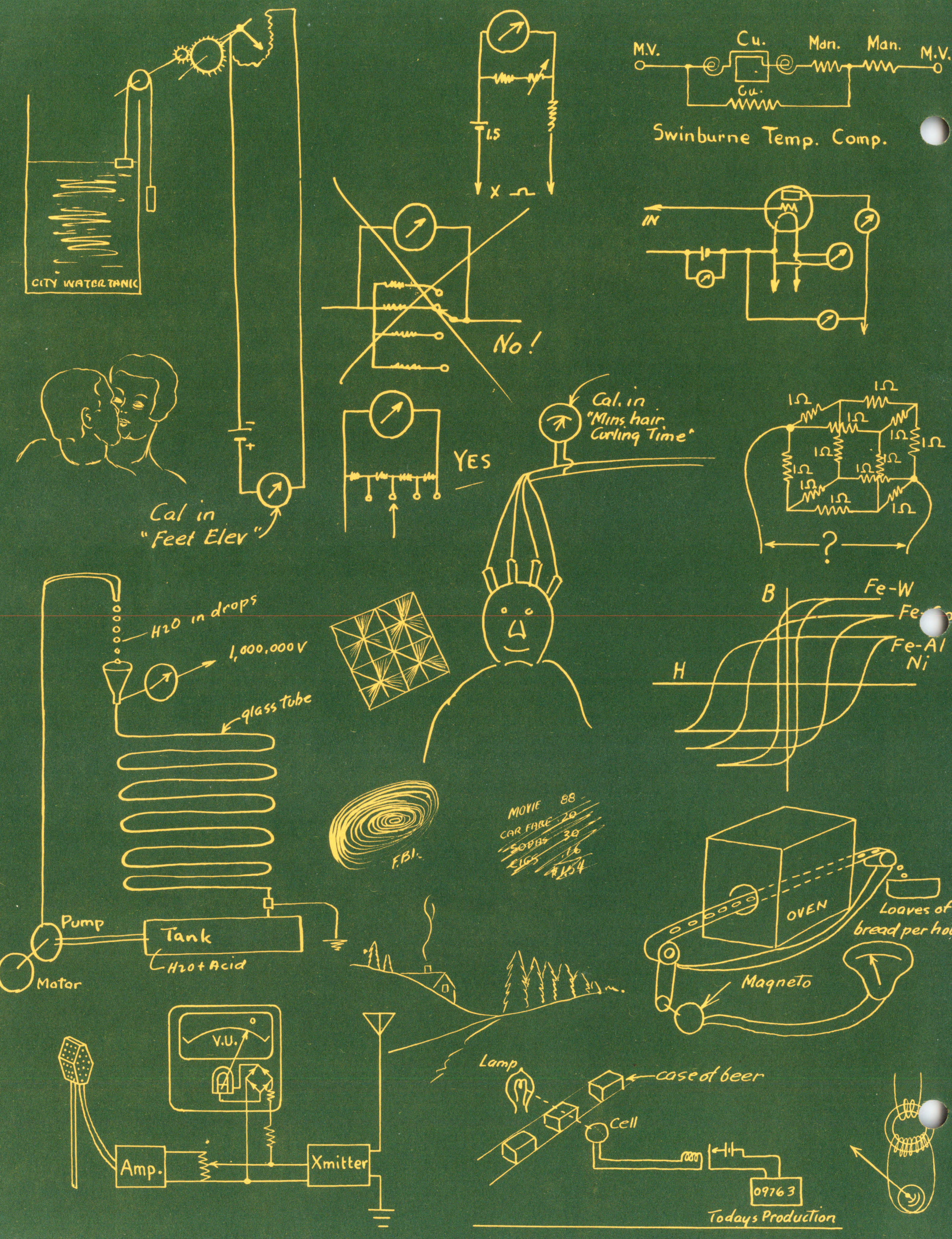
THE INSTRUMENT SKETCH BOOK



WESTON

CIRCULAR E-3-E



CITY WATER TANK
Cal in "Feet Elev"
1.5
X
No!
YES
M.V.
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B
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Fe-Al Ni
H2O in drops
1,000,000V
glass tube
Pump
Tank
H2O + Acid
Motor
F.B.I.
MOVIE 88
CAR FARE 20
SODAS 30
CIGS .16
$1.54
OVEN
Loaves of
Magneto
V.U.
Amp.
Xmitter
Lamp
case of beer
Cell
09763
Todays Production

The Instrument Sketch Book

..............Originally a series of informal sketches of instrument mechanisms, together with explanatory notes compiled to serve as a record of the subjects covered in Weston educational lectures on ELECTRICAL MEASURING INSTRUMENTS.

..............Later arranged in booklet form and dedicated to teachers, students, and all others interested in the principals of operation of these essential tools of science and industry. Revised and expanded from time to time to make this the fifth edition.

The illustrations in this booklet show principles only and are not intended for direct application or repair.

Edited by Henry Berring, Educational Director

WESTON ELECTRICAL INSTRUMENT CORP.

A Subsidiary of Daystrom, Incorporated

NEWARK 5 • N. J. • U. S. A.

THE PERMANENT-MAGNET MOVING-COIL MECHANISM

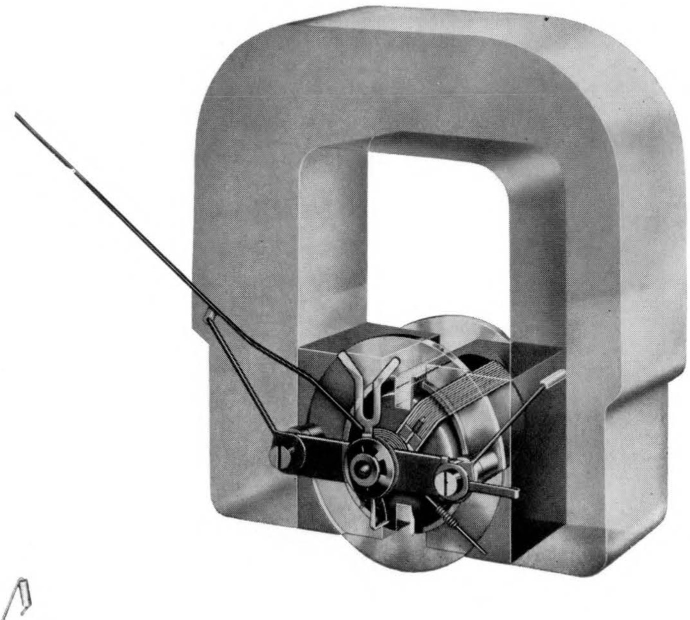
As reduced to practice in the Models 430 and 931

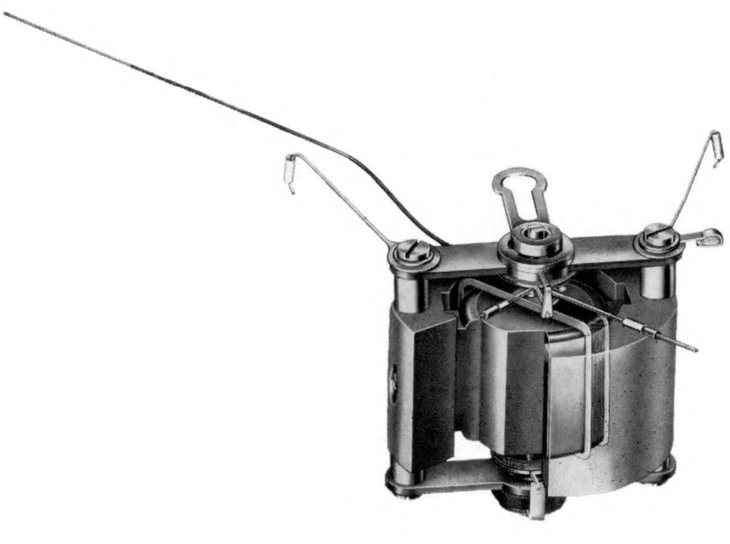
In the manufacture of a device as finely integrated as an electrical measuring instrument the actual fabrication of the parts and their assembly is fully as important as the optimum selection of materials and the best of design.

Fabrication of materials in the Weston plant goes back to fundamentals and in the case of important items such as control springs, the actual alloy is made in our metallurgical department and processed through completely to the final spring. Several large batteries of screw machines allow for the maintenance of the necessary accuracy in small parts. Many of the punch press items are punched and then sheared to size to get the necessary exactness.

Coils are wound from carefully inspected wire, and in many cases are bakelized in an autoclave to produce a solid structure of great rigidity

At the right is the mechanism of the Model 430 — a typical permanent-magnet moving-coil mechanism with U-shaped magnet. This system requires a minimum of electrical energy to move the pointer.





At the left is the mechanism of the Model 931 — a typical permanent-magnet moving-coil mechanism with core magnet. This system is exceedingly compact, light in weight and inherently immune to the effects of external magnetic fields.

THE MOVING-IRON VANE MECHANISM

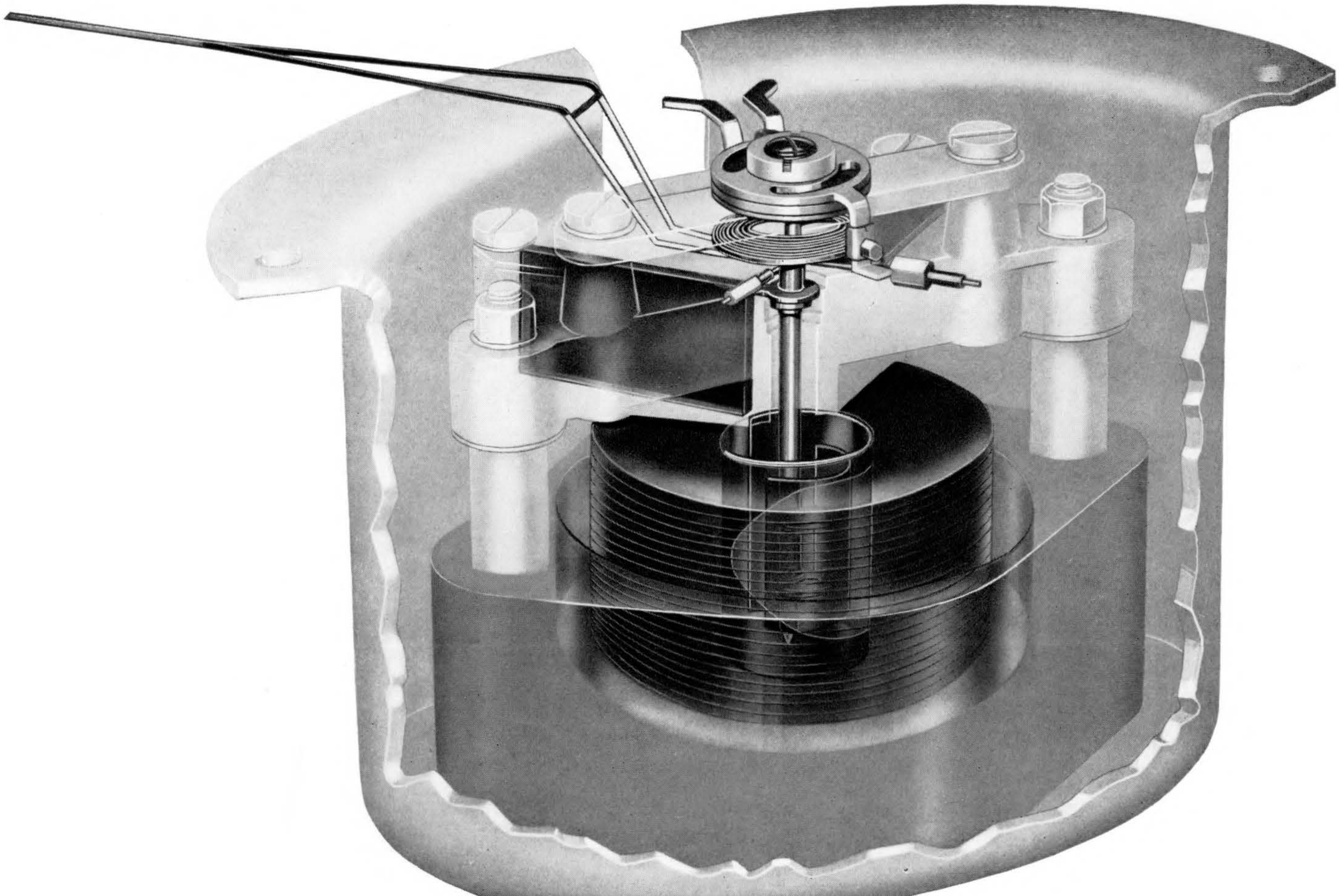
As reduced to practice in the Model 433

and permanence of form. The winding of 1 mil wire on a production basis is a feat rarely attempted but is considered in the Weston plant as just a routine job in the production of high sensitivity instruments.

Instrument assembly proceeds in a rapid and straightforward manner through the use of assembly fixtures for every possible operation which can be expedited and refined by their use. Calibration is against standards always at least five times as accurate as the requirement for the instrument itself, and the standards are all kept in condition by a laboratory charged with this specific job.

But even the development of equipment to function with materials of proper selection and fabrication will not necessarily result in the best product, and it is perhaps to the personnel and their skills which have been developed over a long period of time to which the reputation of Weston instru-

The concentric vane mechanism shown below is used in the Model 433 shown above and is typical of such systems.



THE ELECTRODYNAMOMETER MECHANISM

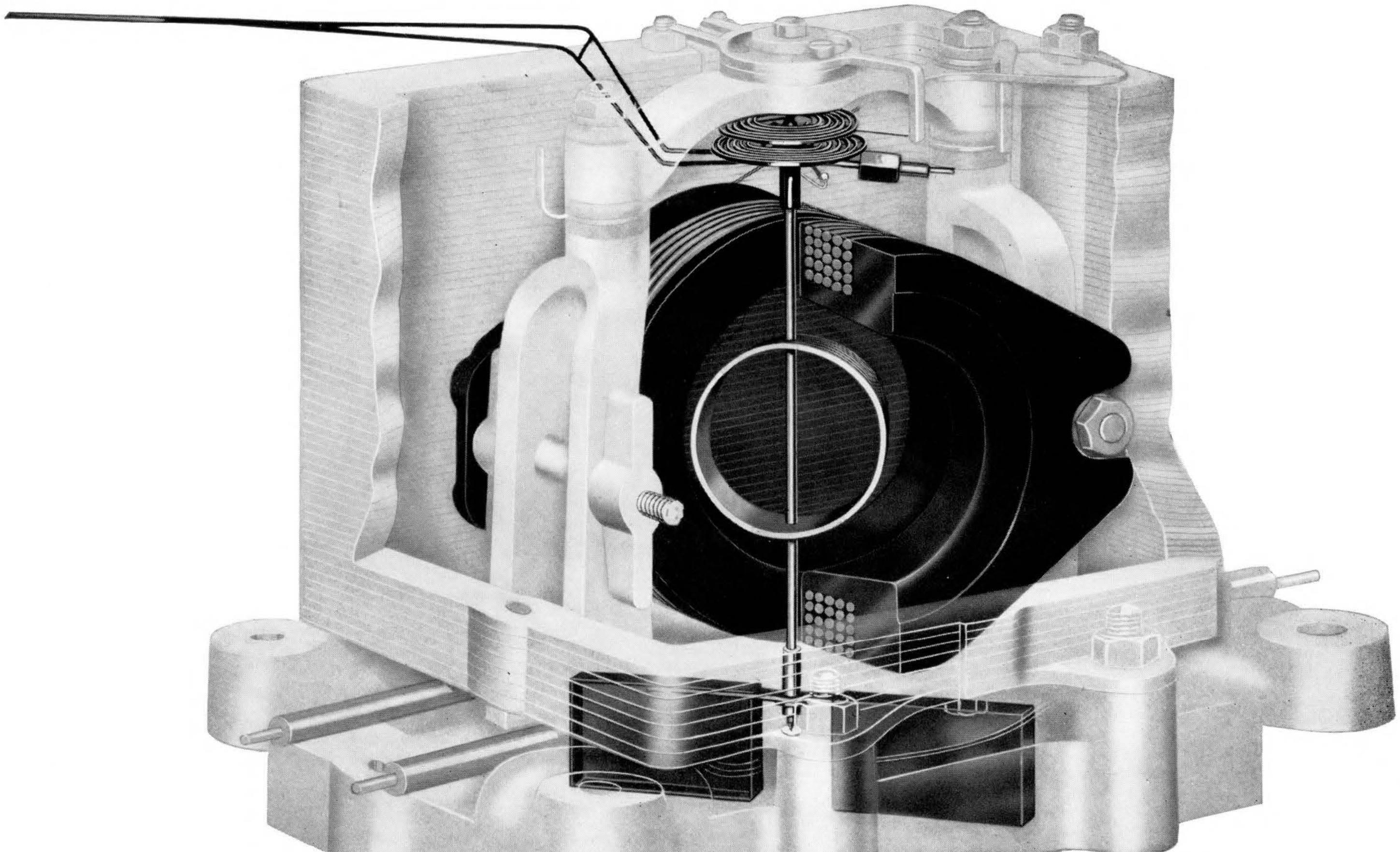
As reduced to practice in the Model 432

ments is due. The great majority of operators have a personal pride in the production of instruments which exceed their required accuracies in terms of both the final electrical result as well as in the tolerances established for the detail parts.

A thoroughly satisfactory instrument must, therefore, be considered as the composite product of the proper materials to start, fabricated with care and accuracy to the optimum designs and assembled and adjusted by a group of people who are honestly endeavoring to make the final product fit the requirements.

Weston has no yearly models and Weston engineers may spend years developing a new instrument. Changes in existing designs are to be avoided rather than encouraged since each change introduces new variables the magnitude of which is not known until years of field experience are passed.

The Model 432 above uses the electrodynamometer movement below which is representative of such systems when arranged for single phase, single moving coil.



The Polarized Iron-Vane Mechanism

The polarized iron-vane system was the first current measuring mechanism to be reduced to practice. Originally dependent upon the earth's magnetic field to provide the control torque it was later made both, more sensitive and more convenient in use by the employment of a permanent magnet. In the form shown schematically in Fig. 5 the mechanism came into use in large quantities as an automobile dashboard ammeter. Better suited to mass production in relatively crude form than to greater refinement, this mechanism has lost its position in the field of electrical instruments and has, instead, made a place for itself in the "indicator" field where precision is not demanded.

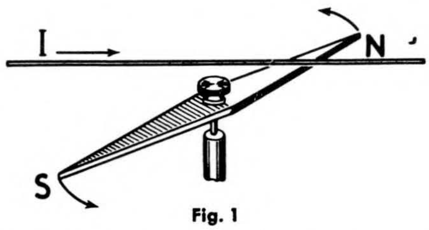


Fig. 1

The original electrical indicator—Oersted—1819.

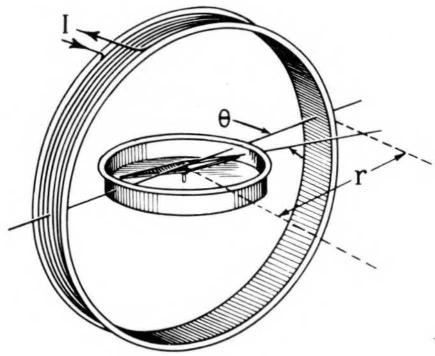


Fig. 2

Tangent Galvanometer, $I = \frac{10\,Hr}{2\pi N} \tan\theta$ amperes.
r = radius of coil.
H = horizontal component of earth's field in gauss.
N = number of turns.

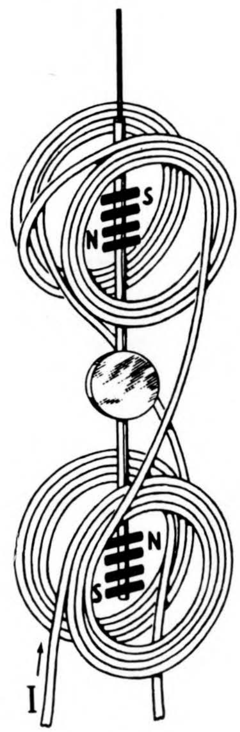


Fig. 3

Early type astatic galvanometer—Kelvin—1858.

Used on early trans-Atlantic cable circuits. Note lower set of needles has reversed magnetic polarity from upper set, thus reducing the restoring force of the earth's field and increasing the sensitivity.

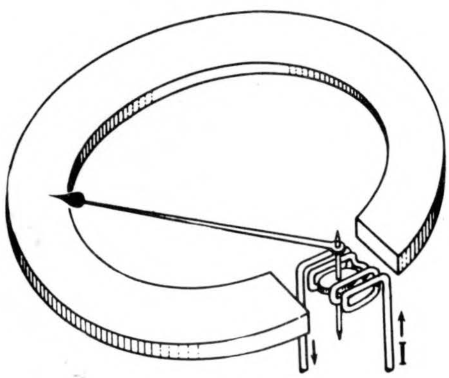


Fig. 4

Simple polarized iron vane mechanism.

Pointer is driven by an iron vane governed by the resultant field of the permanent magnet and that of the current in the coil.

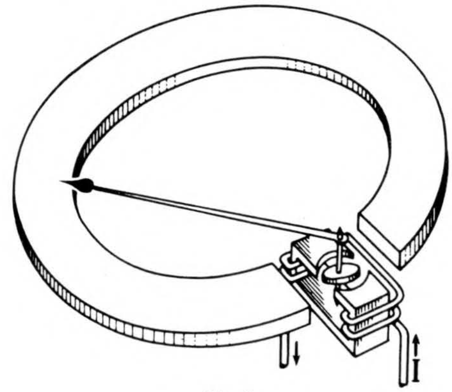


Fig. 5

Complete polarized iron vane mechanism.

Soft iron core adds to sensitivity, requiring fewer turns of wire and improves scale characteristics. Weston prototype—Model 354.

The Moving Iron-Vane Mechanism

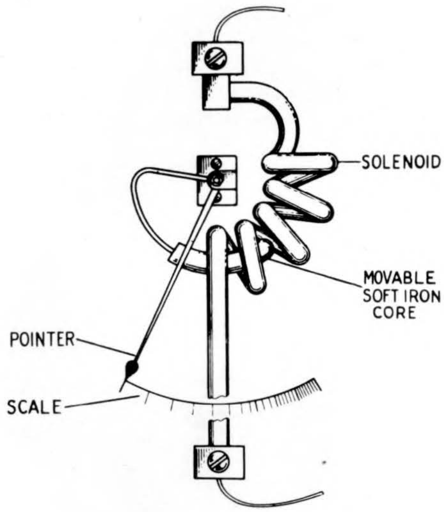


Fig. 6

Early magnetic vane mechanism of the suction type. The opposing force or restoring torque is provided by gravity instead of the present conventional spring. This method was widely used in older instruments. Gravity controlled instruments all had the major disadvantage of being subject to serious position errors.

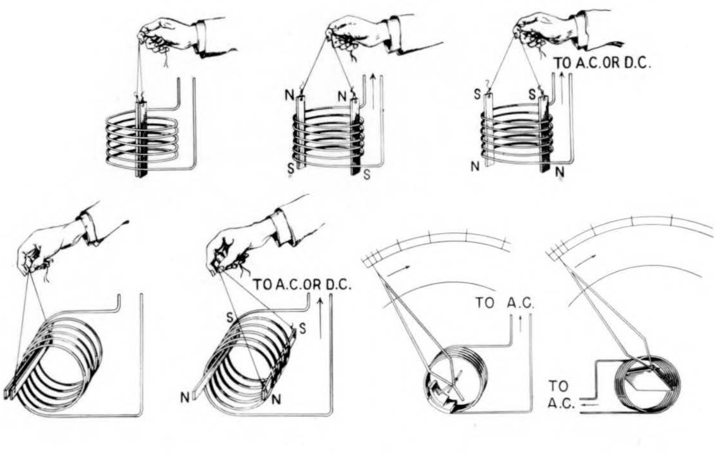


Fig. 7

If two similar adjacent iron bars are similarly magnetized, a repelling force is developed between them which tends to move them apart. In the moving iron vane mechanism this principle is used by fixing one bar in space and pivoting the second so that it will tend to rotate when the magnetizing current flows. A spring attached to the moving vane opposes the motion of the vane and permits the scale to be calibrated in terms of the current flowing.

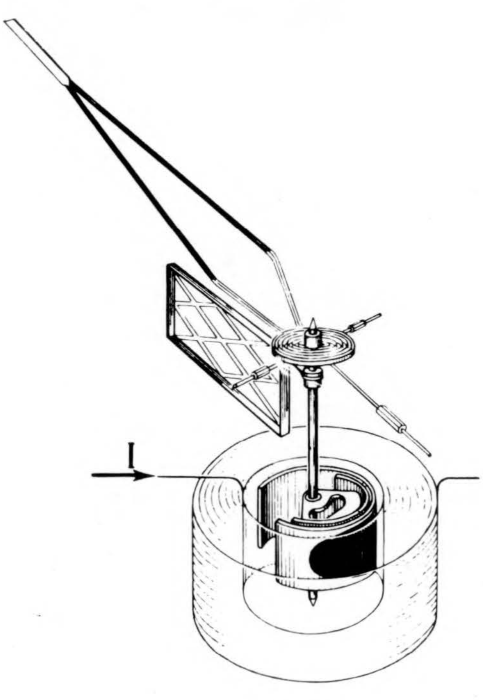


Fig. 8

Concentric vane mechanism—vanes slip laterally under repulsion—only moderately sensitive—square law scale characteristics—short magnetic vanes resulting in small direct-current reversal and residual magnetism errors. With this mechanism it is also possible to shape the vanes to secure special characteristics, thereby opening scale where needed.

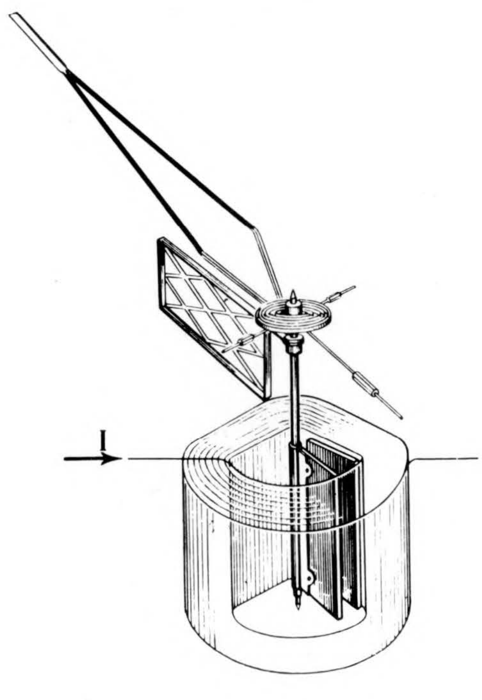


Fig. 9

Radial vane mechanism—opens up like a book under repulsion—most sensitive—most linear scale—requires better design and better magnetic vanes for good grades of instruments. Note the aluminum damping vane, attached to the shaft just below the pointer, which rotates in a close fitting chamber to bring the pointer to rest quickly.

The Electrodynamometer Mechanism

Electrodynamometer mechanisms are the most fundamental of all of the indicating devices now used. Form factor variations do not occur because of the complete absence of magnetic materials such as iron, and the indications are of true rms values. This mechanism is current sensitive—the pointer moves because of current flowing through turns of wire. It is the most versatile of all of the basic mechanisms since the single coil movement as shown can be used to indicate current, voltage, or power, a.c. or d.c., while crossed coil movements can be used for power factor, phase angle, frequency and capacity measurements. Arrangements for these uses are shown on pages 8 and 9.

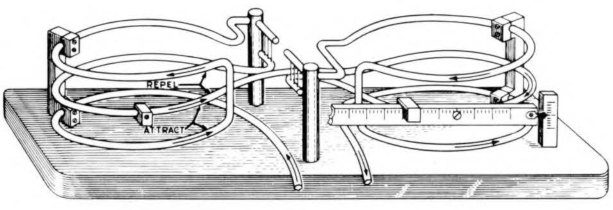


Fig. 10

Current balance—Lord Kelvin—1883.

Like fields repel, unlike attract—thus current can be weighed. This is a simple form of an electrodynamometer mechanism.

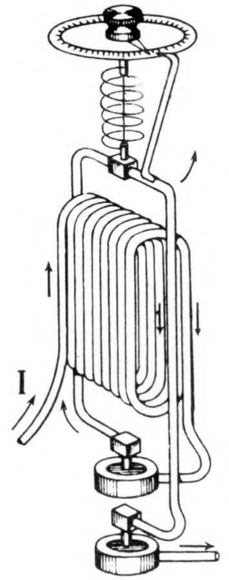


Fig. 11

Early electrodynamometer in which the moving coil was returned to its initial position and the deflection of the spring measured.

Perhaps the most important use of this mechanism is as a transfer instrument between the basic standards of E, I and R, all of which are defined for direct current only, to alternating current in which form most of the power of the world is generated, sold and used.

The torque produced in an electrodynamometer moving coil is proportional to the product of the in-phase components of the currents in field and moving coils; this mechanism measures products.

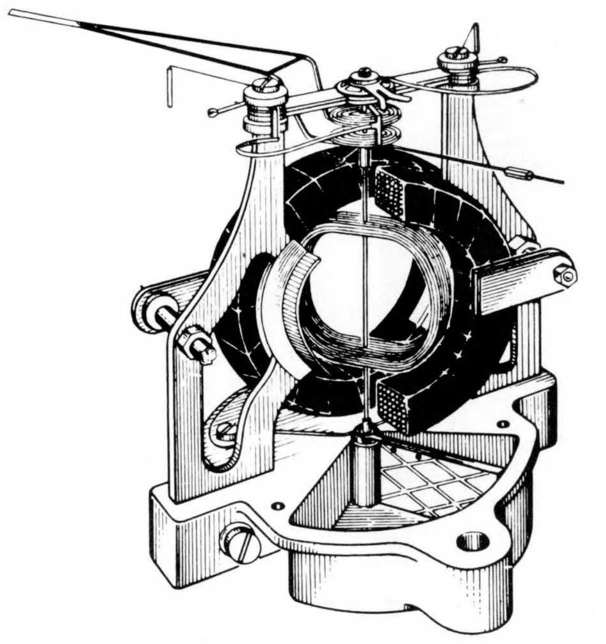


Fig. 12

The Weston Electrodynamometer mechanism shown above is that used in Model 310 wattmeters, Model 341 voltmeters and Model 370 ammeters. With a longer pointer and other minor changes it is the mechanism used in the Model 326 laboratory standard. With the further modification of crossed moving coils, shown schematically on pages 8 and 9, fundamentally the same mechanism is used for measurements of power factor, phase angle and capacity. In this form or with crossed field coils this mechanism measures a ratio by balancing two torques.

Damping vanes similar to those used in moving iron instruments (Figures 8 and 9) rotate in close fitting chambers and provide proper damping for the pointer motion.

If two complete field coil systems are arranged one above the other, each including and acting upon its own moving coil, and if the two moving coils are attached to a common shaft which carries the pointer, the mechanism can be used to measure the total power in a polyphase a-c system (see Figs. 14 through 14d on page 8).

Coil Arrangements in Electrodynamometer & Similar Mechanisms

Physical Arrangement of Coils

SINGLE ELEMENT TYPE

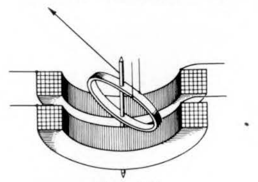


Fig. 13

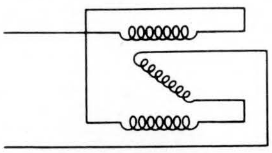


Fig. 13a Milliammeter-Voltmeter

Fixed and moving coils in series for milliammeter, combination in series with a resistor unit for voltmeter.

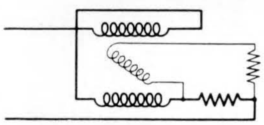


Fig. 13b Ammeter

Fixed coils in series with a resistor which is provided as a shunt for the moving coil.

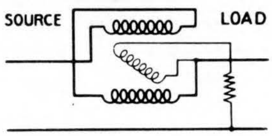


Fig. 13c Wattmeter

Fixed coils in series with the load—moving coil with suitable series resistor connected across the load, or source. Across load, reading includes m. c. circuit power —across source reading includes fixed coil circuit power.

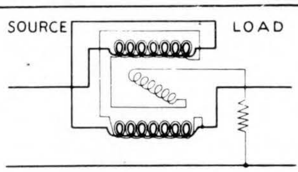


Fig. 13d Wattmeter (Compensated)

Fixed coils incorporate two windings — a heavy winding connected in series with the load—a fine winding connected in series with the moving coil to cancel the effect of the m. c. current, thus resulting in an indication of true power.

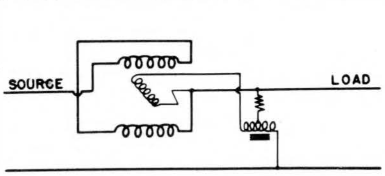


Fig. 13e Single Phase Varmeter

Resembles single phase wattmeter (fig. 13c) But current in moving coil is rotated 90° in time phase.

DOUBLE ELEMENT TYPE

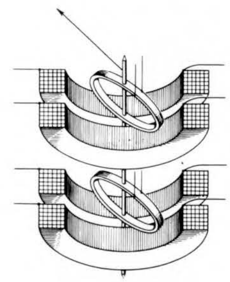


Fig. 14

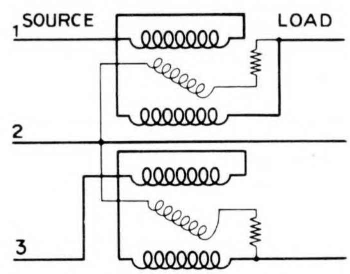


Fig. 14a Polyphase Wattmeter
(2 element type)

Blondels' Theorem states that true power can be measured by one less wattmeter element than number of wires of the system providing one wire can be made common to all element potential circuits. Above connections are suitable for single phase, 3 wire—2 phase, 3 wire—3 phase, 3 wire.

Two phase, 4 wire requires separate connections of potential circuit.

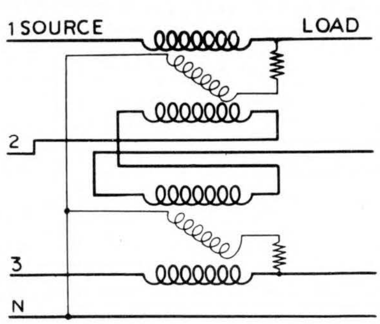


Fig. 14b Polyphase Wattmeter
(2½ element type)

Above arrangement constitutes a compromise on Blondels' Theorem for measurement of 3 phase, 4 wire system power—will indicate true power providing voltages are balanced. Called 2½ element because of split connection of fixed coils. Note current in line 2 passes thru both upper and lower element, in reverse direction, but is displaced in phase by 60° —its effect is thus half. Summation of two elements equals third element required.

DOUBLE ELEMENT TYPE (Cont.)

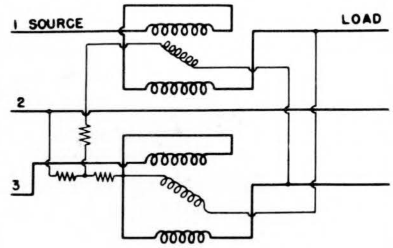


Fig. 14c Polyphase Varmeter for
3 Phase 3 Wire System
(2 element type)

This and the 4 wire version below resemble the polyphase wattmeters of figures 14a and 14b except moving coil connections produce currents 90° rotated in time phase.

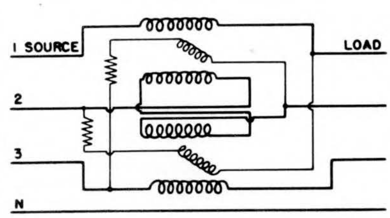


Fig. 14d Polyphase Varmeter for
3 Phase 4 Wire System
(2½ element type)

CROSSED COIL TYPE

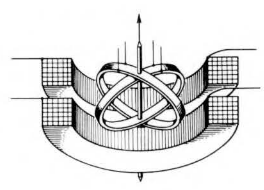


Fig. 15

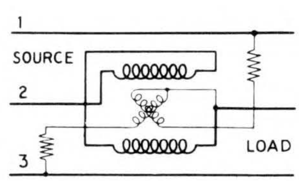


Fig. 15a Power Factor Meter
(3 phase type)

Crossed moving coils are connected to opposite legs of a 3 phase system—Fixed coils connected in series with line used as common for moving coil connection. Moving system assumes a position depending on power factor of circuit. Correct for balanced loads only.

Coil Arrangements in Electrodynamometer & Similar Mechanisms

Physical Arrangement of Coils (Cont.)

CROSSED COIL TYPE (Cont.)

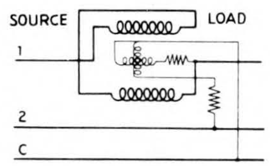


Fig. 15b Power Factor Meter (2 phase type)

Essentially similar to 3 phase except pointer is mounted in line with inner coil. Fixed coils not in the common line.

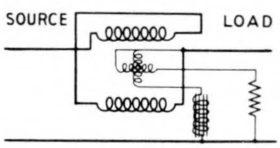


Fig. 15c Power Factor Meter (Single phase type)

Essentially similar to two phase type except that a reactance phase shifting network is used in series with the vertical moving coil.

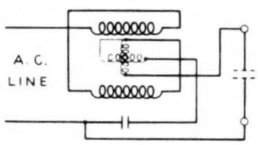


Fig. 15d Microfarad Meter

Two phase mechanism arranged to measure capacity. Ratio of current through test condenser and through standard condenser determines position of movement.

DOUBLE ELEMENT CROSSED COIL TYPE

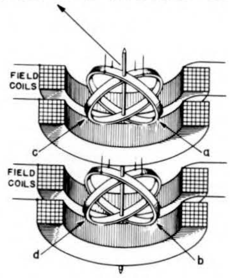


Fig. 16

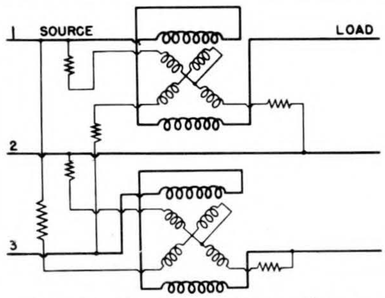


Fig. 16a Vector Power Factor Meter for 3 Phase 3 Wire System (2 element type)

By combining essentially the features of a 2-element polyphase wattmeter (fig. 14a) with those of a similar polyphase varmeter (fig. 14c) an instrument can be made whose moving system will assume a position depending on the ratio of vars to watts in a circuit. This ratio is called the vector power factor. Vector power factor meters will measure this quantity correctly even if the currents in the lines are not balanced.

By similarly combining the feature of 2½ element wattmeter and varmeter it would be possible to make a vector power factor meter for 3 phase 4 wire service.

CROSSED FIELD TYPE

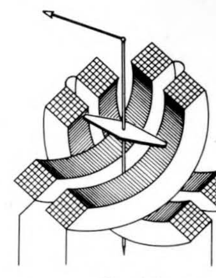


Fig. 17

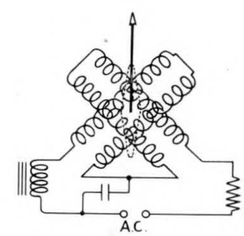


Fig. 17a Frequency Meter

Crossed coils are connected to the line through inductive and capacitive circuit elements so that the relative strength of the two fields becomes a function of frequency. A freely rotatable iron vane will seek the direction of the resultant field. Pointer attached to same shaft as vane will indicate frequency. This is not strictly an electrodynamometer but resembles it in form.

The Hot-Wire Mechanism

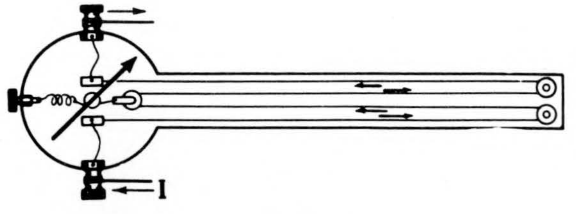


Fig. 18

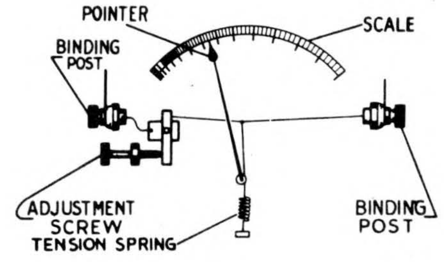


Fig. 19

Cardew voltmeter—earliest hot wire instrument—consisted of a platinum silver wire of small diameter long enough to give resistance to connect directly across circuit being measured and looped over pulleys arranged to cause rotation of a pointer as the wire expanded due to current flow.

In the hot wire ammeter the current being measured caused a wire to heat and thus expand approximately in proportion to I^2. The change in length of the wire was arranged to drive the pointer. Instability due to wire stretch and lack of ambient temperature compensation have made this mechanism commercially unsatisfactory.

Hot wire mechanisms are now obsolete as such, being replaced by the more sensitive, more accurate, and better compensated heating element—permanent-magnet moving-coil combination, known as thermo instruments.

The Hot Wire Mechanism (Cont.)

Thermo instruments measure the effective value of the current flowing; can be used on d.c., a.c., audio or radio frequency; and are used extensively where wave forms or frequencies encountered are such as to cause errors in other types of indicators.

No standard ampere at radio frequency being available, thermo instruments are generally calibrated at 60 cycles, sine wave. Instruments giving excellent performance up to 100 megacycles are available.

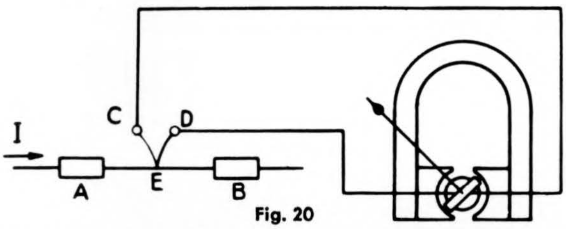


Fig. 20

Basic type of heating element and permanent-magnet moving-coil mechanism for the indication of d.c., a.c. and r.f. A potential is generated in the junction E of the dissimilar metals ED and EC as the current heats the junction. This potential causes a d-c current to flow through the indicating mechanism, which is a function of the heating current in AB. This arrangement provides no compensation for ambient temperature changes.

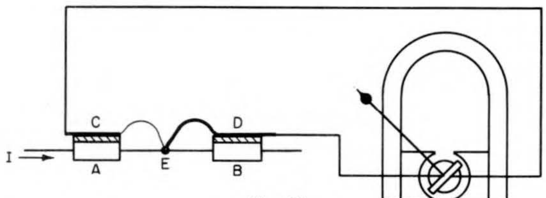


Fig. 21

The Weston compensated heating element produces a thermo-electric voltage in the couple CED which is a function of the current "I" flowing through the circuit AB and causes a temperature rise at point E. Since the couple voltage developed is a function of the temperature difference of its hot and cold ends this temperature difference must be caused only by the current being measured. For accurate measurement, then, points C and D must be at the mean temperature of points A and B. This is accomplished by attaching the couple ends C and D to the center of separate copper strips whose ends are thermally in contact with A and B but which are electrically insulated from them. Fig. 22 shows the physical arrangement of the strips.

The scale of the indicator can be calibrated with evenly spaced divisions in terms of I^2 or with a square law arrangement of divisions—cramped at the left—in terms of I in AB since heating is a function of the square of the current producing the heat. More nearly evenly divided scales can be had with specially shaped pole pieces. (See Figure 43, page 15).

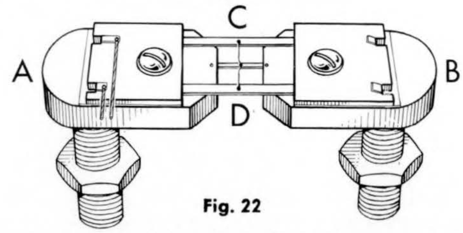


Fig. 22

Weston compensated heating element as used commercially for .5 to 20 amperes in self-contained instruments. Higher ranges are of similar construction except that the heating element is supplied external to the indicator and the connecting lugs are in line with the heating wire or element. Ranges over 60 amperes are provided with air cooling fins. The heating wire .5 to 3 amperes is solid—above 3 amperes it is tubular to reduce skin effect errors.

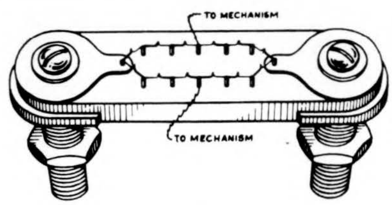


Fig. 23


Fig. 24

Bridge type heating element (Fig. 23) used for currents from .1 to .75 amperes. In this arrangement the voltage generated by a number of junctions is used to drive current through the indicator. Ranges .0015 to .1 ampere use simple heating elements in small vacuum containers, Fig. 24.

The Thermal Watt Converter

A thermocouple arrangement distantly related to the bridge type heating element is used in the thermal watt converter. This device permits the measurement of power by thermoelectric means.

From the principles of geometry it can be shown that the sum S and the difference D of two vectors e and i which enclose the angle φ are,

$$S^2 = e^2 + i^2 + 2\,ei\cos\varphi$$
$$D^2 = e^2 + i^2 - 2\,ei\cos\varphi$$

so that

$$S^2 - D^2 = 4\,ei\cos\varphi$$

If e and i represent momentary values of voltage and current respectively and φ the phase angle, a circuit arrangement capable of measuring $S^2 - D^2$ can, therefore, be used to measure a quantity proportional to $ei\cos\varphi$ which represents the power.

Fig. 25 shows such a circuit. If momentarily the direction of current from the current transformer secondary is that

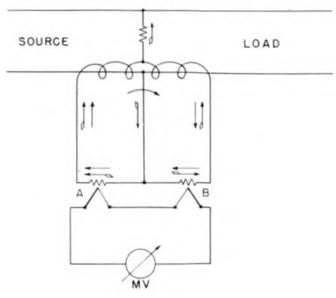


Fig. 25

The Thermal Watt Converter (Cont.)

of the plain arrows and, simultaneously, the direction of current in the potential circuit that of the flagged arrows, it follows that in the insulated heater of one thermocouple (A) these currents aid each other (sum S) while in the other (B) they oppose each other (difference D).

The heat generated in the thermoelement heaters and, through proper design, the temperature differences between hot and cold junctions and thus the electromotive forces of the couples are proportional to the squares of the currents (S and D respectively) in the heaters. The outputs of elements A and B are connected in opposition, hence the total electromotive force developed will be proportional to $S^2 - D^2$ which, as shown, represents the power.

In practice, chains of couples are used instead of single couples, in order to obtain greater electromotive forces, and the couples are self-heated similar to those of bridge type heating elements. This results in an arrangement schematically shown in Fig. 26.

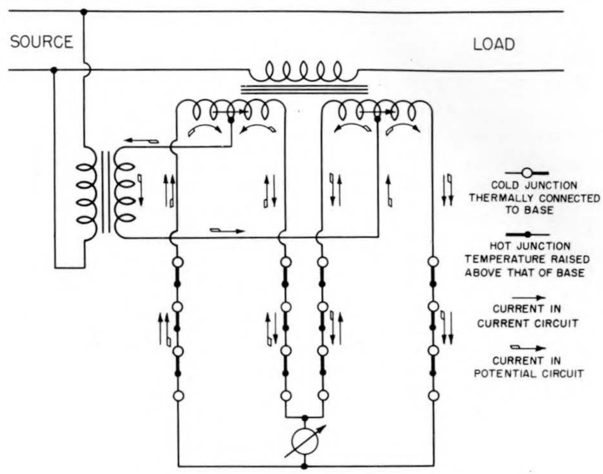


Fig. 26

The Electrostatic Mechanism

The electrostatic mechanism resembles a variable condenser. Of all the mechanisms used for electrical indications it is the only one that measures voltage directly rather than by the effect of current.

Its torque resulting from the attraction between fixed and moveable plates is a function of the voltage between the plates, the plate area and, inversely, the distance between plates. For greater sensitivity this distance must be reduced, clearances permitting, or the plate area (and thus the weight) must be increased. Greater weight, in turn, calls for still greater plate area if sufficient torque is to be developed to overcome pivot friction in most industrial applications. This limits the use of the instrument to certain special applications, particularly in a-c circuits of relatively high voltage, where the current taken by other mechanisms would result in erroneous indications. A protective resistor is used in series with the instrument to limit current flow in the event of a short between plates.

Fig. 27

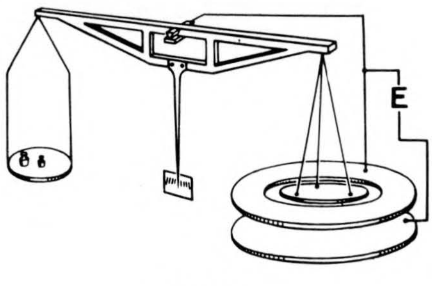


Fig. 28

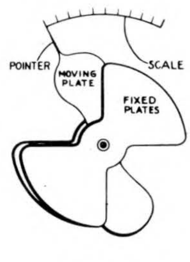


Fig. 29

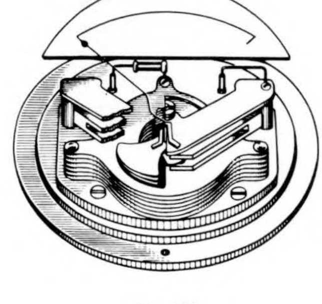


Fig. 30

Gold leaf electroscope (Fig. 27)—like charges on the ends of the leaf cause a separation of the ends. A very sensitive indicator but not an instrument.

Fig. 28 shows a form of the attracted disc electroscope as devised by Sir William Snow Harris in 1834. Guard ring around the disc serves to prevent non-uniformity in the electrostatic lines of force.

A very large example of the attracted disc electrometer mounted in a shielded cage and using quartz pillar supports is used at the National Bureau of Standards for voltage standardization up to 300,000 volts. Using this high voltage electrometer, the ratio of transformation of high voltage potential transformers has recently been checked for the first time by an independent method.

Principle of early electrostatic mechanism (Fig. 29) was devised by Lord Kelvin in 1887. Moving and fixed plates attract each other causing moving plate to rotate against the torque of a control spring (not shown). Position of balance thus becomes a measure of the potential applied. In contemporary form (Fig. 30) such instruments in 3½″ panel size are made with multiple sets of plates, in ranges from 150 to 3500 volts (Ferranti, England).

The Permanent-Magnet Moving-Coil Mechanism

Suspension Galvanometer

The suspension galvanometer shown in Fig. 31 is an early type of moving-coil instrument. A coil of wire is suspended in a magnetic field and will rotate when it carries an electric current (see Fig. 32 for the theory of this effect). The fine filament suspension of the coil serves to carry current to and from it, and its elasticity sets up a moderate torque in opposition to the rotation of the coil. The coil will deflect until its electro-magnetic torque balances the mechanical torque of the suspension. A mirror attached to the coil deflects a beam of light, causing a spot of light to travel on a scale at some distance from the instrument. The effect is that of a pointer of great length but of no mass.

With modern refinements the suspension galvanometer is still widely used for certain laboratory work where extreme sensitivity is required and the delicacy of the instrument is not objectionable.

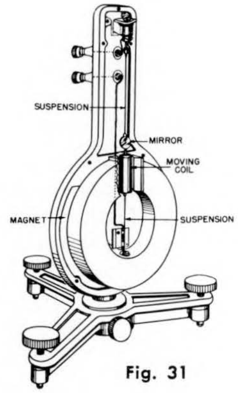


Fig. 31

The Permanent-Magnet Moving-Coil Mechanism

Double Pivoted "U" Shaped Magnet Type

Many persons over a period of more than 130 years have contributed to the permanent-magnet moving-coil mechanism as it is used today. Oersted (1819) discovered the relation between current and magnetism; Faraday (1821) learned that a current carrying conductor would rotate in a magnetic field; Ampere (1821) worked out the laws governing the strength of currents; Sturgeon (1836) first suspended a coil in a magnetic field forming a moving coil galvanometer; Kelvin (1867) placed a soft iron core in the center of the coil shortening the air gap, increasing the sensitivity of the device and improving the scale characteristics; D'Arsonval (1881) patented an instrument of this type; Weston (1888) discovered that the factors governing the permanency of a magnetic circuit lay in the circuit rather than in the magnet, added the soft iron pole pieces and current carrying control springs, and made the first commercial double pivoted permanent-magnet moving-coil instruments as such.

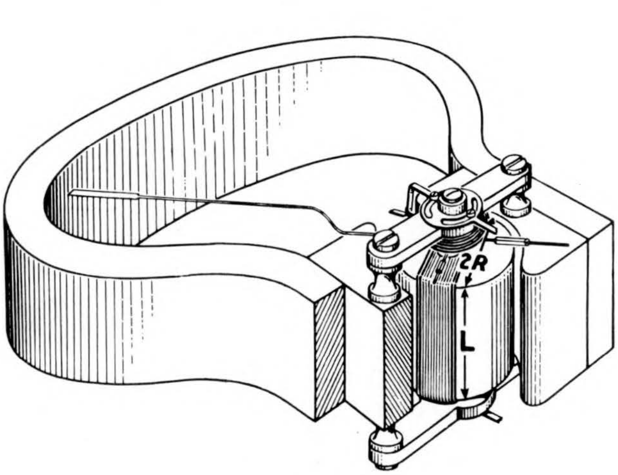


Fig. 32

Since 1888 there have been no changes in basic theory or design of this structure, but numerous changes in materials and technique have increased available sensitivities by 125,000 fold. Few devices in any field can show this improvement; 10 Milliamperes full scale (12500 microwatts) in 1888, .005 milliamperes (.1 microwatt) in 1933, each on a scale of 5.2".

The torque developed by current flowing through the moving coil is given by

$$T = \frac{B2RLIN}{10} = \frac{BAIN}{10}$$

where T = Torque in dyne centimeters
B = Flux density, lines/sq. cm. in air gap
A = Coil area in square centimeters
I = Moving coil current in amperes
N = Turns of wire in moving coil

Instrument torque is usually expressed in milligram centimeters for 100° deflection. Torque in milligram centimeters is equal to dyne centimeters $\times \frac{1000}{981}$

Average torques are:
Model 1 350 mg.cm/100° with 1.9 gram move.
Model 301 18 mg.cm/100° with 200 mg. move.

The generally accepted criterion for the permanency of a permanent magnet is

$$K = \frac{Lm.Ag}{Am.Lg}$$

where K = permanency constant
Lm = effective length of the magnet
Ag = area of the gap
Am = cross sectional area of the magnet
Lg = length of the gap (sum of the two sides)

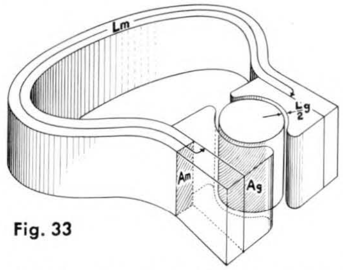


Fig. 33

The value of the permanency constant is associated with the various grades of magnetic materials and may be roughly considered as 100 for tungsten steel, 30 for cobalt steel and 12 for Alnico, all presumably properly heat treated, magnetized and aged. Small changes in steel analysis as well as leakage factors in specific designs may modify the above criteria and for best design a rather complete knowledge of all factors is required.

The Permanent-Magnet Moving-Coil Mechanism
Double Pivoted "U" Shaped Magnet Type (Cont.)

A permanent-magnet moving-coil mechanism is not independent of temperature by itself but may be made so by the appropriate use of proper series and shunt resistors of copper and manganin. Magnets and springs decrease in strength and copper increases in resistance with increase in temperature. The changes in the magnet and the copper tend to make the pointer read low on fixed voltage impressed while the spring change tends to cause the pointer to read high. The effects are not identical, however, with the result that an uncompensated mechanism tends to read low by approximately 0.2 percent per degree centigrade. For purposes of specification an instrument is considered compensated when the change in accuracy due to 10 degrees change in temperature is not more than ¼ of the total allowable error.

The Permanent-Magnet Moving-Coil Mechanism
Core Magnet Type

The discussion on the permanent magnet moving-coil mechanism of the "U"-shaped magnet type on page 12 is basic and valid for any form of moving coil system, without regard to the particular arrangement of the magnetic structure itself. The basic explanation was made with the conventional magnetic system embodying relatively large external horseshoe magnets such as those which have been used for something over a half century. However, instrument engineers have sought for more powerful permanent magnet material in order that more compact magnetic structures could be used.

In recent years these desirable magnetic materials have been made available. With the advent of the Alnico types, heat treated to produce an alignment of the magnetic domains, the long sought design is now possible.

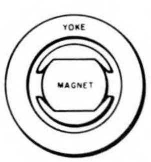


Fig. 34

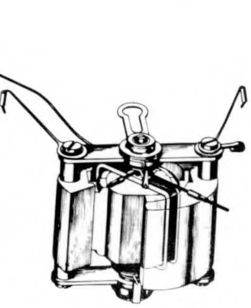


Fig. 35

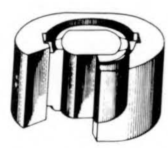


Fig. 36

Now the magnet can be placed inside the moving-coil. References to this desirable feature seem to have been made as early as in the disclosures of D'Arsonval in 1870, although at the time an outside magnet was used. Experimental structures of this sort were studied in the Weston Laboratories as far back as 1935; when the better steels became available, plans were made to produce a core magnet system of this general type.

As might be expected, the detailed design was not simple. A great deal of study was involved in the proportioning of the magnet, the pole shoes, and the return path or yoke. Production during 1948 employed a structure as shown schematically in Fig. 34. The final production design in 1949 is shown in Fig. 35, with the magnetic system detail shown in Fig. 36. It will be noted that the length of the active portion of the magnet is uniform, giving uniform magnetomotive force to the magnetic circuit. The magnet bulges on its sides and the material in these bulges essentially supplies the leakage flux of the sides of the system. The pole piece horns extend outward to furnish a uniform field of flux into the air gap; this is accomplished by the degree of taper, both of the pole tips as well as of the air gap between the pole tips and the magnet. Obviously a design of this kind must be a co-ordinated whole, so that the net result will be an instrument having a uniform field of flux over a large deflection angle.

The system as used in the Weston Model 931 is shown diagrammatically in Fig. 35. It should be noted that in this construction the moving-coil is in line with the pointer. The criterion for permanency of the magnet system must necessarily be somewhat modified because the complete enclosure around the magnet enormously reduces the leakage and gives a protection to the magnet beyond a mere consideration of pure dimensional ratios.

Possibly of greatest importance is the high degree of shielding obtained. It will be noted that flux entering in any direction from some outside source is carried around the magnetic system by the yoke so that it does not enter the air gap and affect the reading.

To gain some picture as to degree of shielding, a 5-oersted field, commonly used for testing, is obtained at a distance of about 16″ from a conductor carrying 1,000 amperes. Such a field will affect an unshielded instrument varying amounts up to 2%; however, it will cause no permanent error. By shielding, as in the Weston Model 622, or through the use of the core magnet principle, the effect of a 5-oersted external field cannot be seen.

Taking another step, let us assume a 50-oersted field which is obtained 16″ away from a 10,000-ampere conductor, or approximately 7 feet from a 60,000-ampere conductor, the unshielded conventional instruments, depending on their detailed design, will be in error from 25 to 50% and may have a permanent change anywhere from 2 to 5%. However, either a well-shielded conventional mechanism, as in Model 622, or the self-shielded core magnet mechanism will show less than 1% transient error and a negligible permanent error.

Special shielding around a magnetic system is always costly in weight and space; but even worse is the fact that the shield necessarily reduces the available flux in the air gap if it is at all effective and of reasonable dimensions. With the core magnet mechanism, the shielding effect is obtained without increasing cost, size or weight, and without loss of flux!

Perhaps a word should be said here about permanence. The very fact that the instrument is relatively immune, inherently, to the effect of external fields, means that it is, by the same token, very stable magnetically. Jolts and jars which might affect conventional magnetic systems have no effect on the core magnet system.

The Permanent-Magnet Moving-Coil Mechanism

As An Amplifier Component†

A unique application of the permanent magnet moving coil mechanism is its use as an electromechanical link in an amplifier.* Its function is that of an error sensing element and converter (for an explanation, refer to page 16) capable of converting d-c to a-c with a power gain rather than the power loss common to most such devices. The following explanation is a deliberate simplification of principle and design in the interest of clarity.

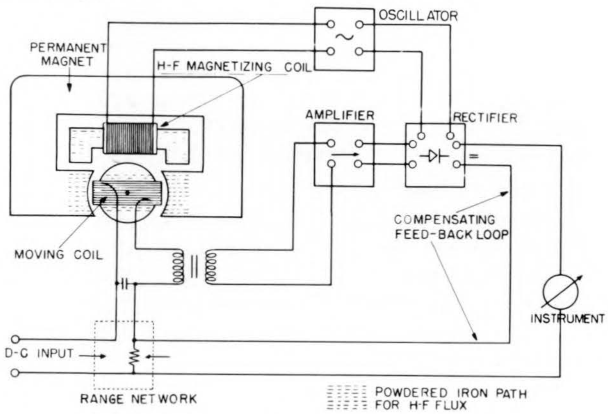


Fig. 37

The magnetizing coil (Fig. 37) on the powdered iron bridge across the permanent magnet is energized from a vacuum tube oscillator. The powdered iron path conducts the h-f magnetic field across air gaps and moving coil, superimposed on the permanent magnet field. Neither flux path accepts much of the flux of the other due to their different magnetic properties.

Direct current from the d-c input causes the moving coil to deflect and thus changes its coupling with the h-f flux. This change regulates the amount of h-f energy carried back into the compensating feedback loop via amplifier and rectifier.

The range network injects a portion of the feedback current back into the moving coil circuit in opposition to the d-c input. The moving coil connections are essentially torqueless, hence the coil will seek a balance position where the electrical torque is zero. Due to the presence of alternating current in the moving coil the balance is not affected by bearing friction.

When the moving coil is in the balance position the current through the indicating instrument is an accurate measure of the d-c input, but the energy available for measurement may be many million times that supplied by the input source. The system is self compensating (always seeks its own balance) and operates as a d-c amplifier of perfect linearity and stability with an amplification (range) determined only by resistance relationships in the range network.

A refinement of the actual design provides increased electromagnetic sensitivity (less moving coil deflection for the same effect). The h-f voltage induced in the moving coil, properly injected into the vacuum tube circuit of the oscillator, has an effect equivalent to changing the inductance-capacitance ratio in the oscillator tank circuit and thus changes its frequency; (see August Hund, FREQUENCY MODULATION, McGraw Hill Book Company, New York, 1942). A frequency sensitive network (discriminator) in the amplifier output varies the phase relationship in the branches of the rectifier circuit and thus varies the d-c output as a function of frequency (phase rectification). The self compensating effects of moving coil rotation upon feedback current and vice versa are the same as previously described.

*INDUCTRONIC® AMPLIFIER

†See, The Induction Galvanometer, A Sensitive Instrument Converter, by R. W. Gilbert, AIEE Transactions, Vol. 70, 1951.

The Permanent-Magnet Moving-Coil Mechanism

Design Details

Fig. 38

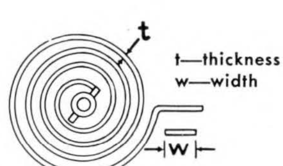


Fig. 39

A typical moving coil for a "P.M.M.C." system. Most voltmeter coils have metal frames for damping—a short circuited turn in a magnetic field; most ammeter coils are frameless—the coil turns are shorted by the shunt. Pointers, springs, and pivots are assembled to the coil by means of pivot bases. The moving system is statically balanced for all positions by three balance weights.

Two phosphor bronze springs, normally equal in strength, provide the calibrated force opposing the moving coil torque. Constancy of performance is essential to sustained accuracy. Permanent set is avoided by establishing a length to thickness ratio of over 1500. Torque of piece of spring material is given by the following equation:

$$\text{Torque} = \frac{\text{constant} \times \text{width} \times (\text{thickness})^3}{\text{length}}$$

From this law it follows that spring thickness must be very accurately controlled in manufacture if the finished spring is to be of the required torque.

The Permanent-Magnet Moving-Coil Mechanism

Design Details (Cont.)

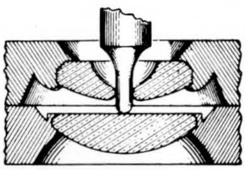


Fig. 40
Ring and End Stone Jewel Bearing

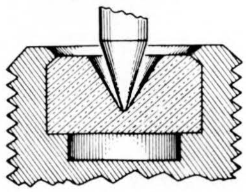


Fig. 41
V Jewel Bearing

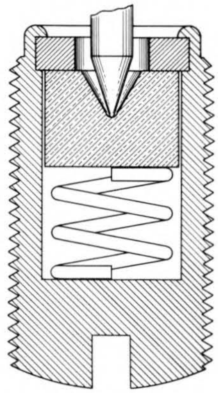


Fig. 41A
Spring-back Jewel Bearing

Jeweled bearings for fine mechanisms and particularly clocks and watches were invented by Nicholas Facio, a Swiss watchmaker, about 1705. Such bearings in timepieces were used because of their low friction, but their form must be such as to keep the tiny teeth of the gears constantly in mesh. A ring jewel is, therefore, necessary to maintain the alignment with the table jewel for end thrust. The jewels are mounted in the watch plates as shown in Figure 40.

For instrument bearings the ring jewel produces entirely too much friction and the V jewel as shown is almost universally used. The pivot may have a radius at its tip from .0005″ to as high as .003″ depending upon the weight of the mechanism and the vibration it will encounter. The radius of the pit in the jewel is somewhat greater so that contact is in the form of a circle a fraction of a thousandth across. The design shown in Fig. 41 has the least friction of any practical type of instrument bearing.

Although the moving elements of instruments are designed to be of lowest possible weight, the minute contact area between pivot and jewel results in large stresses for which the bearing must be designed. For example, a moving element weighing 300 milligrams resting on the area of a circle of .0002″ diameter produces a stress of about 10 tons per sq. inch (20,000 pounds per sq. inch).

If the load is further increased, the contact area will not rise in equal measure so that the stress will grow. Stresses set up by relatively moderate accelerations (jarring or dropping an instrument) may cause pivot damage (friction) except in instruments specially protected (ruggedized).

The jewel bearing in some of the ruggedized instruments is frequently made as shown in Fig. 41A. It is located in its normal position by the spring and may move axially when the shock to the mechanism becomes severe.

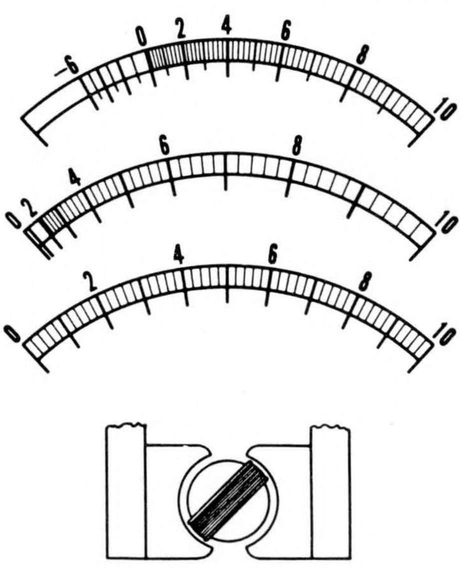


Fig. 42

The conventional permanent-magnet moving-coil mechanism is supplied with core and pole pieces having concentric faces. Such mechanisms produce the scales shown. The lower scale is that of the mechanism itself showing linear placement of the divisions with linear increase in current in the moving coil. The center scale shows square law distribution resulting from the use of a heating element with standard mechanism. The top scale shows logarithmic distribution resulting when this movement is used for DB measurements. Because of cramping at the left, the upper two scales are difficult to read at the lower values.

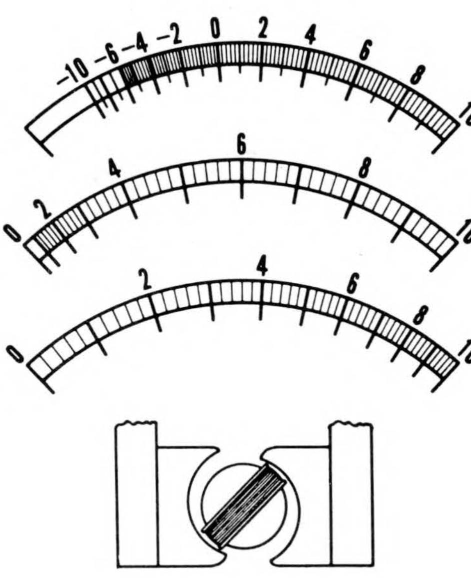


Fig. 43

The permanent magnet-moving coil mechanism may be supplied with specially shaped or eccentric pole pieces resulting in uneven flux distribution in the air gap and a non-linear relation between current in the moving coil and pointer movement. The lower scale shows the effect of the eccentricity illustrated. When used with square law heating elements the resulting scale, center, becomes more linear. The top DB scale is not only more uniform but is readable over a longer portion of the arc. Such special pole pieces, though expensive to produce, are useful in adapting this mechanism to special applications.

The Recording Potentiometer Millivoltmeter

A recording potentiometer millivoltmeter consists of a slide wire carrying a fixed current, a traveling contact, sensing means capable of detecting an electrical unbalance (called "error"), a motor to drive the contact to a condition of balance, a pen which leaves a trace on a chart corresponding to the motion of the contact, and means for moving the chart.

In most modern recorders the unbalance or error sensing means, called the converter, is an electromechanical device in which a vibrating switch contact breaks up direct current into alternating pulses through two sections of the primary winding of a transformer, causing alternating voltage to be generated in the secondary winding. If the polarity of the direct current input is reversed, that of the pulses is likewise reversed and the resulting alternating voltage changes in time phase by 180°.

The amplifier increases the amount of the alternating current from the converter enough to operate the pen drive.

The pen drive is a motor whose shaft moves the pen and the pointer by means of a wire cable running over pulleys. This motor has two windings. One of these is energized from the a-c power supply whose phase is fixed; the other winding is energized from the converter output whose phase varies (see above).

The arrangement of the two windings is such that the motor will reverse its direction of rotation if the phase sequence of the two energizing currents is reversed. On the disappearance of the current in one of the windings the motor stops.

The slide wire is part of a resistance network in which an unknown voltage is balanced against a known portion of a fixed voltage. A sliding contact is moved along a resistance wire, picking off a varying potential relative to one end. In the potentiometer recorder the resistance wire rests on the circumference of a drum and the slide contact is moved by the pen drive. The pen position, therefore, represents the slide contact position.

As the slide contact moves toward the balance point the difference between the potential picked off and the unknown voltage diminishes; this difference (the error) disappears at the balance point and reappears, with reversed polarity, if the slide contact moves beyond.

Converter and amplifier cause the pen motor to rotate in response to the error, — always moving the slide contact toward the balance point. When this point is reached the motor stops.

The chart drive is a mechanical or electrical motor which moves the chart at right angles to the pen travel in proportion to elapsed time. The pointer travels across a scale calibrated in millivolts potentiometer input or in related units; and the pen leaves a record of its position on the chart.

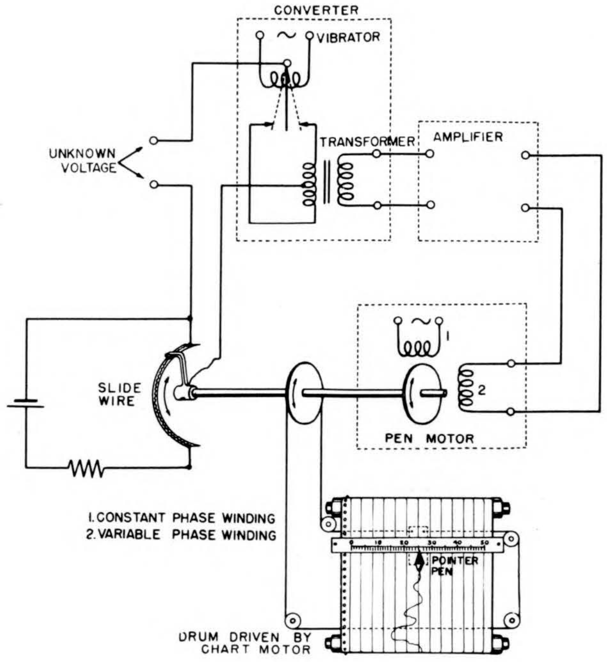


Fig. 44

Accessories

Standard Cells

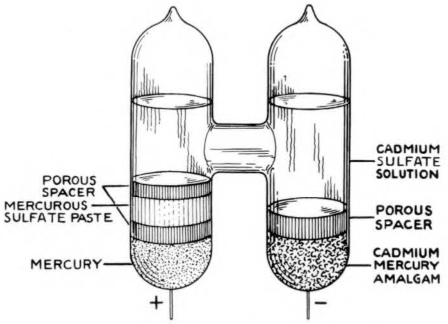


Fig. 45

The Weston cadmium cell, developed and patented by Dr. Edward Weston in 1893 has been recognized and used as the world standard of electromotive force since its acceptance by the International Committee on Electrical Units and Standards in 1908.

The Weston Standard Cell is made in two types, the normal cell containing a saturated cadmium sulfate solution and a type used as a working standard in which the solution is less than saturated above 4°C.

The saturated cell is the basic standard, being reproducible to a very high degree of accuracy, but its temperature coefficient must be taken into account for accurate measurements. Legal voltage for the saturated cell is 1.018636 Abs. Volts at 20°C by international agreement.

The emf of the unsaturated cell is within 1.0188 to 1.0198 Abs. Volts with the exact voltage for each cell being established by comparison with the normal or saturated cell. This cell is a useful working standard because of its negligible temperature coefficient.

Accessories

Standard Resistors

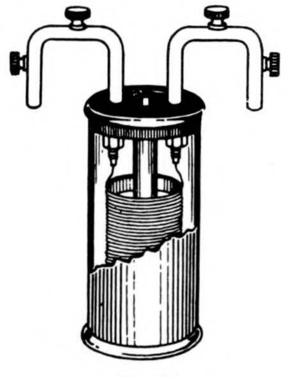


Fig. 46

Resistors used as basic standards in values above 10 ohms are built in the form shown above as designed by the National Bureau of Standards. Carefully heat treated manganin wire is wound on a silk insulated brass cylinder and shellacked in position. Separate connections are provided for input and potential leads. After extended baking to insure dryness the assembly is placed in moisture free oil and sealed in its brass case. Below 10 ohms the construction is the same except mechanically larger. Such units, properly handled and used, maintain their accuracy within 10 parts per million for long periods of time.

Fundamentally, the use of standards of emf and resistance includes, by derivation, the standardization of current through the application of Ohm's law by which the three basic electrical quantities are interconnected. The practical standardization and calibration of electrical measuring instruments is based on these principles.

Shunts

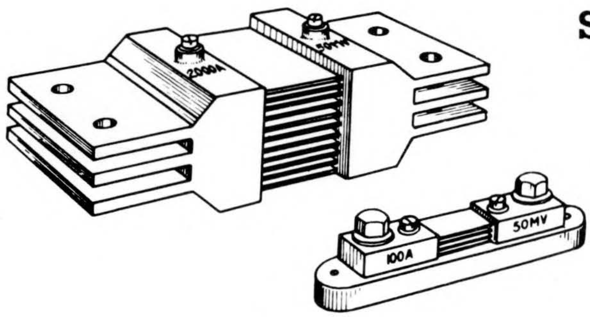


Fig. 47

Only currents up to about 50 ma can be taken into a moving coil through the springs, hence, special provisions are made where current ranges exceed that limit. Direct current instruments of ranges in excess of 50 ma require the use of a parallel resistance circuit formed by one or several shunts. Where these ranges are moderate the shunts are usually self-contained. On higher ranges the shunts become physically large and convert more than a few watts into heat, so that they are used as accessories external to the instrument. (1 kilowatt for 50 millivolts, 20,000 amperes)

The shunt (British for railroad siding) is a current bypass. Small or large, it consists of one or several manganin conductors terminating in copper blocks (Fig. 47). The copper blocks are provided with separate terminals for connection to the instrument to avoid errors.

The manganin sections are soldered into the copper blocks. Shunt construction is such that heat is carried off at a rate sufficient to keep the operating temperature below the softening point of the solder. Adequate conductors tightly fastened, clean contact surfaces and free air circulation are important.

Ammeters for use with external shunts are provided with special leads for shunt connection. Shunts are usually made to produce a standard potential drop such as 50 mv at rated current and the associated d-c mechanism is then built to give full scale deflection on a slightly smaller potential so as to allow for lead resistance. As the leads form part of the mechanism circuit (Fig. 48) their resistance must not be altered.

Usually the current through the mechanism is a negligible portion of the total and the potential drop across the shunt terminals is nearly the same with or without the mechanism in the circuit. In instruments of moderate precision and fairly high current range this difference can be neglected and shunts and instruments made interchangeable. In instruments of high precision and in instruments of low current range, the shunt adjustment must take into account the instrument current; such combinations are usually not interchangeable.

Multi-range shunts should be connected as shown in Fig. 49 to avoid the use of a switch with its variable contact resistance between shunts and mechanism.

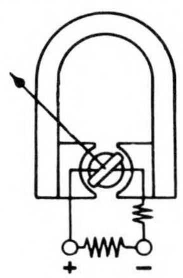


Fig. 48

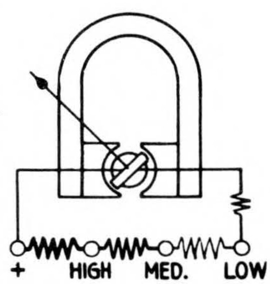


Fig. 49

Because of the relatively high current consumption of a-c instruments, shunts are never used with them for obtaining either multiple ranges or extending the base range. The division of current between mechanism and shunt would become unfavorable and would invite inaccuracies due to the difficulty of obtaining good pressure contacts, as well as the fact that the current division would be a function not merely of the relative resistances of the parallel circuits but also of their relative impedances.

Moreover, a-c mechanisms are not suitable for low millivolt ranges so that shunts would have to have large potential drops and would generate excessive heat. The ranges of a-c ammeters are, therefore, extended with the aid of current transformers, (see page 21).

Accessories

Series Resistors

Series resistors for voltmeter use take various physical forms depending on the application. Self-contained ranges use small compact spools (a) for the more sensitive mechanisms and larger "cards" (b) for those requiring more current. All series resistors in which the heat generated is more than the instrument case can radiate must be external. The special tubular resistor shown at the top (c) is filled with an inert compound, sealed, and electrostatically shielded to insure long life at high voltages in humid or salt atmospheres.

Series resistors are usually wound of wire of such alloys as manganin or constantan which will not vary in resistance with changes in temperature.

When intended for use with a-c instruments for other than a fixed frequency, series resistors must be designed to have the least possible inductance and capacitance so as to avoid objectionable variations in impedance. This is achieved by winding the resistance wire in alternating directions and by proper spacing of turns.

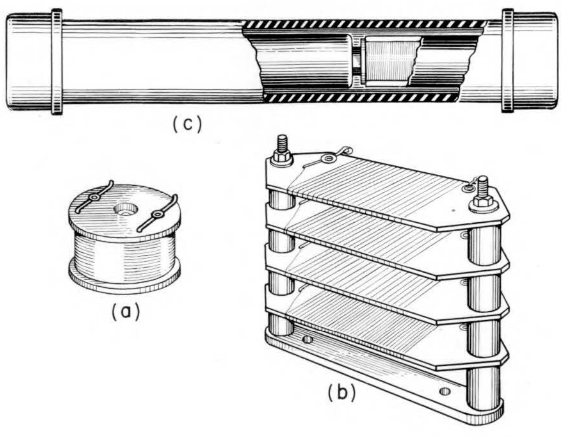


Fig. 50

Copper-Oxide Rectifiers

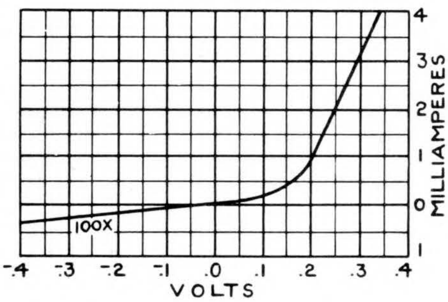


Fig. 51

Copper-oxide rectifiers as used with indicating instruments have current-voltage characteristics as illustrated above. Note that the curve to the right of zero volts is not linear which accounts for the scale characteristics found on low range voltmeters and the inability to track low and high ranges on the same distribution of divisions.

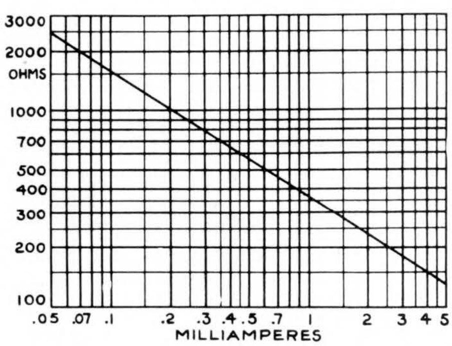


Fig. 52

The current-resistance relation in any given rectifier is logarithmic over its usable forward conducting range. The curve above shows this characteristic for one size of instrument rectifier. This rectifier is used with instrument ranges from 1 to 5 milliamperes.

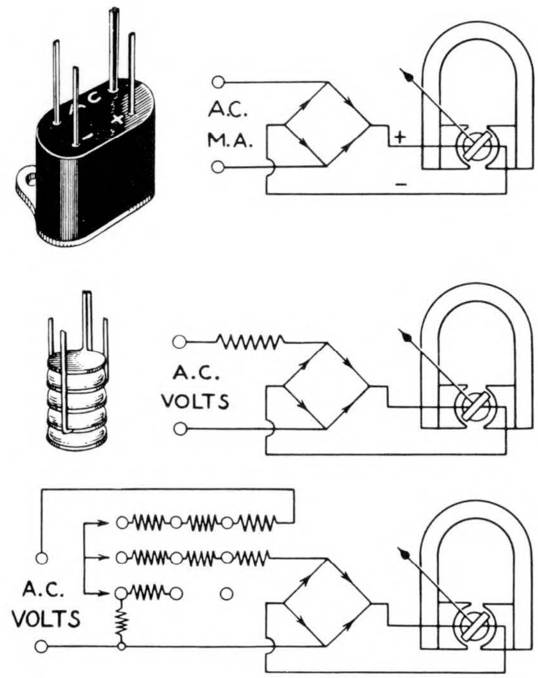


Fig. 53

The copper-oxide rectifier as used by Weston is shown approximately full size above. The assembly of discs is sealed in the bakelite housing to insure constancy of performance with time. The current ranges of a rectifier instrument are limited to the current that the rectifier can safely pass. Shunting is not practical because of frequency errors in the branch circuits so formed. Above approximately three volts multi-range rectifier voltmeters are practical and ranges above 10 volts will usually track on the same scale divisions. Constant impedance voltage measuring circuits, such as are required in many DB and VU applications, are arranged as shown in the lower diagram.

Accessories

PHOTRONIC® Photoelectric Cells

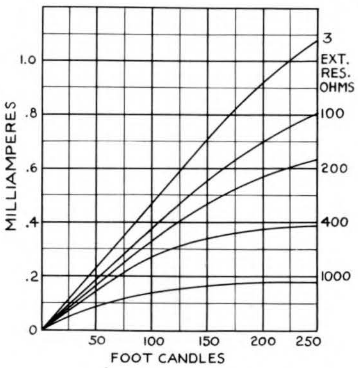


Fig. 54

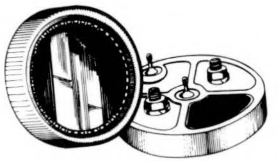


Fig. 55

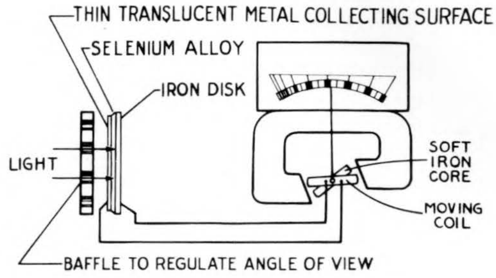


Fig. 56

The Photronic photoelectric cell may be considered as a converter of energy—light to electrical. It is a self-generating "Solid" or so called "Barrier Layer" type of cell. The magnitude of current developed, for levels of illumination normally encountered, is sufficient to operate direct current instruments and relays directly, without amplification or other auxiliary equipment. The curves above indicate current output of a standard Photronic cell at various light values and show the effect of external circuit resistance on linearity.

The photographic exposure meter indicates scene brightness. Having a figure representing the film speed and a reading of the scene brightness, as indicated by the pointer deflection on the instrument scale, the calculator discs are set to these values. The lens opening and exposure time are then indicated for a well exposed picture. Note the shaped pole pieces on the d-c instrument which, in conjunction with the cell characteristics, give a wide coverage of light values on a nearly logarithmic scale.

Tachometer Generators (Magnetos)

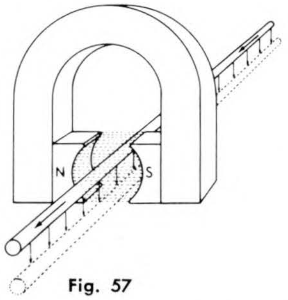


Fig. 57

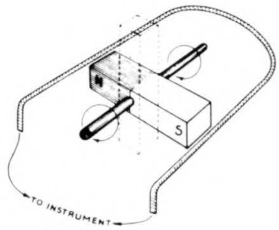


Fig. 58

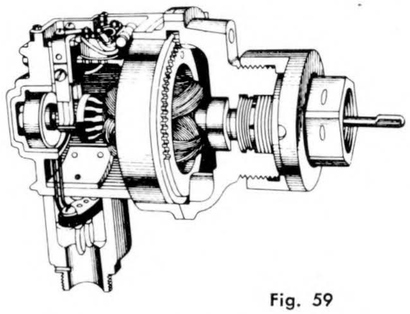


Fig. 59

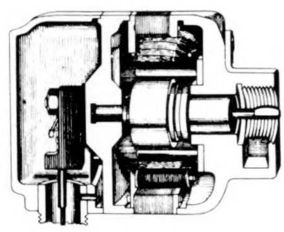


Fig. 60

Relative perpendicular motion between a magnetic field and a conductor results in a voltage generation in the conductor. The figures above illustrate this principle. The magnitude of the voltage is a direct function of the strength of the magnetic field and the speed with which the conductor moves perpendicular to it. Current will flow if the ends are connected to a load, such as an instrument. The polarity of the voltage and, therefore, the direction of current flow will depend on polarity of the field and direction of conductor motion. (Fig. 57)

The same effect can be had by rotating the magnet and holding the conductor still. (Fig. 58)

Only that portion of the conductor sweeping through the magnetic field flux is effective in generating voltage.

By forming the conductor into a loop a greater effective length is possible and both sides of the loop will develop voltage. The polarity of the voltage changes as the loop passes through the vertical axis of the field. Rectification or commutation—change of an alternating polarity to a fixed polarity—is accomplished by the use of segments and brushes as shown.

The magnitude of the voltage generated can be greatly increased by the use of numerous loops properly arranged and connected. For direct current the loops are made to rotate and are connected to segments called a commutator. For alternating current the loops are stationary and connection to the external circuit is direct.

The combination of a tachometer generator and a suitable indicator—direct current for the commutator type (Fig. 59) or alternating current for the rotating magnet type (Fig. 60)—when suitably coupled to a shaft will indicate speed of rotation.

A variation of the alternating current tachometer measures speed in terms of the frequency instead of the voltage generated. This system uses a transformer between generator and instrument.

In any transformer the voltage induced in the secondary winding is proportional to the rate of change of the core magnetization. By using a type of transformer iron whose magnetization reaches saturation very rapidly (during a fraction of each cycle) sharp, brief voltage excursions (pips) are obtained in the transformer output.

After rectification these pulses are conducted into the moving coil of a permanent magnet type instrument where they produce pointer deflections strictly as a function of pulse frequency, hence of generator speed.

Temperature Measuring Devices

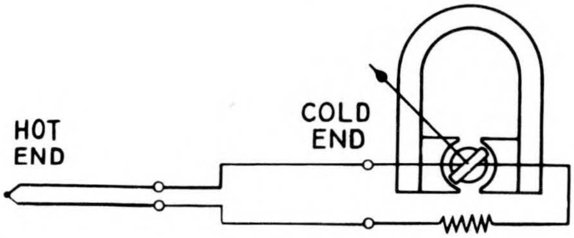


Fig. 61

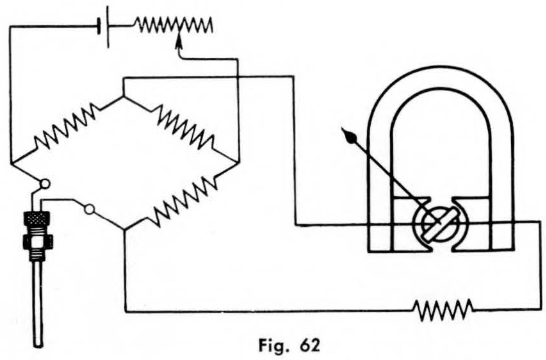


Fig. 62

Two of the principles used in the electrical measurement of temperature are shown; the thermocouple pyrometer above and the resistance thermometer at the right.

As shown in the diagram, the thermocouple pyrometer circuit is relatively simple and possesses the advantage of operating without any external source of energy. It must be noted that this device does not measure absolute temperature, but simply temperature difference between the hot and cold ends. In general this temperature difference should be greater than 200° for the satisfactory application of a direct reading instrument.

The resistance thermometer on the other hand requires a source of energy, frequently a battery of a few dry cells, and measures absolute temperature in terms of the resistance contained in one of the arms of a Wheatstone bridge. A relatively high sensitivity can be obtained, and it is useful for measuring moderate temperatures, say between —200° and +300° F. Ambient temperature variations can be fully compensated.

Used with a conventional instrument, a constant battery voltage is required; used with ratio type indicators as illustrated below in Fig. 63 a correct indication of temperature will be had with battery voltage variations as high as 50%.

Basic temperature measurements are made with the null balance bridge wherein the resistance of the temperature sensitive arm is accurately measured and a conversion table used to determine corresponding temperature. The temperature limits of this method are the resistance-temperature linearity limits of the material used in the variable arm of the bridge. The method is fundamental and the resistance of pure platinum is used as the tie between the basic gas thermometer and ranges of temperature beyond which the gas thermometer cannot be used.

The Direct Current Ratio Indicating Mechanism

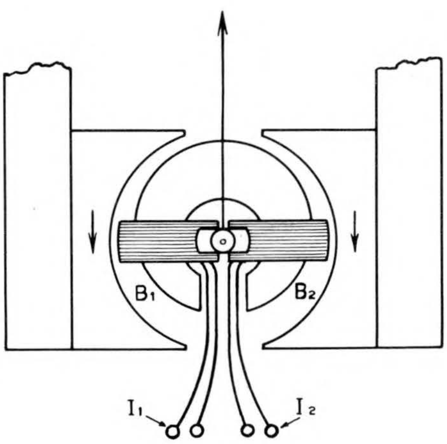


Fig. 63

Shown above is a mechanism in which two independent coils rigidly mounted on opposite sides of a common axis move in an air gap formed by a core mounted eccentrically between the cylindrical pole faces of a permanent magnet. No control springs are attached to the moving system, the current being fed to the coils by fine filaments. The ampere-turns (or flux) developed by each coil will react with the flux in its part of the air gap causing the pointer to move until the product of ampere-turns times gap flux will be equal on each side so that balance is reached.

Except for a multiplying factor to take care of turns ratio and coil areas it can thus be written:

$$I_1B_1 = I_2B_2$$
$$\text{or } I_1/I_2 = B_2/B_1$$

where I_1 and I_2 are the currents in the two coils and B_1 and B_2 the flux densities in the air gap at the points where the coils rest in the state of balance.

The second equation expresses a ratio of two currents in terms of a ratio of two flux densities. In view of the non-uniform and reversed flux distributions in the two sides of the air gap a given ratio of flux densities occurs only once within the total angle of moving system rotation and is, therefore, associated with only one point on the scale. Each point on the scale thus represents only one current ratio and the scale can be so calibrated.

Such an instrument is a ratio meter capable of measuring any condition which can be expressed as a ratio of two currents.

If, in a circuit, the ratio of two currents represents the ratio of a known to an unknown resistance or the $E/I = R$ relationship of Ohm's law the ratio meter becomes an ohmmeter, or, through the use of resistances of appropriate temperature response, a thermometer.

Instrument Transformers

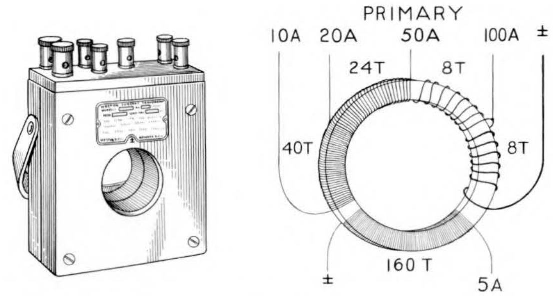


Fig. 64

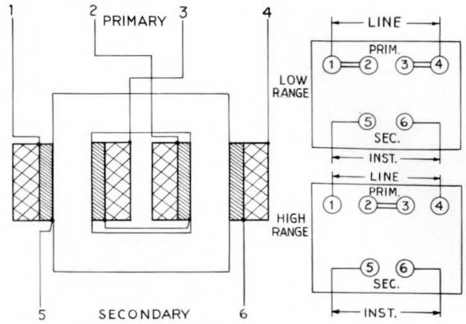


Fig. 65

Current and potential transformers extend the ranges of a-c instruments in the same way as shunts and series resistors work for d-c instruments. Taps on the windings permit a single transformer to operate over a wide range. Basic instrument ranges for transformer use are usually 5 amperes or 115 volts. These are nominal secondary ranges for the transformers and are used for computing ratios for the overall range of the meter and transformer combined. In actual practice the range of the voltmeter may be 150 volts. For relatively high current ranges, the primary often consists of one or more turns passing thru the center hole. (Fig. 64). In the case of one turn, the ratio would be 800:5; two turns 400:5 etc. Standard operating procedure and safety for the current transformer reqiures that the secondary winding always be shorted or connected to the ammeter. Otherwise dangerous potentials may occur on the secondary of the transformer.

Instrument transformers in addition to permitting measurement of large currents and voltages perform the important function of insulating the instrument from the line. This affords safety in use. Insulation protection between primary and secondary windings is usually several times the maximum rated voltage of the transformer.

Above drawing shows a type of potential transformer arranged with means for connecting the two primary coils in multiple or in series. This provides for two ranges in a ratio of 2 to 1. A single secondary winding is used.

The chief errors in instrument transformers are due to ratio and phase angle both of which are controllable in design by using proper flux densities for the magnetic material involved and appropriate construction.

Relays and Controls

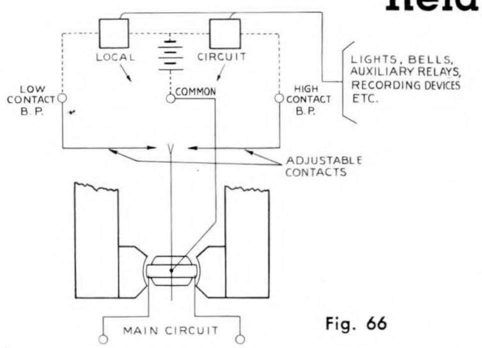


Fig. 66

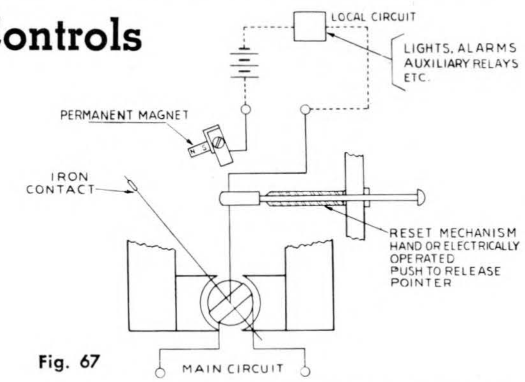


Fig. 67

A relay is an intermediary element between some actuating impulse and the control of an electric circuit carrying electrical energy to be variously applied. Broadly, it is a switch operated by means other than manual.

Instrument type relays employ standard measuring mechanisms and a contact making arm, rather than a pointer. Contacts of non-oxidizing, low resistivity, high thermal conductivity material are used. Current carrying capacity of contacts depends on type of relay and circuit being controlled.

Fig. 66 shows a sensitive type of double throw relay for high and low control—employs a permanent magnet moving coil mechanism. Contacts for this type of relay are usually of platinum-iridium and are capable of handling non-inductive circuits up to 200 ma at 6 volts d.c. Pole pieces and core are shaped to concentrate the magnetic flux at the center in order to give an increased sensitivity over a relatively short deflection.

A special form of instrument relay for use under conditions of vibration and shock incorporates a magnetic holding principle for the contacts. (Fig. 67)

As shown above, the stationary contact is a small, powerful permanent magnet. The movable contact is an iron rider on the pointer. Actuating circuit causes pointer to move into field of fixed contact magnet—positive unshakable contact is made. Release of contacts accomplished by physically pushing movable pointer away. Release may be manual or remote by use of solenoid or special mechanisms.

The relay may be considered as a non-linear amplifier with very high gain. Since the power input to one of these units may be in the order of 5×10^{-10} Watts (5×10^{-7} Amperes, 2000 Ohms) and a contact rating (output) of 5 Watts (50×10^{-3} Amperes, 100 Volts) we have a device with an overall gain of 100 DB.

Relays are an important factor in the solution of many laboratory and industrial control problems. Some of the applications are to control: temperature, chemical processes, water levels, speeds, voltages and currents—the automatic inspection of vacuum tubes, lamps, dry cells and resistors—operating signals on burglar alarms, poisonous or explosive gas detectors—for use with light sensitive apparatus, relaying radio telegraph time signals, controlling street lights, etc.

Composite Application

The circuit of the clamp volt-ammeter (Fig. 68 and Page 27) is shown at the right. Line current is measured by deriving from it a small proportional current through the use of the hinged core current transformer. The secondary current is suitably divided by the multiple range series shunt, then rectified and connected to the permanent-magnet instrument mechanism. Voltage is measured by short-circuiting the transformer secondary and making direct connection to the rectifier with sufficient resistance added in series to produce the desired range. Thus we have here the current transformer, the rectifier meter principle, the fundamental d-c mechanism, the series shunt and the tapped multiplier—all combined to secure the single result of reading alternating currents and voltages with a minimum of connections and without service interruption.

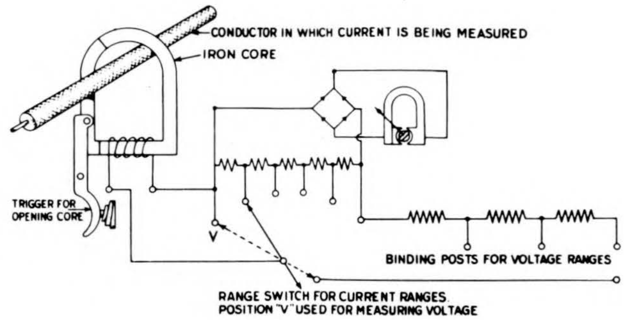


Fig. 68

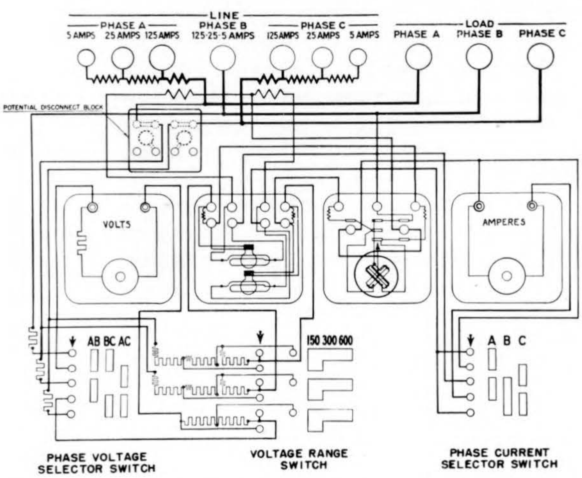


Fig. 69

The industrial analyzer illustrated on Page 27 with its circuit in Fig. 69 is a typical assembly of instruments and accessories conveniently arranged to measure current, voltage and power in single and polyphase circuits. It is also used to measure power factor on 3-phase, 3-wire, balanced circuits.

This device consists of two current transformers, connected to the line side, followed by the voltmeter, wattmeter, power factor meter, and ammeter in a circuit containing the necessary switching.

Note that the composite assembly permits the common use of certain series resistors by more than one instrument.

Cathode Ray Oscilloscope

Many electrical quantities of a transient or cyclic nature and beyond the scope of conventional instruments may be measured by the cathode ray tube.

This device consists of an evacuated glass envelope containing an arrangement of electrodes like those in a radio tube. A heated cathode (5) (6), Fig. 70, serves as a source of electrons. These are accelerated by the anode potential at (2) and reduced to a beam by the intermediate grid and focusing anode (3) (4). This beam impinges on the fluorescent screen at the end of the tube and shows as a spot of light. The electron beam is deflected by the electrostatic field of two parallel sets of plates (1) 90° displaced with respect to each other. One set of plates produces its field in response to the variable in question and the other set of plates in response to a second variable or time. In actual practice the oscilloscope consists of the cathode ray tube proper and usually two high-gain amplifiers, a sweep oscillator and a power supply.

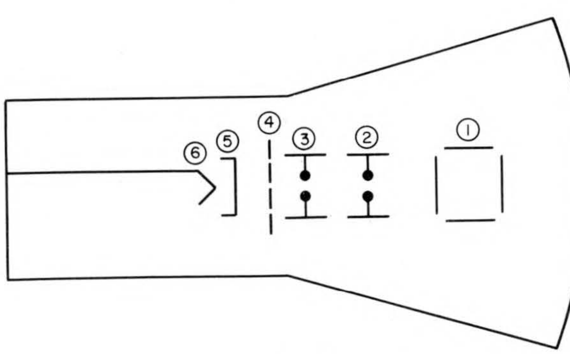


Fig. 70

Some of the common applications for the oscilloscope are:

Audio Amplifier Analysis
Phase Measurements
Wave Form Analysis

Edward Weston

Inventor — Scientist — Industrialist

The following briefly outlines the achievements of Edward Weston, founder of the Weston organization. It is based on information gathered from the library and personal files of the late Edward Weston in 1942, six years after his death, and from notes compiled by Dr. Edward F. Weston, son of the inventor. It is presented here to provide an idea of what the name Weston means in the electrical art. Readers interested in learning more about Edward Weston may refer to his biography "A MEASURE FOR GREATNESS" by David O. Woodbury. McGraw-Hill Book Co., Inc.. New York, 1949.*

A MAN'S GENIUS cannot be rated by his popularity. Among those who have heard the name of Weston associated with electrical and photographic instruments, few seem to know of his work in many other fields and very few realize that we owe him some of the most fundamental contributions to the electrical art.

Edward Weston was born on a farm in England in 1850 and was brought up in a small Welsh town. The work of the great living scientists fascinated him at an early age and so did the rapidly growing industry which was beginning to change the shape of things with steam power and gas.

It was customary in those days that a young man be apprenticed in a trade or profession of his family's choosing. Thus, Edward Weston became associated with a physician but his heart was not in the art of healing. Instead he absorbed all he could of the knowledge of chemistry which he was able to gain from the doctor. The medical part of the work did not appeal to him because he could not regard medicine as an exact science.

So it happened that he left his employer and, following the advice of a stranger whom he met on his way to London, embarked on a vessel bound for New York where he landed in 1870, ready to seek the opportunities of the New World.

The story of his early experiences and hardships would make interesting reading but we must concentrate on the more significant milestones along his road to success. His searching mind was ever critical of the perfection of things already achieved and ready to move forward into new fields of endeavor.

Much of Weston's early work in the United States was in the electro-plating industry which was just then coming into its own. The imperfection of most plating jobs and the crude techniques of the day challenged his ingenuity. He introduced improved electrodes and an acid dip for cleaning or stripping the work prior to plating. In addition, he patented a method of depositing nickel so finely and evenly that the product was a malleable form of this metal, not hitherto known.

These developments and the demand for greater plating capacity called for more electrical power and greater reliability than the primary batteries which then served as sources of current and Weston wanted them replaced by electrical machinery. While the rudiments of dynamo-electric generation were just beginning to be known, he decided to design and build generators for the specific job at hand.

In 1876 he obtained a very basic patent on a multipolar d-c machine with radially projecting pole pieces and an improved commutator which for the first time reduced the number of brushes to no more than two. This work became so important to him that he devoted all his time to the design and manufacture of generators for purposes of electro-plating, and in 1877 the Weston Dynamo Electric Machine Company was organized in Newark, New Jersey. This factory, in the heart of Newark, was the first one making dynamo-electric generators in the United States.

In search for other outlets for his generators, Weston then turned to the field of arc lighting. He began to make generators for this purpose but soon introduced many improvements in the lamps themselves. It was his idea to copper-plate the ends of the carbons for better contact and to produce carbons with special cores for improved light effects. So successful and important was this new work that the company changed its name to Weston Electric Light Company and soon produced complete lighting installations.

As a climax to this work, Weston's company was awarded a contract to illuminate the newly constructed Brooklyn Bridge in New York, a spectacular and most successful undertaking. For 15 years the steam driven generators, the cables, fixtures and the lights which Weston had designed, manufactured and installed, served their purpose until more modern equipment finally took their place.

About the same time Weston began experiments with incandescent light, independent of Edison and other contestants in this field. His great contribution to this new field was a process for producing homogeneous, ductile carbon filaments of predictable resistance. This work was a triumph of his ability to combine seemingly unrelated knowledge and experience in the fields of chemistry, electricity and mechanical engineering. All other contestants including Edison were still experimenting with various natural cellulose fibres which produced lamp filaments of uneven cross section and very short life. Weston converted cellulose fibres into nitrocellulose and, by an ingenious chemical process, back into pure, amorphous cellulose. This material could be rolled and cut into filaments of the desired dimensions which were then carbonized by heating. Finally, a Weston first, these filaments were momentarily flashed in a hydro-carbon atmosphere by passing through them a heavy current of short duration. This caused additional carbon to be deposited as a function of the temperature of each part of the filament so that more carbon accumulated in hotter than in cooler spots. The result was a filament of unprecedented uniformity of cross section and length of life.

The lamp industry was then in the midst of violent patent fights and it seems that the Edison interests

*Reproduced from article by Henry Berring

Edward Weston (Cont.)

ultimately gained control by successfully patenting glass sealing methods without which others could not make evacuated lamps. However, for about 25 years all commercial incandescent lamps employed filaments made by Weston's method, until the tungsten filament came to be used in place of carbon.

Some of Weston's work is reflected in the patents which he obtained and was so basic that it is hard to visualize our present practices without these achievements. When working on dynamo-electric machines he was first to introduce the use of iron laminations in armature and field coil cores,—commonplace today; this principle reduced eddy current losses to a point where the efficiency of these machines became practical.

Altogether, between 1875 and 1884, Weston was granted 139 U. S. patents for an amazing variety of electrical, mechanical and chemical inventions. One of these even specifies the use of thorium oxide as a "getter" in producing a good vacuum, a method similar to the one well known in modern radio tube manufacture.

Strange to say, everything for which Weston's name is best known today stems from work which he undertook after he had withdrawn from the manufacture of generators and lamps and might have enjoyed the fruits of his successes in retirement. But one thing had disturbed him ever since his first experiments in the field of electro-plating, namely, the need for accurate and thoroughly practical devices with which to measure electrical quantities. The instruments then available were laboratory apparatus of the most delicate type. They were so sensitive to electrical and magnetic disturbances that a slight change in position with respect to the earth's field or the presence of iron nails in the shoes of an operator would upset the readings. No means of standardization existed and measurements were merely comparative.

In 1887, Weston built himself a laboratory devoted solely to research on electrical standards and to the development of practical means of electrical measurement.

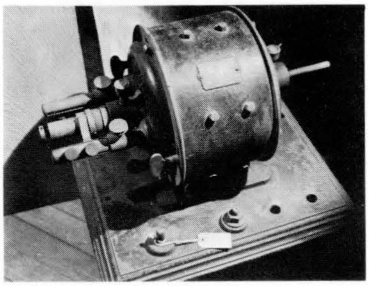
He conducted a study of the conditions under which a magnet would retain its strength and found that this was a question of the magnetic circuit rather than the magnetic material. It might well be said that a truly permanent magnet was first developed by Weston, because the dimensional rules which he was first to pronounce are still accepted as governing the permanency of magnets.

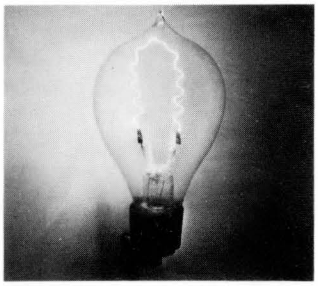
This accomplished, he replaced the filament suspension of the d'Arsonval moving coil galvanometer by jeweled bearings centered above and below the concentric core and pole structure of his improved magnet system.

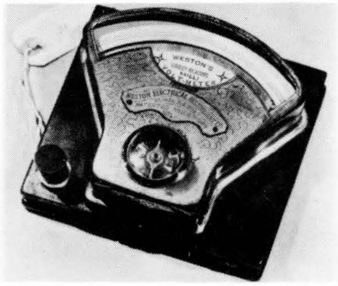
Next he developed alloys for non-magnetic, low resistivity instrument springs which conducted current to and from his instrument moving coil and yet produced control torque of lasting reproducibility. He pronounced rules for the best dimensions of such springs. He devised the manufacture of malleable aluminum from which he could make moving coil damping frames and tubular pointers.

He was first to show that it was possible to produce a resistance alloy of negligible temperature coefficient of resistance of a composition which we call Constantan and went on to modify it until the final product developed no more than a minute thermal electromotive force when in contact with copper. This alloy is now known as Manganin. Without Manganin we would have neither temperature compensated electrical instruments nor standards of resistance.

Surprising as it may seem, it was Weston who first devised the principle of by-passing known portions of a current in what he called a "shunt" in order to measure currents beyond the current carrying capacity of springs and movable coils. He also established the principles of shunt design.







A few of Edward Weston's early inventions . . . Plating Dynamo, Lamp with Weston's Tamadine Filament, Model One—Number One.

One of his greatest contributions was the Weston cadmium standard cell which was internationally adopted as the standard of electromotive force. Edward Weston held patent rights on the cell but relinquished them to give the world free use of this basic standard. This standard cell, together with Weston's Manganin alloy from which resistance standards are made, links his name with the very foundation of our entire system of electrical units and standards of measurement.

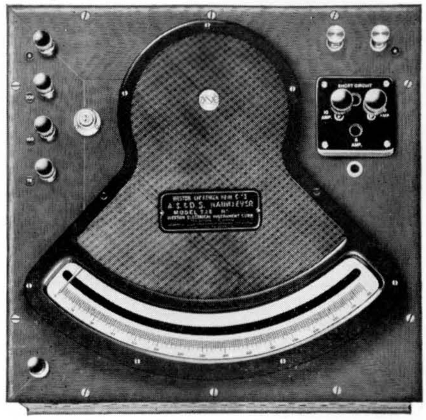
In 1888 he organized the Weston Electrical Instrument Company and began to manufacture electrical instruments commercially. This was the first line of practical, reliable, double pivoted electrical instruments ever made.

Today electrical instruments seem commonplace and, whether we realize the fact or not, are fantastically important. There is no field of science, industry or utility, no means of communication or transportation, no weapon against disease, no device for defense or safety, no implement of pleasure, health or art, no trade and no profession that somehow is not aided in its very existence by electrical instruments. And no electrical instrument has ever been made which does not incorporate many of the basic details and principles first pronounced and devised by Edward Weston.

TYPICAL PRESENT DAY ELECTRICAL INDICATING INSTRUMENTS

Precision Types

Model 1 Portable Precision Instrument



Model 326 Laboratory Standard

TYPICAL INSTRUMENTS are shown on this and the next page in which the basic theory and the mechanisms described are incorporated to make complete devices for specific uses. The instruments shown are indicative of the great variety used in laboratories and industries throughout the world—space does not permit the showing of all of the individual variations.

LABORATORY STANDARDS such as Model 326 represent instruments of the highest accuracy available—international standards of comparison against which other instruments may be calibrated and checked. The companion instrument for DC measurements of current and voltage is of the permanent-magnet moving-coil type. The Model 326 using an electrodynamometer mechanism operates on AC and/or DC to indicate current, voltage, or power. Each instrument has a long mirror scale and is accurate within 1/10 of 1%.

Model 370
Electrodynamometer Type Ammeter

PRECISION PORTABLES like the Model 310 and the Model 1 are used where high accuracy instruments must be taken to the job. They are frequently used as reserve check instruments and often as standards in smaller laboratories. Instruments similar to the Model 310 are available as Voltmeters, Ammeters and Wattmeters, AC and/or DC, (¼%), Polyphase AC Wattmeters, (½%), Power Factor Meters (½%), Frequency Meters (½%), Microfarad Meters (½%) and Phase Angle Meters. All are of the electro-dynamometer type. Model 327 is an extremely precise current transformer for use with laboratory and precision ammeters. Model 327 is an extremely precise current transformer for use with laboratory and precision ammeters. Precision DC voltmeters and ammeters are available in the Model 1 which is of the permanent-magnet moving-coil type.

Model 310
Single Phase Wattmeter

THE WESTON STANDARD CELL was developed by Dr. Edward Weston in 1893 to provide a working standard of the volt, as well as purely a reference standard. Since 1908 the Weston normal cell has been the international standard of the volt. These cells consist of H shaped glass jars filled with mercury, cadmium and their sulfates and will generate an unbelievably constant voltage throughout their lives. The basic voltage standard for this country consists of a group of these cells maintained at constant temperature in the Bureau of Standards, Washington, D. C. A similar group is maintained by Weston for purposes of standardization.

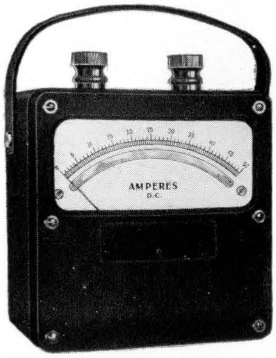
Model 327 Precision Current Transformer

Model 4
Standard Cell

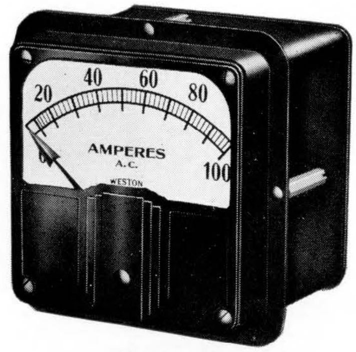
Model 329
Polyphase Wattmeter

TYPICAL PRESENT DAY ELECTRICAL INDICATING INSTRUMENTS

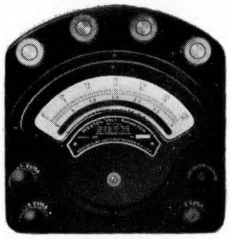
Portable Testing and Switchboard Types



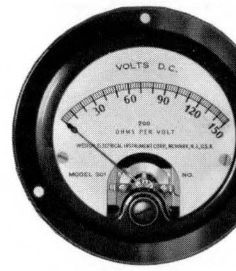
Model 931
Service Portable



Model 924
Rectangular Switchboard Instrument



Model 281
Miniature Portable



Model 301
Small Panel Instrument

SWITCHBOARD INSTRUMENTS are available in a wide range of sizes and shapes as are required by the various communication, industrial and utility needs. In general, switchboard instruments are built with scales and pointers that can be read at a distance and to an accuracy of 1%.

PANEL INSTRUMENTS might be considered as small sized switchboard instruments, generally flush mounted in some piece of built-up equipment such as a radio transmitter, an electric welder, or a piece of service equipment. Size and cost being important factors these instruments are generally built to an accuracy of 2%. The Model 301 is typical of such instruments.

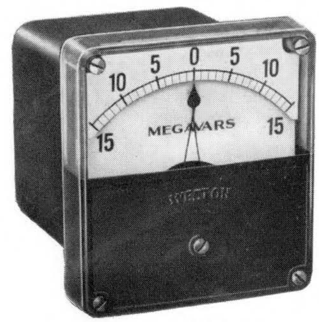
PORTABLE INSTRUMENTS vary over a wide range as to size and accuracy due to the very broad use made of these devices. The simplest portables are made by mounting panel instruments in portable mounting bases giving an assembly such as the Model 375. Small sized assemblies are represented by the Model 281 which incorporates a number of ranges in a very compact arrangement convenient for carrying. Portables for general testing in industry and in the laboratory are represented by the Models 931, 904 and 622. These instruments vary in their size and sensitivities to meet field requirements. Portable instruments in general are made in accuracies of ½ to 1%.

Model 622
Highly Sensitive Portable

Model 271
Fan Shaped Switchboard Instrument

Model 375
Student Galvanometer

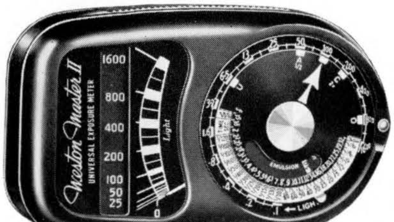
Model 904
Testing Portable



Model 610
Switchboard Instrument with Clear Plastic Front In-line Pointer and Scale

ADAPTATIONS OF PRINCIPLE

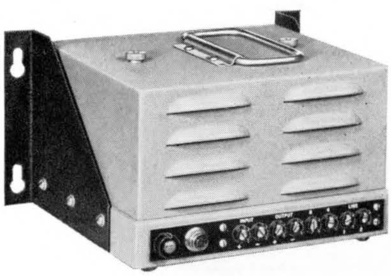
The equipment shown below uses basic indicating mechanisms arranged to perform special functions.



Model 735
Exposure Meter

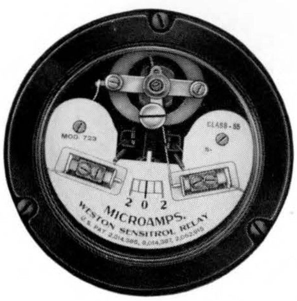
Model 633
Clamp Volt-Ammeter

Model 534
Relay



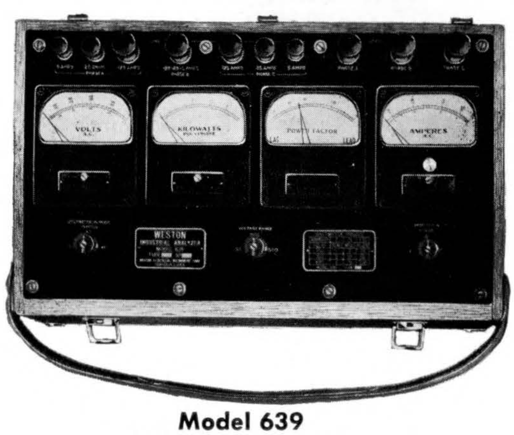
Model 1411
D-C Amplifier

Model 785
Industrial Circuit Analyzer



Model 723
Sealed Relay

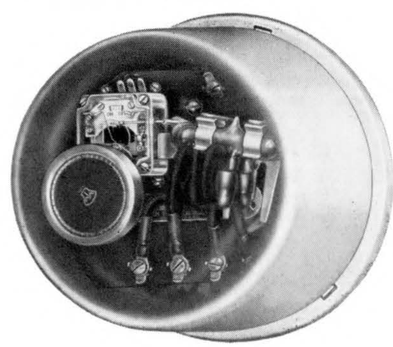
Adaptations of Principle are found in many devices built for special functions in which the indicating mechanism is a part of the complete apparatus. Simplest of these adaptations is the sensitive relay which is an indicating mechanism arranged for control rather than indication. The exposure meter is a complete device in itself arranged to indicate light brightness in terms that can be converted by a calculator into camera settings. More complicated apparatus is represented by the analyzers—devices arranged to take a variety of readings under many different conditions on one or more instruments. By uniquely combining an instrument mechanism with electronic circuitry the inductronic amplifier permits the measurement of minute electrical quantities with another instrument of vastly greater range. Electrical tachometers, thermometers and many other special instruments are adaptations of basic mechanisms, combined with suitable actuating devices.



Model 639
Industrial Analyzer

Model 614
Foot Candle Meter

Model 888
For Aircraft Instrument Landing System

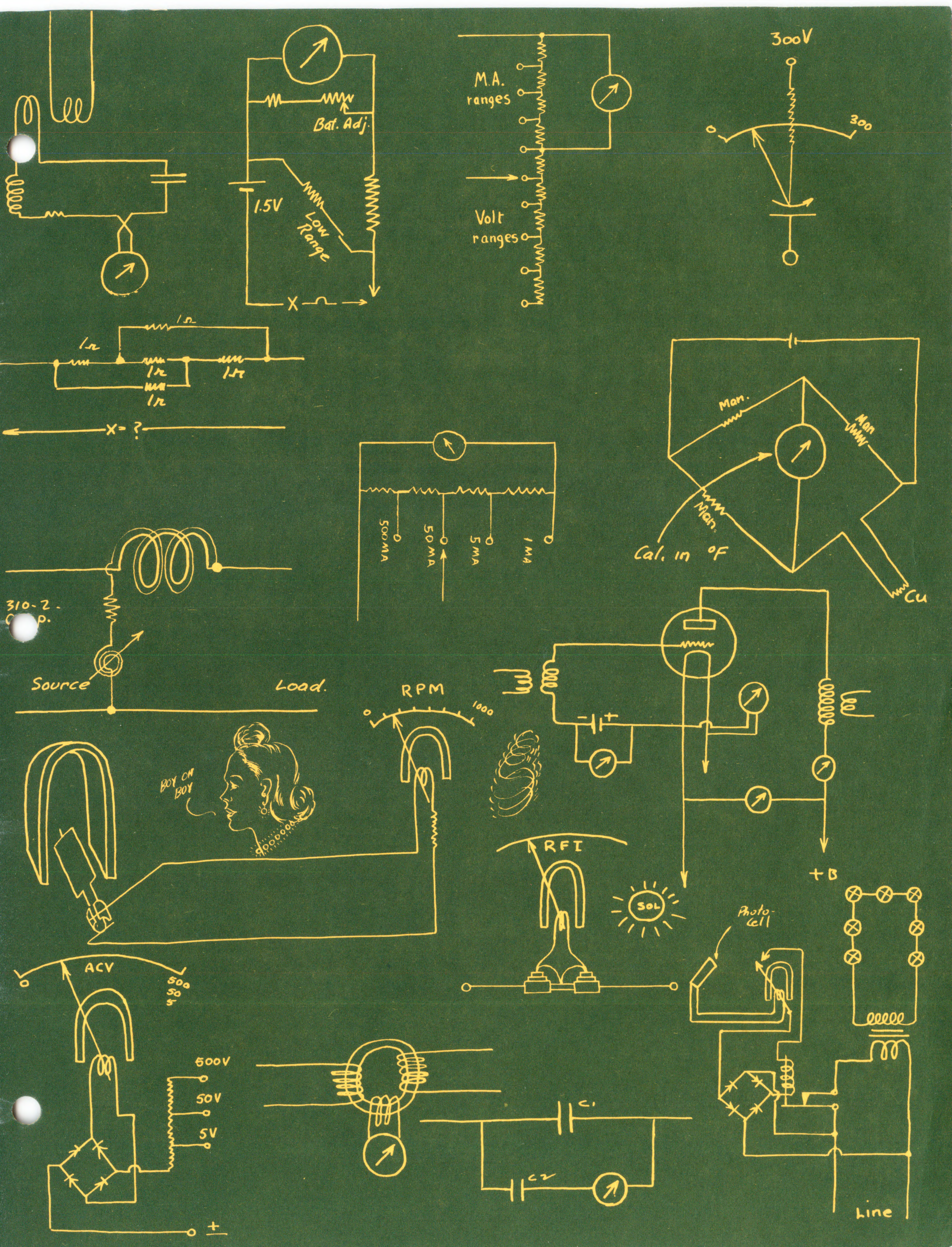


Model 1089
Plug-In Illumination Control

WESTON FACTORY FACILITIES

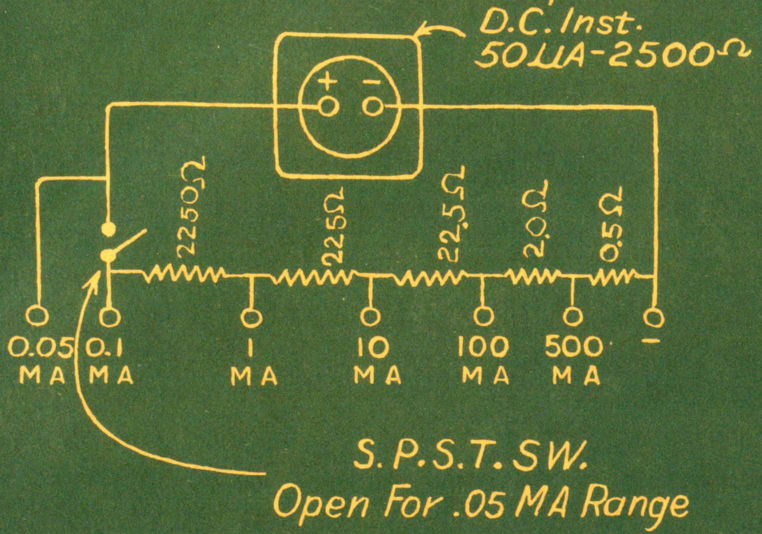
Weston Factory, Newark, New Jersey, approximately one half million square feet of floor space in nineteen buildings on fifteen acres with a population of three thousand eight hundred.

Complete factory facilities for repair and rebuilding Weston products are maintained at the factory, Newark, New Jersey where prompt and efficient service is rendered backed by factory warranty. In addition independent, privately owned repair stations are situated at important central points. The use of these facilities is suggested for minor repairs or adjustments and when factory service would be inconvenient.

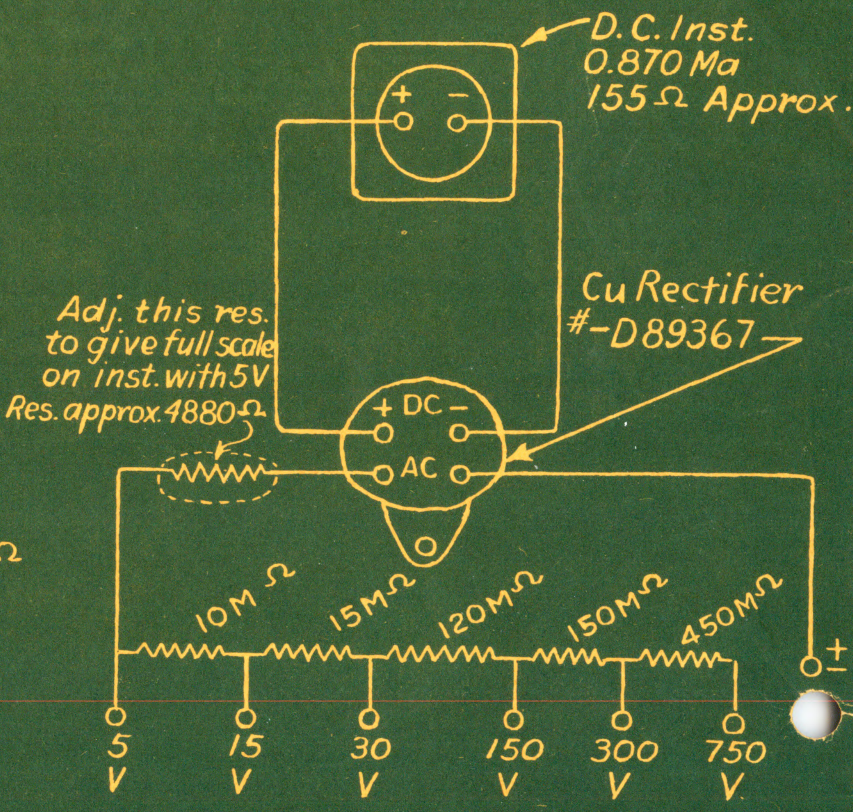


Bat. Adj.
1.5V
Low Range
X
M.A. ranges
Volt ranges
300V
0
300
1Ω
X = ?
500MA
50MA
5MA
1MA
Man.
Man
Man.
Cal. in °F
Cu
310
Source
Load.
RPM
0
1000
BOY OH BOY
RFI
SOL
+B
Photo-cell
ACV
500
50
5
500V
50V
5V
C1
C2
Line
+

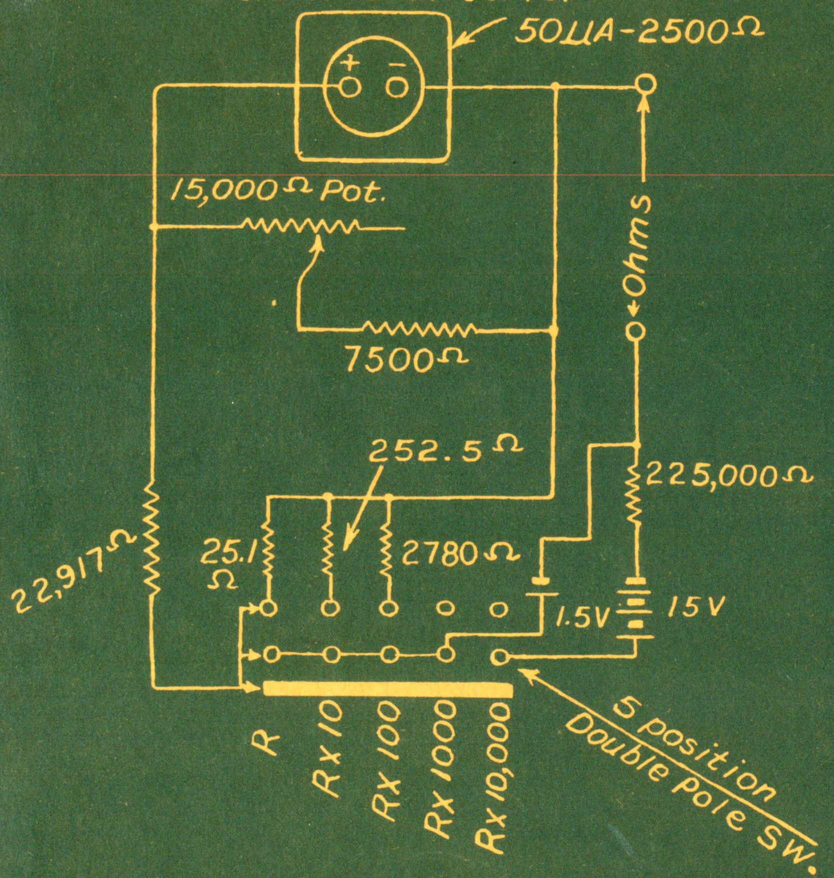
D.C. Milliammeter
Scale 0-10-5 Milliamperes



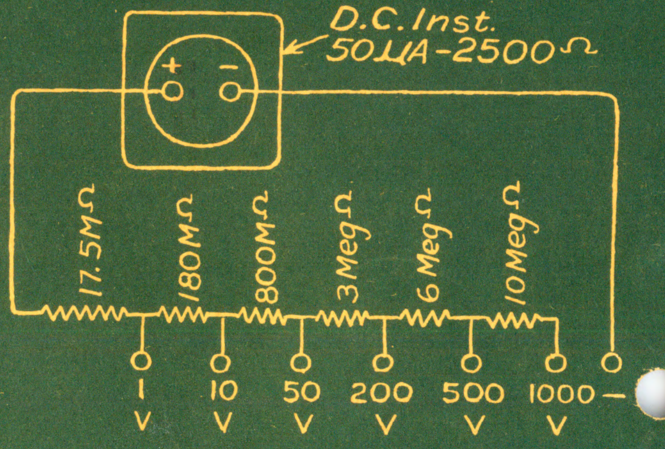
A.C. Voltmeter - 1000Ω/V
Scale 0-750, 30, 15 & 5 Volts



Ohmmeter
Scale 0-3000 Ohms
25 Ohms at Center



D.C. Voltmeter - 20,000Ω/V
Scale 0-10-5 Volts



Note

All resistor units to have a low temperature coeff.
Tc = 0.00035 Ω/Ω/°C or lower