# THE EFFECT OF TEMPERATURE CHANGES AND STRAY FIELDS ON THE ACCURACY OF THE MERCURY-MOTOR D.C. WATTHOUR METER

by

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## Introduction

This thesis, as the title indicates, deals with the effect of temperature changes and stray fields upon the accuracy of the mercury-motor, direct current watthour meter. Most of the work along these lines has been done on the induction type of watthour meters, however, some data is obtainable on the mercury-motor meter.

At the suggestion of Mr. J. E. Housley, Superintendant of the Aluminium Company of America, and Professor J.G. Tarboux, under whose guidance this thesis has been compiled, and with their support and advice, an attempt has been made to determine the effects of the temperature changes and stray fields on the accuracy of one of these meters. The conditions causing these effects are encountered in the plants of the Aluminium Company of America at Alcoa, Tennessee.

## General Survey of Field

[1]The commercial distribution of electricity for power dates from about 1880. Various types of watthour meters were developed during the following ten years and it is interesting to note that the very first were the Faraday disc or mercury-motor meters produced by Hookham and Ferranti in England, its development having been begun in 1883. These early types were quanity or ampere-hour meters, since they consisted simply of a copper disc, partly or wholly submerged in mercury, rotation of which was produced by the interaction of the field of a permanent

[1]Sangamo Meters, Bulletin No. 74.

magnet with an electric current through the disc. It was a comparatively simple step to substitute an electro-magnet for the permanent magnet, thereby producing a field, the intensity of which was directly dependent on the voltage, resulting in a true direct current watthour meter. Improvements and refinements in the details of construction have naturally been made, but the fundamental principle of operation of present day mercury-motor meters is the same as it was forty-five years ago.

This type of meter is supposed to have inherent advantages, principally immunity to stray fields and heavy vibrations and adaptibility to use with shunts for very heavy loads.

Although used extensively and successfully in England and other European countries for many years, this type of meter was not manufactured in the United States until 1905, when it was introduced by the Sangamo Electric Company.

It is generally known that temperature changes do not have such a marked effect upon the accuracy of these meters. The data obtainable on the effect of stray fields on these meters is scarce, most of it dealing with stray fields of low flux densities.

[1]It is estimated that the revenue from the electrical energy produced in the United States in 1916 by central stations alone was $400,000,000. The greater portion of this energy was sold on a basis which involved measuring the energy. It is evident, therefore, that, from a commercial standpoint, the importance of the measurement of energy exceeds that of all other electrical

[1]Farmer, F.M., Electrical measurements in Practice, p.180

measurements. From this it may be seen that the accuracy of these meters must be very good. If temperature changes have a very marked effect on the accuracy of these meters, allowance must be made to compensate the errors due to those changes. If the stray fields affect the accuracy of these meters, another compensation must be made so that accuracy may be obtained. For heavy external fields a laminated shield may be used to direct the stray lines of flux around the meter. The surest method of avoiding these stray fields would be to place the meter far enough away from them that the fields will not pass through the meter. Reasonable care should be exercised, and meters should not be placed too close together nor too close to conductors carrying very heavy currents. The drag element, magnets and disc, are frequently enclosed in a separate shielding case of cast iron, that is, when stray fields are present and unavoidable.

The present theory is that direct current mercury-motor meters and alternating-current induction-type meters are much less liable to stray field errors because they contain iron and their field intensities are therefore very much greater than in the commutator-type meter.

It is known that fields do affect the accuracy of these meters, but it remains to be determined at just what flux density of the field, and the direction of the lines of flux, the meter's accuracy will be affected. The intensity of the stray field that will cause the meter to be inaccurate after the field has been removed is another point to be determined.

## Purpose

The object of this thesis is to determine the effect of temperature changes and stray fields on the accuracy of the mercury-motor D.C. watthour meter.

It will be attempted to show that the temperature changes around one of these meters while it is in operation does not have a very marked effect on it's accuracy. Also it will be shown that a stray field does have a marked effect on the accuracy of the meter while it is in operation, and if the stray field's flux density is high enough, the meter's accuracy will be permanently affected.

## General Theory

[1]An instrument which measures electrical energy is called a watthour meter. All watthour meters are practically a small motor in which one revolution represents a certain amount of energy and the speed is proportional to the power. The revolving element operates a registering mechanism on which the energy consumption corresponding to the total number of revolutions is recorded. [2]The principle of operation of the mercury-motor watthour meter is best explained by using Figure 1, which shows diagrammatically the circuits and scheme of operation. D is a solid copper disc floating in mercury; F is a float which supports the shaft and eliminates a lower jewel bearing; H is a laminated iron core and C is a chamber filled with mercury. The flux produced in the core, H, by the shunt coil, traverses the disc at two points which are diametrically opposite. The

[1]Electrical Measurements in Practice, Farmer, F.M., p. 180
[2]Electrical Measurements in Practice, Farmer, F.M., p. 183

DIAGRAMMATICAL SKETCH OF D.C. MERCURY-MOTOR-TYPE WATTHOUR METER

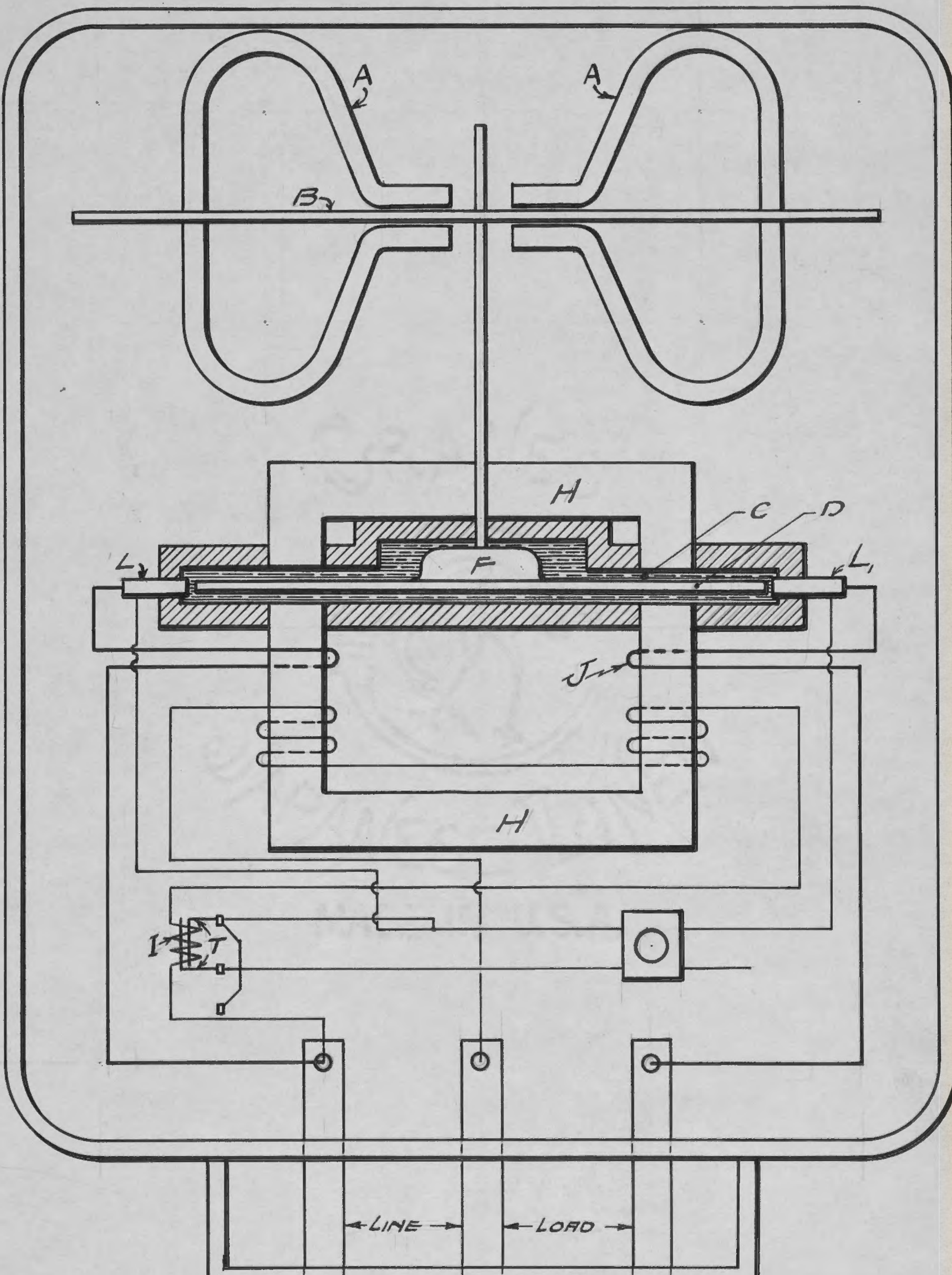



FIGURE 1.

line current passes from L to $L_1$, through the high resistance mercury and diametrically through the low resistance copper disc. This disc being cut by the flux, a torque is produced which is proportional to the current and to the potential. The upper thrust of the entire moving element is about 0.1 ounce, this being the only bearing friction, as the lower pivot of the moving element is guided by a ring jewel set in the armature. In order to make the speed of the disc, D, proportional to the power, a mechanical load must be provided, in which the counter torque will be proportional to the speed. This load takes the form of a circuliar damping disc, B, of thin copper or aluminium, which revolves between the poles of two permanent horseshoe magnets, A, with poles very close together. The eddy currents induced int the disc react with the permanent magnet field, producing a counter torque which will always be proportional to the speed. As the load current increases, the torque of the motor element increases and the speed increases, because there is practically no counter e.m.f. in the armature. But as the speed increases, the counter torque of the disc, B, also increases and the speed is finally reached where the two torques balance each other and the speed remains constant. Thus, theoretically, the speed will always be proportional to the pwer flowing the circuit.

The friction due to the disc rotating in the mercury is compensated by connecting two wires of dissimiliar metals which form a thermo couple, T, in parallel with the mercury chamber terminals, L, $L_1$, This couple is surrounded with a heating coil, I, connected in series with the potential circuit.

The e.m.f. produced by the couple causes current to flow through the disc, thus producing the necessary additional torque to overcome the effect of friction at light load. The increased mercury friction at high speed is compensated by a series half turn, J, on the core, H.

[1]The advantages of the mercury-motor watthour meter for direct current are the elimination of the commutator as well as the wire-wound armature and brushes, and the decrease of wear on the lower pivot and jewel, commonly used in induction type meters. these things tend to decrease the expense of operation.

A practical difficulty has been that, in time, the mercury is very likely to become contaminated and cause an increase in the friction of the meter.

The effect of the temperature changes on one of these meters may be determined by comparing it's readings at different temperatures with the readings of a similiar meter, the same amount of energy being passed through the two meters. The changes of temperature may be obtained by enclosing the test meter in a heat insulated box, using space heaters to get various temperatures above room temperature. The standard meter is placed outside the box where it is subjected to room temperature. The current elements of the two meters may be connected in series while the potential elements are connected in parallel, this arrangement allowing the same energy to pass through both meters.

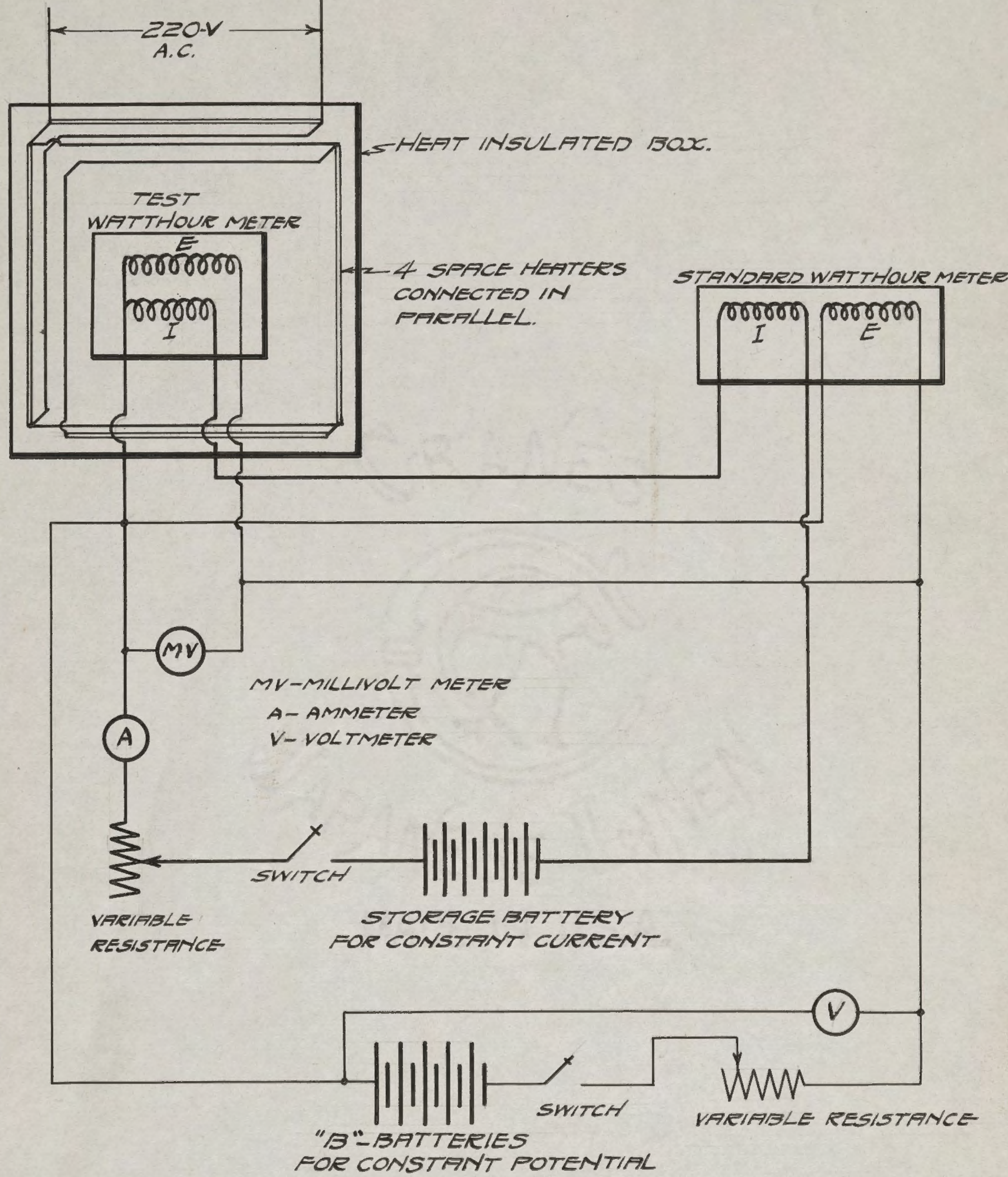
[1]Laws, F.A., Electrical Measurements, p. 484.

With the two meters connected as shown in figure 2 the disc revolutions of the meters, for the same energy and time, may be compared for different temperatures, assuming the the standard meter to read with an accuracy of 100 per cent. The percentage of error may be calculated for the various temperatures.

[1]The temperature of a watthour meter in service may be altered either through self heating or by change of room temperature. If the temperature rises, the resistance of the disc increases so that while driving torque is decreased, the retarding torque is lessened in about the same proportion, the two effects thus tending toward compensation. There are certain other effects; for instance, the drag magnets decrease in strength and as their effect depends on the square of their strength, a 1% change will change the retarding torque 2%. The permeability of the iron and the iron losses are also changed. The net effect is different in different meters. [1]In any case the average range of error will not exceed 2½ per cent from 4 degrees F. to 104 degrees F.

[2]The dimensions, resistance and temperature coefficients of the various circuits in the mercury-motor watthour meter are so combined that no appreciable error results from wide variations in room temperatures. For instance, an increase in temperature will increase the resistance of the damping disc, thus producing less eddy currents for a given speed, and, therefore, less counter torque ; consequently the meter would tend to

[1]Canfield, D.T., Bulletin No.22. Indiana Purdue Eng. Exp. Station.
[2]Sangamo Meters, Bulletin No.74. p.18.




CONNECTIONS USED IN DETERMINING EFFECTS OF TEMPERATURE CHANGES ON THE MERCURY-MOTOR-TYPE D.C. WATTHOUR METER

FIGURE 2.

speed up. However, a similiar change occurs in the resistance of the potential winding, resulting in a decrease in the motor field and a corresponding decrease in the motor torque, the combined results being that the speed remains practically unchanged.

The temperature coefficients of the motor and generator elements in the meter are such that the errors in registration on wide variations in room temperature are small, particularly in the cases of all meters above ten amperes operating from shunts. The meters have a tendency to run slow on a decrease in temperature, and fast on an increase in temperature. On higher voltages the error is very small as the additional resistance in series with the potential coils has a very low temperature cofficient.

In shunted watthour meters, temperature errors are almost entirely eliminated, as a combination of the meter with a current shunt, having no temperature coefficient, causes an opposite and almost equal error on varing temperature to that obtained in the unshunted meter, the two errors, therefore, practically cancelling. Sangamo shunted watthour meters of all capacities have an error on varying temperatures averaging less than 1 per cent for 25 degrees F.

The effect of a stray field on the mercury-motor watthour meter may be determined by placing the meter within this field. This external field is obtained by passing a direct current through a large coil of wire which is placed around the test meter. In this case the lines of flux pass through the meter parallel to the meter's armature shaft. The standard meter is connected as shown in figure 3, about three feet from the test meter and inside of an iron shield. The shield directs any stray flux, near the meter, around the meter through the iron.

[1] The average flux density, in lines per square centimeter, of the stray field inside this coil may be determined by using a formula. The average flux density inside a coil wound on a surface generated by the revolution of a rectangle, with sides "a" centimeters and "b" centimeters respectively, about axis R centimeters from the center of the rectangle, taking "b" parallel and "a" perpendicular to the axis is,

$$B = \frac{0.2\ NI}{a} Ln \frac{R + \frac{a}{2}}{R - \frac{a}{2}}$$

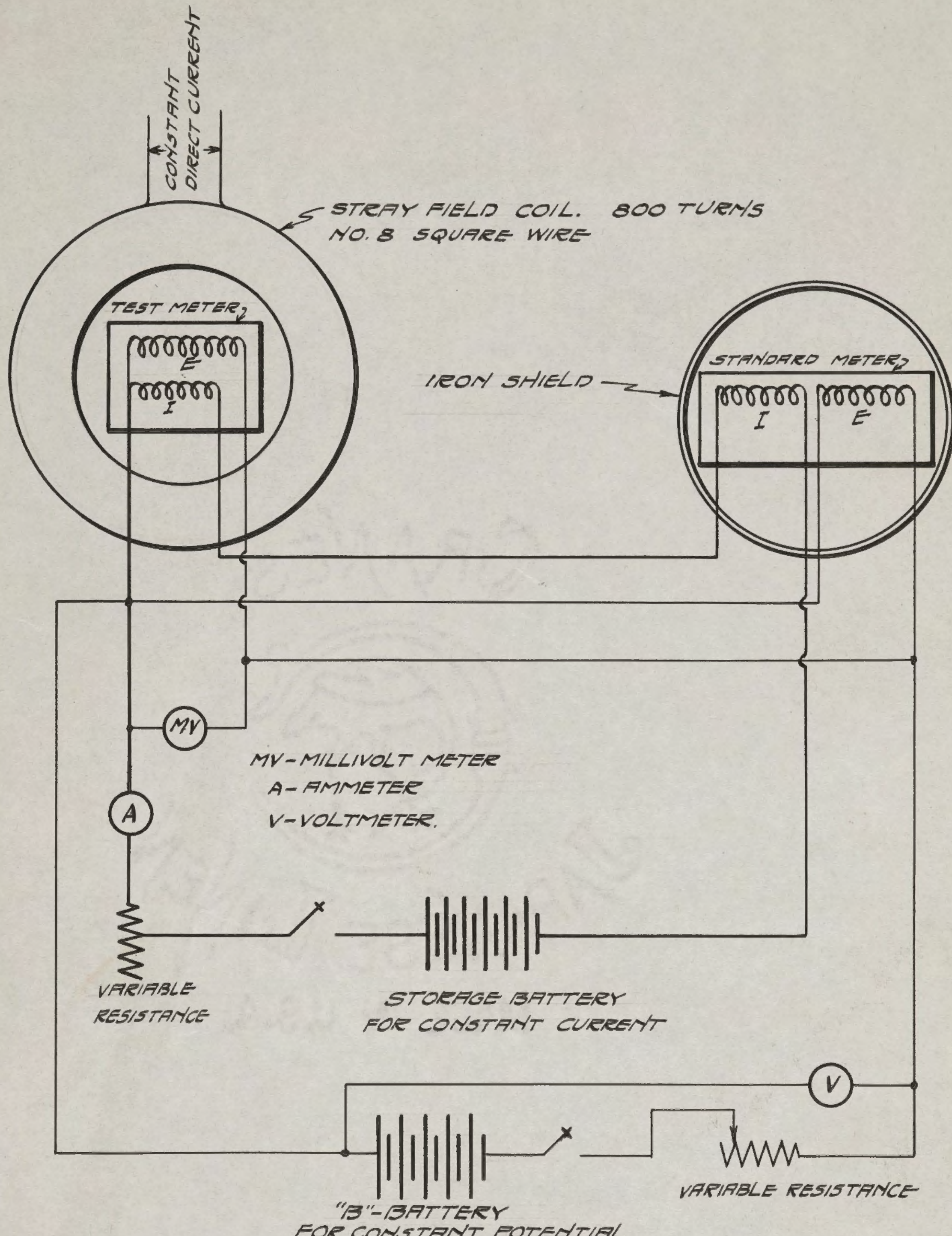
where N = no. turns of coil and I = currents in amperes. For finding the perpendicular distance **d**, of the equivalent flux density from a straight wire, the formula is--

$$B = \frac{0.2\ I}{d} \quad \text{or} \quad d = \frac{0.2\ I}{B}$$

In this formula it is assumed that the current through the conductor is of uniform density through out the wire, and d is negligible compared with the length of the conductor.

[2] Certain types of watthour meters are readily affected by external magnetic fields, particularly those which contain no iron, such as the usual types of continuous-current commutator meters. This external field may weaken or strengthen the drag magnets, increase or decrease the retarding torque, or, and more generally, increase or decrease the strength of the field in which the armature element is rotated. The effect on the magnets can be eliminated by using two or more magnets astatically

[1] Hudson, Engineering Manual, p. 190
[2] Electrical Measurements in Practice, Farmer, p--197




CONNECTIONS USED IN DETERMINING EFFECTS OF STRAY FIELDS ON THE MERCURY-MOTOR-TYPE D.C. WATTHOUR METER

FIGURE 3.

arranged, a practice which is now common. The effect on the drag disc and on the meter field can only be eliminated either by removing the source of the field or by so locating the meter that there will be no component of the field in a direction which will give trouble. The usual sources of such fields are electrical conductors, and often these can be relocated so that there will be no influence on the meter.

Continuous-current mercury-motor type meters and alternating-current induction type meters are much less liable to stray field errors because they contain iron, and their field intensities are therefore much greater than in the commutator-type meter.

[1]To determine the effect of a stray field on watt-hour meters, a field of one gauss was superimposed upon that of the current element in such a manner as to produce the greatest effect. This field is equal to that at a distance of 25 centimeters from a conductor carrying 125 amperes, and is about five times the horizontal component of the earth's field at Washington, D.C. Up on reversing this stray field of one gauss at full load, 0 % change was noted in the meter's accuracy.

The effect of a weak stray field and a strong stray field upon the test meter is somewhat different. If the external field is raised to a certain flux density through the meter, the meter will fail to operate, this value being 168 lines per square centimeter approximately. When the flux density is raised to 296 lines per square centimeter, and then the entire

[2] Fitch, T.T., & Huber, C.T., Bulletin of Bureau of Stds. Vol. 10, p--168

stray field removed from the meter, the permanent magnets are almost wholly demagnetized, thereby, causing the counter torque of the drag disc to be nearly negligible, and the disc revolutions to be increased in speed about 165 per cent. If the flux density is raised to 41.5 lines per square centimeter the increase remains 165 percent, but if the flux density is raised to 168 lines per square centimeter, the meter again fails to operate.

This external field weakens the drag magnets and decreases the retarding torque, and upon reaching a certain flux density, decreases the strength of the field in which the armature rotates until it is of a negligible value. The eddy currents in the damping disc caused by the external flux passing through the disc may be large enough that the torque produced by the armature will not overcome it.

Description of the Method and Apparatus Used

For determining the effect of temperature changes on a mercury-motor watthour meter, an insulated box was built up of 1/2 inch thick cellotex. The inside deminsions were 24 inches square and 18 inches high. A 6" by 6" hole was cut in one side of the box near the top. In this hole a 6"by 6" section of plate glass was placed, so observations could be made on the meter inside of the box. Four 220 volt, 500 watt space heaters, 24 inches long were connected in parallel around the sides of the box. The temperture inside of the box was changed by allowing current to pass through the space heaters for different periods of time. The test watthour meter was placed inside of this box. A thermometer was hung down unside of the box near the meter and was observed through the glass opening.

The meter used as a test meter was a Sangamo type D-5 d.c. watthour meter of 10 amperes, 510 volt capacity. This meter was supplied with two shunt leads, each 25 feet long, and an external resistance. The shunt leads were placed inside the insulated box, and the external resistance was removed from the circuit, the voltage of the potential element of the meter being reduced to 100 volts for compensation. A diagramatic sketch of this meter and its internal connections is shown in figure 1.

A switchboard meter of the same type, but of 550 volt capacity, was used as a standard meter. It was connected to the test meter as shown in figure 2, that is, with the two current elements in series and the two potential elements in parallel. A storage battery, in series with a variable resistance an ammeter, and the two meter's current elements furnished the current elements with a constant current. The potential elements of the twometers, with the shunt leads on the test meter were connected in parallel with each other and three "B" batteries. The "B" batteries were in series with a slide wire reostat so that a constant potential of 100 volts could be obtained across the potential coils. A voltmeter was connected across the line to get the voltage across the potential coils. A milli-voltmeter was connected across the ends of the two shunt leads to measure the milli-volt drop of the shunt leads and potential elements of the test meter. With this arrangement the voltage and current through these two meters were held constant, thereby, producing a constant energy to be measured by both meters. By keeping the same milli-volt drop and voltage for different temperatures on the test meter, a comparison of disc revolutions was made. The test meter was allowed to heat up until it was approximately the same temperature throughout. The milli-volt drop across the shunt leads and potential elements of the test meter at room temperature, with 10 amperes flowing through the current element, was used in every case when the temperature was changed.

By assuming the test meter to read with 100 per cent accuracy at room temperature, 90° F., the per cent error at different temperatures was calculated. The reading of the standard meter was assumed to be correct in all cases. Disc revolutions were counted for readings of both meters during the same period of time while constant current and voltage was applied.

In determining what effect a stray field has on a mercury-motor watthour meter, the same set up was used, excepting the insulated box was taken from around the test meter and replaced by acoil of wire as shown in figure 3, and an iron shield was placed around the standard meter to direct any stray flux around the meter. The coil of wire used was built up of no. 8 , square wire, using a machine lathe for winding it. The coil had 800 turns and an inside diameter of 9 1/4 inches, an outside diameter of 17 inches, and was 5 3/4 inches high. The test meter was placed within the center of the coil, with the axis of the armature shaft in line with the axis of the coil. This arrangement allowed the lines of flux from the coil's field to pass through the meter, parallel to the meter's armature shaft.

It was intended to vary the current in the coil by by 5 ampere steps, but 30 amperes were allowed to flow through it before adjustment had been made on the direct current motor-generator set which was supplying the D.C. current. This current produced an average flux density of 296 lines per square centimeter through the test meter. The permanent magnets of the meter were nearly totally demagnetized. After removing this external field the test meter ran with an error of 165 per cent, the speed being faster. When the current in the field coil was raised to 4.2 amperes, which corresponds to an average flux density of 41.5 lines per square centimeter through the test meter, the speed of the test meter still showed an error of 165 per cent. This increase of speed was measured over the speed of the disc in the test meter at room temperature. When the current in the coil was increased to 17 amperes the test meter failed to operate. This current produces an average flux density of 168 lines per squire centimeter through the test meter. The distance of the equivalent flux density from a straight round conductor, carrying 30,000 amperes was calculated in each case.

There were many sources of error involved in this test. Probably the greatest source was in counting the revolutions of the disc of the two meters. Variations in the voltage and current during the test would have some effect upon the meter's operation, but it probably wouldn't be noticeable. The current in the stray field coil might have varied during the stray field test, which would have caused a change in flux density through the meter, which would, in turn, affect the meter's accuracy.

Observations and Calculations

Determination of the voltage used on the potential element of the test meter when the resistance box is excluded fr from the circuit,

Resistance of potential element, $R_p$ = 2,675 ohms,

Resistance of resistance box, $R_b$ = 10,380 ohms,

Total resistance, $R_t = R_p + R_b$ = 13, 055 ohms.

Rated voltage of meter, E = 510 volts.

Current through potential element,

$$I = \frac{R_t}{E} = \frac{13,055}{510} = 0.383 \text{ amperes.}$$

Voltage with resistance box out of circuit,

$$E = I R_b = 0.383 \times 2,675 = 102.5 \text{ volts.}$$

Temperature change effect on accuracy of mercury-motor watthour meter with connections as in figure 2:

| Temperature & degrees F. | Meters I amperes | Meters E volts | Disc Revolutions Standard Meter | Disc Revolutions Test Meter | Millivolt drop across shunt leads & potential elements, Test Meter | Per Cent Error |
|---|---|---|---|---|---|---|
| 90 | 10 | 100 | 100 | 151.9 | 64 | 0 |
| 100 | " | 100 | 100 | 153.0 | 64 | 0.725 |
| 110 | | 100 | 100 | 149.9 | 64 | 1.32 |
| 120 | | 100 | 100 | 150.0 | 64 | 1.25 |
| 90 | 10 | 100 | 100 | 151.0 | 61 | 0 |
| 100 | | 100 | 100 | 149.6 | 61 | 0.927 |
| 110 | | 100 | 100 | 148.9 | 61 | 1.39 |
| 120 | | 100 | 100 | 149.8 | 61 | 0.795 |

$$\% \text{ error} = \frac{153-151.9}{151.9} = 0.00725 = 0.725 \%$$

With connections as in figure 3. Effect of stray field on mercury-motor d.c. watthour meter after having passed an average flux density of 296 lines per square centimeter through the meter:

| Temperature: Degrees F, | Meters I Amperes | Meters E Volts | Disc Rev. Std. Meter | Disc Rev. Test | $I_f$ in field coil | B Av. ø density thru meter-Lines / sq. cm. | d | % Error |
|---|---|---|---|---|---|---|---|---|
| 90 | 10 | 100 | 100 | 400 | 0 | 0 | | 165. |
| 90 | 10 | 100 | 100 | 400 | 4.2 | 41.5 | 144.6 | 165. |
| - | - | - | - | - | 17.0 | 168.0 | 35.7 | - |
| - | - | - | - | - | 30.0 | 296.0 | 20.3 | - |

d = distance of equivalent flux density from a straight conductor carrying current of 30,000 amperes.

$$\text{Percent Error} = \left( \frac{400 - 151}{151} \right) \times 100 = 165\ \%$$

For determining average flux density inside of field coil:

$$B = \frac{0.2\ NI}{a} \ \text{Ln}\ \frac{R + \frac{a}{2}}{R - \frac{a}{2}}$$

R = 16.68 cm., N = 800 turns, I = 4.2 , a = 3.875"= 9.85 cm.

Substituting these values in the formula above,

$$B = \frac{(0.2)(800)(4.2)}{9.85} \ \text{Ln.} \frac{16.68 + \frac{9.85}{2}}{16.68 - \frac{9.85}{2}}$$

$$B = 68.3 \ \text{Ln.} \ \frac{16.68 + 4.92}{16.68 - 4.92}$$

$$B = 68.3 \ \text{Ln.} \ \frac{21.6}{11.92}$$

$$B = 68.3( \text{Ln.}\ 21.6 - \text{Ln.}\ 11.76)$$

$$B = 68.3 ( 3.072 .- 2.464 )$$

B = 41.5 lines per square centimeter.

For determining the distance of equivalent flux density from a straight conductor carrying 30,000 amperes:

$$B = \frac{(0.2)I}{d}$$

$$d = \frac{0.2(I)}{B}$$

$$d = \frac{(0.2)(30,000)}{41.5}$$

$$d = 144.6 \text{ centimeters.}$$

## Conclusions.

From the results of this test it may be stated that:

(1) The affect of temperature changes on the accuracy of a shunted mercury-motor type direct current watthour meter was not very marked, an error of 1.39 percent being noted in a temperature rise from 90 degrees F. to 120 degrees F. The meter shows a decided tendency to be self compensating to the changes of the surrounding temperatures.

(2) The effect of stray magnetic fields on the accuracy of this meter was pronounced, that is, when the stray field was of a high density. When an average flux density of 296 lines per square centimeter was passed through the meter parallel to the shaft of the armature, the permanent magnets were nearly totally demagnetized and the meter stopped operating. Upon removing the stray field, the meter had an error of 165 percent in it's accuracy.

The importance of shielding a meter of this type from heavy external fields may be noted from this test. A meter should either be shielded from surrounding stray fields or placed far enough away from them that they will not pass through the meter.

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Approval

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval that the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves this thesis only for the purpose for which it is submitted.

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