A COMPARISON OF AMERICAN DIRECT-CURRENT SWITCHBOARD VOLTMETERS AND AMMETERS

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CONTENTS

I. INTRODUCTION

A comparative test of switchboard voltmeters and ammeters was recently made at the Bureau of Standards for the Bureau of Equipment of the Navy Department. All American makers whose addresses were known, who make instruments of the specified size and type, were given an opportunity to submit instruments. Each of eight different makers submitted a voltmeter and an ammeter. The range of the voltmeters was 0 to 150 volts and of the ammeters

0 to 200 amperes, the latter having separate shunts. As the test was quite comprehensive in regard to this type of instruments, it appears desirable to publish some of the results. A general view of the voltmeters is shown in Fig. 1.

Descriptions of electrical instruments usually give only very general information. For some purposes, however, it is necessary to have at least approximate numerical values of the details of construction and operation of such instruments. For this reason the results of various tests and measurements are given in this article.

The test was divided into two parts—(1) the performance of the instruments, and (2) the determination of their structural constants and dimensions of parts.

The points covered under these two main heads are indicated in the contents, II and III. The test was, of course, carried on separately for the voltmeters and the ammeters. In the figures and tables shown, the voltmeters of the different makers are designated as A, B, C, D, E, F, G, and H. Similarly the ammeters are designated as a, b, c, d, e, f, g, and h, the same letter, capital or small, corresponding to the same maker. The order of the lettering bears no relation to the grouping in the photographic plates.

II. PERFORMANCE OF THE INSTRUMENTS

1. ACCURACY OF CALIBRATION

Figs. 2 and 3 show the errors in calibration of the voltmeters and the ammeters, at room temperatures of 18 and 25° C, respectively. The error at zero refers to the voltage or current indicated on open circuit. A few years ago European makers introduced the use of a zero adjustment on portable instruments and it has since been adopted to a considerable extent by makers in this country. Such an adjustment is also found on the instruments of one maker in this test, and it seems desirable that all should be so provided.

Two other errors are to be looked for in the instrument calibration, the scale error and the adjustment of the sensibility. With the zero in adjustment the instrument can be made to read correctly at any one point of the scale by adjusting its sensibility,

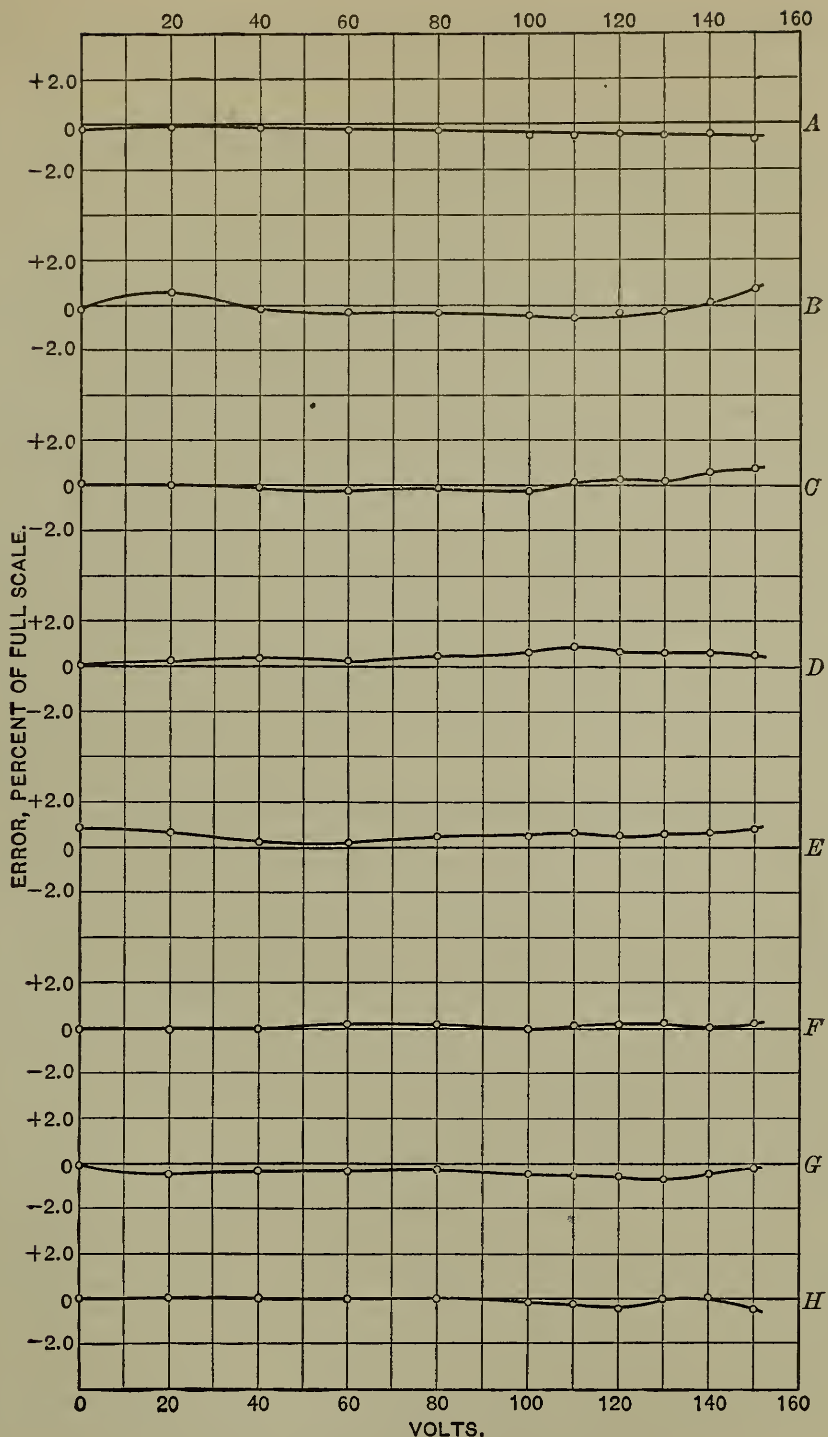

Fig. 2.—*Calibration Curves of Voltmeters*

and if the scale fits the instrument, it will then be correct throughout its range. It is desirable that the flux density in the air gap

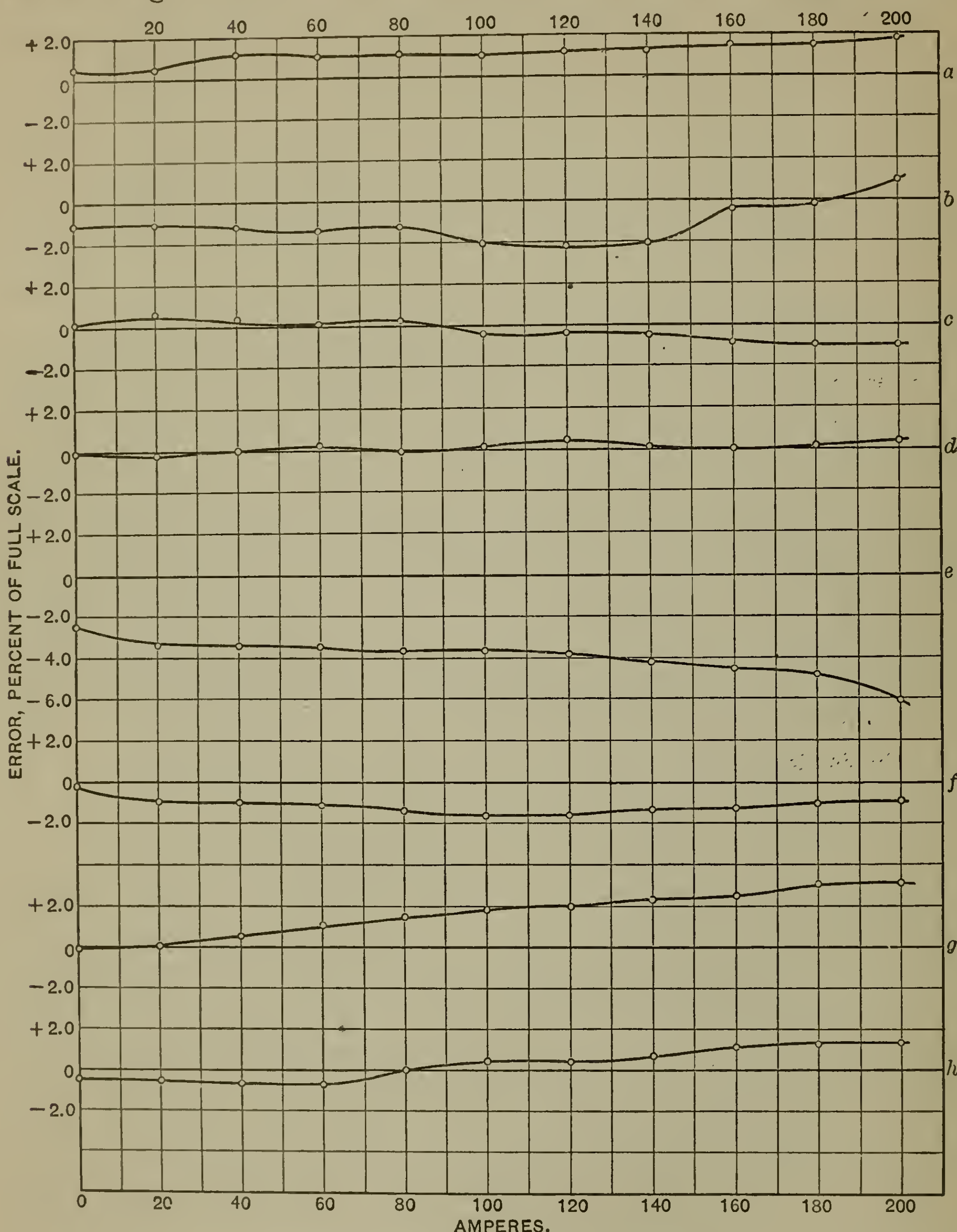

Fig. 3.—*Calibration Curves of Ammeters*

should be uniform, as in that case the scale will be one of equal divisions. As to making the final adjustment of the sensibility, this can be done in several ways. In a voltmeter the strength of the magnets or springs may be changed, or the series resistance may be altered.

In an ammeter the shunt is an additional factor which may be changed. Another method is to shunt the moving coil circuit. In an analogous manner the magnetic circuit may also be shunted by a small piece of iron. While all these methods are used, in practice the one that has been most generally employed is that of altering the series resistance.

It will be noticed that the errors of calibration are small on all the voltmeters, while in the case of the ammeters they are much greater. The irregularities in most of the curves show that the scales do not fit well, aside from the fact that the sensibility is not closely adjusted. Although accuracy is more difficult to obtain in ammeters than in voltmeters, partly owing to the low resistance of the millivoltmeter circuit, still the errors shown on some of these ammeters are excessive, taking into consideration the fact that all were new.

2. RESISTANCE AND POWER CONSUMPTION

In Tables I and II are given the results of the test coming under the remaining headings on performance. The power loss in direct current voltmeters is so small that it is unimportant, although the values vary by a factor of more than two. For ammeters it is of course desirable to have the drop at the shunts as low as is consistent with accuracy of indication. Some engineers specify a drop of from 60 to 75 millivolts at full scale, and it will be seen by reference to the table that good performance, except as to temperature coefficient, can be secured with even less drop than this.

(a) **Shunts—Temperature Effects, etc.**—Another important point is to design the shunts so that the heat developed will be dissipated without an undue rise of temperature. For this purpose the best practice is to use a number of resistance plates connected in parallel between comparatively heavy lugs, with the spaces between the plates open above and below. This facilitates convection currents in the air in carrying away the heat produced in the shunts.

TABLE I

Performance of Voltmeters

Voltmeter	A	B	C	D	E	F	G	H
Resistance (ohms)	12450	16180	18400	7540	12350	14380	16760	14190
Watts at 150 volts	1.81	1.39	1.22	2.99	1.82	1.56	1.34	1.58
Per cent change from standing one hour at 150 volts [1]	−0.2	−0.2	−0.1	−0.1	−0.3	0.0	+0.1	−0.2
Per cent change from reversing a stray field of 4 gausses	0.8	2.2	1.5	1.1	2.5	2.3	1.2	1.7
Damping. Time in seconds to come to rest after closing on 120 volts	0.8	4.8	2.1	1.2	4.6	2.4	2.8	3.7
Mechanical balance. Maximum deviation of index, per cent of full scale [2]	0.0	0.4	0.2	0.1	0.3	0.1	0.1	0.1
Insulation resistance between coil and case, in megohms	>75	15	37	>75	75	>75	25	>75
Temperature coefficient. Per cent change per degree C [3]	−0.01	−0.03	−0.03	−0.02	−0.02	−0.01	+0.02	−0.01

[1] The minus sign indicates that less voltage was required at the end of the period.

[2] In this test the instrument is turned at different angles.

[3] The minus sign indicates that less voltage was required at the higher temperature

TABLE II

Performance of Ammeters

Ammeter	a	b	c	d	e	f	g	h
Resistance of millivoltmeter (ohms)	1.3	3.7	2.7	0.9	2.0	1.3	4.8	3.2
Shunts:								
Millivolts at full load	50	74	60	49	70	50	61	97
Watts loss at full load	10	14.8	12	9.8	14	10	12.2	19.4
Temperature rise in plates at full load °C	53	73	69	38	70	66	62	82
Temperature rise in lugs at full load °C	40	59	58	20	45	58	50	43
Thermal emf. after one hour at full load, millivolts	0.0	0.7	0.0	0.0	0.4	0.3	0.1	0.1
Total change of resistance from 25° to 50° C (per cent) [4]	+0.5	+0.1	+0.2	+0.1	+0.4	0.0	+0.1	+0.1

[4] The plus sign indicates an increase in resistance with rise of temperature.

TABLE II—Continued.

Performance of Ammeters—Continued.

Ammeter	a	b	c	d	e	f	g	h
Per cent change from standing deflected at full load for one hour [5]	−0.5	−1.2	−0.9	−0.1	−1.6	−0.4	−0.3	−0.6
Per cent change from reversing a stray field of 4 gausses	0.7	1.5	1.4	1.1	3.5	1.6	0.8	1.9
Damping. Time in seconds to come to rest after closing circuit on 160 amperes	1.1	2.6	1.6	1.4	5.8	2.1	2.4	2.4
Mechanical balance. Maximum deviation of index, per cent of full scale [6]	0.9	0.7	0.7	0.4	0.6	0.6	0.8	0.7
Insulation resistance between case and coil, in megohms	75	75	37	75	>75	>75	9	75
Temperature coefficient. Per cent change per °C. [7]	+0.11	+0.08	+0.09	+0.15	+0.15	+0.32	+0.28	+0.20

[5] The minus sign indicates that less current was required at the end of the period.

[6] In this test the instrument is turned at different angles.

[7] The plus sign indicates that more current was required at the higher temperature for the same indication.

3. CHANGE IN INDICATIONS DUE TO STANDING UNDER LOAD—ZERO SHIFT, ETC.

In direct current voltmeters there are two principal causes of change in indications from standing under load—zero shift and change of resistance. None of these voltmeters, however, showed any appreciable zero shift, but they did show change of resistance of the same order as the change in indications.

In direct current ammeters the principal causes of this change are zero shift of the millivoltmeters, the change of resistance, and the thermoelectric effect in the shunts. Where this thermoelectric effect exists, an emf will be found at the shunts after the circuit is opened, due to the extra heating of one junction by the current. The same effect will be produced by any condition which occasions unequal heating of the ends of the shunt, such as a bad contact at one end or a difference in the size of the conductors connected to the shunt.

Table III gives the computed per cent changes due to thermal emf and to heating under full load, compared with the observed change in indication from standing deflected under the same conditions. The computed values are based on the values found separately for the thermal emf of the shunts and their change of resistance under load. It will be noticed that the thermal and heating effects account for most of the change, especially as such instruments can not be relied upon to repeat their readings better than 0.2 or 0.3 per cent. This is partly due to the fact that no parallax mirror is provided in switchboard instruments, and hence the error of reading is greater than in portable instruments of the same type.

TABLE III

Ammeter	a	b	c	d	e	f	g	h
Change due to thermal emf ..Per cent..	0.0	1.0	0.0	0.0	0.6	0.6	0.1	0.1
Change due to heating ....do....	0.8	0.3	0.6	0.2	1.1	0.0	0.2	0.3
Sum ....do....	0.8	1.3	0.6	0.2	1.7	0.6	0.3	0.4
Observed change ....do....	0.5	1.2	0.9	0.1	1.6	0.4	0.3	0.6

4. EFFECT OF STRAY FIELD

To simulate the effect of a stray field a current of 100 amperes was passed through a coil of two turns 62.5 cm in diameter. The instrument under test was placed so that its moving coil was at the center of this external coil, where the magnetizing force in air would be 4 gausses, and with coil and instrument in such relative position that the field due to the external coil was in the same direction as that in the air gap of the instrument. The above field strength is about five times the strength of the earth's field and is equal to the field at a distance of 25 cm from a straight bus bar carrying 500 amperes. As the effect was obtained by reversing this magnetizing force, the change in the field is about ten times the earth's field, or forty times that of the horizontal component, which is usually the only one effective in causing an error. In practice, however, the greatest trouble from stray field is that due to heavy currents in the neighborhood of the instrument. The results of this test are given in Tables I and II. Small fields will produce no appreciable effect when acting at right angles to that in the air gap of the instrument.

5. DAMPING

One of the most important points in the practical use of an instrument is its damping. It is important, not only for the ease and convenience of taking readings, but the accuracy of the readings will often depend upon it. Good damping also reduces the wear on the pivots due to the swing of the pointer with unsteady current or voltage, and it lessens the danger of injury in cases of momentary overload. The universal method used for damping direct-current moving-coil instruments is to wind the coil on an aluminum frame, which acts as a magnetic damper. The amount of damping depends upon the amount of metal used in the frame, the torque, the moment of inertia of the moving element, and the flux in the air gap. In a voltmeter the damping due to the coil itself is negligible, because of the large external resistance in series with it; but in an ammeter it is an appreciable part of the total damping. As a measure of the efficiency of the damping, the length of time required for the needle to come to rest after closing the circuit was measured by a stop watch. The results for the voltmeters are given in Table I, for the ammeters in Table II.

The best-damped instruments come to rest as quickly as an accurate reading can be made, while the more poorly damped ones made seven or eight (single) swings before coming to rest, so that there was a very decided difference in the ease with which readings could be made.

An interesting relation between *damping* and *ratio of torque to weight* is brought out by these instruments, and is discussed later in paragraph III 1b.

6. MECHANICAL BALANCE OF MOVING SYSTEM

For this test the instruments were turned in different positions and the maximum change of position of the index observed. The results are given in Tables I and II.

The moving element is usually provided with two sets of adjustable weights carried on arms placed at right angles. By adjusting these the center of gravity can be brought to the axis.

7. INSULATION RESISTANCE

This test was made with 500 volts direct current applied between case and coils. In Tables I and II the sign $>$ indicates that the resistance was greater than 75 megohms, as that was the limit of sensibility of the apparatus used.

8. TEMPERATURE COEFFICIENT

In the voltmeters the temperature coefficient is a summation effect of the temperature coefficients of the strength of the magnets and springs and the resistance of the coils. In the ammeters there is the added effect of the change in resistance of the shunts. In the voltmeters, which have large series resistances, the principal changes should be those due to the magnets and springs, as resistance materials of negligible temperature coefficient are readily obtainable. The elasticity of the springs has a temperature coefficient of about -0.04 per cent per degree C; that is, they are weaker at higher temperature. The temperature coefficient of the magnets may be plus or minus; but it is usually of the same order and sign as that of the springs, that is to say, the magnetic field is weaker at higher temperatures.

In the tables it is noticeable that the ammeters have a much larger temperature coefficient than the voltmeters. This is due largely to the millivoltmeters, which have a low resistance, a considerable proportion of which is copper. Consequently they have a high temperature coefficient. It is not feasible to wind the moving coil with manganin wire as the resistance would be too high to work on the available millivolt drop unless the design were so changed that more wire could be wound upon it. While it could be made to work in this way, the moving element would be too heavy for good performance. The temperature coefficient could also be greatly reduced by using larger shunts, giving a higher drop, say 200 millivolts; this allows the use of manganin wire in series with the copper coil. As this would increase the cost of the shunts and the power consumption, there is no reason for varying from the present practice, because the temperature errors of switchboard ammeters as now made are of comparatively little consequence.

9. RUGGEDNESS OF MOVING SYSTEM

Both ammeters and voltmeters were tested by reversing the current when standing at full scale deflection. This is a test that such instruments should withstand, and none of those in this test showed any damage from this treatment.

TABLE IV

Moving Elements

	Weight in grams	Full scale torque	Ratio torque to weight	Full scale milliamperes	Number turns in coils	Ampere turns
Voltmeters:		Mm-grams [8]				
A	1.72	9.4	5.5	12.0	69.5	.83
B	3.02	2.9	1.0	9.3	53.5	.50
C	1.64	5.0	3.0	8.1	58.5	.47
D	2.82	21.0	7.4	19.9	103.0	2.06
E	2.88	8.8	3.0	12.1	155.5	1.88
F	3.48	15.0	4.3	10.4	195.5	2.04
G	1.73	2.9	1.7	8.9	45.5	.41
H	3.50	8.6	2.5	10.6	116.5	1.24
Millivoltmeters:						
a	2.55	6.2	2.4	37	11.0 [9]	.40
b	4.66	3.7	0.8	20	24.5	.49
c	2.17	3.7	1.7	23	12.4	.29
d	3.26	7.6	2.3	53	13.3	.71
e	3.71	3.1	0.8	36	22.5	.81
f	4.36	6.7	1.5	38	26.5	1.01
g	2.70	2.1	0.8	13	21.5	.28
h	4.60	8.7	1.9	31	36.5	1.13

[8] The centimeter-gram is the unit of torque used by English and German writers.

[9] The effective number of turns is given where several sections were wound in parallel.

III. DETAILS OF CONSTRUCTION

1. THE MOVING SYSTEMS

a. Torque, Weight, Number of Turns.—Fig. 4, shown at the end of this article, is a photograph of the moving elements of the eight different types of instrument, and Table IV gives the numerical constants relating to them. About the only differences between the moving element of a voltmeter and that of a millivoltmeter of the same make are the size and material of the springs and the size of the wire with which the moving coil is wound. The bearing which the ratio of torque to weight has upon the performance is pointed out in the following section. The other factors given in Table IV are of interest, as they show the requirements for the necessary torque.

b. Ratio of Torque to Weight.—Although the importance of the ratio of the torque to the weight of the moving element has often been pointed out, the full significance of this constant is not as generally appreciated as it should be, and unfortunately designers of instruments sometimes allow other considerations to prevent them from keeping this ratio up to a proper value.

The friction between pivots and jewels is proportional to the weight of the moving part, and though this latter is small the area of the pivot which has to carry the weight is extremely small, so that the resulting pressure per unit area becomes very large. In the analogous case of the bearing in a watthour meter Haskins has recently stated that this pressure may reach 200 tons per square inch.[10] An angular displacement of two or three minutes of arc may be detected in the movement of the needle of an instrument, and hence the limiting resisting torque due to the friction of the pivots must be less than the very slight torque obtained by twisting the spring through this very small angle, or the friction will be evident in the motion of the needle. When it is considered that this condition must be maintained under service conditions of wear and vibration, the prime importance of the ratio of torque to weight becomes evident.

[10] C. D. Haskins: General Electric Review, **13**, No. 9, Sept., 1910.

The weight, full scale torque, and the ratio of torque to weight are given in Table IV both for the voltmeters and the ammeters.

An interesting relation between *damping* and the *ratio of torque to weight* is brought out in Table V, in which the instruments have been given relative ratings for both characteristics, the number 1 indicating the best and the number 8 indicating poorest performance in each case. Such a comparison should, theoretically, be made using ratio of torque to moment of inertia instead of the ratio of torque to weight, but since the coils have the same general shape the moment of inertia may be taken as proportional to the weight.

TABLE V

	Voltmeter								Millivoltmeter							
	A	B	C	D	E	F	G	H	a	b	c	d	e	f	g	h
Rating according to damping	1	8	3	2	7	4	5	6	1	6	3	2	7	4	5	5
Rating according to ratio of torque to weight	2	7	4	1	4	3	6	5	1	8	4	2	6	5	7	3

In the case of the voltmeters, the ratings do not differ by more than one except in the case of voltmeter E. This voltmeter has a weak field, and the torque is kept up by using a large number of turns, but the damping is poor, owing to the large moment of inertia and the weak field. Consequently, it is much underdamped, though it has a fairly high ratio of torque to weight.

In the case of the millivoltmeters, g and h show the most difference in the two ratings. They have about the same field strength and the damping is practically the same, but one of them has secured a larger ratio of torque to weight, chiefly by using a larger millivolt drop.

TABLE VI

The Constants of the Magnets

[The dimensions are given in centimeters and the flux densities in gausses per square centimeter]

Millivoltmeter	Length l_m	Cross section q_m	Pole piece surface q_a	Total air gap l_a	$K=\frac{l_m}{q_m} \Big/ \frac{l_a}{q_a}$	H Flux density in air gap	Total flux	B Flux density in steel
a	26.4	4.38	11.0	0.260	255	1590	17500	4000
b	25.9	3.94	10.9	.293	246	427	4660	1180
c	34.7	3.02	11.2	.255	505	1450	16200	5400
d	22.4	3.90	9.1	.173	302	2790	25400	6500
e	30.4	2.93	10.6	.450	244	213	2250	770
f	23.7	2.50	11.0	.287	363	875	9630	3800
g	27.7	4.01	8.8	.310	196	551	4850	1210
h	24.7	4.70	13.7	.320	225	740	10100	2200

2. THE MAGNETS—DIMENSIONS, AIR GAP, ETC.

Fig. 5, shown at the end of this article, is a photograph of the magnetic systems of the instruments, and the numerical constants relating to them are collected in Table VI. Tables IV and VI are similar in form to those of Heinrich and Bercovitz in their article on "Die Technischen Messinstrumente" in the Handbuch der Elektrotechnik.

The quantity K appearing in Table VI is the ratio of two ratios; that is, the ratio of the length of the magnet to its cross section divided by the ratio of the length of the air gap to its cross section. Heinrich and Bercovitz divide this ratio K by 100 and call that the safety factor against demagnetization. This is arbitrary, of course, but it is evident that this factor should be large. The values given were taken from the magnets of the millivoltmeters, but they apply also to the voltmeters except, of course, that the flux densities may vary in different magnets.

As the reliability of this type of instrument depends largely upon the permanency of the magnet, it is important that a good magnetic circuit be used. To concentrate the field and make it as uniform as possible, soft iron pole pieces are used with the magnet. The pole pieces used by one maker are merely shells instead of a solid mass of iron. The effect of this is essentially the same as an increase in the air gap, which is, of course, undesirable, as it makes the real permanency factor lower than the value found by the formula. Another maker uses laminated pole pieces. Theoretically this should give better uniformity of field, but in this instance, as the laminations were left unfinished, the lack of uniformity would probably be greater, due to the variations in the length of air gap.

3. MISCELLANEOUS DETAILS OF CONSTRUCTION

A few details of design and construction having to do with convenience in use and reliability of operation deserve to be mentioned.

Legibility of a switchboard instrument is a necessary requirement. Two of the makers have used large figures and heavy lines, making the instruments readily legible at a distance of 20 or 30 feet. The small figures and fine lines used by the other makers cause their scales to be indistinct. There should also be a decided contrast between scale and case for ease in reading. Dull white cardboard scales used with cases of dull black finish gives the best results. The index should be of such shape and size that it may be easily seen at a distance, yet having a sharp tip which can be used for close settings if required. The set index used by two of the makers on their voltmeters is advantageous in keeping a constant setting.

Some makers persist in the use of soft rubber tubing for covering lead wires and terminals. The sulphur used in vulcanizing the rubber attacks the metal. In the case of small wires this often causes a break, while in case of terminals it corrodes the contact surface. In a millivoltmeter the corrosion of contact surfaces is liable to cause the instrument to be seriously in error.

Accessibility for repair is an important point that should be kept in mind by the manufacturers. Although it is desirable that instruments should be repaired by the manufacturers, in many minor defects it becomes quite necessary for an instrument to be repaired at the place of use, and for this reason it should be readily accessible.

In this connection voltmeter H and ammeter h deserve special mention, in that the makers have put a coat of white enamel on the inside of the cases. This not only gives them a neat and trim appearance, but also minimizes the liability of trouble from dirt, fibers, and the like, by allowing such foreign substances to be readily detected.

The word "volts" or "amperes" should be placed on a conspicuous part of the instrument. Its omission often causes trouble for an inexperienced switchboard attendant.

It is to be seen that the general lines of design are very similar in all the instruments, the manufacture having reached the stage where even the general dimensions used are about the same. These instruments may be taken as typical of American direct-current practice, and although no foreign makers were represented in the series of tests, this statement might well be extended to include European practice also. The most decided departure from type is in the use of the single air gap in the case of the instruments of one maker.

Evidently further improvements in direct-current switchboard instruments are to be looked for mainly in the refinement of details of design and construction.

We are indebted to Mr. H. B. Brooks and Mr. P. G. Agnew for many valuable suggestions in connection with this work and to Dr. C. W. Burrows and Mr. R. L. Sanford for some experimental data.

WASHINGTON, March 1, 1911.

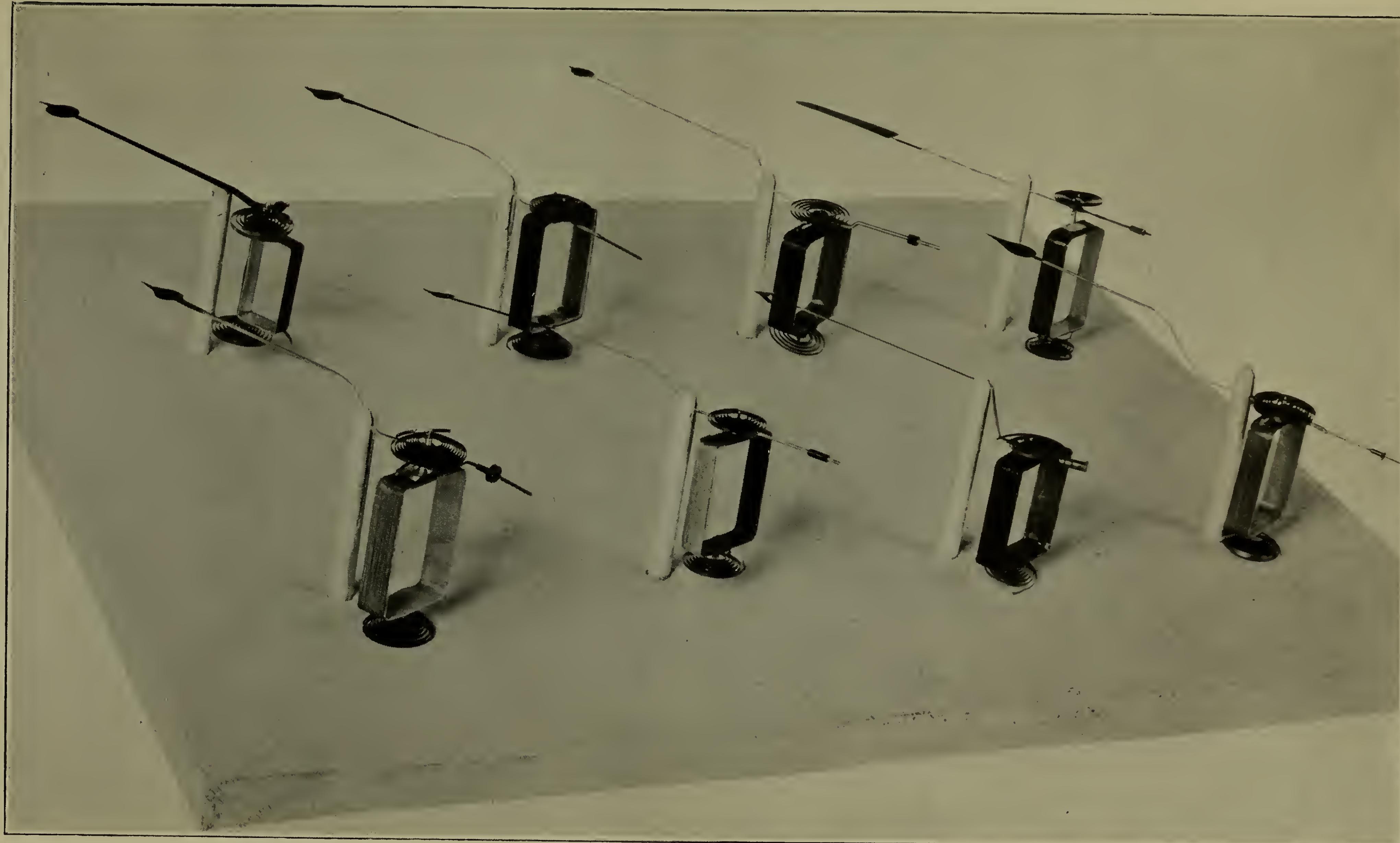

Fig. 4.—*The Millivoltmeter Moving Elements*

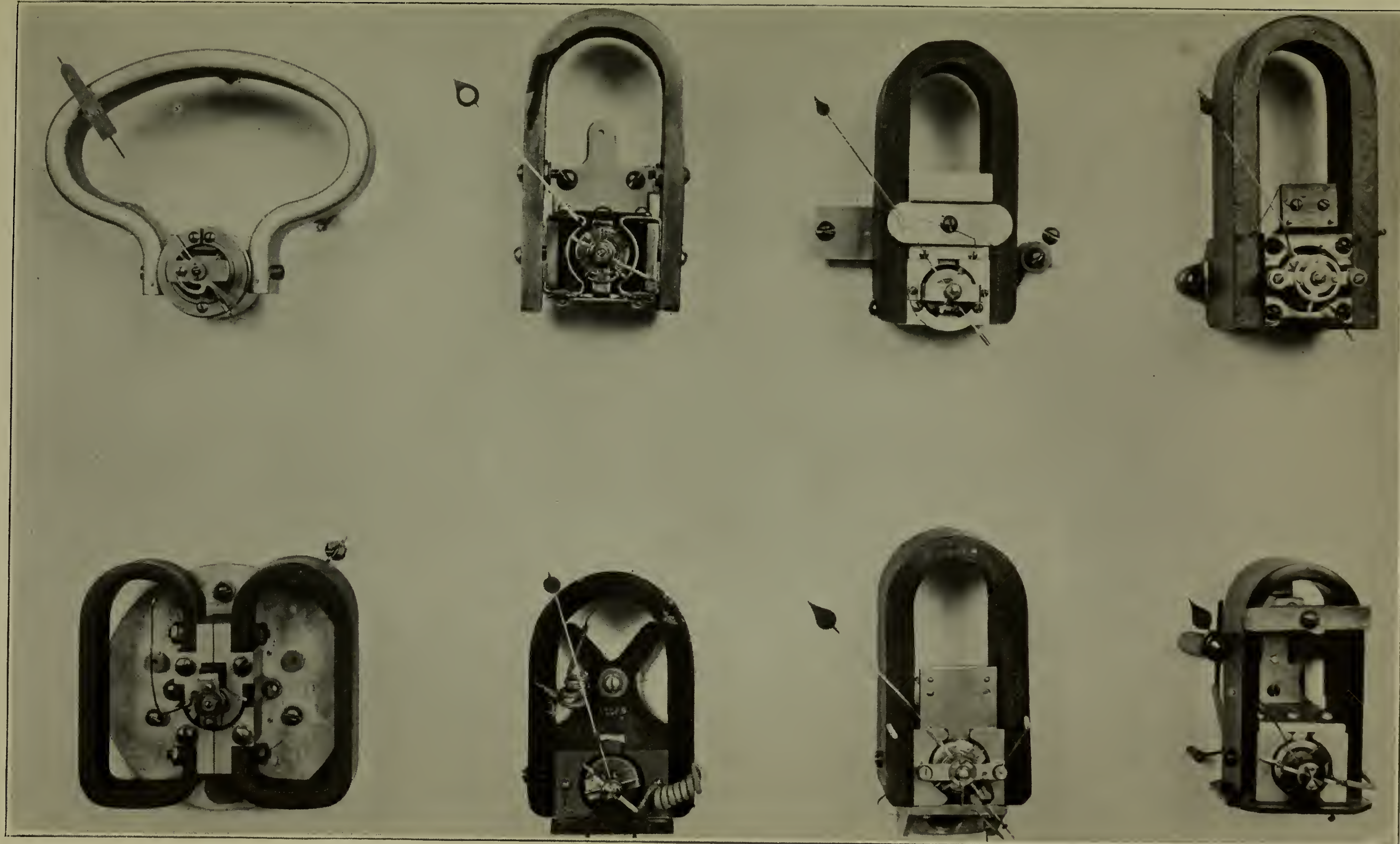

Fig. 5.—*Millivoltmeter Magnets with Moving Coils Assembled*