

SOME NEW APPARATUS FOR THE MOST EXACT
COMPARISON AND ADJUSTMENT OF RESIST-
ANCE STANDARDS AND THE DETERMINATION
OF TEMPERATURE COEFFICIENTS.

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[Read at the stated meeting, held November 22, 1892.]

A little over a year ago I had the honor to present to the notice of the Section some general considerations with reference to the manufacture and adjustment of standard resistances.* During the course of the paper which I then read I exhibited and explained the operation of, to the Section, a piece of apparatus originally suggested to me by Prof. H. S. Carhart, of Michigan University,† and later modified by myself and intended for the very exact comparison and adjustment of standards and the determination of their temperature coefficients. This apparatus was then and still is being used by Messrs. Queen & Co. as part of their equipment for the commercial doing of this work. This piece of apparatus I have not here to-night, but will sketch it upon the board later in order to bring its details clearly before us. I expressed myself, at that time, as believing it to be perfectly simple and easy to quickly adjust any single standard of resistance by the aid of this apparatus with a certain accuracy of $\frac{1}{100}$ per cent. Since the reading of that paper this method and apparatus have been in constant daily use in our laboratory, and my belief is its convenience and accuracy has been confirmed and strengthened. In the use of the apparatus we have, I

* "Resistance Standards: their Manufacture and Adjustment," *Journal of the Franklin Institute*, April, 1892.

† The first apparatus, made according to Prof. Carhart's design, was made by me either in 1887 or 1888, while I was still a student at the University. It is still in the laboratory there, and in constant use, and is, I am told, as good as ever.

think, at one time or another, been obliged to note every weak point in its theory or construction, and to provide such temporary means as might be obtainable for getting around difficulties as they arose. On a basis of an experience thus obtained I have recently designed and built an improved form of this apparatus, which is in every way greatly superior to the apparatus I then showed, and which I believe, from reports which I have received of the apparatus used at the leading laboratories of the world for this same purpose, is capable of giving closer comparisons, and of being used to obtain the value of a single standard to a higher degree of accuracy than any other arrangement of apparatus in the world; with this improved apparatus in the hands of a skilful observer, I consider it entirely

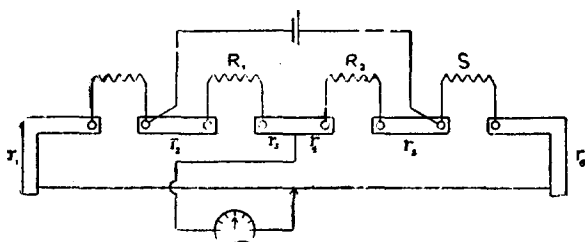


FIG. 1.

possible to determine the value of one coil in terms of another to an accuracy of $\frac{1}{100}$ per cent. and even greater.

As the details of the arrangement and method are not fresh in the memories of most of you, I will hastily run over the general theory of the method, and of its application by means of the early apparatus, and then set forth the improvements which have been made and embodied in this newest form. Let *Fig. 1* represent, diagrammatically, the orthodox slide wire bridge in which X is the unknown resistance (nearly equal to the coil S), to be accurately measured in terms of S , and R_1 and R_2 are resistances roughly equal to one another and to S . The balance reading will then fall near the centre of the bridge. The heavy copper end straps are of resistances which may be designated by r_1 and r_2 , the resistance of the other connectors by

r_2, r_3, r_4 and r_5 , as shown. When a balance is obtained, we have

$$\frac{R_1 + r_2 + r_3}{R_2 + r_4 + r_5} = \frac{X + r_1 + x_1 \rho}{S + r_6 + (L - x_1) \rho} \quad (1)$$

x_1 being the reading;

L being the whole length of the bridge wire;

ρ being the resistance of a single division of the bridge wire.

Reversing the position of X and S , and balancing again, we have

$$\frac{R_1 + r_2 + r_3}{R_2 + r_4 + r_5} = \frac{S + r_1 + x_2 \rho}{X + r_6 + (L - x_2) \rho} \quad (2)$$

From (1) we have

$$\frac{R_1 + r_2 + r_3}{R_1 + R_2 + r_2 + r_3 + r_4 + r_5} = \frac{X + r_1 + x_1 \rho}{X + S + r_1 + r_2 + L \rho} \quad (3)$$

and from (2)

$$\frac{R_1 + r_2 + r_3}{R_1 + R_2 + r_2 + r_3 + r_4 + r_5} = \frac{S + r_1 + x_2 \rho}{X + S + r_1 + r_2 + L \rho} \quad (4)$$

$$\therefore X + r_1 + x_1 \rho = S + r_1 + x_2 \rho \quad (5)$$

and

$$S - X = \rho (x_1 - x_2)$$

or

$$X = S - \rho (x_1 - x_2) \quad (6)$$

so that the unknown X differs from the standard S by exactly the resistance of the bridge wire over which the slider moves in changing from one position of balance to the other when the coils X and S are interchanged; we also see that the expression is entirely independent of the length of the bridge wire, and also of the resistance of the connecting coppers. We may, therefore, measure as small differences as we please by merely making the resistance of our bridge wire small enough.

I will now sketch the earlier apparatus, *Fig. 2*. This was a device for quickly and easily interchanging the two coils, X and S , of *Fig. 1*. Upon a suitable insulating base are

mounted a number of copper straps and plates as shown; these are so arranged as to place four coils in exactly the same relation to one another as in *Fig. 1*. The lettering upon the two figures is the same. The coils X and S have their terminals resting in mercury cups; the coils R_1 and R_2 , being eliminated in the measurement, are simply fastened firmly into the binding posts. The galvanometer and battery circuits are as shown. In the

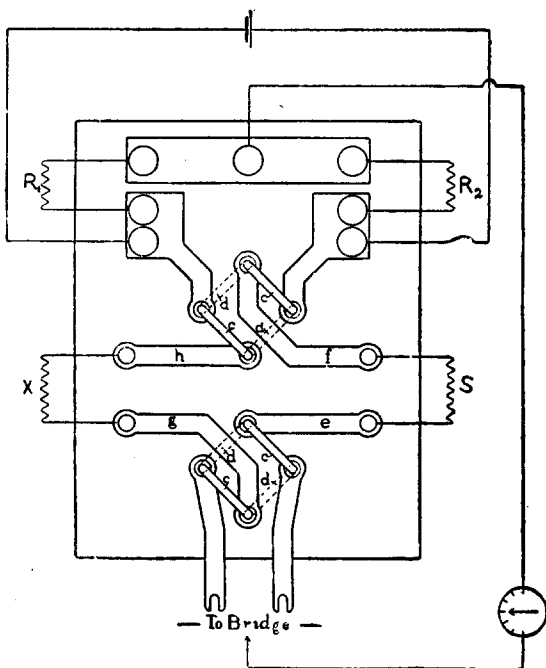


FIG. 2.

centre of the apparatus are seen two groups of mercury cups, each group forming a square; these groups are connected together, as shown, by the heavy copper rods C . By now running around the circuit from the left, clockwise, it will be seen that the order of the four coils is exactly the same as in *Fig. 1*. If, now, we alter the position of the heavy connecting rods C , to the position indicated by the dotted lines, the coils X and S will be interchanged as will be readily obvious by again following around the circuit. In

practice each *pair* of connectors is held in a little hard rubber platform, *C*, *Fig. 3*, so that but two movements are required to effect the change; being held loosely in the platform they will adjust themselves to the surface of the bottom of the cup, and thus make thoroughly good contacts. Inspection will show that this apparatus is a perfectly symmetrical arrangement, and that, consequently, the connector resistances need not be considered: thus, with the commutator rods, as shown by the heavy lines, and passing around the circuit from the bridge, clockwise, we have in circuit on the left, *g*, *X* and *h*, the other pieces being very obviously *pairs*, and on the right *f*, *S* and *e*. Turning the commutator through 90° to the positions indicated by the dotted lines,

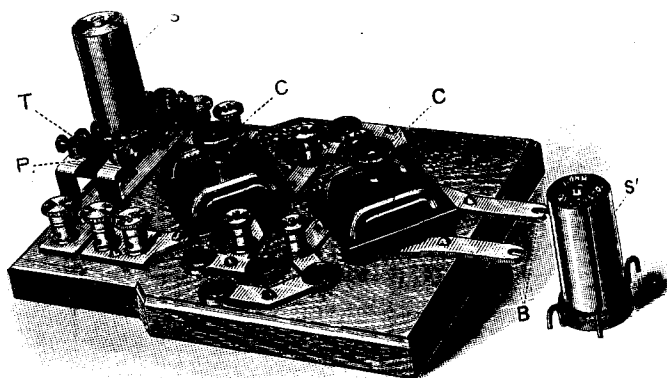


FIG. 3.

starting from the left again we have *e*, *S* and *f*, and from the *right* *g*, *X* and *h*; since $e = h$ and $f = g$, it is the same whether they are on one side or the other, and therefore only the resistances *X* and *S* have really been interchanged. To *use* this apparatus it is only necessary to insert the two slotted terminal straps into one of the gaps of an ordinary slide wire bridge. In the work which we have been doing we have been using a special form of slide bridge designed by myself, and having three wires, each a metre long, which can be thrown into multiple with one another if desired.

Having thus described the earlier form and arrangement of the apparatus I will now speak of its inconveniences and defects. The first one arises when we attempt to obtain

the value of the resistances of the bridge wire per unit division. This, of course, might be obtained by connecting the ends of the wire directly to a Wheatstone's bridge arrangement and obtaining its resistance by ordinary methods. The resistance, however, is necessarily very low, as we shall see from the following considerations: Suppose we have a standard ohm and a resistance of platinoid nearly equal to the ohm, whose temperature coefficient we wish to exactly determine. We place our two coils in oil baths with both at (say) 15° C. and obtain a balance; we then carefully raise the temperature of the platinoid to (say) 30° C., and balance again. The difference, in terms of resistance of the bridge wire, will be the actual increase in resistance of the platinoid. The rise of resistance of platinoid per degree C. is about 0.00023; multiplying this by 15 and we have 0.00345 ohm as about the actual increase of resistance due to the raising of the temperature from 15° C. to 30° C. Let us suppose also that the value of the coefficient must be obtained to the fifth decimal place, or in other words that the resistance 0.00345 must be measured with a maximum error a trifle less than 0.00008 of an ohm. With the average slide wire bridge a skilled observer is able to set the slider, it may be assumed, successively, with an error of setting not less than about $\frac{1}{10}$ mm. Consequently $\frac{1}{10}$ mm. of the wire must measure at least as low as 0.00008 ohm, and hence the whole wire 1,000 mm. long will measure 10,000 times this or $\frac{8}{10}$ ohm. To measure even as low a resistance as this even to $\frac{1}{25}$ per cent. is not at all an easy matter by ordinary methods. In practice the resistance of a metre wire should be as much less than the value given above as possible as a greater *length* of wire would then be used when *X* or *S* were changed; its non-uniformity would, consequently, become relatively less important, and errors of setting would bear a smaller ratio to the whole length used. It would also be much better, if possible, to measure the resistance of the bridge wire in terms of the resistance of the standard itself, as we would thus eliminate any difference of adjustment between the single standard and any box which we might use for the purpose of measuring the resistance of

the bridge wire by ordinary methods. We are, indeed, able to very accurately use this method and apparatus in measuring its own bridge wire. To do this we merely place a heavy short copper strap of negligible resistance in place of X and a resistance Q , somewhat less than the resistance of the single wire, at the right (diagram of *Fig. 1*). Taking our two balances as before, we have from (6)

$$Q - o = \rho (x_1 - x_2) \therefore \rho = \frac{Q}{x_1 - x_2} = \frac{Q}{\delta_1} \quad (8)$$

To find now, the resistance of Q place it in multiple with the standard S , at the right, and again determine the difference, in this case S_2 , we shall have

$$\frac{Q S}{Q + S} = \rho \delta_2 \quad (9)$$

and eliminating Q between (8) and (9) we have

$$\rho = S \cdot \frac{\delta_1 - \delta_2}{\delta_1 \delta_2}$$

A third way, which I have used a great deal, is to place a standard one and ten-ohm coil in multiple upon one side against a standard one-ohm coil upon the other. In the early form which I have described it was very difficult to accomplish any of this placing in multiple as there was but one pair of mercury cups upon a side; consequently, we were obliged to make an accessory double pair of cups with connectors to hook into the regular standard cups; this introduced another mercury contact, in itself a bad thing, and also an additional copper resistance which disturbed the symmetry of the apparatus, and hence, the rigid accuracy of the equations preceding. In the improved design of apparatus which I have here, *Fig. 3*, provision has been made for the placing, if desired, of two coils upon each side, and this in a way which does not in the least disturb the original symmetry of the apparatus. In the diagrammatic sketch of this, *Fig. 4*, there is shown a ten- and one-ohm coil in multiple on one side against a one-ohm on the other side; observe, also, that the cups are so placed that the coils clear one another perfectly, and have ample room

about them for the necessary oil or water-bath. The distance between these cups is one and five-sixteenths inches, the usual distance between terminal coppers of the B. A. form of standard, which distance will, for the sake of uniformity, probably be retained by all instrument makers for a long time to come.

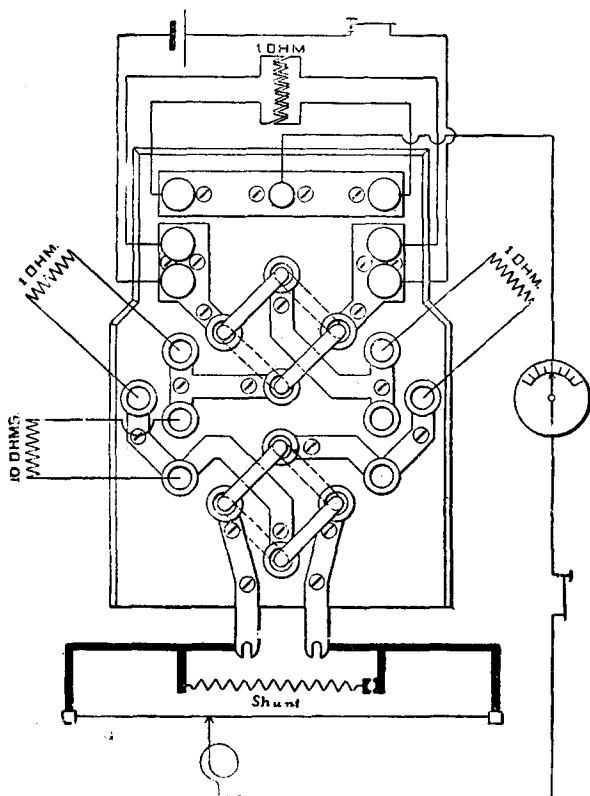


FIG. 4.

The resistance of the coils R_1 and R_2 disappears in the course of the measurement, as is seen from inspection of equations (5) and (6). It is hence not necessary that the *value* of these resistances be known; all that is desired is that they should be *approximately* of the resistance of the coils under comparison in order that the balance may fall near the centre of the wire, and that their resistance should

not change during the progress of the measurement. To insure this latter it is sufficient to wind the two coils upon the same spool, and in the first apparatus I ever made of this kind, while I was in the laboratory at Ann Arbor, these two coils were simply enclosed in a plain round wooden box. Later on it occurred to me, however, to place them upon a spool mounted upon a little stand having a pair of terminals upon each side fitting into the binding posts at *T*; the apparatus was thus compacted and made better appearing, and the coils could be more readily removed and others substituted in case standards of a greater or less value were to be compared. In this last design the spool itself is so made as to be removable from the *platform* instead of the whole platform having to be taken off. The terminals of the platform end in little copper binding posts *T*, which receive terminal rods coming from the coils themselves; these coils are wound upon a spool enclosed in a small cylindrical brass case *S*, mounted upon a rubber sub-base *P*. Each case has engraved upon its top the values of the enclosed resistances, as " one-ohms^2 ," " ten-ohms^2 ," etc. If we desire to adjust ten-ohm standards instead of one-ohm standards, we merely unscrew the little milled head screws, at the side of *T*, lift off the spool and replace it by another one of suitable value.

I stated above that, in our laboratory, we are using a three-wire slide metre bridge of special design. At one time we thought this a very fine thing, but have modified our opinion and now consider it a very ordinary piece of apparatus. It is, to be sure, much better than the average bridge to be met with; what I mean is that compared with what we have learned how to make, this bridge is quite a poor affair. In the first place, I believe any design of a Wheatstone's bridge which is intended for exact work is fundamentally bad if it makes use of a straight wire of any length stretched between two points. I have several reasons for this belief. A bridge used in the average laboratory cannot but be subjected to considerable variations of temperature from one time to another; sometimes this will not be over 5° or 10° for an entire month at a time;

again it may be 20° in about as many hours. As the bases of most slide-wire bridges have been of wood having a coefficient of expansion considerably different from those of the German silver or platinum iridium wires mounted upon them, it is evident that their temperature variations must produce, at times, considerable strain upon the soldered junctions of wire and end pieces when the wire has been tightly stretched, and it *must* be tightly stretched if good work is done. Probably the greatest strain, however, does not arise so much from the difference of expansion coefficients as from the change produced in the dimensions of the wooden support by reason of its absorbing or giving out moisture; for purposes of instrument construction it is practically impossible to find wood so well seasoned as not to deform in a very short time. It is, consequently, not surprising that very few straight slide wires ever remain in position very long. In fact, I have never yet seen a straight wire bridge upon a wooden base, with wire stretched tightly enough to make an accurate measurement, whose wire would hold fast without pulling out for a week. The only remedy is to either place the wire upon a compensating base or else to arrange the wire so that it may be slackened when not in use. In the "three-wire" bridge previously spoken of, the wires were fastened to sliding copper end plates which could be tightened and fastened to the end pieces proper by having copper connecting straps. But this having to tighten the wires is a nuisance, requires some strength, and is apt to mean slightly different settings and consequent lengths of wire at different times. I have here a design of a three-wire straight bridge which we have just completed and from which the first instrument is now being made in our shop. Instead of a solid base the support for the wires will be a skeleton frame work of brass rod, the coefficient of expansion of which is not very far distant from that of the alloys which are usually used for bridge wires. A straight-wire bridge has, however, still another defect, to my mind, fully as serious as the one mentioned. This is the tendency to the development of thermal currents, particularly where the wire is joined to the end coppers;

the ends of the wire being a metre apart it is entirely possible and indeed probable that differences of temperature will exist in the air at the two ends of the wire of sufficient amount to develop thermal electro-motive forces of very appreciable values. To make perfectly clear how important a consideration this is I must again refer to the theory of this "Carey-Foster" method. Let us assume that we are comparing two standard ohm coils together and that we wish to know one in terms of the other to an accuracy of $\frac{1}{2000}$ per cent., *i. e.*, that we must have a deflection of the galvanometer needle when the slider is but $\frac{1}{200000}$ ohm from perfect balance. We will assume that we are using one cell of battery giving about one volt effective E. M. F. at the junction with the bridge arms. Since there are two ohms on each side the fall through $\frac{1}{200000}$ ohm is $\frac{1}{400000}$ volt. Let us also assume the bridge wire to be German silver, and the terminal ends to which the wire is fastened copper. The thermal E. M. F. of this couple assuming that the one end is at a temperature of 19° C. and the other at 21° C., a difference of but 2° C. is, according to Professor Tait's table of thermo-electric heights,*

$$\begin{array}{r} \text{German silver} - 1,207 - 5.12 t \\ \text{Copper} + \frac{136 + .95 t}{1,343 - 6.07 t} \end{array}$$

$$\text{E. M. F. per degree} - 1,343 - 6.07 \times 20 = 1,464 \text{ C. G. S.}$$

$$\text{E. M. F. of couple } 1,464 \times 2 = 2,928 \text{ C. G. S.} = \frac{3}{100,000} \text{ volt.}$$

This value just obtained is a trifle greater than the E. M. F. which must be detected by the galvanometer and will, of course, throw our observations out by exactly the same amount and prevent our obtaining the required accuracy. If this happens when there is only 2° difference between the ends and when but $\frac{1}{2000}$ per cent. is aimed at, how will it be when there is 4° or 5° difference, as there often is, and an accuracy of $\frac{1}{3000}$ or $\frac{1}{4000}$ per cent. to be attained, and in addition innumerable other thermal E. M. F.'s due to other portions of the apparatus?

* Everett's *Units and Physical Constants*, 2d ed., pp. 174.

Of course, there are other ways of eliminating the influence of thermal currents. The simplest is to use the galvanometer in place of the battery and to close the battery circuit upon the bridge wire. This plan is, however, not to be recommended. Another good way is to reverse the battery current, the thermal E. M. F., thus acting at one time *with* and at another *against* the battery E. M. F.; the mean of the two is then the balance reading. This is easily accomplished in the apparatus which has been diminished by first taking readings with commutators turned parallel and then with commutators at right angles; *e. g.*, (*Fig. 5*), there would be four commutator positions necessary, as below :

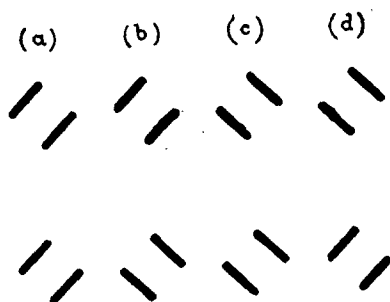


FIG. 5.

The difference of the mean of (a) and (b) and the mean of (c) and (d) would represent the desired difference between X and S , which we desire.

The orthodox straight-wire bridge also occupies considerable space and spreads the apparatus necessary for many of the more common measurements out in an undesirable manner, besides in the case of regular Wheatstone bridge work requiring one to get himself into all sorts of impossible positions in order to obtain and read his balance. On account of all these reasons, I personally favor a wire bridge, having the wire bent one or more times about a circle or cylinder rather than the straight-wire pattern. A circular-wire bridge, if well made, does all that the straight pattern will do and does it much more conveniently; it occupies but little space and brings the readings where they can easily be read; the ends of the wire are close together, so that there is prac-

tically no difference in temperature between them and the form is necessarily such that the wire cannot pull out of the end junctions. The contact also is usually a rolling wheel contact giving a tangent point of contact, and hence is not liable to injure the wire, as are most of the cutting "knife edge" contacts on the usual forms of straight bridge. These conclusions as to the relative efficiency of straight and circularly laid wires in slide-wire apparatus are not merely theoretical; they are practical, having been founded upon my own personal experience with both types in the making of very accurate measurements, and upon the experience of those associated with me, who are using the method every day in commercial work.

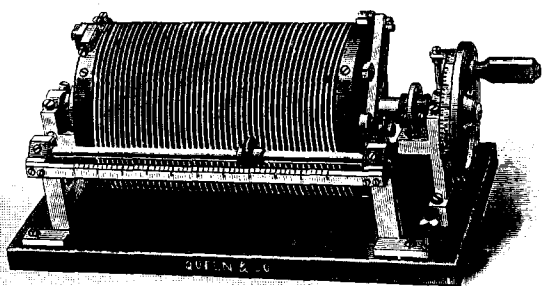


FIG. 6.

I have, therefore, designed and constructed a cylindrical arrangement of bridge wire to go with this latest form of commutating device just described. This is shown in *Fig. 6*, and in diagram in *Fig. 7*. The wire is here coiled upon a polished hard rubber cylinder 4 inches in diameter and 7 inches long; this cylinder is highly polished and the wire stretched in a screw thread cut in its surface. There are fifty turns of wire upon the cylinder. In front of the cylinder is a scale running the entire length of the cylinder, and between the cylinder and scale a small wheel sliding upon a bar carried by the same supports as the scale. This wheel bears snugly against the wire, the end supports being strips of spring brass. Its circumference is platinized and turned to as true a circle as possible, so that the tangent contact is very sharp and definite. As the cylinder is caused to revolve upon its axis, by turning the handle at the end, the little

contact wheel travels along the scale always in contact with the wire. The long scale indicates how many complete turns have been made. In order to obtain the fraction of a turn the wheel at the end is divided into 100 parts and each of these parts is easily divided, by the eye, to tenths. This graduation is read by reference to a zero mark at its side, visible in the cut. The bridge wire is thus divisible into $50 \times 100 \times 10 = 50,000$ parts. In order, however, to measure accurately the extremely small resistances represented by the increase of resistance of (say) a platinum silver one-ohm standard for 10° C. increase of temperature, we must have a lower resistance bridge wire than could be obtained by bending any *flexible* wire upon a cylinder but four inches in diameter. The wire has, consequently, been

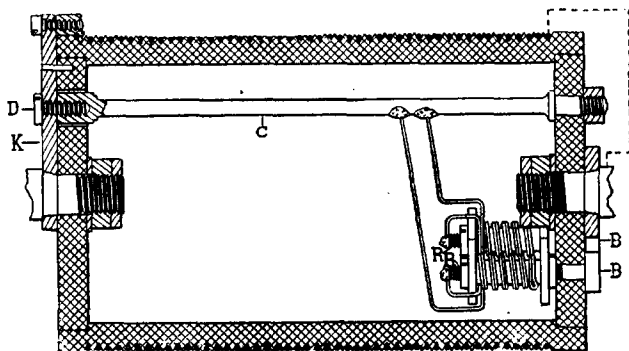


FIG. 7.

shunted by two shunts placed inside the cylinder itself; these shunts are such that the total resistance of the bridge wire may be either one-ohm or $\frac{1}{10}$ ohm, as desired, and are arranged so that either may be used by simply plugging in a small plug at the end of the cylinder. If we use the $\frac{1}{10}$ ohm shunt the smallest difference measurable with the combined apparatus is $\frac{1}{50000} \times \frac{1}{10}$ ohm = 0.000002 ohm; it is thus easy to measure with great accuracy extremely small differences between two coils or to determine temperature coefficients, even though extremely small.

The method of arranging the shunts in this apparatus is worthy of notice; they are so placed that their adjustment, by the maker is easy and convenient. Referring to *Fig. 6*,
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the shunts are each mounted upon rods *R*, screwing into the end blocks *B*; one end of each shunt is soldered to its rod. The other ends of each shunt are soldered to the rod *C*. In adjusting, the right-hand head of the cylinder is slipped out of position, carrying with it the shunts and rod *C*; the shunts are adjusted as accurately as possible and the head slipped back. As the head slips into place the rod *C* shoulders against a heavy copper strap *K*, connecting with the left-hand end of the bridge wire. A copper screw *D* then taps into both the strap *K* and rod *C*, thus making a clean, fresh screw connection between them; a careful measurement of the total resistance is now made, the amount of necessary correction noted and the head again slipped out. A very few trials will suffice to get the desired resistance with great accuracy.

The heavy copper end straps, to which the ends of the bridge wire are soldered, are coned very tightly upon the shafts of the cylinder. These end shafts are of solid copper one-half inch in diameter, and revolve in heavy copper bearings brazed directly to the straps going to the commutating attachment. On the inside of each bearing is formed a massive mercury cup, in which revolves a copper ring $1\frac{3}{8}$ inches in diameter and $\frac{1}{8}$ inch thick; these rings have been sprung upon each end bearing and fit very tightly. Over half a square inch of their surface is always under the surface of the mercury, which is always kept at the same height. The surface of copper contact is so large and the thickness of mercury so small that the resistance at these places is negligible; it is also constant. A sliding brush contact will not answer for work of this kind, as the contact resistance is apt to be variable. In order to prevent the mercury from spreading, by capillary attraction, over the adjacent copper surfaces, each copper ring is clamped, just outside the shaft, between rubber washers recessed and filled with sticky wax. This wax, pressing against the copper, will, it is hoped, aided by the thick bands of lacquer, keep the mercury in its proper place.

Particular attention must be drawn to the fact that every particle of metal forming, in any way, part of the circuit or

in contact with it, is of copper in both the commutator and cylindrical bridge with the exception of the wire itself. This is necessary not only to keep the resistance of the circuit small, but also to avoid *thermal currents and contact E. M. F.'s*. In the earlier apparatus referred to in the first part of this paper, it has been impossible to do the highest grade of work without thoroughly wrapping a large part of it in cloths or paper to keep down the thermal currents, and this, despite the fact that about the only metal *except* copper, was in the binding posts; these, however, are sufficient to generate disturbing E. M. F.'s of sufficient magnitude to effectually mask the results desired, and it was seen to be imperatively necessary to get rid of this *entirely*. In the present apparatus the binding posts, connectors, cups,

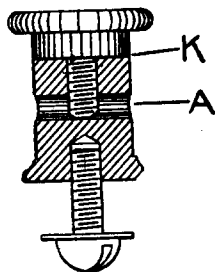


FIG. 8.

shafts, shunt rods *C* and *K*, the terminal blocks of the shunt coils and all are copper; only the junctions of the wire itself can possibly give trouble, and this, experience has shown, need not be feared in the cylindrical bridge.

It is obvious that by simply replacing *X* and *S*, *Fig. 1*, by negligible resistances we convert the arrangement into the simple Wheatstone's bridge. Hence, in the apparatus in *Fig. 3* we need but to place short, heavy copper wires in place of the standards on each side to enable us to use the device for ordinary work.

Often it is desirable to measure spools of wire quite accurately (say to $\frac{1}{20}$ per cent.), as, for instance, in the adjustment of a high-grade resistance box, where the coils must be as accurate as possible before putting into the set since any adjustment *then* would involve the loosening and

re-making of a solid joint and much inconvenience. With this apparatus this work can be done in one-fifth the time necessary with the usual apparatus, and with a more certain accuracy. Since, in such cases, it would not be worth while to solder wire ends to heavy coppers for immersion in the mercury cups, and since, indeed, the accuracy wanted does not require it, binding posts have been provided for this purpose just back of the mercury cups. These posts are of the "double grip" style, designed by Queen & Co. (shown in section in *Fig. 8*), and will catch the finest wires securely, either in the hole *A* or between the surfaces *K*; the resistance of quite heavy copper conductors may thus be measured.

Many results obtained with and showing the performance of this apparatus might be given. The following, transcribed from one of our laboratory note-books, is sufficient, however, to show the exceedingly high accuracy obtainable. It is the record of a standardization of a coil recently sent to us by one of the large universities for an exact determination of its value. The data, as will be observed, were obtained on four different days, when, of course, minor conditions and the personal equation were likely to be very different.

ELIOTT OHM, NO. 106.

(a) October 27, 1892.

Millimetres to balance, . . . — 358.3	value in ohms, . . . — 0.01250
Temp. of standard (E No. 186), 13° 0 C.	value of standard, . . . 0.99675
Temp. of ohm (No. 106), . . . 13° 25 C.	value of ohm No. 106, 0.98425

(b) October 27, 1892.

Millimetres to balance, . . . — 355.0	value in ohms, . . . — 0.01239
Temp. of standard (E No. 186), 12° 7 C.	value of standard, . . . 0.99667
Temperature of ohm No. 106, 13° 3 C.	value of ohm No. 106, 0.98428

(c) October 27, 1892.

Millimetres to balance, . . . — 429.3	value in ohms, . . . — 0.01502
Standard (A), —	value in standard, . . . 1.00608
Temperature of ohm No. 106, 42° 1 C.	value of ohm No. 106, 0.99106

(d) October 27, 1892.

Millimetres to balance, . . . — 424.8	value in ohms, . . . — 0.01487
Standard (A), —	value of standard, . . . 1.00608
Temperature of ohm No. 106, 42° 3 C.	value of ohm No. 106, 0.99121

(e) October 28, 1892.

Millimetres to balance, . . . — 171·4	value in ohms, . . . — 0·02091
Standard (A), —	value of standard, . . . 1·00608

Temperature of ohm No. 106, 18°·0 C.	value of ohm No. 106, 0·98517
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(f) October 28, 1892.

Millimetres to balance, . . . — 596·3	value in ohms, . . . — 0·02087
Standard (A), —	value of standard, . . . 1·00608

Temperature of ohm No. 106, 18°·1 C.	value of ohm No. 106, 0·98521
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(g) November 7, 1892.

Millimetres to balance, . . . — 293·9	value in ohms, . . . — 0·01029
Standard (B), —	value of standard, . . . 0·99588

Temperature of ohm No. 106, 18°·1 C.	value of ohm No. 106, 0·98559
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(h) November 10, 1892.

Millimetres to balance, . . . — 284·3	value in ohms, . . . — 0·00995
Standard (B), —	value of standard, . . . 0·99587

Temperature of ohm No. 106, 19°·5 C.	value of ohm No. 106, 0·98592
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(i) November 10, 1892.

Millimetres to balance, . . . — 284·8	value in ohms, . . . — 0·00997
Standard (B), —	value of standard, . . . 0·99585

Temperature of ohm No. 106, 19°·3 C.	value of ohm No. 106, 0·98588
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ACCURACY OF RESULTS.

Date.	Test.	Value.	T—° C.	Accuracy of Agreement with Temperature Coefficient Applied Between.
October 27, 1892	(a)	0·98425	13°·25 C.	
October 27, 1892	(b)	0·98428	13°·3 C.	(a) and (b) $\frac{1}{500}$ per cent.
October 28, 1892	(e)	0·98517	18°·0 C.	
				(e) and (f) $\frac{1}{500}$ per cent.
October 28, 1892	(f)	0·98521	18°·1 C.	
November 7, 1892	(g)	0·98559	18°·1 C.	
				(g) and (h) $\frac{1}{500}$ per cent.
November 10, 1892	(h)	0·98592	19°·5 C.	
November 10, 1892	(i)	0·98588	19°·3 C.	(g) and (i) $\frac{1}{1000}$ per cent.
				(h) and (i) $\frac{1}{1000}$ per cent.

DETERMINATION OF TEMPERATURE COEFFICIENT.

(1) From (c) we have 0·99106 ohms at 42°·1 C.

From (e) we have 0·98517 ohms at 18°·0 C.

Difference is 0·00589 ohms for 24°·1 C.

$$\therefore \text{Temperature coefficient} = \frac{0·00589}{24·1 \times 0·98517} = 0·000252$$

(2) From (<i>d</i>) we have	0.99121 ohms at 42° 3 C.
From (<i>f</i>) we have	0.98521 ohms at 18° 1 C.
Difference is	0.00600 ohms at 24° 2 C.

$$\text{Temperature coefficient} = \frac{0.00060}{24.2 \times 0.98521} = 0.000252$$

SUMMARY.

Between October 28th and November 7th, the temperature was, at times, very low. This caused the increase noted in (*g*), (*h*) and (*i*) over (*e*) and (*f*). The fall between (*a*), (*b*) and (*e*), (*f*) was due to the heating to which the coil was subjected in (*c*), (*d*). This coil, No. 106, was of platinum silver, and this *permanent increase* if subjected to low temperatures and decrease if too high temperature are well-known characteristics of the alloy. The present value of the coil is given by (*g*), (*h*), (*i*): this value holds, providing the limits 12° 0 C. and 25° 0 C. are not exceeded. After noticing the permanent change in resistance above referred to, I wrote to Professor Carhart, who had sent us No. 106, telling him of it and saying that it probably occurred as a result of the heating necessary in getting its temperature coefficient, but did not give him the coefficient we had obtained. In his letter of reply, he said: "I meant to tell you not to heat the standard, as we have very carefully determined its coefficient. It is not over 0.00025, I think." This, as contrasted with our value given above, is a difference of but $\frac{1}{5000}$ per cent., and shows how close work can be done with the apparatus in the hands of different observers in different places at different times.

Since the preceding portion of this paper was written, considerable additional work of the character which has been discussed has been done under my direction, with the previously described, and kindred forms of, apparatus. The results have been even more gratifying than those which have been given.

In connection with the work another new design of the apparatus has been produced which may seem to some to offer points of further advantage. The new design is shown in perspective in *Fig. 9*. As will be noted, the bridge

and commutator are here combined in one piece so that the apparatus is complete in itself. The arrangement is, upon

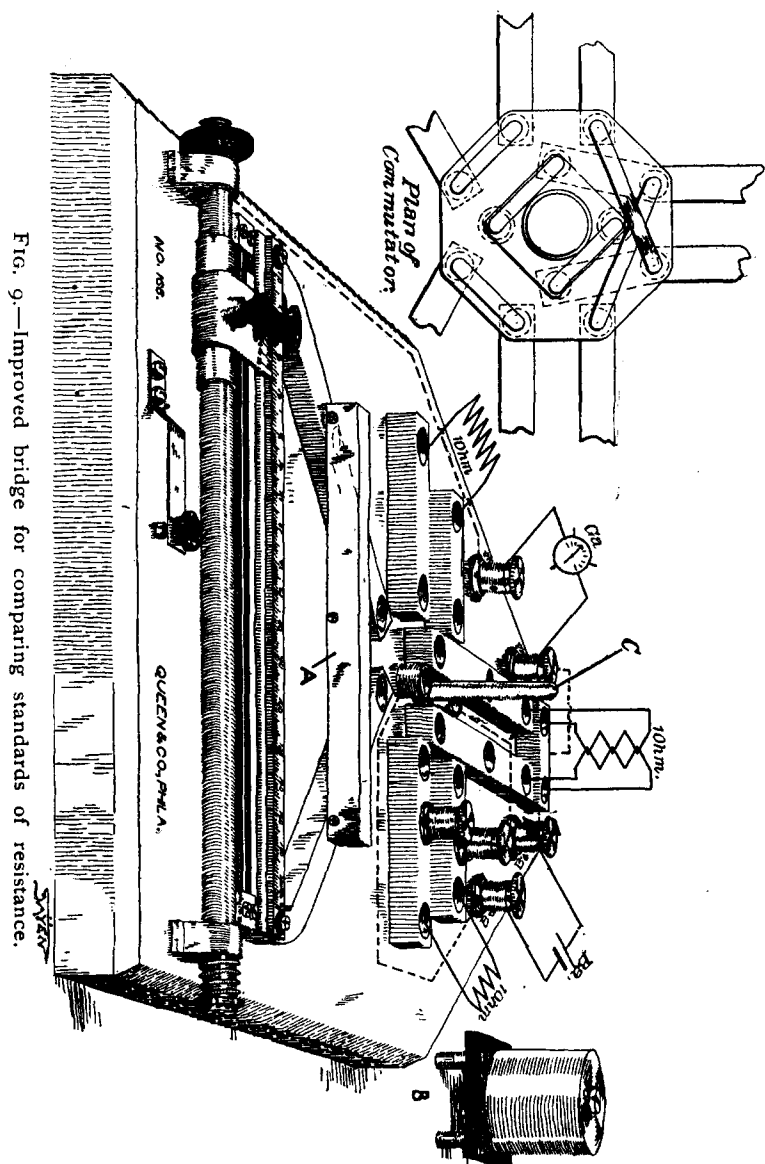


FIG. 9.—Improved bridge for comparing standards of resistance.

the whole, exactly the same as that shown in *Fig. 3*, the principal differences between the two being in compactness

and simplicity of construction. The two commutators of *Fig. 3* are so arranged that but *one* movement is required to effect the commutation, instead of two. This commutator, moving upon the rod *C*, really consists of two parts, one fitting upon the other. By using the upper head the whole platform is moved and the coils *X* and *S* (*Fig. 1*) are interchanged. By moving the lower head only, the *battery* alone is commuted, thus enabling us *perfectly* to eliminate all thermal effects. This is a very important matter, as the E. M. F.'s used are all so small that thermal potentials may prove greater than those employed, as was earlier pointed out. *The ability to commute the battery only is, consequently, of vital importance if good results are to be attained.* The pattern shown in *Fig. 3* accomplished this by four movements (*Fig. 5*), as was shown; the new design, therefore, enables us to save two movements.

The two accessory coils *S*, *Fig. 3*, are here mounted in much the same way, but their terminals simply drop into mercury cups instead of being gripped by binding posts. The two coils under comparison are placed at the sides as before; by means of the binding posts a coil may be placed in multiple with the standard in determining the resistance of the bridge wire by the second method.

The bridge wire is permanently a part of the apparatus; it is twenty centimetres long. The slider is provided with a vernier by means of which the wire may be read to one-twentieth millimetre. A very fine adjustment of the slider may be obtained by means of the screw nut attached to the rod upon which the slider usually moves, but to which it may be rigidly clamped if desired. In order to have as low a resistance bridge wire as may be necessary, shunts are used, as in the cylindrical bridge, *Figs. 6* and *7*. The shunt is a wire of suitable size mounted upon a rubber strip and covered by a little zinc box *A*; two copper terminals, to which the shunt is attached, drop into two mercury cups so as to shunt the bridge wire. Different shunts may be used for different ranges of work. Each shunt may have stamped upon it the value of resistance of unit bridge wire division obtained by its use. This mode of varying the resistance

of the bridge wire is much superior to the employment of a number of wires which may either be bodily changed or with which may be used an adjustable slider which may be placed so as to run above any particular wire desired. The greatest advantage lies in the fact that using shunts it becomes worth while to work down the bridge wire until it is perfectly uniform in resistance; a shunt will then merely lower its total resistance. If the wires are bodily changed either this large amount of labor must be applied to each one or else a different calibration curve must be used for each wire. Another objection would be the difficulty of always getting the same contact resistances at the ends of the wire; if made with mercury they would be variable, owing to the instability produced by the contacts of the slider.

The apparatus is very simple to make, all the copper work being ordinary market-copper bars one-half inch square and bent into the required shape, the cups being drilled in the bars themselves. It is also very compact, measuring but $11 \times 10\frac{1}{2}$ inches over all.

BOOK NOTICES.

Highway Construction. Designed as a text-book and work of reference for all who may be engaged in the location, construction and maintenance of roads, streets and pavements. By Austin T. Byrne, C.E. New York: John Wiley & Son. Pp 685. Price, \$5.

At a time when there is so great interest manifested in the highways of our country any work touching upon the subject must command attention, and the author has conferred a service in compiling, so far as possible, data from every available source, digesting and classifying it in such manner as to make this work an encyclopædia for specialists.

Amongst the many good points of the book may be mentioned his list of the literature of the subject from which he drew his inspiration, although we fail to notice in it some of the standard authorities, such as McAdams, McNeill, Telford, the Consular Reports of the State Department on "Streets and Highways in Foreign Countries," 1891, so rich in precedent, as well as the comprehensive compilation published in 1890, by the *Engineering and Building Record*, entitled "Pavements and Roads."

The broad scope of this work is shown at once by an enumeration of its chapter headings, beginning with Pavements and their Materials; Stone, Wood, Asphaltum, Brick, Broken Stone; Miscellaneous: continuing through