STANDARDIZING ELECTRICAL MEASURING INSTRUMENTS.

(a) BY THE POTENTIOMETER METHOD.

(b) AN IMPROVED DIRECT READING POTENTIOMETER.

BY ELMER G. WILLYOUNG.

During the early days of applied electricity, yet easily within the memory of even the youngest among us, so rapid has been its development, electrical devices in general were, as a matter of course, but very poor affairs as compared with those of the present. One machine was a dynamo if it would but produce current no matter how fluctuating, nor at what cost of internal energy consumption; another a motor if one of its parts would but rotate when supplied with electrical energy regardless of the rate of this rotation or whether constant or not under conditions of variable load. Having such uncertain quantities to deal with, electrical measuring instruments were, similarly, but few in number and of the crudest possible construction—not measuring instruments at all in any true sense of the word, but merely indicators, and very poor ones at that. An instrument was supposed to be a non-essential, a decoration for fancy dynamo rooms, and perfectly equivalent by an incandescent lamp for all practical purposes. Indeed, this idea has not yet entirely disappeared, and we may still occasionally find plants running with nothing more than the pilot lamp to go by.

In general, however, all this is now changed. Business competition and the popular demand for electricity has caused rapid and steady improvement all along the line until now we have much time and study devoted to the problem of how to raise machine efficiencies a fraction of one per cent. or so, how to

build armatures so as to secure more perfect ventilation and consequent reduction of internal heating, how to produce as good results with a little less iron, a little less wire, a little less wear, etc. Losses in joints, switches, etc., hitherto so small as to have been neglected must be guarded against and, if present, reduced to the smallest possible amount. The whole problem of manufacture and installation has become one of the gaining of petty victories.

All this has reacted upon the instrument maker. In order to measure these small effects, very perfect and accurate instruments are necessary, and great improvements have been made in this direction. The commercial measuring instrument of to-day is, indeed, an entirely new appearance, and demands exactly the same application of mechanical principles and scientific methods as is demanded in the construction of bridges and steam engines.

The necessity of a complete outfit of proper measuring instruments, voltmeters, ammeters, ground detectors, etc.,—as a factor of economical operation in all kinds of lighting and power systems, is now almost universally conceded, and we find such instruments all over the country in vast numbers. In the stations we have the station instruments; for general all round testing work, measuring drops, joint and switch resistances etc., the portable instrument is useful.

As at present made, all of these various instruments have in them dangerous elements of change. If the instrument has a permanent magnet, then the strength of its magnet is liable to be seriously affected in time by the perpetual jars and vibrations to which it is subjected; proximity to strong fields, especially if variable, will tend to produce similar results. Any instrument containing springs is also likely to vary in its indications in time through slow changes of elasticity in the springs be they ever so carefully gauged. A hot wire instrument may change on account of the change in radiating quality of the surface of the working wire produced by its slow oxidation; molecular changes in the wire are also liable to go on when continually heated, since our experience with standard resistances shows us that changes of this kind do go on very slowly even with wires kept at normal temperatures. And so of any type of commercial instrument which may be mentioned—none of them can be absolutely trusted not to change.

This being so, we must, therefore, frequently examine these various instruments and determine if such changes have taken place, and, if so, what has been their magnitude. As a rule this is done at present not by the owner of the instrument, but by the instrument maker, the instrument being taken down and sent back to the maker from time to time for recalibration, or, if it is not, it should be. This, in itself, is expensive—express charges must be paid—time must be spent in correspondence—often, if not always, a charge is made for the work of restandardizing. Not only this, but there is no surety whatever that these restandardized instruments may not again “get out” while on their way back to the owner, as the sharp, “high frequency” jars of transit are known to be very hard upon magnets and fine mechanism.

Consideration of the above, long ago convinced me that this restandardizing should be done by the stations themselves in all cases except when quite small, and that some arrangement of apparatus should be devised which would make the utilization of some absolute standard method inexpensive and convenient, and possible to any one of ordinary intelligence. After a good deal of thought and personal experience, I became convinced that the only method which could be made to at all satisfy these requirements was the potentiometer method. Before speaking specifically of the improved apparatus which I have devised for the commercial utilization of this method I wish to discuss briefly the potentiometer method in general and to outline what I consider its advantages over all other methods.

THE POTENTIOMETER METHOD. Broadly, the potentiometer method consists in opposing some known *proportion* of the drop of an unknown E. M. F. through a given resistance to a definitely *known* E. M. F., the proportion being so chosen that no current is produced by the latter known source. This condition being established, an equation involving the unknown E. M. F. as the only unknown quantity immediately obtains. The method in general is fairly well known, being variously called the standard cell method, the Poggendorf or Rayleigh-Poggendorf compensation method, the Rayleigh method, etc. It is not by any means so widely known, however, as it deserves to be.

Diagrammatically the method is represented in Fig. 1. Here A B is a wire of high resistance and any desired length stretched between two fixed points. B_a is the battery whose unknown E. M. F. we desire to know, supposed higher than that of s. c. which

is a known standard cell. In series with s. c. is a galvanometer, G_a . B_a and s. c. are so placed as to oppose one another so that when the circuits are closed a position, s , of the slider upon the wire may be found such that the fall of E. M. F. of B_a between s and B

FIG. 1.

will exactly equal the E. M. F. of s. c. There will then be no deflection of G_a , and we will have

$$\frac{E_{Ba}}{E_{S.C.}} = \frac{A B}{S B} \text{ or } E_{Ba} = E_{S.C.} \frac{A B}{S B} \quad (1),$$

an equation involving only a known E. M. F., and the ratio of two lengths. The resistance $A B$ should, of course, be chosen so large that the internal instance of B_a is negligible as compared with it. In practice this form of the method is commonly known as the Rayleigh or Rayleigh-Poggendorf compensation method; and instead of a straight wire, $A B$, this is equivalented by two resistance boxes of about 5,000 ohms each. This arrangement is shown in Fig. 2. Plugs are removed in R and R' so as to have in all a *total* of, say, 5,000 ohms out. This total is maintained

FIG. 2.

constant, whatever plugs are taken out of one box, being inserted in another. When a balance is secured, the resistance in the two boxes must be counted up and then equation (1) applied.¹

1. The galvanometer, in both Figs. 2 and 4, has inadvertently been omitted; it should, in both instances, be placed in the "derived" circuit similarly to fig. 1.

This arrangement of the method is very suitable for making comparisons of standard cells, B_a being merely any form of constant battery. A balance having been secured for s. c. it is then removed and another standard cell, s_1 , substituted; a new balance is then gotten. By properly choosing B_a and making the total of $R + R'$ 10,000 ohms, we may cause each ohm difference in balance between different cells, to signify a difference of 0.01 per cent. If a properly sensitive galvanometer be used, a variation of one ohm from balance is very easily seen. This arrangement is also very accurate, and easily used in determining the temperature coefficient of a cell, the cell being surrounded by a water bath, and balance being obtained for different temperatures.

A modification of this method was proposed some years ago by Dr. Fleming, and is shown in Fig. 3.¹ It is, as is evident, exactly the same as Fig. 1, save that a resistance, R , is inserted in

FIG. 3.

the main circuit. Here B_a , instead of being the E. M. F. to be measured, is merely any fairly constant source, such as *e. g.*, a cell of storage battery. The wire, $A B$, is stretched along a scale uniformly divided into, say, 150 parts, 100 of which are then made to correspond to a fall of B_a of one volt by adjusting s to a position corresponding to balance, if this assumption were true, and then *making* it true by an adjustment of the variable resistance, R . If $A B$ is so great that the current produced by B_a is small compared with its normal discharge rate, then the difference of 1.5 volts between A and B may be assumed constant for a considerable period, especially as the circuits should be closed only long enough for balance. Any *inconstancy* may be immediately detected by again placing s at the balance point. Balance should

1. See "Short Lectures to Electrical Artisans," by J. A. Fleming; also "Electrical Measuring Instruments," by Jas. Swinburne—Proceedings. Institution of Civil Engineers, Vol. C.X., Session 1891-92, Part IV.

persist without further adjustment of R . To measure any unknown E. M. F., now, s . c. is simply removed, and the unknown source substituted for it. If this source is less than 1.5 volts then a position of s will be found, at which there will be balance, and the number of parts between s and B will give the E. M. F. directly by pointing off two places of decimals. Should the E. M. F. be higher than 1.5 volts, then it may be placed in series with a high resistance, and the E. M. F. over a portion only of this resistance measured. The two place reading of s multiplied by

$$\frac{\text{whole of high resistance}}{\text{portion of high resistance in derived circuit}}$$

will again be the unknown E. M. F. desired.

Not only may we thus measure E. M. F. but, by arranging as in Fig. 4, we may also measure *current* by this method if we know the resistance of shunt s . Similarly, we may measure resistances by comparing the fall of E. M. F. around a known resistance with that

FIG. 4.

around the unknown resistance placed in series with it, a constant current being maintained through both.

The advantages of the potentiometer are:

(1.) It is a zero method; a calibrated galvanometer is, therefore, not necessary.

(2.) Accuracy depends only upon a standard cell and a standard resistance, and results obtained by the best authorities over a number of years, show that both of these may be relied upon within extremely small limits of error, with proper treatment, for a practically indefinite time.

(3.) It requires but simple apparatus, always obtainable, and ordinary care. It can be used without inconvenience in regions of great mechanical instability and of intense and variable magnetic fields.

OTHER METHODS OF STANDARDIZING.

The advantages of the potentiometer method can, perhaps, be better appreciated by briefly recapitulating the other possible methods. These are but few in number. We have:

THE DIRECT INSTRUMENTAL METHOD.

Here the values must be obtained by direct measurement with instruments which do not contain elements of change. About the only instruments satisfying this condition are the tangent galvanometer in some form or other, and the Thomson balance.

THE TANGENT GALVANOMETER.

Disadvantages:—(a) The instrument must be very accurately constructed and is hence costly.

(b) To secure accuracy, the instrument must have a suspended system which is liable to continual break-down, and is difficult of repair except by an expert.

(c) Accuracy depends upon the constancy of H , the horizontal magnetic component; this depends upon local conditions and varies with change in position of neighboring magnetic materials and with the temperature of fixed masses of such metals.

(d) Indications are greatly affected by variable currents or magnetic fields in the vicinity.

(e) Mechanical stability must be had; hence such an instrument is difficult to use in stations or localities where mechanical vibration is large.

(f) The instrument must be very carefully adjusted in the first instance—this requires considerable time and skill. It must, therefore, be *permanently* set up in combination with the observing telescope or lamp and scale, in a room or part of a room which must not be used for any other purpose in order that the outfit may not be disturbed.

THE THOMSON BALANCE.

This instrument is much superior to the tangent galvanometer, requiring much less skill in use and practically no adjustment. It is not affected by being moved about from place to place if carefully handled, and is not appreciably varied by magnetic changes of small amount.

Disadvantages:—(a) It is affected by fluctuating currents or fields of large value if very near.

(b) A large number of instruments is required to cover very much of a range of measurement, any one instrument only measuring within limits of 1 to 100 as *e. g.*, from 1 to 100 centi-amperes, 1 to 100 amperes, etc.

THE VOLTAMETER METHOD.

This depends upon the maintenance of a steady current for at least 20 minutes or a half hour through an electrolytic solution, usually silver or copper, and an accurate weighing of the amount of decomposition thus produced.

Disadvantages:—(a) It is slow, but one value being obtainable in this time.

(b) It requires considerable skill in making accurate weighings with a delicate balance; also in adjusting the current values used to the area of the electrodes, since otherwise the amount of decomposition is irregular and unreliable.

THE VIENNA SHUNT METHOD.

This is an indirect method in which the current is obtained by measuring the *E. M. F.* produced at the terminals of a suitable shunt by its steady flow. The shunt resistance must, of course, be known.

Disadvantages:—(a) The E. M. F.'s to be thus measured are usually quite small and must be measured by a very sensitive galvanometer. This galvanometer must itself be calibrated, a work requiring considerable time and skill. This calibration, once obtained, cannot be depended upon from day to day owing to the fact that the slightest change in level in the instrument, irregular loss of magnetism in the needle, if a Thomson galvanometer, or of torsional rigidity in the suspension, if a D'Arsonval galvanometer, will alter it. In a Thomson galvanometer the indications are greatly thrown out by even very small changes in the local magnetic field such as may be produced by keys or a knife upon the person, or active circuits even when some considerable distance away.

(b) Great mechanical stability is usually required in order that observations of the reflected beam of light may be possible.

(c) Thermal E. M. F.'s are met with which are tedious to eliminate or allow for.

(b) AN IMPROVED DIRECT READING POTENTIOMETER

This instrument, invented by the writer and illustrated in Fig. 5, is capable of being used for measurements of voltage from 0 up to 1,500 volts, and of current from 0 up to any required upper limit, with a maximum error of not over $\frac{1}{10}$ per cent. It is based

FIG. 5.

upon the form of potentiometer originally suggested by Dr. Fleming, which is shown in diagram in Fig. 3. Some good suggestions were also obtained from the improved form of Mr. Crompton.¹

1. See *Electrician*, (Lon.) May 12, 1893, p. 32.

A diagram of the arrangement of circuits in my improved form of apparatus is shown in Fig. 6. The wire AB of Fig. 3 is here equivalented by three sets of coils marked respectively Q , M , and S . The regulating resistance (R of Fig. 3) is made up of two parts, one resistance, R_Q , consisting of coils, and the other, R_S , being made up of a bare wire of resistance equal to one of the coils of R_Q . This wire is laid back and forth upon about 350° of an ebonite cylinder and has a fixed brush, P , so arranged with reference to it that P short-circuits more or less all of the v 's simultaneously, thus giving a large range of variation for a very small angle of rotation. The quick and rough regulation is effected by R_Q , while the finer adjustment is obtained by R_S .¹ The two series of coils, M and S , have at their centers two switches which are in series with the galvanometer and unknown $E. M. F.$; moving these switches over the coils is exactly the same as shifting the points s and b of the derived circuit in Fig. 3. M is the medium movement, each coil being $\frac{1}{10}$ of the entire resistance between A and B , while S is the very slow movement, each of the nine coils in S being equal to $\frac{1}{10}$ of the resistance of one of the coils of M . In order to get a rate of separation of the two derived circuit terminals by steps of 10 times the value of a coil of M , a third series of resistances, Q , is provided. This is a rather peculiarly arranged affair, its function being to take out resistance from between the derived circuit terminals and place it outside, or *vice versa*, the total resistance between A and B remaining always constant. The construction of this arrangement is shown in Fig. 8; here merely the diagram of circuits can be depicted. It is evident that this change of resistance from one part of the circuit to the other accomplishes exactly the same result as is obtained by M and S , viz., the separation or bringing together of the two derived circuit terminals. We have, therefore, the entire resistance, AB , divided into 1,500 parts, and the derived circuit terminals separable along this resistance by steps of 100 parts, using Q ; ten parts, using M ; and single parts, using S . This means an ability to set to 1 part in 1,500 or to $\frac{1}{1500}$ per cent.

In order to make the measurement of any unknown potential convenient and quick, a suitable arrangement of switches is provided. In the lower part of the diagram, R is a high resistance

1. Instead of this form of regulator I have thought of substituting some form of carbon or graphite resistance since all that is needed is invariability for a certain period. E. G. W.

connected between two points F and G. To F is permanently joined one derived circuit terminal. The other derived terminal passes, by way of a key, κ' , through a galvanometer and thence to a switch, w, which plays over a number of contact points connected as shown. The two points, s. c.-1 and s. c.-2, are joined each to a terminal of a Carhart one volt cell, the other terminals of which are joined in common to G.¹ The remaining points are connected to points along FG, dividing the whole resistance in the ratio $\frac{1}{1000}$, $\frac{1}{100}$, $\frac{1}{10}$ and $\frac{1}{1}$. In this way, with w on one or the other of the standard cell contacts, we may by proper setting of Q, M and S, and adjustment of the regulators R_s and R_Q get the E. M. F. between A and B accurately 1.5 volts; we may, also, compare the two cells with one another, and thus detect any possible variations in either, as the probability that both would change alike, in the event of any change taking place, is extremely small. By now setting w on R, any unknown E. M. F. joined to F and G and less than 1.5 volts immediately becomes measurable. Should the E. M. F. be greater than 1.5 volts and less than 15 volts, w is set on $R \times 10$ instead of on R; greater than 15 and less than 150 volts on $R \times 100$; greater than 150 and less than 1,500 volts on $R \times 1,000$. When measuring, current leads are brought to F and G from the shunt terminals and the E. M. F. measured like any other unknown E. M. F. In order to avoid the risk of accidentally getting too large a current through either of the standard cells, a high resistance, $H R$, of about 10,000 ohms is permanently placed in the galvanometer circuit. A shunt is also placed around the galvanometer which may be thrown in or not, as desired, by means of the little switch placed for the purpose.

Some of the details of construction employed in this instrument are, it is believed, sufficiently interesting to be worthy of description. Fig. 7 shows a novel way of economizing space and material in the construction of the coils and contact points suggested by Mr. H. L. Sayen. The contacts instead of being brass rod or portions of rod, as usual, are tubes having a metal end. Into these tubes the coil, wound on a slim spool as usual is slipped, one end of the wire being soldered to the open end of the tube. Holes just large enough to receive these tubes are then drilled into the rubber top of the instrument and the tubes slipped up from below with closed ends uppermost until stopped by a flange which has previously been soldered around the tube at about $\frac{3}{4}$ inch

1. "A One-Volt Standard Cell," by Henry S. Carhart. *Am. Jour. of Science*, vol. xlv., July, 1893.

from its end. A rubber plate, *P*, about $\frac{1}{8}$ inch thick and also drilled through with holes corresponding to the tubes, is slipped over them from below, and screwed fast to the under portion of the top plate. All the tubes are thus firmly clamped in place by means of their flanges. The other ends of each coil are then soldered to the next tube, etc.

Fig. 8 shows the construction of the resistance exchanging arrangement, *Q*. There are two concentric circles of segments as pictured, these segments being provided with spring pieces. The coils are joined between diagonal segments. Pivoted at their center is a switch formed of a circular plate of hard rubber, carrying at its periphery a number of angled brass wedges or knives

FIG. 6.

corresponding to the segments of the coils. Instead of *one* of these wedges is a *pair* of contact pieces corresponding to *a* and *b*, of Fig. 6, and joined to the rest of the circuit as shown in that figure; each piece of this pair makes contact with but *one* segment. It is obvious, therefore, that as the switch rotates, the series is always broken between *a* and *b*, while the continuity of all the rest of the series is maintained by the wedges which pass between the segments and keep them metallically joined.

In order to get at the standard cells in case either or both of them should show any signs of giving out, all that is necessary is to remove the four screws in the raised block seen in the upper left-hand corner of Fig. 5. This will expose the binding posts to which the cell terminals are joined, the cells themselves being

contained in two brass tubes passing down through the top. The binding screws are loosened and the cell or cells drawn out, when they can be shipped back to the maker for exchange.

FIG. 7.

FIG. 9.

This form of potentiometer is practically direct reading, the required values of E. M. F., being numerically set down upon the face of the instrument when balance is attained. The manner in which this is effected is very readily seen from inspection of Fig. 9, which shows a composite view of one of the switch devices *m* or *s*. Fixed to the switch handle so as to rotate with it and above the contact and contactor itself is a disk, *A* of Fig. 7, of hard rubber; this has engraved upon its upper surface a series of numbers cor-

FIG. 8.

responding to the coils of the series, and differing in value by an amount equal to the value of the resistance of each coil in terms of the whole resistance between *A* and *B*. Thus the disk of *Q*

having fourteen resistances, each $\frac{1}{14}$ of the whole resistance, is engraved with the series of numbers 0.100, 0.200, 0.300, etc., up through 1.400.; *s*, on the other hand, is engraved 0.001, 0.002, 0.003, etc., through 0.009.; *m* in the same way has its disk, which is engraved 0.010, 0.020, 0.030, etc. In the instrument these three switch devices are grouped together as shown in the general view and in plan in Fig. 10. A raised metal box, in shape something like a three-leaf clover, covers their operative portions. In each box there is cut a rectangular hole just large enough to expose a single one of the numbers engraved upon the rubber disk below. These numbers are so placed upon the disk that the one visible, indicates the number of parts of the whole resistance, which by virtue of the position of *its* switch are placed between the points of the derived circuit. The sum of the three numbers displayed is, therefore, the total number of parts of the whole placed between the derived circuit terminals by virtue of the position of *all* the switches, the number of tenths being taken from one, of hundredths from another, and of thousandths from the third.

In practice the operation of the instrument is exceedingly convenient and speedy. It is first turned to $\frac{S. C.}{1}$ and *q*, *m* and *s* turned until they read 1.000, since the Carhart one-volt cell gives exactly one volt E. M. F. The galvanometer switch being turned to "Galv. Shunted," *k* and *k'* should be depressed for an instant. (In the instrument a *single* ivory button projecting up through the top operates a double contact below). If the index swings to "R High" the two regulators, *R_s* and *R_q*, should be turned "Up," as shown by the arrow engraved upon them; if to "R Low," then the regulators should go down. The key being thus alternately depressed and the regulators altered, when balance is finally approached the shunt may be removed from the galvanometer by throwing the switch to "Galv. Direct," which will make the adjustment more sensitive, and the process continued until balance is perfectly attained. This having been done, we know that the points *A* and *B* differ in E. M. F. by exactly 1.5 volts. To assure ourselves of this we may turn *w* to $\frac{S. C.}{2}$ and again depress the key; this should also give a balance. To measure, now, any unknown E. M. F., it is joined to the terminals *F* and *G*; the switch *w* should be turned to *R*, *R* $\times$ 10, *R* $\times$ 100 or *R* $\times$ 1,000, according

as we believe the E. M. F. to be between 0—1.5, 1.5—15, 15—150, or 150—1,500 volts. If we have no idea what the E. M. F. is, as is very rarely the case, then we may try the points successively. Shunt the galvanometer and depress the key; if needle swings to "R High" turn Q, M and S "Down," as shown by the engraved arrow until the needle swings to "R Low." If the needle cannot be reversed with W on this point, try the next one, and so on until finally, if the E. M. F. does not exceed 1,500 volts, reversal can be accomplished; then remove the shunt from the galvanometer and balance as accurately as possible. This done, the reading of the

FIG. 10.

dials, R, multiplied by 1, 10, 100 or 1,000, according to which of the points W is on will be the desired E. M. F. If current is being measured, proceed in the same way, only multiplying the E. M. F. thus obtained by the resistance of the shunt in order to get the current itself. The accuracy of the work may be checked at any time by throwing W back on one of the standard cells, and Q, M and S back to 1.000; perfect balance will usually persist, provided the main battery, B_a, has any charge worth speaking of.

In order to guard against any possible change in the E. M. F. between A and B, during a series of measurements, due to change

in the battery, B_a , the latter should be of good size, say with a discharge rate of four or five amperes at any rate. The resistance between A and B is 120 ohms, being always constant; this means a current of about $\frac{1.3}{1000}$ amperes through A B, *while the key is closed*; as the key is only closed for an instant at a time, this drain cannot affect even to the most infinitesimal extent the E. M. F. between A and B.

It may seem as if the large number of rubbing contacts necessitated by this device, 28 in all, was a feature liable to introduce considerable error into the result. This is, however, not the case, for, assuming the largest possible variation in each contact resistance to be 0.001 ohms, (the writer has never found it larger than this in switches of ordinarily decent mechanical construction) we have, as the maximum total variation in Q , 0.028 ohms. The total resistance of A B being 120 ohms, this is seen to be less than 4 parts in 12,000 or but a little over 0.02 per cent.

In connection with this, it is interesting to note that in adjusting the resistances of the coils Q , M , and S ; the maximum allowable error of adjustment is a constant percentage of the *total* resistance A B, rather than of the individual coils. Hence if the 8 ohm coils of Q are adjusted to $\frac{1}{25}$ per cent., comparatively easy for coils of so high value, the 0.8 ohm coils of M need only be adjusted to $\frac{1.0}{25} = \frac{4}{100}$ per cent. and the 0.08 ohm coils of S to 4 per cent. to secure the same accuracy as regards the total of A B, *i.e.*, as regards *result*. The low resistances, therefore, are no more difficult of adjustment than those of the highest value, if indeed they are not easier, so that the resistances as a whole are easily brought within the required limit of not over $\frac{1}{25}$ per cent. error in result.

The value of this instrument as a convenient and quick way of obtaining absolutely reliable determinations of current and E. M. F. is, we believe, very great. There are scores of engineers, laboratories and stations who constantly find it necessary to secure a standardization of their ammeters or voltmeters. To make a voltmeter determination takes a great deal of time, even if but one value is to be gotten, and an amount of skill and painstaking, not always immediately available. The absolutely steady current, suitable solution, chemical balance, etc., are also adjuncts not always at hand. To keep any form of standard instrument about for purposes of comparison is usually not feasible. If the instrument has springs, the springs may change. If permanent magnets they are almost bound to change. Other forms of apparatus more

free from variable elements, as *e. g.*, tangent galvanometers, are easily affected by strong fields and mechanical disturbances and require either to be always kept set up absolutely undisturbed, or else to have considerable time spent upon them each time before using, in order to adjust them into good condition. In the potentiometer there are practically no variable elements, at least within limits practically infinitesimal in practical measurements. Dependence is placed solely and entirely upon standard resistances and standard cells, both of which have been thoroughly investigated by many workers, and the variations of which are well understood. The apparatus is simple and compact, and its mode of use can be successfully learned by a schoolboy in a few moments.¹ Being a zero method it is absolutely unaffected by neighboring currents or magnetic fields and the galvanometer being a dead beat and jewel suspended D'Arsonval, may be used under the most severe conditions of mechanical shock and vibration. On board ship it is believed absolutely the *only* apparatus which could possibly be used.

1. The dimensions over all are 11 in. by 14 in. by 5 in. deep; weight less than 10 lbs.

DISCUSSION.

MR. R. O. HEINRICH :—Assuming that Mr. Willyoung's introductory remarks in regard to the unsatisfactory constancy of commercial voltmeters and ammeters be true, it should be borne in mind that in the best types of commercial measuring instruments this condition of affairs is not due so much to the principles and methods employed in the construction of such instruments, as to the very exacting conditions under which they are used. We may safely say that with proper care, instruments employing electromagnetic or permanent magnetic fields are at least as constant as standard cells, and in considering therefore the advisability of adopting one or the other method for the purpose of comparing and standardizing commercial instruments, convenience and simplicity become the most important factors. I think there is no question that a direct reading instrument is by far the most preferable, under "direct reading," being understood that the instrument gives direct indications which are read on a scale, without any further manipulation than connecting the instrument in circuit.

The potentiometer method in the hands of a skilled person is undoubtedly a very valuable one, being a zero method and entirely independent of surrounding magnetic fields. It is, however, not a direct reading method in the above sense of the word, and it becomes very tedious and even unreliable, if comparisons with fluctuating currents have to be made. This, I believe, is one very potent reason why all attempts of introducing the potentiometer method in the form of a commercial measuring instrument have lacked success.

The "dangerous elements of changes" attributed by Mr. Willyoung to all other methods, are in my opinion not at all obviated by the use of a standard cell, at least such cells as are now to be had in the open market.

Mr. Willyoung mentions in his paper that his apparatus is capable of being used for measurements of voltage from 0 up to 1,500 volts, and of currents from 0 up to any required upper limit with a *maximum error of not over one-tenth of one per cent.* Mr. Willyoung is to be highly congratulated if his statements are borne out by actual facts. I have found very great difficulty in obtaining an absolute accuracy of one-tenth of one per cent. working with the best appliances under the best conditions in a laboratory. But assuming that the general construction of the apparatus, the introduction of a complicity of sliding contacts for comparatively low resistances, the adjustment of such resistances and finally the sensibility of the galvanometer used in the apparatus will allow such remarkable accuracy after the instrument has left the factory, it remains to be proven whether the standard cell employed, and in general any standard cell can be relied upon to such a degree of accuracy for any reasonable length of time.

On the strength of information collected from various sources and on that of my own experience I am very loath to accept Mr. Willyoung's statement in the affirmative, at least not without a good deal of reserve.

Dr. Kahle, of the Imperial Physico-Technical Institute of Berlin, in a most exhaustive treatise on the Clark cell (*Zeitschrift für Instrumenten Kunde*, vol. xii, p. 117 and (vol. xiii, pp. 191 and 293) mentions (vol. xiii, p. 303) that six Clark cells, made according to the instructions of the Board of Trade, were sent to him from Cambridge, England. Of these six cells, two were spoiled in transit. The remaining four were tested at intervals for a period of nine months together with five cells made in Berlin according to the above mentioned instructions. The results of these tests are given in Table I. For the convenience of comparison I give the differences of these cells from the normal E. M. F. in percentages. Dr. Kahle gives the differences in hundred-thousandths of a volt.

TABLE I.

Date of Test.	Set up in England and sent to Berlin.				Set up in Berlin.				
	E_1 .	E_2 .	E_3 .	E_4 .	I.	II.	III.	IV.	V.
Sept. 14, 1892...	-0.035	-0.037	+0.007	-0.011	+0.016	+0.017	-0.036	-0.039	+0.010
" 15, " ..	-0.034	-0.020	+0.011	-0.009	+0.016	+0.015	-0.038	-0.041	+0.012
Oct. 31, " ..	-0.004	+0.013	+0.014	+0.010	+0.002	-0.009	-0.029	-0.004	-0.014
Nov. 1, " ..	-0.004	+0.017	No test.	+0.010	+0.002	-0.009	-0.029	-0.004	-0.016
" 10, " ..	-0.178	0.000	"	-0.116	+0.004	-0.070	-0.091	-0.110	-0.103
" 12 " ..	-0.142	-0.098	"	-0.070	+0.008	-0.050	-0.050	-0.070	-0.067
April 19, 1893...	-0.184	-0.370	+0.004	-0.104	+0.000	-0.092	-0.020	-0.362	No test.
June 14, " ..	-0.131	-0.035	+0.005	-0.067	+0.002	-0.060	-0.022	-0.191	"
" 17, " ..	-0.252	-0.030	+0.007	-0.055	No test.	-0.064	-0.025	-0.167	"

It will be seen from this table that of the four English cells only one, and of the five cells prepared in Berlin only three would answer Mr. Willyoung's requirements.

Dr. Kahle ascribes the desultory and sometimes very considerable variations to the general construction of these cells, since the variations were shown when the cells had never been disturbed and had been kept at almost constant temperature during the entire period of the test.

In the same article he says:

"The E. M. F. of the Feussner cell (a Clark cell of somewhat large dimensions with mercurous sulphate and mercury electrode retained in a porous cup) and especially of the English cells, even at constant temperature, depends entirely upon the conditions of temperature to which the cell was exposed during the previous day. This uncertainty of E. M. F. surpasses in the Feussner cell 0.001 volt (0.07 per cent.) and may amount to 0.003 volts (0.21 per cent.) to 0.005 volts (0.35 per cent.) in

"the English cells. * * * * On account of the large and "indefinite changes with change of temperature, of the E. M. F. "of the Clark cells, it has been tried to replace it with others "which are claimed to behave more favorably in this respect. "Prof. Carhart has reduced the temperature coefficient of the "Clark cell by using a zinc sulphate solution which is concentrated at 0°C. The advantage gained by this is, however, annulled by the disadvantage that such cells according to the "experience collected here, cannot be reproduced with such "exactness as the cells with zinc sulphate crystals in excess. It "is very difficult to make a solution which is saturated at exactly "0°C. If it is saturated for a temperature deviating only a few "tenths of a degree from zero, a deviation of the E. M. F. "amounting to several ten thousandths of a volt from the normal "will be the consequence."

However this may be for the reproduction of these cells by any person skilled in the arts, my experience has been that Professor Carhart knows how to reproduce them with admirable agreement. Their portability seems also to be very satisfactory.

Of the 19 Carhart cells which have passed under my observation I have a definite knowledge of the condition when received, of only eight. Seven of these showed a very good agreement amongst themselves in a test made about two weeks after they were received. Cell 332 was tested two days after receipt, and showed an E. M. F. 0.075 per cent. above the normal of 1.440 volts. Tested two months later its E. M. F. had dropped 0.117 per cent. below its original value.

In point of constancy the results have been less satisfactory, the changes being most likely due to leakage.

It is quite evident that in Professor Carhart's modified Clark cell, the slightest leakage must be detrimental since this would at once alter the concentration of the zinc sulphate solution. Although there seems to be a marked improvement in the cells received lately from Professor Carhart, it will be seen from Table III. that in five of the ten cells a continual dropping of

TABLE II.

Carhart-Clark.	1 Set up.	2 Received. *	3 Test, August, 1893. Compared with No. 284.	4 Difference in per cent. 284 Standard.	5 Difference in per cent. 210 Standard.
No. 202.....	Sept. 25, 1891	Feb. 10, 1892	0.9976	— 0.24	— 0.09
" 203.....	" 26, "	" " "	0.9981	— 0.19	— 0.04
" 204.....	" " "	" " "	0.9983	— 0.17	— 0.02
" 205.....	" " "	" " "	0.9979	— 0.21	— 0.06
" 207.....	" " "	" " "	0.9986	— 0.14	+ 0.01
" 209.....	" " "	" " "	0.9987	— 0.13	+ 0.02
" 210.....	" " "	" " "	0.9985	— 0.15	0.000
" 275.....	Nov. 19, 1892	August, 1893	0.9998	— 0.02	
" 284.....	" 24, "	" " "	1.0000		

TABLE III.

Date of Test.	311	312	313	314	315	316	317	275	284	332	Temp. at test.	Average of Cells 311 to 317.	Average E.M.F.
Nov. 7, 1893	1.0000	1.0001	1.0001	1.0001	1.0002	1.0000	1.0001	No test	No test	No test	14.9	1.00006*	
Dec. 7, "	"	1.0000	0.9999	0.9998	0.9997	0.9997	0.9998	0.9992	0.9997	"	18.75	0.99999	1.4402 I.V.
Dec. 14, "	"	1.0000	1.0000	0.9999	0.9997	0.9997	0.9997	0.9993	0.9997	"	19.00	0.99999	1.4402
Dec. 18, "	"	1.0000	0.9999	0.9999	0.9996	0.9996	0.9999	0.9992	0.9996	"	18.80	0.99989	1.4402
Dec. 20, "	"	1.0000	0.9999	0.9999	0.9996	0.9996	0.9998	0.9992	0.9997	"	19.60	0.99988	1.4402
Jan. 16, 1894	"	0.9999	0.9999	0.9999	0.9996	0.9996	0.9999	No test	No test	"	20.50	0.99987	1.4401
Jan. 24, "	"	1.0000	0.9999	0.9999	0.9994	0.9993	0.9997	"	"	"	19.80	0.99982	1.4401—
Mar. 21, "	"	1.0000	0.9999	0.9999	0.9994	0.9990	0.9997	"	"	1.0005	18.30	0.99979	1.4400
May 7, "	"	0.9999	0.9999	0.9999	0.9993	0.9987	0.9998	"	"	1.0005	19.85	0.99975	1.4400—
May 9, "	"	1.0000	0.9999	0.9999	0.9993	0.9987	0.9998	"	"	1.0005	19.60	0.99976	1.4400
May 25, "	"	1.0000	0.9999	0.9999	0.9992	0.9986	0.9997	0.99919	0.99953	0.99933	19.51	0.999736	1.4439+
May 10, "	"	0.9997	0.9998	0.9998	0.9992	0.9986	0.9997	No test	0.99953	0.99933	19.85	0.999741	1.4439+
June 5, "	"	0.99995	0.99999	0.99990	0.99927	0.99857	0.99972	0.99918	0.99951	0.99933	20.40	0.999740	1.4439+

The comparisons were made taking 311 as standard. The E. M. F. of 311 was determined by five silver voltmeter tests and gave an average of 1.44031 inter. volts. Prof. Carhart's figures for the same cell 1.4402, satisfactory proof that this cell remained very constant. The figures in the last column show that the average E. M. F. of the cells 311 to 317 differs not more than 0.014 per cent. from the normal 1.4402 intern. volts whilst cells 315 and 316 have reached very nearly the $\frac{1}{10}$ per cent. limit. Another proof that a large number of cells should be used to obtain accordant results. It will be interesting to investigate further how the cells showing tendency to change will behave during the hot summer weather, since this seems to me to be critical to the seals of most cells.

*The first horizontal line is Prof. Carhart's figures.

the E. M. F. has taken place. These cells were kept continually in an oil bath, covered completely by oil, and were subjected to only very small variations of temperature. Cells 275 and 284 had been kept in open air in the laboratory from August '93 to November '93. Cells 147, 150, 202 to 210 were also kept in open air in the laboratory and had to undergo changes of temperature during the year between 15° and 30° centigrade; the same would be the case for cells used in an apparatus as proposed by Mr. Willyoung.

Remarks to Table II.—Cells 202 to 275 were compared with 284 as standard. Assuming that at that time 284 was very nearly correct, since it was just received, and still shows in Table IV a fair agreement with the normal E. M. F., the figures in column 4 would give the percentage difference from the normal E. M. F. Cells 202 to 210 were returned on account of these changes, therefore no further test could be made. The figures in column 5 are rather interesting, as they show that a number of cells of

TABLE IV.

Carhart-Clark.	Set up.	Received.	Test, May 25, 1894. E. M. F. at 15° C.	Correct Value at 15° C.	Difference in per cent.
Cell No.					
147	Mar. 22, 1890	1891	1.430	1.441	— 0.75
150	" 29, "	" "	1.431	1.441	— 0.69
275	Nov. 19, 1892	August, 1893	1.438	1.440	— 0.14
284	" 24, "	" "	1.439	1.440	— 0.08
311	" 7, 1893	November, 1893	1.4404	1.4402	+ 0.014
312	" " "	" "	1.4404	1.4403	+ 0.007
313	" " "	" "	1.4402	1.4403	— 0.007
314	" " "	" "	1.4402	1.4403	— 0.007
315	" " "	" "	1.4390	1.4404	— 0.10
316	" " "	" "	1.4384	1.4401	— 0.12
317	" " "	" "	1.4400	1.4403	— 0.02
322	Dec. 15, 1894	March, 1894	1.439	1.440	— 0.08

TABLE V.

Clark Cells.	Set up.	Received.	Test, May 25, 1894, at 15° C.	Correct E. M. F. 15° C.	Difference in per cent.	Remarks.
Wirt-Clark, 252 A..	?	April, '91.	1.422	1.434	— 0.85	Signs of leakage.
" 252 B..	?	" "	1.415	"	— 1.35	" "
" 265 A..	?	" "	1.371	"	— 4.4	Signs of leakage.
" 265 B..	?	" "	1.390	"	— 3.6	" "
Weston-Clark, 1....	May, 1891	Prepared in Weston Laboratory.	0.986	"	— 24.2	Apparently in good condition.
" 2....	" "		1.432	"	— 0.14	Glass cracked in seal- ing, leaked.
" 3....	" "		1.433	"	— 0.07	Apparently in good condition.
" 4....	" "		1.432	"	— 0.14	" "
" 5....	" "		1.430	"	— 0.28	" "
" 6....	" "		1.432	"	— 0.14	" "
" 7....	" "		1.381	"	— 3.7	Cracked in sealing, leaked.
Feussner-Clark, 457	Begin. '93	July, 1893	1.371	"	— 4.4	Leakage, spoiled in transit.

the same batch may compare very well and still differ considerably from the normal E. M. F. *A very good proof against the assumption that two standard cells, kept under the same conditions, are correct if they agree with each other.*

Cells 147 and 150 (Table IV.) are now almost dried up, the seal being completely covered by effloresced zinc sulphate; they had shown signs of leakage already in the early part of 1892. Cells 202 to 210 showed whitish spots between the seals and the glass. A yellowish white coat on the seal was explained by Prof. Carhart, as silicate of sodium acted upon by the air.

Table V gives the results of tests of Clark cells of various origin. With very few exceptions the cells have changed considerably more than one-tenth of one per cent.

The Wirt-Clark cells were contained in two Wirt voltmeters, *i. e.*, direct reading potentiometers. Instrument 265 when received gave the following results on April 14th, 1891:

Standard 100 volts.....	100.2	265 A.	+0.2	per cent.
	100.35	265 B.	+0.35	"
10 volts.....	10.35	265 A.	+3.5	"
	10.70	265 B.	+7.0	"

On May 25th, 1894:

Standard 100 volts.....	77.0	265 A.	—23.0	per cent.
	79.0	265 B.	—21.0	"
10 volts	9.73	265 A.	— 2.7	"
	9.53	265 B.	— 4.7	"

In Table V the cells are shown to differ from the normal — 4.5 and — 3.6 per cent. at May 25th. It is evident that the sliding contacts and changes in the resistances have in the course of time introduced a much larger error than the cells. The instruments were not used, but had been standing in the laboratory for three years.

Weston-Clark cell 1 is a remarkable case; in-so-far as no sign of leakage could be detected, and that the cell was apparently in faultless condition. There is then a record of 31 standard cells, of which 21 have given out at this date. It would be difficult to say what the useful life of these cells has been, since no record was kept at sufficiently close intervals.

My experience with the Calomel cell has been too limited to allow of forming a definite opinion. With two Calomel cells the following results were obtained by silver voltmeter determination.

Cell 303.	April 3d.....	1.00001	intern. volts at 20° C.
	April 6th.....	1.00009	" " "
	April 16th.....	1.00002	" " "
	May 10th.....	1.00010	" " "

One test made May 8th gave the E. M. F. of the same cell as 0.99922 intern. volts at 20° C. Previous to this test the cell was used very continually during one hour, a grounded circuit

giving trouble in adjusting. Although the circuit contained resistances, considerably more than 100,000 ohms in series with the cell, it is thought that the continual use caused the drop in E. M. F., the more so as a comparison with Carhart-Clark cell 311, made shortly after the experiment, indicated also a lower E. M. F. than usual. A silver voltameter test made two days later gave a result agreeing well with previous determinations.

These determinations would make the E. M. F. of this particular cell 0.99961 intern. volts at 15° C.

Carhart Calomel cell 5 loaned through Professor Carhart's courtesy for comparison with cell 303 showed by comparison 1.00018 intern. volts at 15°C, a difference of 0.06 per cent. between the two cells. These two cells seem to have stood transportation well and make a very satisfactory showing. How they will behave under more exacting conditions with an occasional abuse is a question yet to be determined.

It is evident, however, that the standard cell which Mr. Willyoung proposes to use, has to be a very much superior article to anything which we now have, in order to fulfil the requirements of remaining for a reasonable time within an accuracy of one-tenth of one per cent. Moreover, allowing for occasional abuse of the apparatus and taking it into consideration that a multiplicity of sliding contacts is used in connection with comparatively low resistances, I should consider an accuracy of 0.2 per cent. quite remarkable.

On the other hand I know from experience and from carefully kept records extending over five years, that there is no difficulty whatever in maintaining an accuracy of 0.2 per cent. with direct reading instruments as defined previously, and employing electromagnetic or permanent magnetic fields, and affording the same flexibility in range as the potentiometer described.

The use of the potentiometer method for commercial measuring instruments dates back quite a few years. The Wirt and Howell voltmeters were constructed on this principle. Dr. Feussner describes a potentiometer in 1890 in *Zeitschrift für Instrumenten Kunde* and points out, how the instrument may be made direct reading in substantially the same way as Mr. Willyoung describes. Mr. Crompton's potentiometer is referred to in Mr. Willyoung's paper. It is rather significant that, in spite of these various attempts, the actual use of such instruments is very limited indeed.

For the commercial calibration of a large number of instruments the method is altogether too slow. For occasional comparisons of instruments in daily use a direct reading instrument of known standard qualities seems preferable, the accuracy attainable with such instruments being amply sufficient for all practical purposes.

For laboratory use, where time is usually a minor consideration, the potentiometer would be commendable; but when it

comes to accuracies as high as one-tenth of one per cent., I should always take the silver voltameter and a standard resistance as a last resort for a check on the standard cell.

FIG. 1.—Rheostat for Rayleigh's Compensation Method.

In regard to one detail of construction I would say that one idea used also by Mr. Willyoung occurred to me some time ago. Mr. Weston designed a potentiometer which was to shorten the tedious adjustment of resistances in Lord Rayleigh's method. Fig. 1 shows its general arrangement. A resistance of 10,000

FIG. 2.

ohms is kept in circuit continuously with an auxiliary battery. It will easily be seen from the diagram that by moving the cranks of any of the four dials, resistance cut in on the circuit

containing the standard cell *c* (on the *a* side) is cut out on the opposite side (*b* side). This potentiometer necessitates, however, the adjustment and use of 80 resistance coils. In the modification shown in Fig. 2, the number of resistance coils is reduced to 40 although the same number of steps from one to 10,000 is obtained. The identity with Mr. Willyoung's idea will be found in the arrangement of dials *c* and *d*. These two dials are identical in their arrangement, taking dial *c* for a description; the two halves *a* and *b* of the crank carrying the sliding contacts serve to make a short-circuit between the segments of *E*, *F* and *G*, *H*. The upper part of these two dials forms always up to the position of the crank, counting from left to

FIG. 3.

right, a part of the circuit containing the standard cell, whilst the lower part is up to the position of the crank in series with the auxiliary battery. Fig. 3 will show this more clearly.

$a + b + c + d$ is then the resistance of the circuit containing the standard cell, whilst the total resistance is always kept constant at 10,000 ohms.

Such an arrangement may of course be made direct reading in the sense taken by Mr. Willyoung, by proper adjustment of the current through the total resistance of 10,000 ohms; it has the advantage of very much higher resistances which I believe essential for accuracy whenever sliding contacts are used.

In summing up my remarks I would say that I do not wish to appear opposed to the use of standard cells, or to that of the

potentiometer method. I consider both in the hands of an experienced and careful man extremely valuable and useful. I do not believe, however, that the use of the potentiometer method avoids "dangerous elements of change" any more than any other instruments of standard qualities.

I should consider it an injustice to the user of an apparatus to make him believe that he can measure to a certain percentage of accuracy, when the chances are so very great that he does nothing of the kind.

I am not a believer in "universal portable instruments," with which anything and everything can be done; usually they are crowded into much too small space.

My doubts about sliding contacts in connection with low resistances have been expressed before.

From a superficial inspection of Mr. Willyoung's apparatus I should expect difficulty and trouble in regard to proper insulation, especially if higher voltages are to be measured. If the galvanometer used is of the same sensibility as the one contained in Queen and Company's portable testing sets, I should consider its sensibility insufficient for the attainment of an accuracy of one-tenth of one per cent., as claimed.